EFFECTIVE APPROACHES TO SIMULATION OF THERMAL STRATIFICATION AND MIXING IN A PRESSURE SUPPRESSION POOL

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Abstract

Pressure Suppression Pool (SP) is an important passive element in a Boiling Water Reactor (BWR) safety system. Containment pressure depends on the efficiency of steam condensation inside the SP. Thermo-gravitational stratification induced by steam injection at small flow rates can reduce steam condensation capacity of the SP and significantly increase pool surface temperature and steam partial pressure in the wetwell. Parameters which are important for the SP operation are time scales of (i) stratification development, and (ii) mixing of initially stratified SP. In the present work we discuss "Effective Heat Source" (EHS) and "Effective Momentum Source" (EMS) approaches to prediction of stratification and mixing time scales in the SP. The GOTHIC code is used as a computational platform. The data from the POOLEX tests STB-20 and STB-21 is used for validation. Analysis of the simulation results obtained with EHS and EMS models and comparison with experimental data confirms (i) reasonably good accuracy of the EHS model in predicting of temporal evolution of stratification in a large scale pool, and (ii) feasibility of the EMS approach for predicting of characteristic time scales of mixing in the pool.

1. INTRODUCTION

The work presented pertains to a research program whose objective is to evaluate and eventually improve performance of methods, which are used to analyze thermal-hydraulics of pressure Suppression Pools (SP) in Boiling Water Reactor (BWR) plants under different transients and accident conditions. SP is an important passive element in a Boiling Water Reactor (BWR) safety system. Reactor containment pressure in Loss of Coolant Accident (LOCA) and in case of Safety Relieve Valve (SRV) operation depends on the efficiency of steam condensation in the SP. This paper focuses on late stages of LOCA scenarios, when steam injected at small flow rate condenses rapidly in the pool; hot condensate flows up in a narrow plume above steam injection source and spreads into a thin hot layer at the pool's free surface. If momentum of the plum is not big enough to mix the pool, then stable thermal stratification is formed in the pool. Stratification can significantly impede the pool's pressure suppression capacity and increase the pool surface temperature which defines partial pressure of steam in the wetwell of the containment. Stratification also affects conditions for operation of different safety and non-safety systems which use SP as a source of water. Heat exchangers and high momentum jet mixers installed in the SP are used to chill and mix the SP. As non-passive and non-safety systems the mixers and the heat exchangers can fail or can be temporarily unavailable (e.g. in case of station blackout). Therefore important is to understand behavior of the SP during long transients with steam blowdown flow rate changing in time and with activation of systems for mixing and cooling of the pool at arbitrary time moments. In this work we consider time scales of thermal stratification development and mixing of initially stratified pool as most important characteristics for the SP operation.

Numerous experimental and analytical studies have been performed in the past to develop better understanding and simulation tools for prediction of basic phenomena of steam condensation, thermal stratification and mixing in a pool. Separate effect experimental studies of mixed convection flow phenomena have received considerable attention since the late

1970s. A review of the early woks is given by Incropera and Dewitt (1996). Discussions of experimental results with analytical interpretations for transient stratification of SPs were reported in Fox et al. (1992) and Smith et al. (1992). It was claimed that experimental results for transient stratification of BWR pressure suppression pools could be predicted using numerical solutions of one-dimensional differential equations describing the effect of buoyant jets on the vertical temperature distribution. Important experiments and analytical studies on mixed convection have been performed by Peterson and coworkers at University of California, Berkeley. Experimental studies on transient thermal stratification in pools with shallow buoyant jets and plumes were discussed by Peterson et al. (1991). Peterson (1994) provided a criterion for assessing when the momentum injected by forced jets would break up stratification in large enclosures. A method for reduction of the governing conservation equations for mass, momentum, energy to simpler one-dimensional forms under stratified conditions in an enclosure also has been proposed (Peterson, 1994). Peterson and Gamble (1996) presented a scaling method for the design of scaled experiments for studying jet-induced heat and mass transfer in large enclosures. Kuhn et al., (2002) studied heat transfer in a jet-agitated enclosure with a heated or cooled bottom surface. A correlation was proposed using a weighted relation to balance the contributions of natural convection and forced convection to heat transfer. Niu et al. (2007) studied mixed-convection and heat transfer augmentation by forced jets inside a large enclosure with a vertical cooling surface in order to support validation of the BMIX++ code (Berkeley mechanistic MIXing code in C++) (Zhao, 2003; Niu et al., 2007). The BMIX++ code is a one-dimensional Lagrangian transient flow and heat transfer code. The code is used if Archimedes number (ratio of square of Reynolds number to Grashof number) is low and stratification can develop, for high Archimedes number the enclosure is assumed to be a well mixed lumped volume.

Direct Contact Condensation (DCC) of steam in subcooled water as a common phenomenon in many two-phase systems has been a subject of intensive research since 70ies. Past experimental and theoretical studies are focused on three closely related topics (i) steam jet penetration length (e.g. Kerney et al., 1972; Weimer et al., 1973); direct contact condensation heat transfer (Chun at al., 1996; de With, 2009); and (iii) hydrodynamic regimes of steam injection (Chan and Lee, 1982; Liang and Griffith, 1994; Cho et al., 1997; Youn et al., 2003; Petrovic-de With et al., 2007).

One of the reasons for studying steam injection flow regime was that in chugging oscillation regime (Chan and Lee, 1982; Liang and Griffith, 1994) pressure impulses can be strong enough to threaten integrity of concrete containment. Experimental investigation of steam condensation and CFD analysis of thermal stratification and mixing in subcooled water of In-containment Refueling Water Storage Tank (IRWST) of the Advanced Power Reactor 1400 (APR1400) were performed by Song et al. (2003), Kang and Song (2008) and Moon et al. (2009). The IRWST is, in fact, a BWR SP technology adopted in PWR designs to reduce the risk of containment failure by condensing steam in a subcooled pool of water. Contemporary CFD codes don't have a standard model for direct contact condensation. Therefore a lumped volume model for condensation region was used by Kang and Song (2008) to provide boundary conditions for temperature and velocity of condensed and entrained water in the CFD simulations. Only stable flow condensation regime was addressed (Kang and Song, 2008; Moon et al., 2009). Similar approach to modeling of steam injection was initially proposed by Austin and Baisley (1992).

Integral test facilities POOLEX (Laine and Puustinen, 2006) at Lappeenrata University of Technology, Finland, and PUMA (Cheng et al., 2006) at Purdue University, US were designed to study effect of steam and non-condensable gas injection on thermal stratification and mixing in a large volume of the SP.

Analysis of stratification tests performed in the Pressure Suppression Test Facility (PSTF) for a SBWR (simplified boiling water reactor) with the modified TRACG code is discussed in

Gamble et al. (2001). In the modified TRACG code the mass and energy deposited by the jet in a cell is modeled with a “source” while entrained liquid from a cell is modeled as a “sink” (Gamble et al., 2001). Good general agreement with the test data is reported by Gamble et al., (2001). However, proposed computational model has quite high degree of freedom in selection of parameters and configurations of “sinks” and “sources”. That may affect predictive capabilities of the model in cases when experimental data is not available for calibration of the model.

Results of experiments in a scaled-down SP designed to study condensation and mixing phenomena for a LOCA event in a SBWR design are reported by Norman and Revankar (2010a). Analysis of the experiments performed with the TRACE code (Norman and Revankar, 2010b) indicated that the code is deficient in predicting thermal stratification.

GOTHIC code was used by Li and Kudinov (2008) to simulate thermal stratification development and cooling of stratified pool under the test conditions of STB-20 POOLEX experiment. Injected steam was completely condensed inside the blowdown tube in the STB-20 test. It was proposed to simulate the effect of steam injection by an equivalent heat source uniformly distributed over the surface of the blowdown pipe. It was demonstrated that GOTHIC code is capable in predicting development of thermal stratification and cooling of the pool, and also it is a computationally efficient tool to study hundreds of thousands seconds long transients (Li and Kudinov, 2008).

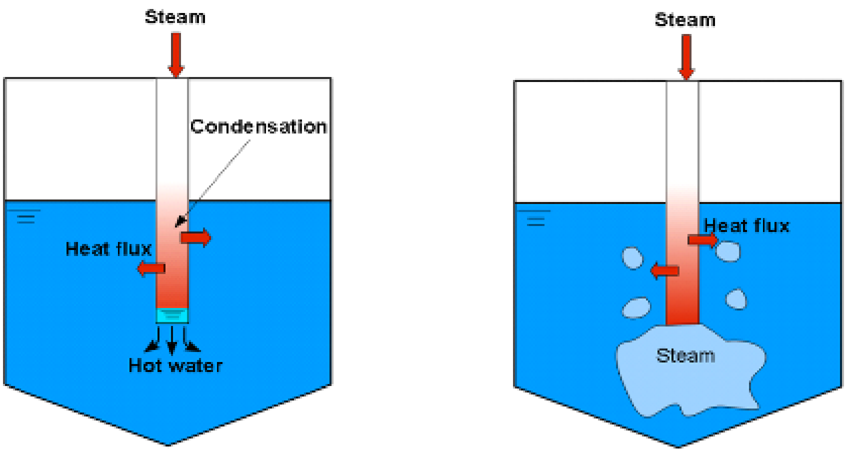
Sate of the art in research on condensation and mixing in the pool is summarized below:

I. The influence of steam injection and condensation regimes on stratification and mixing has not been addressed systematically, although experimental databases on condensation, mixing and stratification are quite representative for each of the separate effects.
II. Existing simulation tools have considerable limitations in predicting transient scenarios of the SP operation and in resolving feedbacks between the SP and other plant containment systems:
    a. Lumped-parameter scaling models are not capable to describe dynamical characteristics (e.g. time scales of mixing) of thermal stratification and mixing in different scenarios (e.g. SP mixing systems switched on/off for a short time, momentum inertia, history effects in the pool mixing/stratification, etc.).
    b. General purpose 1D thermal-hydraulic codes (such as TRACE and RELAP) were not designed for predicting stratification. It is possible to introduce modification in such codes (e.g. Gamble et al., 2001) to achieve stratification and mixing in simulations, however such modifications are often design specific and may require calibration to match experimental results for each particular case. BMIX++ 1D code was designed to predict thermal stratification in large enclosures, but it doesn’t have a model for predicting effect of steam condensation phenomena.
    c. Higher fidelity CFD (RANS, LES) methods are not practical due to excessive computing power needed to calculate transient 3D high-Rayleigh-number flows in real geometry of a BWR containment.
    d. Well validated model for DCC is not available yet in CFD codes. Accuracy of CFD model prediction is contingent upon the accuracy of a lumped parameter model which has to provide boundary conditions (temperature, mass and momentum source) to simulate the effect of condensing steam jet. Such models have not been developed yet for the condensation oscillations and chugging regimes.

The objective of the present research is to develop reasonably-accurate and computationally affordable simulations methods for predicting of thermal stratification and mixing transients in the SP. Toward this objective, we employ a general-purpose thermal-hydraulic code GOTHIC, using its distributed-parameter CFD-like option as a computational vehicle. Specifically, in the present work we discuss implementation of the “Effective Heat Source” (EHS) and the “Effective Momentum Source” (EMS) approaches to prediction of stratification and mixing in the SP. The POOLEX experimental data (Laine and Puustinen, 2006) is used for validation. We demonstrate that stratification and mixing are not predicted correctly if direct injection of steam into the pool is modeled with GOTHIC standard models. Validation of the EHS and the EMS models confirms (i) reasonably good accuracy of the EHS model in predicting of stratification development in a large scale pool; (ii) feasibility of the EMS approach for predicting of characteristic time scales for mixing in the pool.

2. DISCUSSION OF RESULTS

The data from the POOLEX tests STB-20 and STB-21 is used for validation in this work. The POOLEX water tank is 5 m height and 2.4 m in diameter. Vertical blow down pipe 200 mm in diameter with the outlet directed downwards is submerged by 1.81 m into the water pool. Three vertical trains of thermocouples are installed in the pool for measuring of temperature distribution. More detailed description of the facility and test data is available in Laine and Puustinen, (2006).



a) small flow rate of steam b) large flow rate of steam

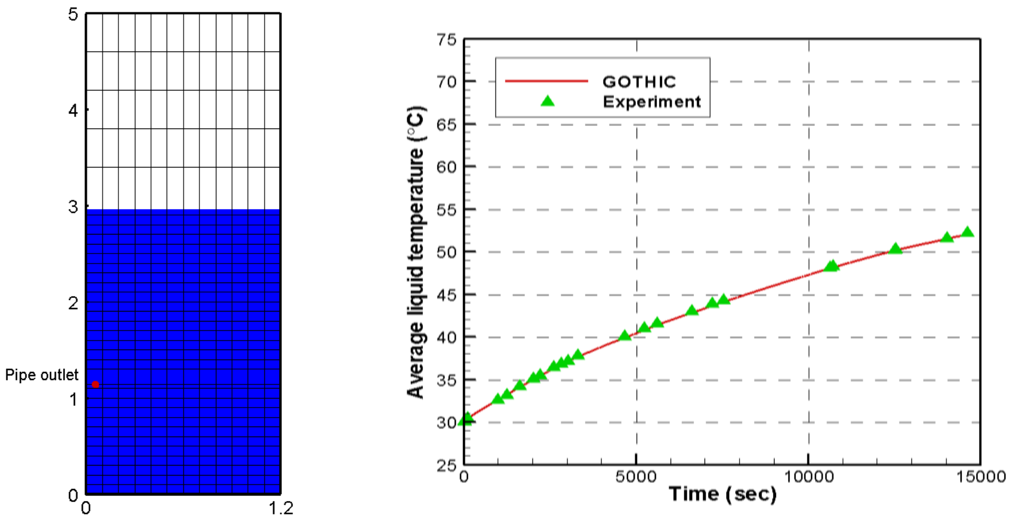
Fig. 1: Two characteristic flow regimes of steam injection into a subcooled water pool

Fig**.** 1 depicts two different characteristic regimes of steam injection into a pool of subcooled water which are considered in the present work. In the first case (Fig**.** 1a) steam is completely condensed inside the blowdown pipe and only a hot condensate flows out of the pipe (as in the STB-20 test). Momentum provoked in such regime is normally too small to mix the pool volume, while heat source is sufficient to develop thermal stratification. Second regime (Fig. 1b) is characterized by considerable amount of steam (or non-condensable gases) flowing out of the blow down pipe. In this case significant momentum injected in the pool can cause mixing of stratified layers as it was observed in the STB-21 test by Laine and Puustinen (2006).

2.1 Effective Heat Source (EHS) Approach to Simulating of Stratification Development at Small Rate of Steam Injection

For predicting of thermal stratification development at small steam flow rate the EHS (Effective Heat Source) has been proposed by Li and Kudinov (2008). According to the experimental observations from the POOLEX STB-20 test, it is assumed that steam is condensed completely inside the blowdown tube. In this case the effect of the steam injection is taken into account by introducing a heat flux (effective heat source) which is distributed uniformly over the surface of the blowdown pipe and is equal to the total heat released by completely condensed steam. The heat source causes development of thermal stratification in the pool. In the EHS approach it is further assumed that momentum introduced in the pool by the condensate flowing out of the pipe outlet is negligible.

The first step in the validation of the EHS model is to demonstrate that average temperature in the pool can be accurately predicted by GOTHIC. This implies that heat losses at the free surface of the pool and through the walls of the tank are calculated correctly. This is important step, considering that POOLEX tank is open to atmosphere of the lab and the walls of the tank are not isolated.



a) b)

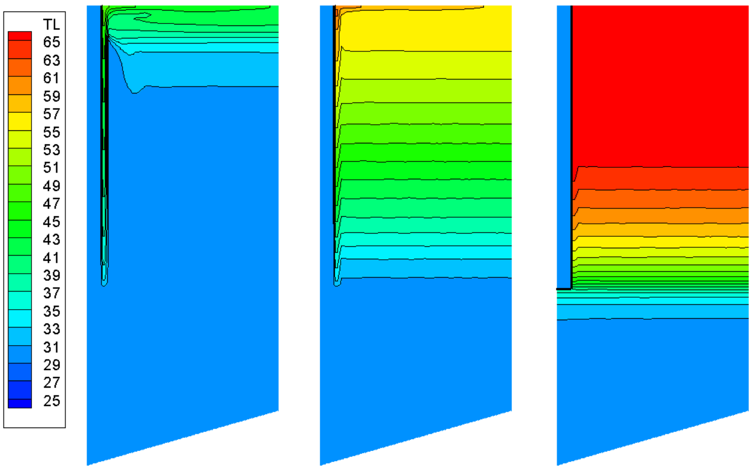
Fig. 2: GOTHIC simulations: a) mesh with liquid and gas space; b) comparison of experimental and predicted averaged liquid temperature in STB-20

Water level in the tank can increase considerably due to steam injection in a long transient. In this case, liquid free surface has to be explicitly modeled in the simulation. That can significantly increase computational time. In the previous work (Li and Kudinov, 2008) changes of water inventory were neglected in analysis of the POOLEX STB-20 experiment. In present work two GOTHIC models were developed and applied. In the first model only part of the tank volume filled with liquid is considered in simulations to reduce computational expenses. Heat loss on the pool free surface is simulated by time dependent heat flux (Li and Kudinov, 2008). In the second model the gas space of the tank is also considered in simulations. Water pool geometry is modeled as 2D axisymmetric in both cases. The coarsest grid used in analysis has in vertical direction 29 cells in liquid part, 1 cell with liquid-gas interface and 4 cells in gas space, and in horizontal direction 12 cells. Mesh cell size is 0.1m×0.1m in liquid part, 0.5m×0.1m for the cell with interface, and 0.4m×0.1m in the gas space of the tank (Fig. 2a). Heat conduction through the blowdown pipe wall and through the tank walls is modeled with the GOTHIC models for thermal conductors. A large size lumped volume connected to a pressure boundary conditions simulates atmosphere of the lab. A 3D connector is used in the open tank to model flow and heat transfer between the lab and the pool.

Results presented in Fig. 2b suggest that GOTHIC can predict heat losses from the open tank and thus averaged liquid temperature in the POOLEX experiments. Average temperature predicted by GOTHIC in the models with and without gas space is practically identical.

Temperature distribution in the tank (Fig. 3) shows the process of thermal stratification development. As can be seen in Fig. 3a, a buoyant raising boundary layer is formed along heated pipe surface. Hot water flows up and spreads along the free surface of the pool.

Fig. 4 shows good agreement between experimental data for time dependent vertical temperature distribution in the STB-20 and results predicted by the GOTHIC with EHS model with and without considering the gas space in the tank. Temperature of the very top layer of the pool is slightly overestimated (Fig. 4) in both cases during first 5000 seconds of the transient which can be attributed to underestimation of the momentum by the EHS model.



a) b) c)

Fig. 3: Temperature distribution in the tank during heating phase predicted with grid 24x59: a) t= 500 s; b) t=5000 s; c) t=14600 s

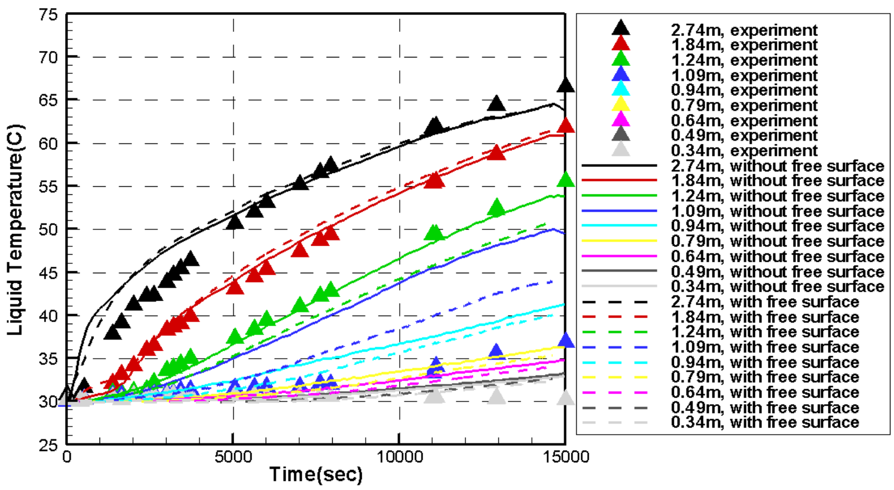
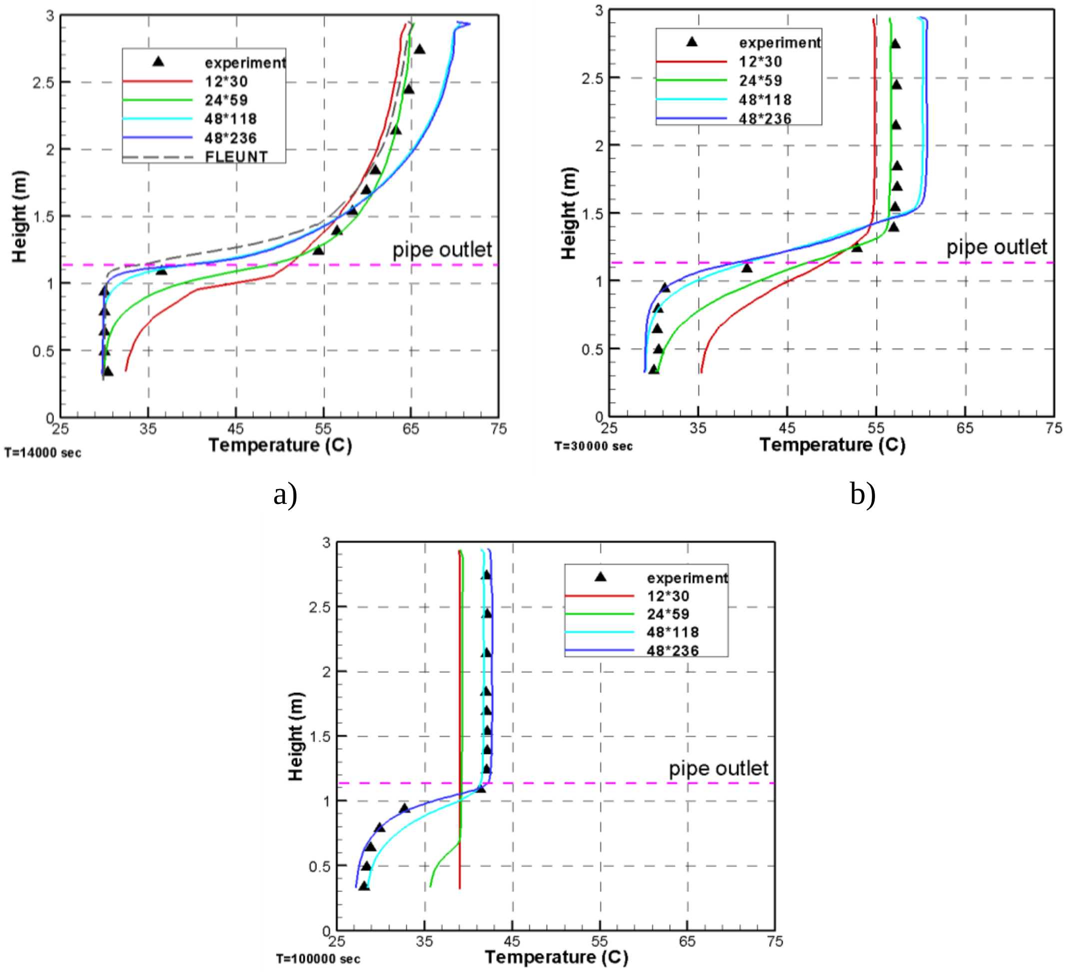


Fig. 4: Temperature history in simulation with heat source and with/without free surface

Results of the grid convergence study are presented in Fig. 5. The first GOTHIC input model which is considering water filled space only is used to reduce computational time. Effect of grid refinement on improvement of the numerical solution quality can be seen in Fig. 5, especially in the layer below the pipe outlet. One can see that results obtained on the grids 48x236 and 48x118 are very close to each other. Over-prediction by several degrees of the water temperature above 1.6 m and respectively under-prediction of water temperature below 1.6 m can be because of underestimated mixing in the pool when momentum induced by steam injection is neglected.

Simulations with EHS approach were also performed with CFD code Fluent. Standard *k-ε* turbulence model was used in the simulations. Results presented in Fig. 5a shows that Fluent also can predict well development thermal stratification. However, GOTHIC is preferred for containment applications because it has quite developed set of well validated build-in physical models for two phase flow phenomena and different engineering components such as valves, pumps, heat conductors, etc.



c)

Fig. 5: Vertical temperature distribution with different grid resolutions at time:
a) t=14600 s b) t=30000 s c) t=100000 s

Data about computational efficiency of the GOTHIC code in simulation of thermal stratification development is presented in Table 1.

Table 1: Computational efficiency

Code	GOTHIC	
Computer	Pentium IV, 2.8 GHz	
Physical time	187,600 s (~**52 hrs**)	
Mesh cells	48*118	48*236
Computational time	7 days	15 days
Physical/Computational time ratio	0.31	0.144

2.2 Simulation of Direct Steam Injection into the Pool in the STB-20 Test

In this work we also present results of simulation of STB-20 test with direct steam injection modeled in GOTHIC. Specifically, a flow boundary condition was connected to the blowdown pipe supplying transient steam injection with characteristics (pressure, temperature, flow) which were measured in the test. Blowdown pipe was modeled by a lumped volume. Another flow path connects blowdown pipe volume with the pool.

As can be seen from comparison of data presented in Fig. 6 and in Fig. 4, results obtained with modeling of direct steam injection into the pool are qualitatively wrong. The pool volume is predicted to be well mixed starting from the beginning of steam injection (Fig. 6). Beginning of thermal stratification development is observed at about 3000 seconds (Fig. 6). Maximum temperature difference in the pool is predicted to be about 15ºC, while experimentally measured temperature difference is 35ºC (Fig. 4). Comparison of instantaneous velocity fields and total liquid momentum plotted in Fig. 7 indicates that mixing predicted with direct steam injection (Fig. 6) is caused by strong circulation in the pool. Maximum liquid velocity obtained with EHS approach (0.077 m/s in Fig. 7a) is much smaller than that predicted with direct steam injection into the pool (0.35 m/s in Fig. 7b). Total momentum predicted with EHS is 10 times smaller than that in case of direct steam injection (Fig. 7c). Possible reasons for the overestimation of momentum induced in the water pool could be explained in Fig. 8. As can be seen in Fig. 8, GOTHIC predicts that steam is not completely condensed inside the pipe and that there are strong oscillations of steam-water flow inside the pipe. Both buoyant plum of steam bubbles and flow oscillation are considerable sources of momentum in the pool. As steam injection flow rate decreases (according to the test conditions Laine and Puustinen, 2006), predicted flow of steam leaking out of the pipe also decreases (Fig. 8a). Although some flow oscillations are still observed after 3000 seconds, the induced momentum (Fig. 7c) is insufficient to provide complete mixing in the pool (Fig. 6).

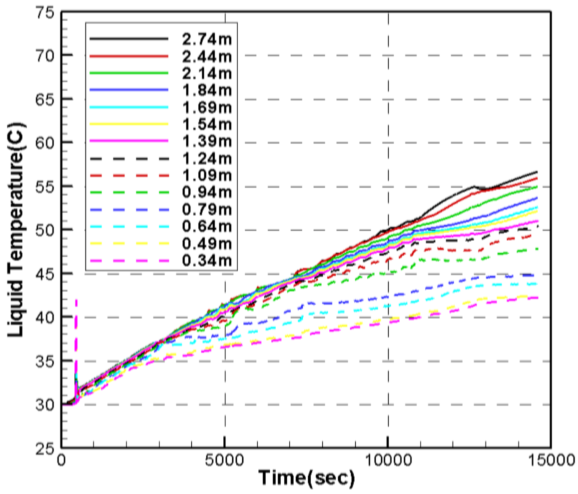
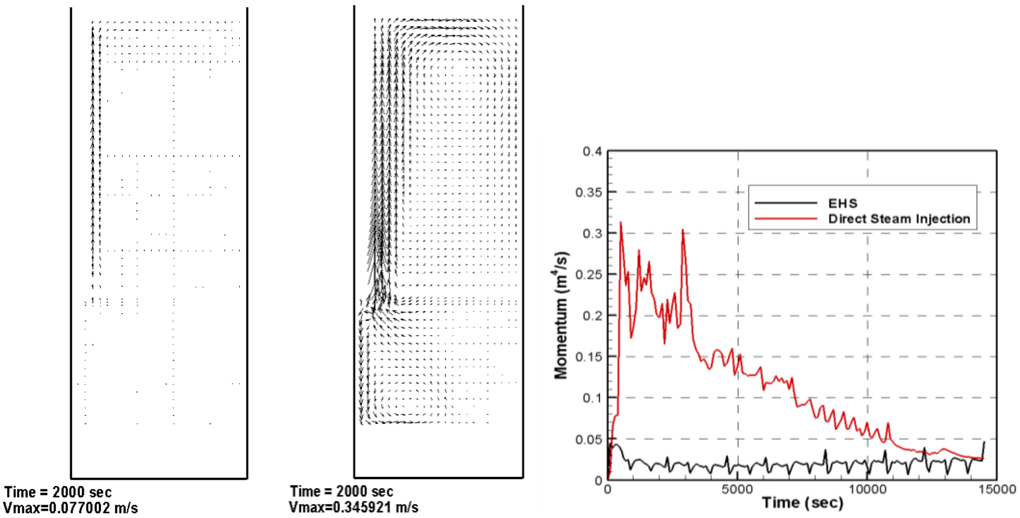


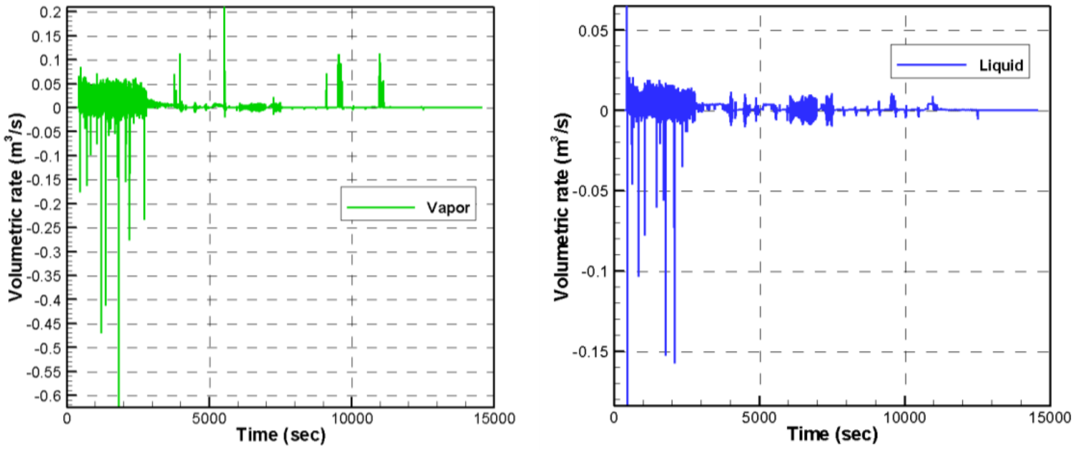
Fig. 6: Simulation of STB-20 test with direct steam injection. Temperature history at different elevations in the pool

Analysis of presented results suggest that (i) EHS approach enables sufficiently accurate prediction of thermal stratification development in a large scale pool at small flow rate of steam injection; (ii) to predict accurately mixing in a pool at higher steam flow rate, GOTHIC requires a model which can provide correct momentum source induced by the steam injection. Simulation of direct steam injection into the pool with models currently available in GOTHIC doesn't provide correct momentum source which leads to artificial mixing in the pool.



a) b) c)

Fig. 7: Simulations of the STB-20 test. Velocity field at 2000 seconds:
a) modeling with EHS; b) modeling of direct steam injection; c) total momentum



a) b)

Fig. 8: Volumetric rate of a) vapor b) liquid

2.3 Feasibility Study of the Effective Momentum Source (EMS) Approach

The Effective Momentum Source (EMS) approach follows main ideas proposed initially by Austin and Baisley (1992) and further developed by Kang and Song, (2008). The EMS requires a closure model which can predict effective source of momentum induced by steam injection and then take into account this source of momentum in GOTHIC simulations. As a first step towards development of the EMS approach we perform a feasibility study in this work. Specifically we address the question if thermal-hydraulics of mixing in the pool can be predicted with GOTHIC if effective source of momentum is provided. The data on mixing of initially stratified pool in the POOLEX experiment STB-21 (Laine and Puustinen, 2006) is used for the feasibility study. Stratification in the pool was developed at low steam flow rate during first stage of the STB-21 test (4000 sec). Then rapid increase of the steam flow rate was provided for about 600 seconds. As a result the pool was mixed and all thermocouples installed at different elevations indicated uniform temperature distribution in the pool (Fig. 9).

We define characteristic time scale of mixing Δt_{mix} as the interval of time starting from the beginning of the increased steam flow rate till the moment when temperature is distributed uniformly in the pool (see Fig. 9). The objective of the feasibility study is to demonstrate if GOTHIC can predict Δt_{mix} with reasonable accuracy. It worth mentioning that mixing in different layers of the pool occurs at different rates. In Fig. 9 one can see that mixing rate is higher in the bottom layer of the pool, which is located below the pipe outlet (thermocouples T101-T106, Laine and Puustinen, 2006). The topmost layer with hottest temperature (T114) is mixed last. Generally speaking this means that one can introduce a mixing time scale for each layer of the pool.

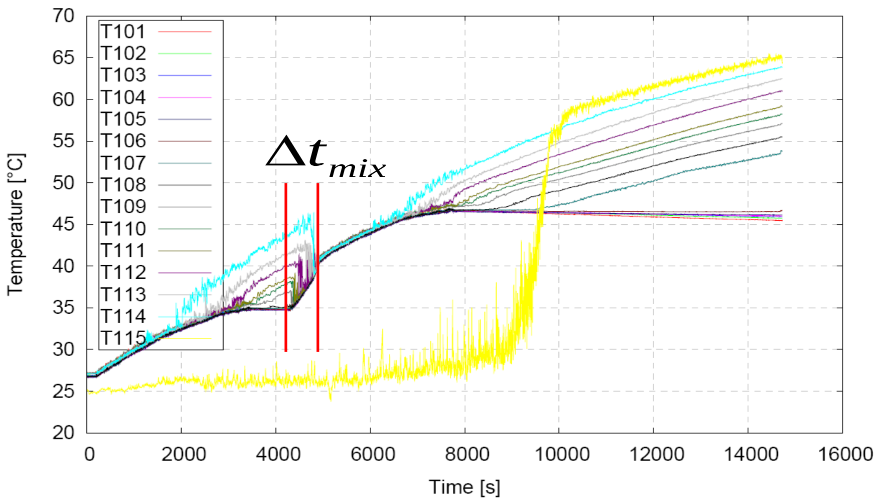
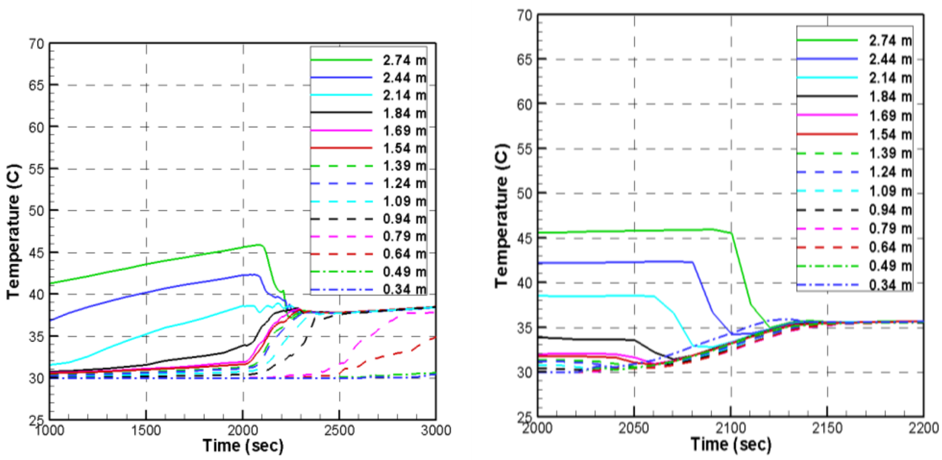


Fig. 9: History of vertical temperature distribution in STB-21 (Laine and Puustinen, 2006)

To provide effective momentum in the GOTHIC model a pump element is installed in the junction between two adjacent control volumes right under the pipe outlet. For the effective momentum source, both value of momentum and its direction are to be specified.

Two cases with vertical upward and downward direction of the effective momentum are studied in this work. Fig. 10 shows results of the simulations of mixing in different layers. Apparently downward direction of the effective momentum (Fig. 10b) provides better qualitative agreement with the experimental results because mixing starts in the bottom layers and propagates gradually to upper layers as it was observed in the STB-21 test (Fig. 9).

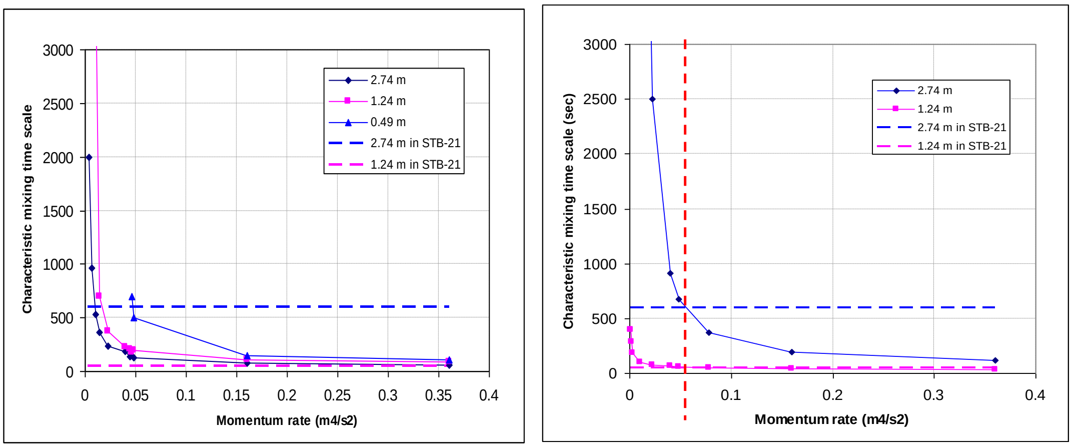


a) b)

Fig. 10: Results of mixing prediction in STB-21 with EMS:
a) upward direction of effective momentum; b) downward direction of effective momentum

Two time scales of mixing in the layers below and above the pipe outlet respectively are introduced for quantitative comparison between experimental and simulation data. In Fig. 11

the mixing time scales predicted by GOTHIC for upper and lower layers of the pool are presented as a function of the momentum rate provided by the pump. Results obtained with upward and downward direction of effective momentum are presented in Fig. 11a and Fig. 11b respectively. Experimentally observed in the STB-21 test (two horizontal lines) time scales are also shown in the figures for comparison. As can be seen in Fig. 11, the mixing time scale increases rapidly if the pump momentum rate is smaller than some threshold value. If downward direction of the effective momentum is used then time scale for mixing of the bottom layers is smaller than that for the upper layers. Analysis of the results indicates that the best agreement with the experimental data for the mixing time scales can be achieved in case of the downward direction of effective momentum with momentum rate about 0.055 m^4/s^2 (Fig. 11b). In this case both time scales of mixing in the top layer and in the bottom layer can be simultaneously reproduced in the GOTHIC simulation.



a) b)

Fig. 11: Calculated mixing time scales in different layers as functions of the momentum rate: a) upward direction of the effective momentum; b) downward direction of the effective momentum

3 SUMMARY AND OUTLOOK

Development and validation of reasonably-accurate and computationally affordable simulation tool for predicting thermal stratification and mixing transients in the prototypic SP are objectives of the present research work. A general-purpose thermal-hydraulic code GOTHIC is used as a simulation platform for implementation and validation of the “Effective Heat Source” (EHS) and the “Effective Momentum Source” (EMS) approaches. The POOLEX tests STB-20 and STB-21 data is used for validation. Validation of the EHS and the EMS models indicates (i) reasonably good accuracy of the EHS model in predicting of temporal evolution of stratification in a large scale water pool at low steam flux conditions; and (ii) feasibility of the EMS approach to predicting of characteristic time scales of mixing in the pool. Further development of the EMS approach requires adequate closure models for prediction of effective momentum in different flow regimes of steam injection into a subcooled pool.

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