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Experimental analysis of steam mixing and thermal stratification phenomena related to small steel containment studies

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ABSTRACT

To study the mixing and thermal stratification caused by the plumes or buoyant jets in the small steel containment during the LOCA or MSLB accidents, temperature was measured experimentally. Using steam as the working medium, the experiments were conducted with various jet inlet temperatures and spray water flow rates to identify their influence on the thermal stratification phenomena. Temperature distributions with height are given to illustrate the thermal stratification in containment. The performed analysis shows that recirculating stratified fluid existed in only lower part of containment while steam mixing and temperature homogenization happened in upper part of containment. Rayleigh-Benard convection, which is often neglected in big steel containment stratification, and convection caused by negatively buoyant jet and plume entrainment are considered to be the major factors causing steam mixing. It is suitable to consider such thermal stratification and steam mixing in developing a more accurate and detailed model for small steel containment and system design of SMRs.

1. Introduction

Passive Containment Cooling System (PCCS) plays a critical role in the advanced PWR. AP1000 – the generation III nuclear power reactor designed by Westinghouse has two independent containments in PCCS, the inner cylindrical steel container and the outer reinforced concrete structure. The inner cylindrical steel container with elliptical upper and lower heads is the main heat transfer surface since it is exposed to the external ambient air partly as part of the PCCS' air cooling flow passage.

In the containment, one of the key issues relevant to the passive cooling or natural heat convection is the thermal mixing and stratification phenomena which may occur during the LOCA or MSLB (Zhao and Peterson, 2010). Generally, strong stratification is observed in large enclosures, induced by temperature and/or concentration gradients. The transport and condensation of the steam is strongly affected by its mixing with the ambient non-condensable gas. Due to large differences between the molecular weights of water vapor and air/nitrogen, and the typical differences in their temperatures, large density differences can exist between the injected buoyant jet fluid and the ambient enclosure fluid (Peterson, 1994).

A useful definition of stratification is a lack of horizontal gradients in the ambient fluid (Woodcock et al., 2001). The study of stratification and mixing is performed by Baines and Turner (Baines and Turner, 1969). They described that how stratification is built up in an enclosure when plume released and it is associated with Richardson number. Hunt et al. (2001) in his research have demonstrated that the heat sources such as the plumes or the buoyant jets can potentially generate the stratification or well-mixed ambient in some smaller enclosures. Peterson (Peterson, 1994) in his scaling analysis has developed the criteria for the prediction of the ambient fluid stratification in the containments or enclosures, and for an injected buoyant jet, the ambient fluid is stably stratified when

$$S_1 = \left(\frac{H_{sf}}{d_{bjo}}\right) Ri_{d_{bjo}}^{1/3} \left(1 + \frac{d_{bjo}}{4\sqrt{2}\cdot\alpha_T H_{sf}}\right)^{2/3} > 1 \quad (1)$$

$$Ri_{d_{bjo}} = \frac{(\rho_a - \rho_o) g d_{bjo}}{\rho_a U_o^2} \quad (2)$$

where H_{sf} is the height of an enclosure, d_{bjo} is the diameter of the jet source, $\alpha_T = 0.05$ is the Taylor's jet entrainment constant, ρ_a is the

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Nomenclature

d	diameter
D	mass diffusion coefficient
g	gravitational acceleration
Gr	Grashof number
h	specific enthalpy
H	height *ns*
k	thermal conductivity
k_m, k_u	entrainment coefficients
n	number of jets
ns	number of species/phases
P	pressure
Pr	Prandtl number
Q	volume flow rate
Q'	volume rate of entrainment per unit length
Ri	Richardson number
$\boldsymbol{S}$	vector of source terms
S_1, S_2, S_3	value of stratification criterion
S'	source rate per unit volume
S'	sink rate per unit volume
T	temperature
U	velocity
z	vertical coordinate

Greek symbols

α_T	Taylor's jet entrainment constant
δ	boundary layer thickness
ρ	density
χ	mass fraction

Subscripts

a	ambient
bj	free buoyant jet
bl	wall jet (boundary layer)
k	index number
o	entrance/nominal value
sf	ambient, stratified fluid

ambient fluid density, ρ_o is the source fluid density, g is the gravity constant, and U_o the jet source speed. Richardson number gives the ratio of potential energy to kinetic energy that represents the ratio of the buoyancy to inertial force in thermal convection.

For a buoyant plume when

$$S_2 = \frac{4.17}{k_m}\left(\frac{H_{sf}}{d_{bjo}}\right)^{5/3} Ri_{d_{bjo}}^{1/3} \gg 1 \tag{3}$$

horizontal density gradients in the ambient fluid become negligible. Value for the constant k_m is approximately 0.35. Gebhart et al. (Gebhart et al., 1988) give the length scale for the location of the transition from forced jet to buoyant plume for cylindrical buoyant jets, Z_{trans}

$$\left(\frac{\rho_a U_o^2}{(\rho_a - \rho_o) g d_{bjo}}\right)^{-1/4} \left(\frac{\rho_o}{\rho_a}\right)^{-1/4} \left(\frac{Z_{trans}}{d_{bjo}}\right) = 1 \tag{4}$$

And for a wall jet when

$$S_3 = 73.1\left[1 + 0.494 Pr^{2/3}\right]^{4/5} Pr^{16/15} Gr_{H_{sf}}^{1/5} \gg 1 \tag{5}$$

then horizontal density gradients in the ambient fluid become negligible.

The criteria provides a method to study atmosphere temperature and pressure in containment after LOCA or MSLB. If stratification phenomenon exists, horizontal density gradient or even temperature gradient become negligible, which is helpful to improve computational speed and accuracy. It is important for system design and accident analysis to simulate thermal-hydraulic performance, to recognize influence of the factors such as temperature distribution, fluid velocity on system operation (Kim and Youn, 2008), to predict distributions of pressure, temperature, and steam concentration, and to evaluate whether the circulation can establish in the containment accurately and efficiently. The experiments performed in the TOSQAN facility in Saclay (France) (Kljenak et al., 2006) focus on containment atmosphere mixing and stratification, and the two-dimensional axisymmetric CFD model proposed in the paper is consider to be adequate and could be applied to similar simulations. Experiments carried out in PANDA and MISTRA facilities (Studer et al., 2012) studied gas stratification break-up induced by mass sources. With a good agreement between the tests results and CFD simulation, it demonstrated that the interaction Froude number can be used to identify the ability of the air jet to dilute the stratified layer. M. Povilaitis (Povilaitis et al., 2011) described the MISTRA test facility and the performed experiment M5, the gas flow model of the COCOSYS code. The performed analysis shows that results obtained using volume flow rates calculated from the empirical formula were inaccurate since large flow rates will cause too-homogenous atmosphere.

A one-dimensional model has been developed by (Yu et al., 2014) and used to calculate transient temperature and pressure under LOCA or MSLB accident. Supported by the stratification criterion mentioned above, this model can determine where and when to use the one-dimensional code or lumped-parameter code for the calculation. When strongly stratified, ambient temperature and concentration distributions can be considered one-dimensional, the conservative equations are modified to be applied to circulation and coupling heat transfer simulation, and the steam condensation is also considered in this model. And the plume jet model is used to simulate the steam jet.

Although the criteria given by (Peterson, 1994) can be used in judgement as to whether stratification has occurred, it cannot be used to illustrate where the stratification will occur or spatial scale of stratification. In large containment, like AP600, ambient fluid may stratify in the whole space, but that need to be discussed in small containment.

Small modular reactors (SMRs) are part of a new generation of nuclear power plant designs with a power generally rating from approximately 10 to 300 MWe (Carelli and Ingersoll, 2015). There is renewed interest in the development and application of SMRs due to the advantages of flexible on-site construction, heightened nuclear materials security, and increased containment efficiency. The size of SMR containments can be much smaller than conventional PWR containments. For example, compared to 39.62 m in diameter and 65.63 m in height of the containment in AP1000 (Lin et al., 2010), the Westinghouse SMR containment design reduce to 9.8 m in diameter and 27 m in height (International Atomic Energy (IAE) Agency, 2012). And steel containment vessel has been taken in the design of SMR, such as NuScale reactor. The influence of LOCA or MSLB accidents to the steel containment in SMR cannot be considered to be same as large containment like