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Effects of gas velocity and break size on steam penetration depth using gas jet into water similarity experiments

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ABSTRACT

A method is given to predict the steam penetration depth under an incidental Steam Generator Tube Rupture (SGTR) accident. Several similar experiments were performed by injecting gas into water to simulate the steam jetting into liquid Lead Bismuth Eutectic (LBE). The steam penetration behaviors including flow regimes and cavity phenomena were captured by visualization method and a semi-empirical correlation was modified for the penetration depth based on dimensional analysis and experimental data. The results showed that the penetration depth was proportional to the density ratio of gas jet to liquid coolant, gas velocity, and break size of tube. Further predictions with similarity theory have been conducted. The penetration depth was about 0.7 m during a large break (a double-ended break) of one SG cooling tubes under a postulated SGTR accident of lead-based reactor.

1. Introduction

Due to its good neutronic, thermal-hydraulic and chemical stability characteristics, Lead Bismuth Eutectic (LBE) has been proposed as the primary candidate coolant material for lead-based reactor and Accelerator Driven subcritical System (ADS), which play a significant role in safety, economics and sustainability of nuclear system (Tuček et al., 2006; OECD, 2007; Wu et al., 2015a). In recent years, the study on lead-based reactor has been carried out in several countries. In Russia, an experimental and industrial small-scale modular LBE-cooled reactor SVBR-75/100 has been developed, which is intended primarily for the regional scale nuclear power plant (Zrodnikov et al., 2011, 2006). In Europe, the ELSY (European Lead-cooled System) project was initiated in 2006, which aimed at demonstrating the possibility of designing a safe fast critical reactor. The LEADER (Lead-cooled European Advanced Demonstration Reactor) project and the CDT-FASTEF (Central Design Team-fast spectrum transmutation experimental facility) project were initiated as part of the 7th Framework Programme. A small lead cooled fast reactor demonstrator, sized at 120 MW, designated as ALFRED (Advanced Lead-cooled Fast Reactor European Demonstrator) is underway (Cinotti et al., 2011). In China, the Institute of Nuclear Energy Safety Technology (INEST/FDS Team), Chinese Academy of Sciences (CAS) carried out R&D activities about advanced reactor system, particularly in terms of reactor conceptual design (Wang et al., 2015a,b; Wu and FDS Team, 2006, 2007a, b, 2008, 2009a; Qiu et al., 2000; Wu et al., 2011; Wu, 2007), neutronics theory and coupling method (Wu et al., 1999, 2015b; Wu and FDS Team, 2009b; Li et al., 2007a), reactor material and key technologies (Huang et al., 2004, 2007, 2009; Li et al., 2007b; Wu et al., 2002, 2010). Based on the experience gained in these research, INEST/FDS team performed the China LEAd-based Reactor (CLEAR) project which was selected as the reference reactor for the Accelerator Driven subcritical System program. The objective of the first stage is to develop a 10 MW lead-bismuth cooled research reactor (CLEAR-I) (Wu et al., 2014, 2016; Wu, 2016; Wu and FDS Team, 2016).

The pool-type configuration of lead-based reactor usually adopts Steam Generators (SGs) or primary Heat Exchangers (HXs) placed inside the primary pool (Cinotti et al., 2007), and the core, primary pumps and other main components are also set in the pool. Large number of pipes housed in the SGs and the pressure of the secondary water loop is as high as 4 MPa (Wu et al., 2014), so the probability of a tube rupture cannot be ignored (Dinh, 2007; Sa et al., 2011). Because of the steam ingress into the reactor core

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with reactivity insertion, the consequences of a postulated Steam Generator Tube Rupture (SGTR) accident have been considered as an important issue to address in the reactor design process. During a SGTR accident, water/steam mixture in the secondary circuit is discharged through the failure site in the form of jet into the LBE pool. The discharged water is rapidly boiled and evaporated due to the rapid depressurization and the direct contact with the high temperature liquid metal. A steam jet could be dragged into the reactor core which has a potential positive void worth due to the high actinide load of the fuel (Wang et al., 2008; Gu et al., 2015; Ciampichetti et al., 2012). Therefore, one of the primary safety concerns in the design stage is the steam penetration depth in coolant and steam ingress into the reactor core.

The common characteristic of the phenomenon in SGTR is intense steam-liquid metal interactions, which occurs in regimes not studied previously. Due to the opaqueness of liquid LBE, flow visualization is limited to observing the motions of the steam bubbles. Several experimental studies on penetration behaviors in transparent fluid had been carried out. Saito et al. (1988) performed the study on penetration behaviors of water jet into Freon-11 and liquid nitrogen to investigate the penetration phenomena of molten jet into coolant. Park et al. (1998) conducted the water jet penetration into Fluorinert to simulate the Fuel-Coolant Interaction (FCI) energetics in the coolant injection mode. Some empirical correlations have been proposed based on the experimental data in this field. However, these results were obtained under different experimental conditions and their applicability may be limited. In the field of metallurgical engineering, Han (Han et al., 1996) correlated the experimental data of gas jet penetration into liquid, and proposed a dimensionless correlation based on a dimensional analysis. However, the geometry and operational conditions of this metallurgical engineering equipment are quite different from nuclear reactor systems. Therefore, these correlations may not be directly applied. In the present study, a method is given to predict the steam penetration depth under an incidental SGTR accident of lead-based reactor. The hydrodynamic behavior of penetration depth for steam leakage into lead alloy was conducted by jetting gas into water experiments. The penetration behaviors including flow regimes and cavity phenomena were visualized by high-speed photography technology. A semi-empirical correlation between penetration depth and Froude number was proposed based on a dimensional analysis and experimental data. The steam penetration depth under a postulated SGTR accident of lead-based reactor was approximately predicted by the semi-empirical correlation with similarity theory.

2. Dimensional analysis

The penetration depth of the gas jet injection into water was estimated as a mean value of the depth of the leading edge because slight oscillations were observed after establishing complete steady-state jet. The experimental resulsts from the previous study (Han et al., 1996; Krishnapisharody and Irons, 2013) indicated that fluid viscosity has little effect on penetration depth. Ignoring the liquid surface tension, the penetration depth of the gas jet injected into the liquid is related to the gas momentum, the liquid density, the gravitational acceleration and the nozzle diameter. The penetration depth correlation can be defined as

$$h = (m, \rho_l, g, D_j) \tag{1}$$

Where h is the steam penetration depth, m is the gas momentum at the nozzle, ρ_l is the liquid density, g is the local gravitational acceleration and D_j is the nozzle diameter. The units and dimensions of the parameters from equation (1) are shown in Table 1. Where L, M, T are the basic dimensions of length, mass, and time respectively.

Table 1
Units and dimensions of parameters to penetration depth.

Parameter	Unit	Dimension
Penetration depth ($\boldsymbol{h}$)	m	L
Gas momentum ($\boldsymbol{m}$)	N	MLT^{-2}
Liquid density ($\boldsymbol{\rho_l}$)	kg/m^3	ML^{-3}
Gravitation acceleration (g)	m/s^2	LT^{-2}
Nozzle diameter ($\boldsymbol{D_j}$)	m	L

There are five variables in equation (1) but only three basic dimensions (M, L, T). So, it can obtain two independent dimensionless numbers. The penetration depth, h, can be expressed as

$$h = k_1 m^a \rho_l^b g^c D_j^d \tag{2}$$

Where k_1, a, b, c and d are undetermined coefficients. Substituting the dimension into equation (2) one obtains

$$L = \left(MLT^{-2}\right)^a \left(ML^{-3}\right)^b \left(LT^{-2}\right)^c (L)^d \tag{3}$$

According to the theory of dimension homogeneity

$$M: a + b = 0$$

$$L: a - 3b + c + d = 1 \tag{4}$$

$$T: -2a - 2c = 0$$

From equation (4), it can obtain b = -a, c = -a, d = 1-3a. Substituting into equation (2)

$$\frac{h}{D_j} = k_1 \left(\frac{m}{\rho_l g D_j^3}\right)^a \tag{5}$$

Where m is the gas momentum in the nozzle and defined as

$$m = \rho_j \frac{\pi}{4} D_j^2 v_j^2 \tag{6}$$

Where v_j is the gas velocity at the outlet of the nozzle. Substituting equation (6) into equation (5), one obtains:

$$\frac{h}{D_j} = k \left(\frac{\rho_j v_j^2}{\rho_l g D_j}\right)^a \tag{7}$$

Where k is given by

$$k = k_1 \left(\frac{\pi}{4}\right)^a \tag{8}$$

Defined Froude number

$$Fr = \frac{v_j^2}{g D_j} \tag{9}$$

The function of penetration depth with two independent dimensionless numbers can be obtained, and written as

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