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Modeling and experimental studies on mixing and stratification during natural convection in containments

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ABSTRACT

Mixing and thermal stratification often occur in passive containment cooling systems. Currently, most of reactor system analysis codes do not use the thermal stratification to simplify the calculation. The 2-D or 3-D CFD methods require very fine grids and long running times. In this paper, a new code based on thermal stratification is used to solve heat transfer problems in large enclosures which can give good results in a short time without complex meshing. The models in the code provide the capability to simulate the containment. At the same time, a series of small scale model experiments with air injection are conducted to simulate the LOCA accidents. Simple variable method is adopted in the experiments to study the effects of four different factors on the flow field. The results of the experiments and the codes are compared to verify the validity of the code. Several typical conditions were calculated by a CFD code, and comparison between the running times of these two codes shows the advantage of the model used in the new code.

1. Introduction

Passively cooled containment utilizes a passive containment cooling system (PCCS) which ensures important parameters remain within safety limits throughout postulated accident scenarios. For large periods of these accident transients, containment depends on the natural circulation to remove heat. Previous study has shown that thermal mixing and stratification phenomena tend to occur in passive containment cooling system, which can affect the formation of natural circulation (Peterson, 1994). So it is necessary to make a study of the phenomena when accidents happen in the containment.

Currently, reactor system analysis codes usually use lumped parameters models which can only give very approximate results without considering the thermal stratification phenomena. The CFD methods often require very fine grids to resolve thin substructures or boundary, such as jets and wall boundaries, and such fine grid resolution is difficult or impossible to be provided when studying the reactor response to transients due to prohibitive computational expenses and long running time (Zhao and Peterson, 2009).

For the light water reactors (LWR), post-LOCA gas transport, gas mixing and mass transfer between containment compartments and hydrogen distribution have been identified as high-ranking phenomena, because they mostly impact the risk of containment failure (Auban et al., 2007). Studies related to different LWR designs and accident scenarios conducted at the Paul Scherrer Institute (PSI) in former research programs (Wichers et al., 2001) have shown the importance of stratification that affects the containment end-pressure through its effect on the distribution of light gases in the containment. Several large test facilities, such as Swiss PANDA (Auban et al., 2007) and German THAI (Schwarz et al., 2003), have been used to study these phenomena over the past years.

AP1000 design uses a passive containment cooling system to remove decay heat. Mass transfer is the dominant means of containment heat removal on both inner and outer steel shell surfaces. In the containment, condensation on the containment shell dominates heat removal and is strongly influenced by distribution of steam and non-condensable gases. The containment design used several highly conservative assumptions regarding mixing and condensation. So, long-term cooling in AP1000 design shows the importance of mixing and stratification phenomena in the containment.

As the lumped parameter model and CFD methods are not appropriated for containment heat transfer calculation, new

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Nomenclature

A	area (m^2)
D	mass diffusivity (m^2/s)
h	enthalpy (kJ/kg)
k	thermal conductivity ($W/(m^2\ s)$)
n	total number of jets
P	pressure (Pa)
Q	volume flow rate (m^3/s)
Q'	entrainment rate (m^2/s)
χ	mass fraction
s'	volumetric source (m^2/s)
$\hat{s}'$	sink per unit length (m^2/s)
S'_h	volumetric energy source (kJ $m^2/(kg\ s)$)
$\hat{S}'_h$	sink per unit length (kJ $m^2/(kg\ s)$)
T	temperature (K)
t	time (s)
Z	distance along vertical direction (m)

Subscripts

ns	number of species
sf	stratified ambient fluid

accurate and efficient thermal mixing and stratification methods are needed to improve analysis accuracy and reduce modeling uncertainties (Niu et al., 2007; Zhang et al., 2013). So, the improved modeling capability would increase the confidence on the passive containment performance.

In this paper, a new code based on thermal stratification is used to solve heat transfer problems in large enclosures which can give good results in very short time without complex meshing. A series of small scale model experiments with air injection are conducted to simulate the loss of coolant accidents. In order to verify the validity of the modeling, the experimental data are compared with calculation results. Several typical cases were calculated by the CFD code, by comparing the running time of these two codes shows the advantage of the model used in the new codes.

2. Modeling for mixing in stratified containment

Peterson's scaling analysis (Peterson, 1994; Zhao and Peterson, 2010) showed that the ambient fluid between jets tends to organize into either a homogeneously mixed condition or a vertically stratified condition that can be described by a 1-D temperature and concentration distribution.

For the stratified enclosure, the governing equations for the ambient fluid can be derived and written in the following compact form (Peterson, 1994; Zhao and Peterson, 2010):

$$A(z)\frac{\partial G}{\partial t}+\frac{\partial F}{\partial z}=S \tag{1}$$

where $A(z)$ is the horizontal cross sectional area of the volume at elevation z, and G, F and S are the vectors of conserved quantities, fluxes, and source terms, respectively.

$$G=\begin{pmatrix}\rho\\ 0\\ \rho h\\ \rho\chi_1\\ \vdots\\ \rho\chi_{ns-1}\end{pmatrix}\quad F=\begin{pmatrix}\rho Q_{sf}\\ P\\ \rho h Q_{sf}-Ak\frac{\partial T_{sf}}{\partial z}\\ \rho\chi_1 Q_{sf}-\rho AD\frac{\partial\chi_1}{\partial z}\\ \vdots\\ \rho\chi_{ns-1}Q_{sf}-\rho AD\frac{\partial\chi_{ns-1}}{\partial z}\end{pmatrix}$$

$$S=\begin{pmatrix}-\sum_{k=1}^{n}(\rho Q')_k+\rho S'-\rho\hat{S}'\\ -\rho g\\ -\sum_{k=1}^{n}(\rho h Q')_k+\rho S'_h-\rho\hat{S}'_h\\ -\sum_{k=1}^{n}(\rho\chi_1 Q')_k+\rho\chi S'-\rho\chi\hat{S}'\\ \vdots\\ -\sum_{k=1}^{n}(\rho\chi_{ns-1}Q')_k+\rho\chi_{ns-1}S'-\rho\chi_{ns-1}\hat{S}'\end{pmatrix} \tag{2}$$

Traditional numerical methods used to solve the conservation equations in general have great difficulty in preserving strong gradients in hyperbolically dominated flow (Christensen and Peterson, 2001; Zhao and Peterson, 2010). So, a Lagrangian approach is adopted to solve 1-D transient governing equations for the ambient fluid. It can eliminate "false diffusion" from the discretized equations and give physically acceptable solutions even for coarse computational grids. The Lagrangian method tracks the position of constant mass fluid 'layers'. In practice, the enclosure is divided into a user-specified number of horizontal control volumes and the conservation equations, without the diffusion terms, are then used to calculate the new positions, compositions and enthalpies of the control volumes for each time step. Next the composition and energy is corrected according to the diffusion terms in the conservation equations (Zhao, 2003; Peterson et al., 1998).

In this paper, a jet is considered to be a generic concept of any steady continuous flow structure in an ambient volume with a dominant flow direction and a length scale much less than the ambient volume's scale. Common jets includes plume, jet, buoyant jet and wall jet, etc. (Woodcock et al., 2001). Jet is usually a fluid has high initial speed and is able to continue moving after injection. Plume is contrary to the jet, and its initial speed can be negligible, only rely on the buoyancy effect to make it movement. Buoyant jet is a fluid both has initial speed and buoyancy effect.

As we know, when a loss of coolant accident happens in the containment, different kinds of jets may exist (Cheng et al., 2000). In the code, several jet models are embedded to simulate various kinds of jets, so it can be used in the containment with different kinds of break. Buoyancy driven flows, potentially augmented by break-jet momentum, will play a key role in the

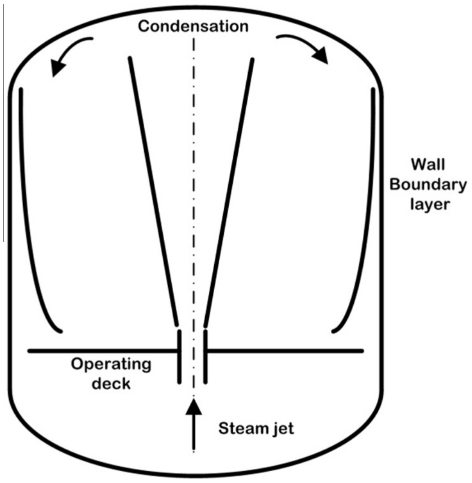

Fig. 1. Conceptual models for containment mixing process.