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Thermal stratification and mixing in a suppression pool induced by direct steam injection

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ABSTRACT

An experimental and numerical investigation of thermal stratification and mixing in a suppression pool is presented. Steam injected into a drywell flows through a blowdown pipe and then down to the pressure suppression pool where direct contact condensation occurs. The steam venting and condensation is a source of heat and momentum. A complex interplay between the two leads either to thermal stratification or mixing of the pool. The experiments are conducted in a scaled down PPOOLEX facility at Lappeenranta University of Technology (LUT). The corresponding numerical simulations are performed using GOTHIC with the Effective Heat Source (EHS) and Effective Momentum Source (EMS) models. The EHS/EMS models, that have been previously proposed, predict the development of thermal stratification and mixing during a steam injection into a large pool of water. The experiments exhibit the development of thermal stratification in the pool at relatively low mass flow rates and then pool mixing when the mass flow rates are increased but later thermal stratification can re-develop even at the same relatively high mass flow rates, which is due to the increasing pool temperature that shifts the condensation to a different regime. The numerical simulations quantitatively capture this complex transient pool behavior and are in excellent agreement with the transient averaged pool temperature and water level in the pool.

1. Introduction

Heat exchange systems that involve direct steam injection into a pressure suppression pool can be found in different industrial applications. In a Boiling Water Reactor (BWR), an important component of its passive safety system is the pressure suppression pool (PSP) that serves primarily as a heat sink in case of a loss of coolant accident (LOCA) and station blackout (SBO) such as during the Fukushima Daiichi accident. The suppression pool is also a source of water for the reactor's cooling systems and for possible severe accident mitigation measures. The steam injection is a source of heat and momentum in the pool that directly affects its thermal behavior and as a result the pool is either thermally mixed or stratified. The corresponding top surface temperature of the pool determines partial pressure of steam and thus pressure in the containment. The thermal state and water inventory of the pool has a significant influence on the possibility of containment failure (Gamble et al., 2000). Hence a reliable prediction of stratification and mixing phenomena is necessary for safety analysis of pressure suppression pool operations.

There have been numerous experimental studies on stratification and mixing in a pool (see Kataoka et al., 1991; Fox, 1992; Smith et al., 1992; Norman et al., 2006; Song et al., 2014; Cheng et al., 2006; Laine and Puustinen, 2006; Laine et al., 2013, 2014 and references therein). Most experimental tests with steam injection have been carried out with small diameter pipes and not all experimental data is readily available for model development and code validation. On the other hand, computational studies on stratification and mixing phenomena have been performed widely using lumped parameter codes and 1 D codes (Peterson, 1994; Zhao, 2003; Zhao and Peterson, 2007), since the use of fine resolution CFD methods (e.g., RANS, LES, DNS) in modeling 3D high Rayleigh number natural convection flows in a large pool, and most importantly, direct contact condensation on the steam-water interface is not practical.

Previously, we have proposed two effective models, namely, Effective Heat Source (EHS) and Effective Momentum Source (EMS) models (Li et al., 2013, 2014a). These validated models (Li et al., 2014b) can be utilized to predict thermal stratification or mixing during steam injection into a large pool of water.

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The EHS model provides thermal effect of steam injection in the form of a distributed heat source with the purpose to conserve mass and thermal energy of the injected steam. In Fig. 1 a schematic diagram of the EHS model is shown. It is assumed that only hot saturated water flows out of the blowdown pipe, i.e. all steam is condensed inside the blowdown pipe. Such approach correctly preserves the mass balance in the system even if some fraction of injected steam is condensed outside the pipe outlet.

The EMS model (Fig. 1) provides time averaged momentum source induced by steam injection. This momentum creates large scale circulation in the pool which can lead to erosion of thermally stratified layer and mixing of the pool. Different regimes of steam condensation in the pool (Li et al., 2014c) result in different dynamics of the free surface oscillations. It was proposed (Li et al., 2013, 2014a) to use "synthetic jet" model (Smith and Swift, 2003) in order to predict effective momentum generated by the oscillations of steam-water interface. Specifically, for a single harmonic oscillation, the velocity scale based on the momentum flux (Smith and Swift, 2001; Krishnan and Mohseni, 2009) is given as

$$U_0 = \sqrt{2}fL \tag{1}$$

where f is the frequency of oscillation and L is the amplitude of oscillation. In (Villanueva et al., 2015), we have proposed a scaling approach to determine the amplitude and frequency of oscillations given the Froude number (which relates the inertial forces to gravitational forces). The momentum rate is then given as,

$$M = \pi\rho U_0^2 d^2/4 \tag{2}$$

where ρ is the liquid density and d is the diameter of blowdown pipe.

In the current paper, the EHS/EMS models are implemented and validated against PPOOLEX-MIX experiments (Laine and Puustinen, 2006; Laine et al., 2013). Six tests from the PPOOLEX-MIX series are used in this study. We will demonstrate the connection of the steam-water interface oscillations to the condensation regimes and consequently the pool's thermal behavior. At low steam mass fluxes, most of the steam condenses inside the blowdown pipe. The steam-water interface stays close to the pipe's exit and the oscillations are negligible. Given the EMS model, the effective momentum due to the oscillations is then zero. However, condensed hot water is also injected into the pool and is a source of momentum but its magnitude is relatively small. Hence, in this regime, the steam injection into the pool will likely result in thermal stratification of the pool. At relatively high steam mass fluxes, the steam-water interface can oscillate that can generate enough momentum to mix the pool provided that the frequency and amplitude of oscillations are large and frequent enough. However, it will be shown here that even if the steam mass fluxes are kept relatively high, the steam-water interface oscillations can die down and the effective momentum decreases significantly thereby resulting in re-stratification of the pool. In connection to the condensation regime map, the pool's bulk temperature increases and the steam condensation regime goes to 'transition' which is exhibited by a reduction in frequency and amplitude of oscillations.

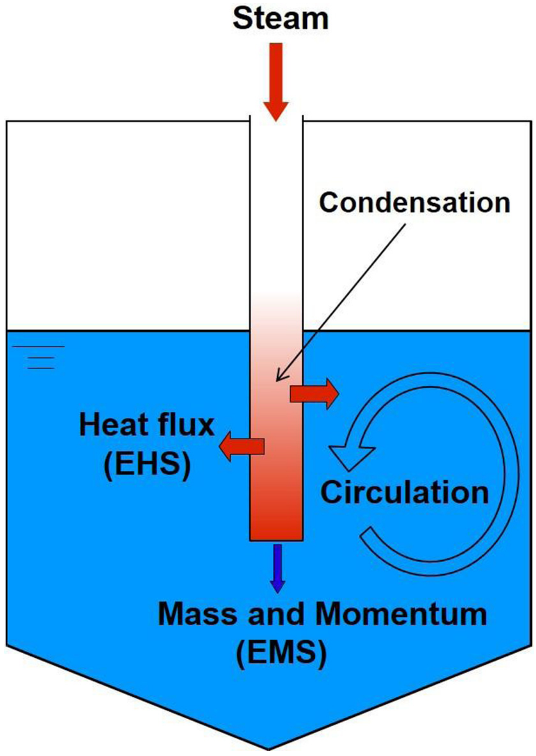

Fig. 1. Schematic of proposed Effective Heat Source (EHS) and Effective Momentum Source (EMS) models.

In the succeeding section, some details of the PPOOLEX facility are presented. Next, details of the implementation of EHS/EMS in GOTHIC® 8.0 are provided. Then it is followed by discussions of the validation of EHS/EMS against the PPOOLEX experimental tests. First, validation of EHS/EMS against PPOOLEX tests that involve the development of thermal stratification and then mixing is presented. Second, validation of the EHS/EMS models against PPOOLEX tests that also include re-stratification is discussed. Finally, conclusions are provided.

2. PPOOLEX-MIX experiments

A series of experiments on steam condensation, thermal stratification, and mixing in a large water pool have been performed at Lappeenranta University of Technology (Finland) with POOLEX (POOL EXperiment) and later modified PPOOLEX (Pressurized POOLEX) facility (Laine and Puustinen, 2006; Laine et al., 2013). In Laine and Puustinen (2006) and Laine et al. (2013, 2014) details on the scaling of the facility in comparison to Olkiluoto 1 and 2 have been provided. The POOLEX/PPOOLEX series are among the few experiments on water pool mixing/stratification at such large scales, and the availability of data was very instrumental for the validation of the EHS/EMS models (Li et al., 2014a,b).

The PPOOLEX facility is a closed cylindrical stainless steel tank with an outer diameter of 2.4 m (see Fig. 2a). It has both a drywell (~3.2 m height) and a wetwell (~4.2 m height) and is considered to be realistically closer to a containment of BWRs than POOLEX. The bottom is close to hemispherical and the drywell wall was insulated while the wetwell was not insulated during the tests. First, steam is injected through a horizontal inlet plenum, then into the drywell, and finally it discharges into the wetwell through a vertical blowdown pipe which is installed close to the central axis of the tank, with a length of about 3.1 m. A vacuum valve is installed between the drywell and the wetwell in order to balance the pressure between the compartments once the steam discharge is stopped. A single train of 16 TCs was installed in the wetwell at different elevations to measure the temperature distribution in the pool.

There are 12 experimental tests performed in the PPOOLEX-MIX series (Laine et al., 2013, 2014). The first subseries, MIX-01 to 06, was done with a 0.209 m diameter of the blowdown pipe while the second, MIX-07 to 12, was done with a smaller 0.109 m diameter of the blowdown pipe. The second subseries covers a wider region in the chugging regime map than the first subseries. A total