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Dimensional analysis of thermal stratification in a suppression pool

Daehun Song [a,b,*], Nejdet Erkan [a], Byeongnam Jo [a], Koji Okamoto [a]

[a] Nuclear Professional School, The University of Tokyo, 2-22 Shirakata, Tokai-mura, Ibaraki 319-1188, Japan
[b] Dept. Human and Engineered Environmental Studies, The University of Tokyo, 5-1-5 Kashiwano-ha, Kashiwa, Chiba 277-8563, Japan

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ABSTRACT

Due to complexity of direct contact condensation (DCC), it is difficult to predict the thermal hydraulic phenomenon in a suppression pool (SP) of LWRs. Especially, the momentum, induced at condensation interfaces, depends on several interrelated parameters such as the steam mass flux, subcooling, and the diameter of the injection nozzle. Complicated interaction of those parameters creates difficulties in developing a comprehensive analytical model, which applicable to various conditions. To investigate the criteria of thermal stratification created by DCC, experiments were performed using a downsized suppression pool. Time resolved temperatures were acquired by vertically aligned thermocouples. Additionally, steam bubbles were visualized by a high speed camera in order to examine bubble shapes according to the mass flux and subcooling. Both steam bubble frequency and amplitude were analyzed for different DCC regimes. Finally, Richardson number was chosen as a suitable parameter for the dimensional analysis of experimental results. Corresponding velocity at far field in synthetic jet theory was employed to calculate Richardson number. The criteria for the occurrence of the thermal stratification were clearly determined according to the Richardson number.

Introduction

Thermal stratification is formation of horizontal layers having different temperatures at different depths due to the density differences in a liquid pool. Although thermal stratification is a desired condition in some sensible heat storage systems, it may lead to heat sink malfunctions due to the extra increase of temperature and pressure particularly in Boiling Water Reactors (BWR). In case of an abnormal operational condition in a BWR, if thermal stratification occurs inside the pressure suppression system, the capability to cool down the system and suppressing the pressure would become significantly lower (Gamble et al., 2001). Moreover, elevated temperatures of the upper region of the pool promote the pressure increase in the gaseous space (wetwell) of the suppression pool.

Since thermal stratification is highly sensitive to momentum and geometry of liquid container, theoretical investigations may have difficulties and they may have extensive sensitivity due to the variation of parameters (Bankoff, 1980; de with, 2009). Because the main momentum input to the system is originated from condensation interface, characteristics of the momentum input and its dependency on the DCC regime should be investigated. The degradation of cooling capacity and pressure suppression capacity of suppression pool is important for safe operation of BWRs (Norman and Revankar, 2010a,b). The thermal stratification criteria should be taken into account in the design stage of nuclear power plants and in the analysis of reactor dynamics in case of abnormal operational conditions such as severe accidents.

Moreover in various industrial two-phase flow systems such as condensers, boilers, the injection of vapor into the liquid form of same substance is a common practice. DCC is a phase change process that the vapor condenses into its liquid phase on the gas–liquid boundary. It is used as a method to depressurize gaseous systems quickly using the large difference of specific volume. For example, the specific volume of saturated steam at atmospheric pressure is 1.679 m^3/kg and the one of saturated water is 1.044×10^3 m^3/kg (Incropera et al., 2007).

By various investigators, the DCC behavior was divided into several regimes according to the subcooled temperature and steam mass flux (Chan and Lee, 1982; Aya and Nariai, 1987; Liang and Griffith, 1994). As steam mass flux increases, the shape of the bubble deforms in the forms of oscillatory interface (OI), chugging bubble, oscillatory bubble (OB) and jet. As subcooling temperature decreases, the bubble tends to be longer by taking ellipsoidal shape and finally escape from the pool surface. The chugging and oscillation of the bubble are known to be generated due to the condensation capacity changes by the interface surface area changes. The

* Corresponding author at: Dept. Human and Engineered Environmental Studies, The University of Tokyo, 5-1-5 Kashiwano-ha, Kashiwa, Chiba 277-8563, Japan. Tel.: +81 3 58416996; fax: +81 4 58418613.
E-mail address: dhsong@vis.t.u-tokyo.ac.jp (D. Song).

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interfacial surface area changes by the unstable pressure variations. The size of the injection pipe is included as an additional parameter for condensation regime (Petrovic de With et al., 2007). They introduced the tree dimensional regime map depending steam mass flux, water subcooling, and injector diameter. DCC is explained by three main regimes; (1) chugging regime (2) jetting regime (3) bubbling regime and four regions; (1) steam plum (2) interface (3) hot water layer (4) surrounding water. Type of DCC regime is important in thermal stratification formation since the different regime demonstrates different momentum near to interface and hot water layer.

When thermal stratification takes place inside of SP, there are two areas; mixing area and non-mixing area. Those are characterized by non-uniform temperature area and uniform stable temperature area, respectively. Mixing area is formed by natural circulation induced by DCC. An interface forms between mixing and non-mixing area, and the mass of coolant located in lower regions of the pool so-called non-mixing area does not contribute to cooling of the system. This mixing interface determines the pressure suppression capacity of a SP. When the mixing interface is higher than the pool bottom, thermal stratification occurs and when the mixing interface touches to the pool bottom, the pool is totally mixed.

There are several experimental and analytical studies about thermal stratification and mixing phenomenon by DCC in the water pools (Cheng et al., 2006; Kang and Song, 2008; Choo and Song, 2010). One large group is working on the validation of thermal stratification and mixing simulation using the experimental data from POOLEX test facility in Lappeenranta University of Technology. It is proposed that the steam injection affects thermal stratification and mixing by means of two main mechanisms; (1) Localized heat source in the pool due to steam condensation and (2) Localized momentum source induced by steam injection (Purhonen et al., 2005; Laine and Puustinen, 2006; Tanskanen and Lakehal, 2008; Li et al., 2011, 2012). Those two models are interpreted as EHS (Effective Heat Source) approach and EMS (Effective Momentum Source) approach. For EHS, wall heat flux was used as energy input to the system and volumetric momentum source near to injection pipe was used for EMS. A few computational tools such as GOTHIC, BMIX++ and NEPTUNE CFD were validated with some experiments (Li and Kudinov, 2010; Zhao et al., 2012; Tanskanen and Lakehal, 2008). They employed the corresponding velocity at far-field from synthetic jet theory to calculate the momentum (Li et al., 2012).

As to our knowledge, a detailed investigation of criteria for thermal stratification generated by DCC does not exist in the literature. In this article, we aim to find out the effects of DCC to thermal stratification in a SP and to propose efficient methods to detect thermal stratification. For this purpose we performed experimental study on a simplistic model of SP, along with the time resolved temperature and pressure measurements. The steam bubble frequency and amplitude were obtained from the time-resolved images recorded by a high-speed camera. Richardson numbers for DCC (Ri_{DCC}) were obtained using corresponding velocity field at far-field.

Dimensional numbers related to thermal stratification created by DCC

There are several dimensional numbers, which are well known in thermal–hydraulics to investigate thermal stratification such as; Grashof number, Reynolds number and Richardson number as defined in Eqs. (1)–(3). Grashof number approximates the ratio of buoyancy to viscous force, where L is the distance from the pipe tip to the bottom surface of SP. Reynolds number represents the ratio of inertial force to viscous force. Richardson number gives the ratio of potential energy to kinetic energy that represents the ratio of the buoyancy to inertial force in thermal convection. It also addresses the importance of natural convection to forced convection.

$$Gr = g\left(\frac{\rho_{sat} - \rho_{amb}}{\rho_{sat}}\right)\frac{L^3}{\nu^2} = \frac{g\beta(T_{sat} - T_{amb})L^3}{\nu^2} \quad (1)$$

$$\mathrm{Re} = \frac{uL}{\nu} \quad (2)$$

$$Ri = \frac{Gr}{\mathrm{Re}^2} = \left(\frac{\rho_{sat} - \rho_{amb}}{\rho_{sat}}\right)\frac{gL}{u^2} = \frac{g\beta(T_{sat} - T_{amb})L}{u^2} \quad (3)$$

Here g is the gravitational acceleration, ρ is the density, T is the temperature, L is the distance between steam injection pipe tip and pool bottom, β is thermal expansion, ν is dynamic viscosity and u is velocity. In the subscript, *sat* refers to saturation and *amb* refers to ambient fluid.

Due to the scaling effects, it is not reasonable to evaluate the experimental results in downsized experimental setup as the direct reflection of phenomena occurring in real scale large systems. As mentioned before, the steam bubble frequency, amplitude and even velocity magnitudes are affected by the steam injection pipe inner diameter even at the same steam mass flux. It could change not only the momentum but also change the characteristics of DCC regime. L is an important parameter regarding to the thermal stratification, because thermal stratification could take place if L is large enough even though the momentum from condensation is very large. However, since the velocity magnitudes sensitive to the pipe inner diameter, L should be considered together with the velocity magnitude.

Due to low driving force compared to the size of the entire SP, the entire flow can be regarded as laminar flow. However turbulent effects could be observed around the condensation interface and in the hot condensate plume. Similar behavior exists even in downsized SP although the amount of turbulent intensity and turbulent kinetic energy would not be downsized at the same rate with the downsizing ratio. Since Ri is the ratio of the buoyancy to inertial force, Ri is regarded as the most critical dimensional parameter for the thermal stratification to be focused on. A global criterion of thermal stratification can be identified by one dimensional parameter, Ri, in spite of scale differences.

When $Ri \gg 1$, natural convection, driven by the buoyancy, becomes stronger than the forced convection and thermal stratification may take place. On the other hand, if $Ri \ll 1$, forced convection, induced by steam injection and condensation oscillation, becomes stronger than the natural convection that leads to mixing of SP water. Since DCC is two-phase phenomenon, mean steam velocity or mean condensate velocity from steam flow rate cannot be exactly regarded as the velocity term for Ri. Although the steam is injected with a particular mean steam velocity, the steam condenses around the pipe tip and the momentum from the steam is not transferred directly to the liquid. Additionally, if the mean condensate velocity is calculated from the condensate volume flow rate and the area of cross section, the velocity is found to be extremely low. For this reason, the velocity should be obtained from the steam bubble oscillations. Fig. 1 schematically represents the corresponding velocity at far-field from condensation interface. The momentum induced by the oscillation of condensation interface creates a velocity field in the liquid. At near-field, DCC could make harsh oscillations with certain amplitudes and frequency but at far-field, it is transferred to the certain velocity and momentum. The corresponding velocity is defined as $\sqrt{s\delta f}$ (Mallinson et al., 1999). The momentum rate can be obtained as shown in the Fig. 1.