LUMPED PARAMETER MODELING FOR MIXING AND STRATIFICATION IN A BWR MARK I PRESSURE SUPPRESSION POOL

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ABSTRACT

As a part of the GOTHIC[1] Fukushima Technical Evaluation project [1, 2 and 3], GOTHIC [4] has been benchmarked against test data for pool stratification [1, 5]. These tests confirmed GOTHIC's ability to simulate pool mixing and stratification under a variety of anticipated suppression pool operating conditions. The multidimensional modeling requires long simulation times for events that may occur over a period of hours or days. For these scenarios a lumped model of the pressure suppression chamber is desirable to maintain reasonable simulation times. However, a lumped model for the pool is not able to predict the effects of pool stratification that can influence the overall containment response. The main objective of this work is on the development of a correlation that can be used to estimate pool mixing and stratification effects in a lumped modelling approach. A simplified lumped GOTHIC model that includes a two zone model for the suppression pool with controlled circulation between the upper and lower zones was constructed. A pump and associated flow connections are included to provide mixing between the upper and lower pool volumes. Using numerically generated data from a multidimensional GOTHIC model for the suppression pool, a correlation was developed for the mixing rate between the upper and lower pool volumes in a two-zone, lumped model. The mixing rate depends on the pool subcooling, the steam injection rate and the injection depth.

KEYWORDS

GOTHIC, BWR, Suppression Pool, Mixing, Stratification

1. INTRODUCTION

In Boiling Water Reactor (BWR) containment design, the suppression pool plays an important role as a heat sink to cool and condense steam released from the reactor pressure vessel and/or main steam line during Loss of Coolant Accident (LOCA) or opening of safety relief valves. At lower steam flow rate conditions, there is a risk of thermal stratification above the discharge pipe exit. The unmixed thermal layers inside the suppression pool can keep the pool surface at higher temperature which reduces its pressure suppression capacity [5].

Hua Li and his research group from Royal Institute of Technology (KTH, Sweden) performed an extensive computational study on condensation, stratification and mixing phenomena in a pool of water [6,7 and 8]. Two and three dimensional GOTHIC models were generated and verification and validation studies were performed using POOLEX experiment results. Artificial oscillations and numerical diffusion were reported when direct steam injection and condensation was modeled using GOTHIC [4]. Li et al. proposed alternative methods to simulate the effect of steam injection referred to as Effective Heat Source (EHS) and Effective Momentum Source (EMS) that account for the total heat release pool and the buoyancy force due to the steam bubbles without relying on the condensation and bubble modeling features in GOTHIC. Results were in good agreement with the experimental data. However, both alternative models were generated within the framework of the experimental measurements and may not be generally applicable [5].

[1] GOTHIC incorporates technology developed for the electric power industry under the sponsorship of EPRI.

To support the application of GOTHIC to the suppression pool performance with stratification, validation studies were conducted using data from a test at the Browns Ferry Nuclear Plant (BFN) [1] described here, and other tests for pool performance with steam injection [5] including one test from the POOLEX series.

The objective of this work was the development of a correlation that can be used to estimate pool stratification in a lumped modelling approach. With the ability to predict stratification established, a 3-dimensional GOTHIC was used to simulate a variety of conditions for steam injection into a Mark I suppression pool. The suppression chamber model was based on the BFN Unit 2 geometric parameters [1]. A simplified lumped GOTHIC model was constructed using the same geometric parameters. The lumped model includes a two zone model for the suppression pool. The steam is injected into the upper volume. A pump and associated flow connections are included to provide some mixing between the upper and lower pool volumes. Using the numerically generated data set from the 3-D model, a correlation was developed for the mixing rate (pump flow rate) between the two pool volumes in the lumped model.

2. BROWNS FERRY NUCLEAR PLANT (BFN) UNIT 2 TEST BENCHMARK STUDY

Potential suppression pool stratification under long term steam release from the Reactor Core Isolation Cooling (RCIC) exhaust at the Browns Ferry Nuclear Unit 2 was investigated in support of the Fukushima Daiichi Technical Evaluation Project [1]. The RCIC system of BFN Unit 2 reactor was in test mode for pressure control from 16:05 on 6/28/1991 until 03:13 on 6/29/1991 (40,080 seconds). The outboard Main Steam Isolation Valves (MSIVs) were closed and the Reactor Pressure Vessel (RPV) pressure was about 5,840 kPa (850 psia). Procedures require that the drywell pressure be maintained below 111.7 kPa (16.2 psia) and the pressure difference between drywell and suppression chamber is between 7.9 and 9 kPa. During the test, neither the pool temperature indicator nor the gas space temperature monitor showed much of an increase in temperature. However, when the 2A Residual Heat Removal (RHR) pump was started, the Suppression Pool (SP) temperature indicator rose rapidly from 30.6 C to 48.9 C (87 to 120 F). When the Suppression Chamber (SC) air temperature recorder was tapped, the indicated temperature jumped from 34.5 to 65.6 C (94 to 150 F) [1]. The pool temperature response indicated that there may have been substantial pool stratification during the test.

For RCIC in test mode with RPV at high pressure and SP at low pressure, the RCIC steam flow was discharged into the SP at 3.08 kg/s (6.8 lbm/s). The free volume of the drywell (DW) and vent system is 4,847 m^3 (171,000 ft^3) and the total volume of the wetwell (WW) is 7,209 m^3 (254,000 ft^3) [1].

The pool temperature instruments are located near the bottom of the SP (2.03 m (6.66 ft) above the torus bottom). The lower end of the RCIC exhaust sparger is at 1.84 m (6.0 ft) above the pool bottom. Normal SP level is 4.51 to 4.59 m (14.8 to 15.1 ft) above the torus bottom [1]. The total vertical RCIC pipe length is 3.2 m (10.5 ft). The sparger section of the exhaust pipe has 1440 uniformly spaced 12.7 mm holes (0.5 in) (40 rows, 24 holes per row) [1].

The containment model was designed to address the stratification inside the suppression pool during the steam release through RCIC sparger. The GOTHIC model nodalization and meshing profiles are given in Figure 1 (a) and (b), respectively. The nominal grid spacing in the pool is 0.2 m (0.65 ft) in the vertical direction, 5.2 m (17 ft) circumferentially and 1.89 m (6.2 ft) across the torus minor diameter. The vertical grid spacing at the pool elevation is 0.4 m (1.3 ft) to capture steam/gas temperature right above the pool surface. The model considers only the constant steam injection through the RCIC sparger. The mixing induced by the RHR pump at the end of the test was not modeled because there was insufficient information for this phase of the test.

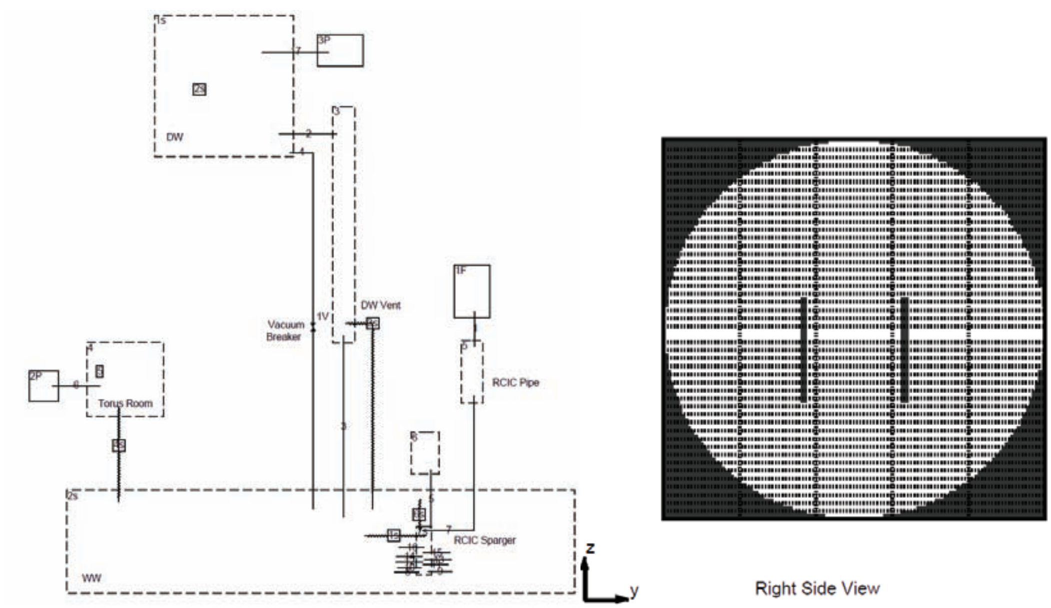
For 3D modeling, GOTHIC is restricted to rectangular coordinates. Curved geometries are modeled using blockages from which volume, area porosities and hydraulic lengths are obtained. To simplify the modeling and to allow finer grid resolution without excess computation time, the torus was treated as a cylinder and only 1/2 of the total suppression chamber was modeled, taking advantage of geometric symmetry. The symmetry plane cuts through the center of the RCIC sparger. The steam injection rate was scaled down accordingly. However, to help relate the modeling with the full plant parameters, all steam injection rates and other size dependent parameters given below are for the full 360° torus.

To approximate the pressure transient, the model includes one-half of the drywell and vent system. Flow Paths 2 and 3 connect the vent volume to the DW and WW, respectively. Flow Path 4 represents the vacuum breaker line between the WW gas space and the DW. Valve component 1V models the vacuum breakers.

As shown in Figure 1 (a), subdivided Volumes 1s and Volume 2s represent the 1D DW and 3D WW geometries. Lumped Volume 3 represents the DW Vent and Volume 4 represents the torus room. A conductor was added to allow heat transfer from the interior of the vent system (drywell vents, header and downcomers) to the WW gas space. Conductors were also added for heat transfer between the WW gas space and the torus room and between the torus room air and the torus room concrete walls.

Volume 5 represents the RCIC Pipe. Volume 6 represents a portion of the remaining RCIC exhaust line. This volume was included to represent some of the remaining RCIC system and to act as a surge volume that helps to limit high pressure oscillations due to collapsing steam bubbles in the exhaust line. Volume 5 represents the submerged RCIC Sparger. The RCIC exhaust sparger volume was subdivided in z-direction and its grid spacing was kept identical to the axial grid spacing of the suppression pool region in the WW Volume 2s. The sparger volume is connected to the pool with nine Flow Paths (FP) spanning the range of the sparger length. Each FP has an equivalent diameter and flow area based on given geometric parameters and total number of openings at each elevation [1].

The assumed initial conditions were 30 C and 101.3 kPa (86 F and 14.7 psia). Steam was injected from boundary condition 1F into the RCIC pipe at 3.08 kg/s (6.8 lbm/s). The steam enthalpy was estimated at 2,785 kJ/kg (1197 Btu/lbm) based on the measured RPV pressure 5,962kPa (865 psia) (saturation conditions assumed). The actual steam enthalpy at the RCIC exhaust would be a little lower. The steam flow rate remained constant throughout the transient. The simulation was run for 43,200 seconds (12 hours), slightly longer than the actual test. However GOTHIC results are compared at the exact test measurement time.



(a) (b)

Figure 1: GOTHIC BFN 3D Model Nodalization (a) and Suppression Pool Mesh (b)

The GOTHIC torus atmosphere and pool temperature predictions are compared with the plant measurements. As shown in Figure 2, the steam/air temperatures at the top of the torus and above the pool surface increased almost linearly throughout the transient. The temperature difference between the top of the torus and near the pool surface remains within a 0-2 C (1.1 F) range, which indicates the atmosphere above the SP was well mixed throughout the test. According to GOTHIC predictions, at t = 40,080 s the steam/air temperature near the pool surface reached 64.2 C (148 F) in good agreement with the BFN Unit 2 plant measurement of 65.6 C (150 F).

As shown in Figure 3, the GOTHIC suppression pool temperature predictions at different elevations demonstrate the thermal stratification in the pool. The injection depth depends on the submergence and the pressure drop across the sparger holes. Referring to Figure 4, GOTHIC calculated that all of the steam was released at elevations higher than 3.5 m (11.5 ft) above from the pool bottom. As a result, the water temperature above 3.5 m is well mixed and increases to 66 C (151 F) while the pool bottom temperature remained at its initial value of 30 C (86 F).

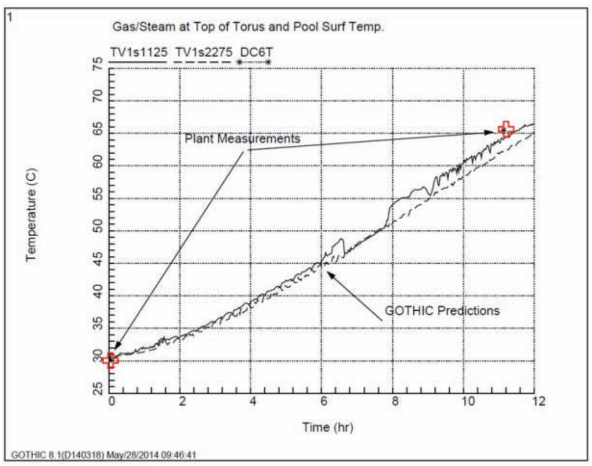


Figure 2: Pool Surface and Torus Temperature

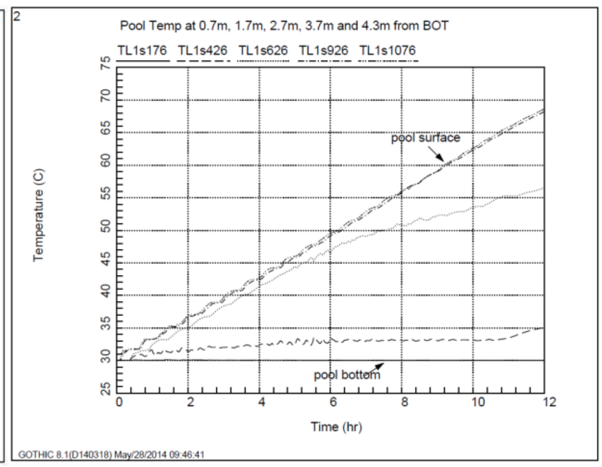


Figure 3: Suppression Pool Temperature

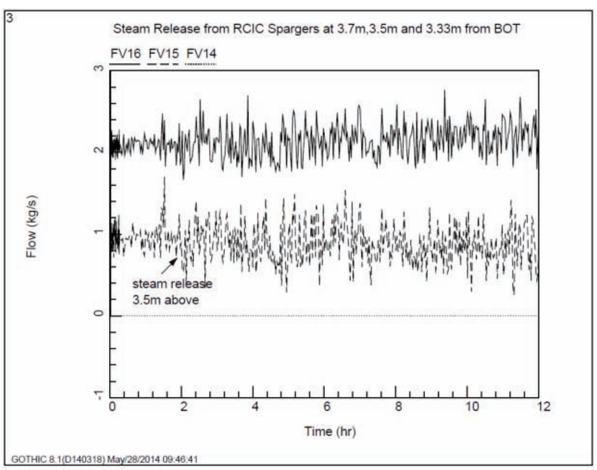


Figure 4: Steam Release from RCIC Sparger

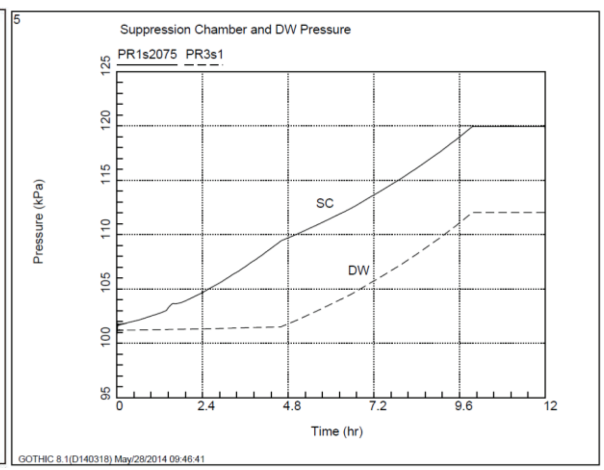


Figure 5: Torus and Drywell Pressure

The increase in pool surface temperature heats the torus steam/gas atmosphere and increases its pressure. As shown in Figure 5, the SC pressure linearly increased until it reached 120 kPa (17.4 psia). At this pressure the suppression system vacuum breakers open and flow into the DW causes the DW pressure to rise. The DW pressure increased linearly until it reached the test operation limit of 111.7 kPa (16.2 psia) and the DW vented to the atmosphere opened. During the RCIC testing, DW venting wasn't continuous as it is modeled in GOTHIC. Instead, venting was reported as on and off during the event due to operator action. In addition, earlier venting was stated during the RCIC testing than predicted by the GOTHIC model. It should be noted that the GOTHIC model was not intended to predict the drywell venting since there is limited information available about how the manual venting was performed.

3. GOTHIC POOL STRATIFICATION MODELLING IN A LUMPED VOLUME

The lumped model nodalization is shown in Figure 6. Volume 1, representing the suppression chamber, is subdivided into two levels. The upper level includes the SC gas space and the top 20% of the SP. The lower level models the remainder of the pool. In a 1D subdivided model, flow is allowed between the two volumes but the 1D nature of the noding does not allow for circulation between the upper and lower volumes. To account for possible convective mixing between the pool near surface and the rest of the pool, Flow Path 7 and associated pump component 1P are included in the model. The surface-to-pool mixing is controlled by the specified flow rate through the pump. Flow Paths 2 and 3 connect the vent volume to the drywell and wetwell, respectively. Flow Path 4 represents the vacuum breaker line between the wetwell gas space and the drywell. Valve component 1V models the vacuum breakers. Lumped Volume 2 represents the DW, Volume 3 represents the DW Vent and Volume 4 represents the torus room. Conductors were added for heat transfer between the wetwell gas space and the torus room and between the torus room air and the torus room concrete walls.

Volume 5 represents the submerged steam injection pipe. The pipe volume is connected to the pool with a single Flow Path 8. The assumed initial conditions were 30 C (86 F) and 101.3 kPa (1.47 psia). Steam was injected from boundary condition 1F into the steam injection pipe.

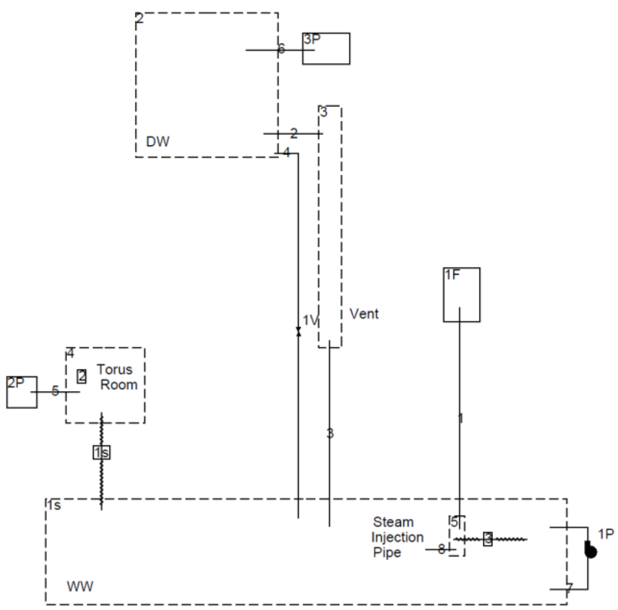


Figure 6: GOTHIC BFN Unit 2 Lumped Model Nodalization

During the steam injection into the pool, the steam condenses near the injection point and the hot water (along with some steam bubbles) rises to the surface. During the early phase of steam injection, hot water spreads across the pool surface and the surface can be significantly hotter than the bulk pool water. As the steam injection continues, the water above the source becomes fairly well mixed.

As seen in the GOTHIC simulation of the BFN Unit 2 RCIC benchmark test, steam was released only from the upper part of the sparger and heated up the pool above the source without significantly mixing the water below that level bottom (Figure 4). In order to capture this effect in a simplified lumped model, the steam flow is added to the near surface water in the upper subvolume. The surface-to-lower-pool mixing is controlled by a pump that circulates flow between the upper and lower volumes. The mixing rate correlation described in this section controls the pump flow rate. The mixing rate is assumed to be a function of following parameters:

1. The flow rate of the steam ($\dot{m}_s$)
2. The submergence ratio (injection depth divided by the total pool depth (d/d_t), see Figure 7)
3. The temperature difference between the condensed steam and the lower pool ($\Delta T = T_s - T_l$) , and the thermal expansion coefficient of the pool water (ε_t)

i.e.,
$$\dot{m}_p = f_1\left(d/d_t\right) f_2\left(\dot{m}_s\right) f_3\left(\Delta T, \varepsilon_t\right) \tag{1}$$

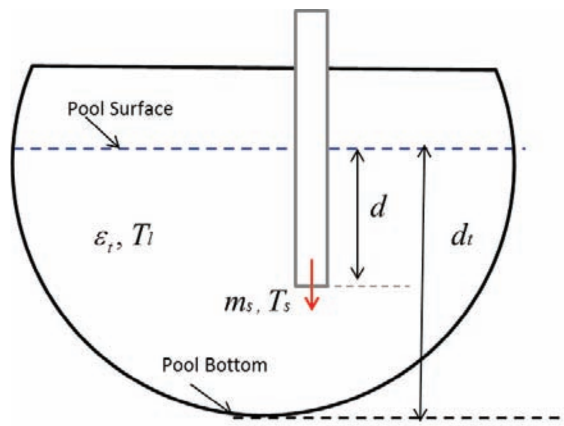


Figure 7: Suppression Pool Parameters

Based on the BFN Unit 2 geometric specifications and initial conditions [1], a series of sensitivity studies were conducted to investigate each individual parameter;

- Case Series I: The injection pipe submergence ratio (*d/dt*) was varied between 0.1 and 1 at constant steam injection flow rate.
- Case Series II: The steam flow rate ($\dot{m}_s$) was varied between 0.02 and 4 kg/s at a fixed steam injection location.
- Case Series III: Variations in pool temperature ΔT and its effect on the thermal expansion term ε_t were studied.

For all the case studies, 3D GOTHIC models were run to give transient predictions of the pool surface. Then, the 3D temperature predictions were used to drive the pump flow rate in the lumped model via a system of control. The control system automatically adjusts the pump flow rate so that the calculated lumped model pool surface temperatures agree with the 3D results. By doing so, the required pump flow rates are obtained for all lumped GOTHIC models.

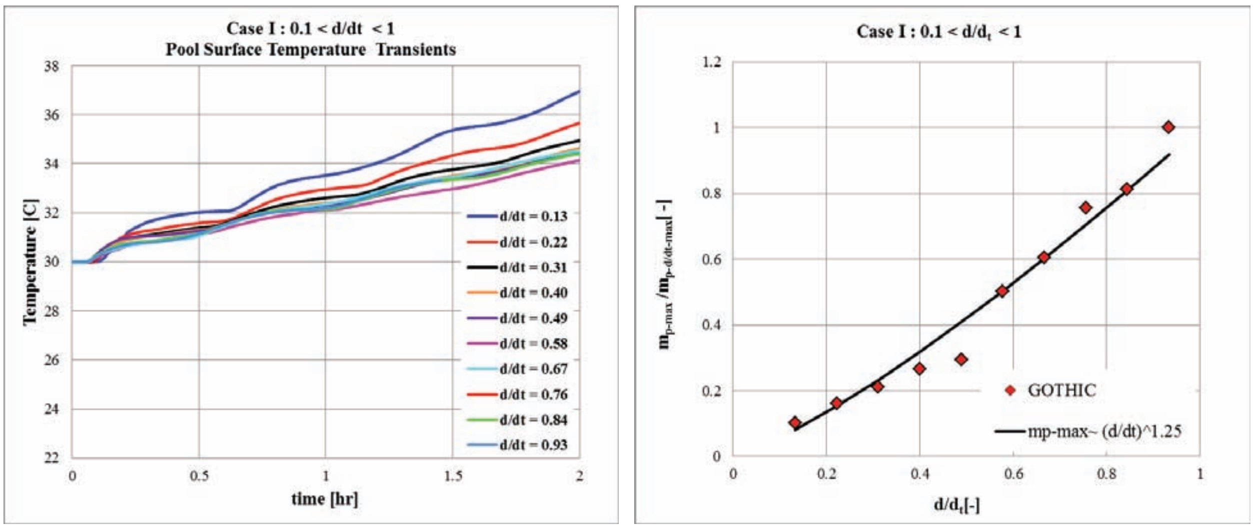
3.1 Case Series I: Steam Injection Location Case Study

In Case Series I, steam is injected at a fixed flow rate of 3.08 kg/s for 7,200 seconds (2 hours) from boundary condition 1F into the pool at nine different depths. As shown in Figure 8 (a), when the steam injection depth was increased, the pool surface temperature predicted by the GOTHIC 3D model decreased.

In the simplified GOTHIC model, the steam was injected into the upper level of the WW control volume which contains only the 20% of the total pool water. The surface-to-pool mixing was controlled by a specified flow from the lower level of the pool through the pump. As the steam injection depth was increased, higher pump flow was needed in the simplified GOTHIC models to maintain the pool surface temperature to match the GOTHIC 3D predictions. The maximum required pump flow rate for each case is presented in Figure 8 (b). The relation between the submergence ratio and the normalized maximum pump flow rate is approximated by,

$$\frac{\dot{m}_{p-\max}}{\dot{m}_{p-d/d_t\max}} = \left(d/d_t\right)^{1.25} \tag{2}$$

$\dot{m}_{p-d/d_t\max}$ is the maximum pump flow rate obtained when d/d_{tmax} = 0.93 (the maximum pool depth ratio).



(a) (b)

Figure 8: Series I - Surface Temperature Predictions (a) & Maximum Required Mixing Rate (b)

3.2 Case Series II: Steam Injection Rate Case Study

In Case Series II, the steam flow was varied between 0.02 and 4 kg/s and injected for 7,200 seconds (2 hours) at a fixed elevation, d/d_t = 0.47. (This is a typical injection depth for RCIC exhaust). It should be noted the steam injection duration (2 hours) in Case Series II is not long enough to investigate the pool thermal stratification especially when the injection rate is low. Longer transient cases (34 hours) are presented in Case Series III.

From Figure 9 (a), it can be seen that at lower injection rates ($\dot{m}_s \leq 0.2$ kg/s) there was only a moderate effect on the pool surface temperature whereas at higher steam injection ($\dot{m}_s > 0.2$ kg/s), the pool surface temperature increased more rapidly. Using the 3D GOTHIC surface temperature predictions as a target control for the controlled circulation flow, the required maximum pump flow ($\dot{m}_{p-\max}$) was obtained for each simplified GOTHIC model. Then, the $\dot{m}_{p-\max}$ predictions were divided by $\left(d/d_t\right)^{1.25}$ to exclude the steam release location effect. To scale the mixing rate to the pool volume, the steam injection rates ($\dot{m}_s$) were divided by the total pool water mass (m_{pool}). As shown in Figure 9 (b),

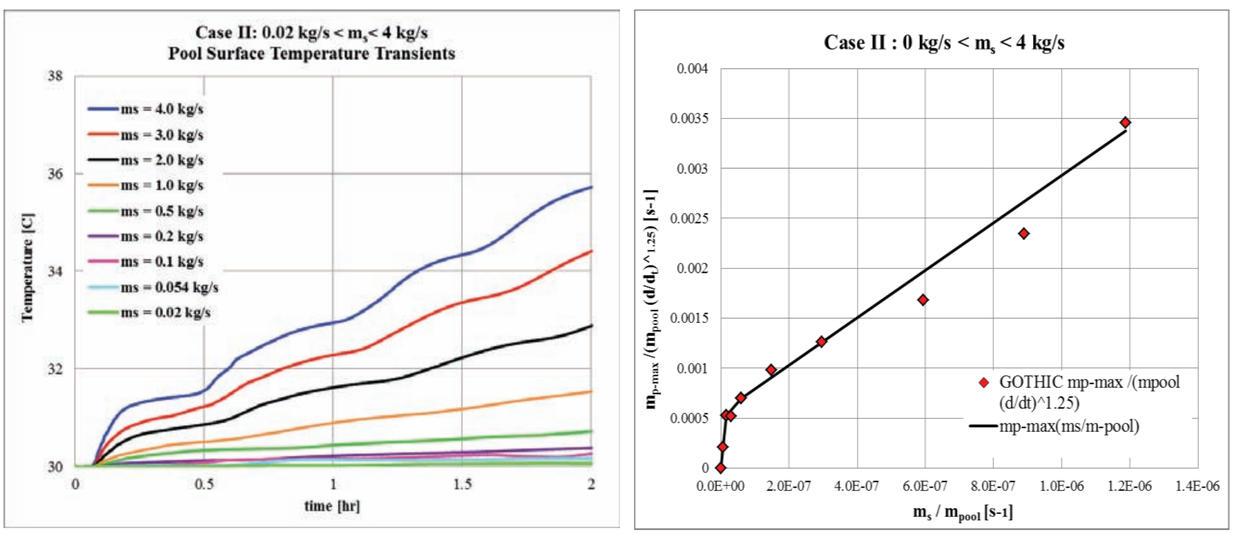
$\dot{m}_{p-\max} / \left(m_{pool} \left(d/d_t \right)^{1.25} \right)$ results are plotted against $\dot{m}_s / m_{pool}$ values. The relationship is defined by three linear correlations between $\dot{m}_{p-\max} / m_{pool}$ and $\dot{m}_s / m_{pool}$:

$$\frac{\dot{m}_{p-\max}}{m_{pool}} = 3.27 \times 10^4 \left(\frac{\dot{m}_s}{m_{pool}} \right) \left(d/d_t \right)^{1.25} \qquad \text{where} \quad 0 \le \dot{m}_s / m_{pool} < 1.6 \times 10^{-8} \ s^{-1} \tag{3}$$

$$\frac{\dot{m}_{p-\max}}{m_{pool}} = \left(3.97 \times 10^3 \left(\frac{\dot{m}_s}{m_{pool}} \right) + 4.61 \times 10^{-4} \right) \left(d/d_t \right)^{1.25} \qquad \text{where} \quad 1.6 \times 10^{-8} \le \dot{m}_s / m_{pool} < 6 \times 10^{-8} \ s^{-1} \tag{4}$$

$$\frac{\dot{m}_{p-\max}}{m_{pool}} = \left(2.38 \times 10^3 \left(\frac{\dot{m}_s}{m_{pool}} \right) + 5.55 \times 10^{-4} \right) \left(d/d_t \right)^{1.25} \qquad \text{where} \quad 6 \times 10^{-8} \le \dot{m}_s / m_{pool} < 1.2 \times 10^{-6} \ s^{-1} \tag{5}$$

$\dot{m}_{p-\max}$ is in kg/s and m_{pool} is in kg.



(a) (b)

Figure 9: Series II - Surface Temperature Predictions (a) & Maximum Required Mixing Rate (b)

3.3 Case Series III: Pool Temperature And Thermal Expansion Case Study

In Case Series III, the previously presented BFN Unit 2 3D GOTHIC model was used for steam injection through the RCIC sparger at four different steam injection rates: 1.0, 1.5, 2.0 and 3.08 kg/s. Steam was injected for 122,400 seconds (34 hours). The RCIC sparger is modeled with a 1D subdivided pipe volume and the sparger volume is connected to the pool with nine Flow Paths (FP) spanning the range of the sparger length [1] so that GOTHIC will automatically calculate the steam injection depth as determined by the buoyancy and drag forces.

The 3D GOTHIC model results showed differences in steam release depth (d) based on variances in steam injection rate ($\dot{m}_s$). At lower injection rates, steam was released through only the highest level of the sparger openings. As the steam flow rate increases, the water level in the sparger is further depressed and the steam injection extends to lower levels of the sparger. These injection depths were supplied as input for the lumped model pump circulation flow rate calculation. In general, the injection depth will not be known. Therefore, it is essential to understand the relationship between injection rate and the injection depth for a sparger. Using the known geometric parameters as shown in Figure 7 and listed in Table 1, an analytical correlation between $\dot{m}_s$ and d can be developed:

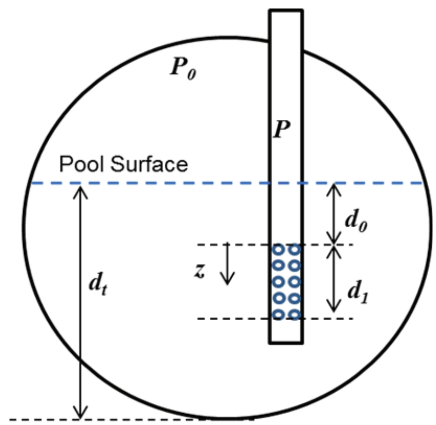


Figure 10: Suppression Pool Geometric Parameters

Table 1: Suppression Pool Parameters

$\dot{M}_0$	Steam mass flow rate into the sparger
u	Steam velocity in the sparger
v	Steam velocity through the sparger holes
P	Steam pressure in the sparger
P_o	Suppression chamber gas space pressure
ρ_w	Suppression pool density
ρ	Steam density
A'_h	Sparger hole area per unit length
A_p	Sparger cross section area
k	Loss Factor for the sparger holes
d_0	Submergence to the top of the sparger hole region
d_1	Distance from the top of the sparger hole region to the depressed water level in the sparger
d	Total release depth
$\boldsymbol{g}$	Gravitational acceleration
R	Steam gas constant
T	Steam temperature

Assuming constant steam density, at any distance, z, from the top of the sparger hole region, the mass balance for the steam flow in the sparger is

$$A_p \rho \frac{du}{dz} = -A_h^{'} \rho v \qquad \rightarrow \qquad v = -\frac{A_p}{A_h^{'}} \frac{du}{dz} \tag{6}$$

The gravitational head of the steam is small relative to that in the pool and is neglected. The force balance for the steam flow through the holes is

$$P-\left(P_0+\left(d_0+z\right)\rho_w \boldsymbol{g}\right)=\frac{k}{2}\rho v^2 \qquad \rightarrow \qquad \frac{dP}{dz}-\rho_w \boldsymbol{g}=k\rho v\frac{dv}{dz} \tag{7}$$

Combining this equation with Equation 6 gives

$$\frac{dP}{dz}-\rho_w \boldsymbol{g}=k\rho\left(\frac{A_p}{A_h^{'}}\right)^2\frac{du}{dz}\frac{d^2u}{dz^2} \tag{8}$$

Neglecting the wall friction, the momentum balance for the flow down the sparger is

$$A_p\left(P_z-P_{z+\Delta z}\right)+A_p\rho\left(u_z^2-u_{z+\Delta z}^2\right)=A_h^{'}\Delta z v\rho u \qquad \rightarrow \qquad -A_p\frac{dP}{dz}-A_p\rho\frac{du^2}{dz}=A_h^{'}v\rho u \tag{9}$$

Combining this equation with Equation 6 gives

$$\frac{dP}{dz}+\rho\frac{du^2}{dz}=\rho u\frac{du}{dz} \qquad \rightarrow \qquad \frac{dP}{dz}=-\rho u\frac{du}{dz} \tag{10}$$

At the top of the sparger section (z = 0)

$$\dot{M}_0=A_p\rho u_{z=0} \qquad \rightarrow \qquad \dot{M}_0=\int_0^{d_1}A_h^{'}\rho v dz \tag{11}$$

The pressure profile in the sparger is unknown. If the pressure in the sparger steam region was uniform, the steam velocity through the holes would vary with depth to the ½ power. However, the pressure in the sparger varies with depth due to the loss of momentum through the holes and friction. Therefore, to a first approximation it is assumed that the hole velocity varies linearly with z, i.e.,

$$v=v_{z=0}(1-\frac{z}{d_1}) \tag{12}$$

Equation 11 reduces to

$$\dot{M}_0=A_h^{'}\rho v_{z=0}\frac{d_1}{2} \tag{13}$$

The unknown pressure gradient can be eliminated by combining Equations 8 and 10, giving

$$-\frac{1}{2}\frac{du^2}{dz}-\frac{\rho_w}{\rho}\boldsymbol{g}=\frac{k}{2}\left(\frac{A_p}{A_h^{'}}\right)^2\frac{d}{dz}\left(\frac{du}{dz}\right)^2 \tag{14}$$

Integrating this equation over the sparger hole length gives

$$-\frac{1}{2}\int_0^{d_1}\frac{du^2}{dz}dz-\int_0^{d_1}\frac{\rho_w}{\rho}\boldsymbol{g}dz=\frac{k}{2}\left(\frac{A_p}{A_h^{'}}\right)^2\int_0^{d}\frac{d}{dz}\left(\frac{du}{dz}\right)^2dz \tag{15}$$

Using Equation 6 in the right hand side gives

$$-\frac{1}{2}\int_0^{d_1} du^2 - \int_0^{d_1} \frac{\rho_w}{\rho} \boldsymbol{g} dz = \frac{k}{2}\int_0^{d} dv^2 \qquad \rightarrow \qquad u_{z=0}^2 + \frac{2\rho_w}{\rho}\boldsymbol{g} d_1 = -k v_{z=0}^2 \tag{16}$$

Combining this equation with Equations 11 and 13 gives

$$\frac{\dot{M}_0^2}{A_p^2 \rho^2} - \frac{2\rho_w}{\rho}\boldsymbol{g} d_1 = -4k \frac{\dot{M}_0^2}{d_1^2 \rho^2 A_h^{'2}} \qquad \rightarrow \qquad \frac{d_1^2}{A_p^2} - \frac{2\rho_w \rho \boldsymbol{g} d_1^3}{\dot{M}_0^2} = -\frac{4k}{A_h^{'2}} \tag{17}$$

If ρ is known, then the above equation can be solved for d_1.

The average steam density in the sparger can be estimated from

$$\rho = \frac{P_0 + (d_0 + d_1)\rho_w \boldsymbol{g} + \dfrac{2k\dot{M}_0^2}{\rho\left(A_h^{'} d_1\right)^2}}{RT} \qquad \rightarrow \qquad RT\rho^2 - (d_0 + d_1)\rho_w \boldsymbol{g}\rho - \frac{2k\dot{M}_0^2}{\left(A_h^{'} d_1\right)^2} = 0 \tag{18}$$

Equation 17 and 18 can be solved iteratively for d_1.

If the sparger is angled θ from vertical, then the equations to be solved are:

$$\frac{d_1^2}{A_p^2} - \frac{2\rho_w \rho \boldsymbol{g} d_1^3 cos\theta}{\dot{M}_0^2} = -\frac{4k}{A_h^{'2}} \tag{19}$$

$$RT\rho^2 - (d_0 + d_1)\rho_w \boldsymbol{g}\rho cos\theta - \frac{2k\dot{M}_0^2}{\left(A_h^{'} d_1\right)^2} = 0 \tag{20}$$

Knowing the geometric parameters and steam injection rate, one can use Equation 20 to estimate the lowest steam release location and calculate the maximum steam release depth *d* as,

$$d = (d_0 + d_1)\cos\theta \tag{21}$$

The required submergence ratio for Equations 3, 4 and 5 is

$$d/d_t = \frac{(d_0 + d_1)\cos\theta}{d_t} \tag{22}$$

With the known submergence ratio versus steam injection rate for a vertical sparger, the mixing correlation can be used to model the steam release to the pool from a RCIC or HPSI turbine exhaust. Similar to previous case studies, in Case Series III, first the 3D GOTHIC pool surface temperature results were obtained for each steam flow rate. Using pool surface temperatures as control variables, required pump flows were calculated for all simplified GOTHIC models. As shown in Figure 11, the general trend of the pump flows started with a maximum flow rate and then decayed exponentially over the time.

The mixing induced by the condensed steam is due primarily to the buoyancy force arising from the difference in the condensed liquid density and the pool bulk density. The density difference gradually decreases as the pool temperature increases over the time. Thus, it is expected that the temperature difference between the bulk pool and condensed steam ($\Delta T = T_s - T_l$) as well as the variations in thermal expansion of the pool water (ε_t) over the time are important parameters in the mixing rate.

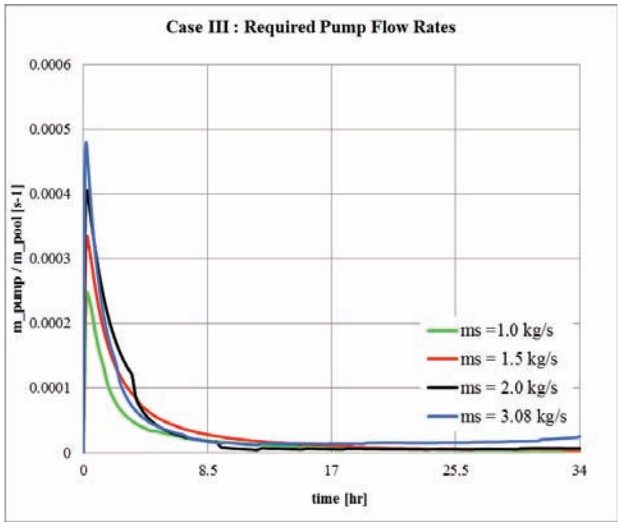


Figure 11: Series III - GOTHIC Required Pump Flow Rate / Pool Liquid Mass [s^{-1}] Predictions

Based on Figure 11 a power function form is assumed,

$$\dot{m}_p = \dot{m}_{p-\max}(d, \dot{m}_s / m_{pool})\lambda\left(\Delta T \varepsilon_t - \beta\right)^n \tag{23}$$

The $\dot{m}_{p\max}(d, \dot{m}_s / m_{pool})$ function was previously defined in Equations 3, 4 and 5. Based on curve fitting and trial-error methods using the GOTHIC models, the best fit λ, β and n constants are

$\lambda = 2x10^{-6}$ $\beta = 0.0215$ $n = -1.75$

Substituting these constants back into Equation 23 and combining it with Equations 3, 4 and 5 gives the comprehensive form of the required pump flow rate correlations as,

$$\frac{\dot{m}_p}{m_{pool}} = 3.27\times10^4\left(\frac{\dot{m}_s}{m_{pool}}\right)\left(d/d_t\right)^{1.25} 2\times10^{-6}\left(\left(T_s - T_l\right)\varepsilon_t - 0.0215\right)^{-1.75} \tag{24}$$

for $0 \le \dot{m}_s / m_{pool} < 1.6\times10^{-8}\ s^{-1}$

$$\frac{\dot{m}_p}{m_{pool}} = \left(3.97\times10^3\left(\frac{\dot{m}_s}{m_{pool}}\right) + 4.61\times10^{-4}\right)\left(d/d_t\right)^{1.25} 2\times10^{-6}\left(\left(T_s - T_l\right)\varepsilon_t - 0.0215\right)^{-1.75} \tag{25}$$

for $1.6\times10^{-8} \le \dot{m}_s / m_{pool} < 6\times10^{-8}\ s^{-1}$

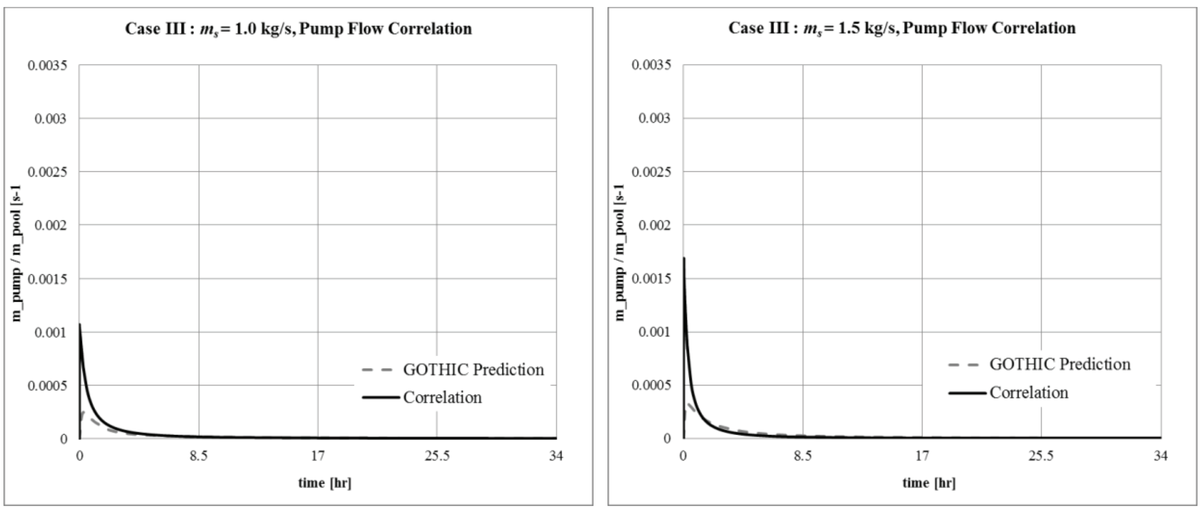
$$\frac{\dot{m}_p}{m_{pool}} = \left(2.38\times10^3\left(\frac{\dot{m}_s}{m_{pool}}\right) + 5.55\times10^{-4}\right)\left(d/d_t\right)^{1.25} 2\times10^{-6}\left(\left(T_s - T_l\right)\varepsilon_t - 0.0215\right)^{-1.75} \tag{26}$$

for $6\times10^{-8} \le \dot{m}_s / m_{pool} < 1.2\times10^{-6}\ s^{-1}$

Table 2: Suppression Pool Parameters

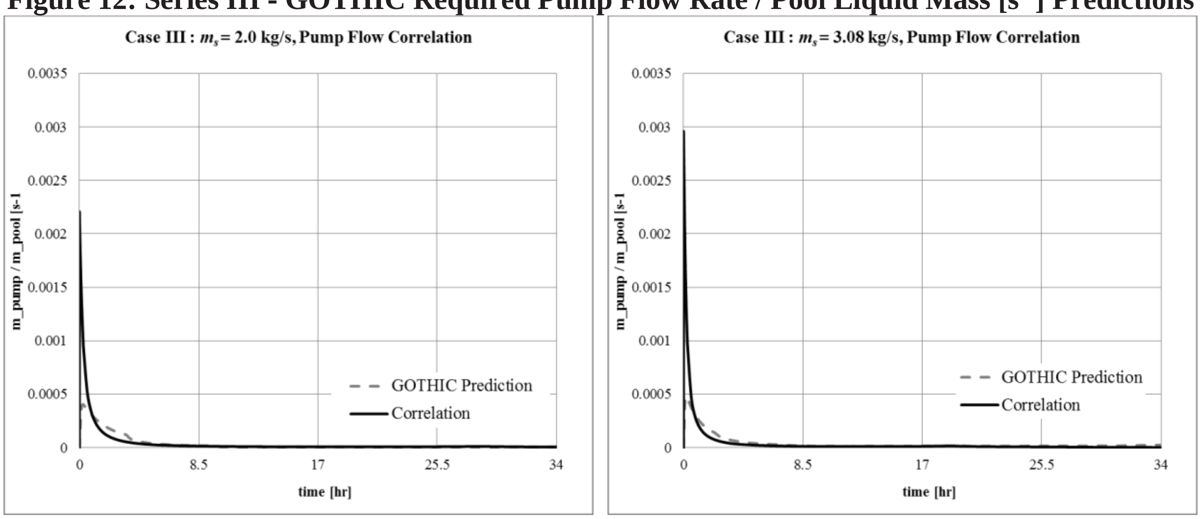
$\dot{m}_p$	Pump Flow Rate, [kg/s]
$\dot{m}_s$	Steam Flow Rate, [kg/s]
m_{pool}	Pool Water Mass, [kg]
T_s	Saturation Temperature of Steam [C]
T_l	Bulk Temperature of Pool [C]
ε_t	Thermal Expansion Coefficient of Water [1/C]
d	Steam Release Depth [m]
d_t	Total Pool Depth [m]

Using Equations 24 to 26, pump flow rates are recalculated and results are compared with the flow rates that are required to match the GOTHIC 3D predictions and presented individually in Figure 12 and Figure 13. For the first few minutes of the simulation, the correlation predicts higher pump flow rate than the required values, however this does not have an impact on the pool temperature predictions since the pool was initially well mixed.



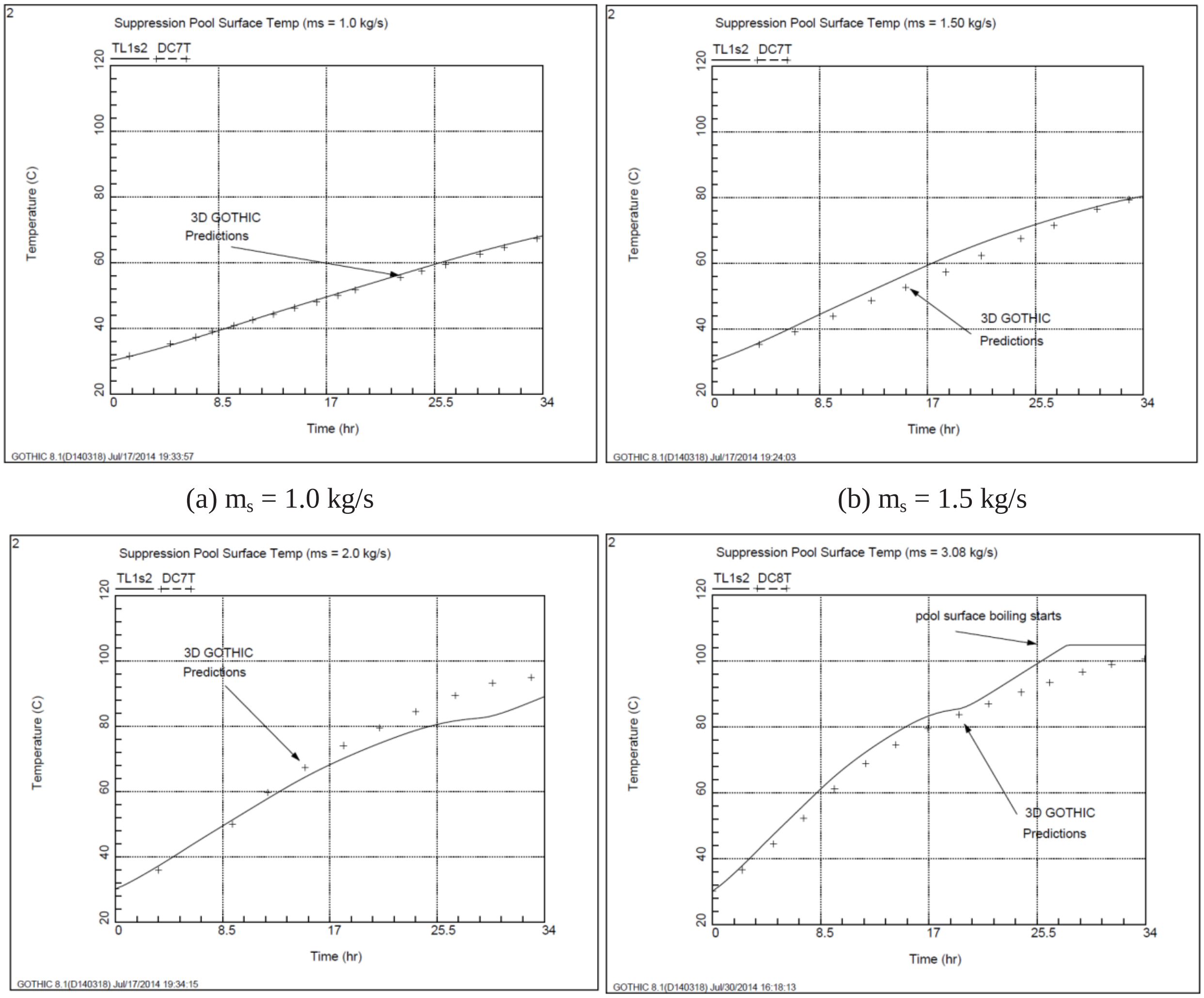
(a) m_s = 1.0 kg/s (b) m_s = 1.5 kg/s

Figure 12: Series III - GOTHIC Required Pump Flow Rate / Pool Liquid Mass [s^{-1}] Predictions



(a) m_s = 2.0 kg/s (b) m_s = 3.08 kg/s

Figure 13: Series III - GOTHIC Required Pump Flow Rate / Pool Liquid Mass [s^{-1}] Predictions



(a) m_s = 1.0 kg/s

(b) m_s = 1.5 kg/s

(c) m_s = 2.0 kg/s

(d) m_s = 3.08 kg/s

Figure 14: Comparison of GOTHIC Lumped and 3D Model Results

It should be noted that, later in the transient, as the pool temperature T_l gets closer to the condensed steam temperature T_s, the last term in the given correlation (Equations 24, 25 and 26) goes to zero or negative which results in an excessive pump flow and over mixing of the suppression pool. In order to avoid modelling unrealistic pump flow in GOTHIC analysis the temperature difference (T_s - T_l) is limited to >50 C (90 F).

As a final check of the mixing correlation, Equations 24, 25 and 26 were implemented as control variables in the simplified GOTHIC models and used to control the required pump flow rate to circulate the liquid inside suppression pool. In Figure 14 (a-d), the suppression pool surface temperature results from the lumped model are compared with previously obtained 3D GOTHIC predictions. At smaller steam injection rates, the mixing flow correlation used in the lumped GOTHIC model gives good agreement with the detailed 3D GOTHIC model calculations. When the steam injection rate is increased, and the pool surface temperature gets closer to its boiling point, discrepancies between the 3D and lumped modeling prediction up to ±5 C (±9 F) were observed.

4. CONCLUSIONS

A series numerical experiment was performed using three dimensional modeling capabilities in GOTHIC and a correlation was developed that can be used to estimate pool mixing and stratification effects in a BWR MARK I pressure suppression pool with a lumped modelling approach.

Using 3D GOTHIC BFN Unit 2 model, a numerical test matrix was generated. The effects of steam injection rate, its injection location (depth) and the temperature difference between the condensed steam and the pool, and the thermal expansion coefficient of the pool water were tested. A two zone model for the suppression pool with controlled circulation between upper and lower zones was used to develop and test a pool mixing correlation during steam release into the pool. Using the numerically generated data set, a mixing correlation was developed for the mixing rate between the upper and lower pool volumes. An analytic expression for the injection depth for a sloped RCIC or HPSI sparger was also developed.

The mixing flow correlation used in the two zone lumped model showed good agreement with the detailed 3D GOTHIC model calculations, especially when the steam injection rate is small. At higher steam injection rates the pool surface temperature approached the boiling point and agreement between the lumped and 3D models degraded but was still within ±5 C (±9 F). Ideally, the lumped modeling mixing correlation should be validated against data that was not used to develop the correlation. However, pertinent additional data is not readily available at this time.

The 3D Browns Ferry Suppression Chamber model contains 2300 cells and the 12 hours test simulation run-time required approximately 4080 minutes using parallel process with 6 cores. The lumped-parameter model ran in 16 minutes on a single core.

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