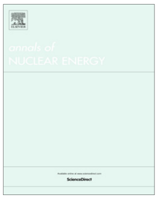
Annals of Nuclear Energy 75 (2015) 570–580

Contents lists available at ScienceDirect

Annals of Nuclear Energy

journal homepage: www.elsevier.com/locate/anucene



Experimental investigation of void distribution in suppression pool over the duration of a loss of coolant accident using steam–water two-phase mixture

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A R T I C L E I N F O

Article history:
Received 22 October 2013
Received in revised form 19 June 2014
Accepted 23 August 2014
Available online 25 September 2014

Keywords:
Pressure suppression chamber
Suppression pool
Void distribution
Blowdown
LOCA

A B S T R A C T

Studies are underway to determine if a large amount gas discharged through the downcomer pipes in the pressure suppression chamber during the blowdown of Loss of Coolant Accident (LOCA) can potentially be entrained into the Emergency Core Cooling System (ECCS) suction piping of BWR. This may result in degraded ECCS pumps performance which could affect the ability to maintain or recover the water inventory level in the Reactor Pressure Vessel (RPV) during a LOCA. Therefore, it is very important to understand the void behavior in the pressure suppression chamber during the blowdown period of a LOCA. To address this issue, a set of experiments is conducted using the Purdue University Multi-Dimensional Integral Test Assembly for ESBWR applications (PUMA-E) facility. The geometry of the test apparatus is determined based on the basic geometrical scaling analysis from a prototypical BWR containment (MARK I) with a consideration of downcomer size, downcomer water submergence depth and Suppression Pool (SP) water level. Several instruments are installed in the test facility to measure the required experimental data such as the steam mass flow rate, void fraction, pressure and temperature.

In the experiments, sequential flows of air, steam–air mixture and pure steam-each with the various flow rate conditions are injected from the Drywell (DW) through a downcomer pipe in the SP. Eight tests with two different downcomer sizes, various initial gas volumetric fluxes at the downcomer, and two different initial non-condensable gas concentration conditions in the DW are conducted. Three distinct phases, namely, an initial phase, a quasi-steady, and a chugging phase are observed. The maximum void penetration depth is observed in the initial phase. A reduction in the void penetration depth is observed in the quasi-steady phase. As a result of low non-condensable gas concentration, chugging is observed at the tail end of the experiment. Chugging provides renewed void penetrations comparable to those in the initial phase. It is determined that the void distribution and area of void penetration in the SP is governed by the gas volumetric flux at the downcomer and the non-condensable gas concentration in the downcomer.

1. Introduction

During a LOCA, the ECCS plays a significant role in flooding the Reactor Pressure Vessel to prevent the reactor core from uncovering and in removing decay heat from the reactor core. The primary source of supply water for the ECCS pumps is stored in the pressure suppression chamber of a BWR MARK I containment. There is a potential to challenge the performance of the low pressure ECCS due to large amounts of entrained gas in the ECCS suction piping located in the pressure suppression chamber of BWR MARK I containment (US NRC, 2010). Therefore, it is important to understand the physical phenomena in the pressure suppression chamber during a LOCA and to study the void distribution in the pressure suppression chamber resulting from the dynamics of the Drywell (DW) to pressure suppression chamber venting phenomena. The void distribution, bubble velocity, and bubble plume size, are the key parameters in this analysis of the physical phenomena.

In a LOCA, the steam and superheated water are expanded into the DW resulting in the pressure in the DW and downcomers in the pressure suppression chamber rising rapidly. In the initial phase of the blowdown, mostly non-condensable gas exists in the DW and is forced through the downcomers located in the pressure suppression chamber. The steam and non-condensable gas mixture injec-

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http://dx.doi.org/10.1016/j.anucene.2014.08.052
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Nomenclature

A	area
D	diameter
c	non-condensable gas concentration
j_g	gas volumetric flux
l	non-dimensional void penetration length
L	location from the center of downcomer exit
T	temperature
t	time
s	second
v	velocity
v_b	axial bubble velocity
v_{ub}	averaged upward bubble velocity

Greek symbols

α	void fraction
τ	time

Subscript

a	axial direction
avg	time-averaged value
ini	initial phase
b	bubble
g	gas
m	model
max	maximum value
p	prototype
$quasi$	quasi-steady phase
r	radial direction
st	steam
z	z direction

Acronyms

ADS	Automatic Depressurization System
BWR	Boiler Water Reactor
DW	Drywell
DPV	Depressurization Valve
ECCS	Emergency Core Cooling System
LOCA	Loss of Coolant Accident
SP	Suppression Pool
SRV	Safety Relief Valve
MSL	Main Steam Line
RPV	Reactor Pressure Vessel

tion is subsequent to the pure non-condensable gas mixture injection. Mostly steam injection occurs near the end of the blowdown. Therefore, the void distribution in the pressure suppression chamber over the blowdown period of a LOCA is affected by several important local phenomena.

During the initial phase of blowdown, water, initially standing in the downcomers, is accelerated into the pressure suppression chamber as a liquid slug and the downcomers become voided. Then, the formation of a large bubble of mostly non-condensable gas is introduced at the exit of the downcomer. The continued gas injection from the DW results in the volume expansion of this bubble at the exit of the downcomer. After that, this large bubble may deform and disintegrated bubbles spread around the downcomer and then move upward to the water surface. Notably, during this initial phase, some disintegrated bubbles are potentially entrained into the bottom of the pressure suppression chamber due to the circulating liquid flow caused by the initial liquid slug in downcomer injection. When the steam and non-condensable gas mixture are released into the pressure suppression chamber, condensation happens at the exit of the downcomers. This produces chugging phenomena at the exit of the downcomers with rapid condensation.

Five blowdown simulation experiments were performed (Fitzsimmons et al., 1979; Kadlec and Muller, 1976; Kukita et al., 1984; Aust et al., 1987; Laine, 2002). Most of them focus on investigation of dynamic and structural load caused by the gas injection, condensation and chugging phases in the pressure suppression chamber. No detailed information on the void fraction and void penetration in the SP was collected during those blowdown experiments. Only the research performed at POOLEX facility by Laine has examined gas bubble behaviors in the pressure suppression chamber and ECCS strainer by visual information observed from the video-camera during the blowdown. However, even in the POOLEX facility, there is a lack of void instrumentation.

In this study, the actual blowdown period in the DW and subsequent injection of sequential flows of air, steam–air mixture, and pure steam with the various flow rate conditions was simulated using the Reactor Pressure Vessel (RPV), DW and SP of the PUMA-E facility (Ishii et al., 2006). The major components in the SP of PUMA-E facility is scaled from a prototypical BWR containment (MARK I) with consideration of downcomer size, SP water level and downcomer water submergence depth. The conductivity probes are the key instrument applied to measure local void fraction in the SP including the axial bubble velocity and bubble size over the blowdown. Furthermore, the high-speed camera was used to obtain the visual information of the bubble plume around the downcomer exit. The recorded visual information was used to estimate void penetration length during the blowdown. The main objective of this study is to develop a physical understanding and to acquire experimental data for the void distribution and fluid dynamics in the pressure suppression chamber of a BWR over the blowdown period of LOCAs.

2. Experiment

2.1. Simple scaling approach

In this study, the pressure suppression chamber in MARK I containment is considered as the prototypic facility. To determine the main geometries of the test facility and the initial inlet boundary flow conditions for test conditions, a simple geometrical scaling was applied in this study and briefly described here.

The length ratio is applied to determine the water level in the SP, downcomer submergence depth while the downcomer diameter ratio is used to determine the downcomer diameter size. The length ratio is defined as

$$Le_R = Le_m/Le_p \tag{1}$$

the diameter ratio is defined as

$$D_R = D_m/D_p \tag{2}$$

where subscripts m, p, and R are the model, prototype, and ratio between the model and the prototype, respectively.

To determine the initial inlet boundary flow in a downcomer ($v_{z,m}$) in this study, the basic boundary flow scaling is developed here. It is assumed that the time ratio (τ_R) is set as

$$\tau_R = \tau_m/\tau_p = 1 \tag{3}$$