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Experimental investigation of void distribution in Suppression Pool during the initial blowdown period of a Loss of Coolant Accident using air–water two-phase mixture

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A B S T R A C T

During the initial blowdown period of a Loss of Coolant Accident (LOCA), the non-condensable gas initially contained in the BWR containment is discharged to the pressure suppression chamber through the blowdown pipes. The performance of Emergency Core Cooling System (ECCS) can be degraded due to the released gas ingestion into the suction intakes of the ECCS pumps. The understanding of the relevant phenomena in the pressure suppression chamber is important in analyzing potential gas intrusion into the suction intakes of ECCS pumps. To obtain the basic understanding of the relevant phenomena and the generic data of void distribution in the pressure suppression chamber during the initial blowdown period of a LOCA, tests with various blowdown conditions were conducted using the existing Suppression Pool (SP) tank of the integral test facility, called Purdue University Multi-Dimensional Integral Test Assembly for ESBWR applications (PUMA-E) facility, a scaled downcomer pipe installed in the PUMA-E SP, and air discharge pipe system. Two different diameter sizes of air injection pipe (0.076 and 0.102 m), a range of air volumetric flux (7.9–24.7 m/s), initial void conditions in an air injection pipe (fully void, partially void, and fully filled with water) and different air velocity ramp rates (1.0, 1.5, and 2.0 s) are used to investigate the impact of the blowdown conditions to the void distribution in the SP. Two distinct phases of experiments, namely, an initial and a quasi-steady phase were observed. The maximum void penetration depth was experienced during the initial phase. The quasi-steady phase provided less void penetration depth and was categorized by oscillations in the void penetration. The initial void conditions in an air injection pipe and air volumetric fluxes were only found to significantly impact on the void distribution in the SP.

1. Introduction

1.1. Issue of ECCS performance

The ECCS in a BWR is critical in keeping the reactor core covered during blowdown from a LOCA and for removing decay heat during recovery. The pressure suppression chamber in the BWR containment is a primary source of supply water for the ECCS pumps suction. During the initial blowdown period of a LOCA, the non-condensable gas initially contained in the BWR containment is discharged to the pressure suppression chamber through the downcomer pipes. The possible impairment of the ECCS due to a significant amount of entrained gas in the ECCS intake pipes of a BWR during the LOCAs is addressed in the Generic Safety Issue (GSI) 193, BWR ECCS suction concerns. This issue applies to MARK I, II, and III BWR containment designs (US NRC, 2010). For example, the geometrical characteristic of the pump intakes pipes and downcomer pipes in the MARK I pressure suppression chamber is shown in Fig. 1.

1.2. Relevant phenomena

In the event of a LOCA, the steam or superheated water are released into the DW. As a result, pressure in the Drywell (DW) and blowdown pipes to the pressure suppression chamber increases rapidly. At the initial phase of the blowdown, mostly non-condensable gas is forced through blowdown pipes into the

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Nomenclature

A	area
D	diameter of downcomer pipe
D_b	averaged bubble diameter
j_g	air volumetric flux
l	void penetration length
L	location from the center of downcomer pipe exit
L_b	bubble chord length
Le	length
Q	volumetric flow rate
Q_a	air volumetric flow rate
t	time
T	interval time
t_v	velocity ramp rate time
s	second
V	velocity
V_b	axial bubble velocity
V_{ub}	averaged upward bubble velocity

Greek symbols

α	void fraction
τ	time

Subscripts

a	axial direction
avg	time average value
m	model
max	maximum value
p	prototype
quasi	quasi-steady phase
R	ratio
r	radial direction
vc	vent clearing
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
MSL	Main Steam Line
RPV	Reactor Pressure Vessel
SP	Suppression Pool
SRV	Safety Relief Valve

pressure suppression chamber. This is followed by the steam-non-condensable gas mixture injection. In the later phase, mostly steam is vented. In the initial phase, water initially standing in the blowdown pipes is accelerated into the pressure suppression chamber and the blowdown pipes become voided. A large bubble of mostly non-condensable gas is then formed at the exit of the blowdown pipes. The gas injection from the DW results in the expansion of this bubble at the tip of the blowdown pipes. After that, this large bubble may deform and smaller disintegrated bubbles spread and rise to the water surface. When the steam and non-condensable gas mixtures come into the blowdown pipes, condensation occurs at the exit of the blowdown pipes. This eventually induces chugging at the exit of the blowdown pipes with rapid condensation. During the blowdown phase, gas bubbles possibly entrain into the intake pipes of ECCS pumps if the inlet of pump intake is located in proximity of gas penetration.

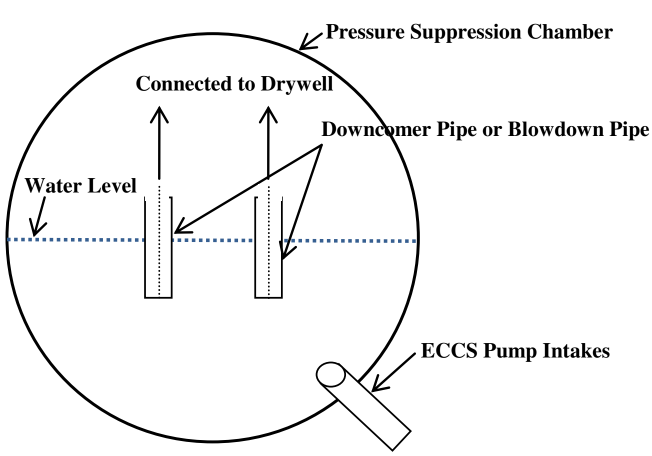

Fig. 1. Geometrical characteristic of the MARK I pressure suppression chamber (US NRC, 2010).

1.3. Relevant previous investigations and needed research

Several experiments using large scale test facilities have been conducted to simulate a LOCA event in the BWR pressure suppression chamber (Kadlec and Muller, 1976; Fitzsimmons et al., 1979; Kukita et al., 1984; Aust et al., 1987). In those experiments, the structural loading and pressure in the pressure suppression chamber caused by the gas injection and steam condensation during the blowdown period were mainly investigated. Only the experiment performed at the POOLEX facility (Laine, 2002) has attempted to investigate the distribution of the gas bubbles in the pool during a LOCA event using the visual observation data. The previous works have not provided generic understanding of the relevant phenomena including quantitative investigation of the void distribution and gas bubbles characteristics in the pool during the initial blowdown period. Therefore, this study was performed to obtain generic understandings and data for further analyzing potential gas entrained into the intakes of ECCS pumps in a LOCA period.

1.4. Mark I containment and PUMA test facility

The MARK I containment is considered as the prototype facility in this study. The MARK I containment is early containment design used in a BWR nuclear power plant. The diagram of MARK I containment as shown in the Fig. 2 (US NRC, 1980). The main components of the MARK I containment include the drywell enclosed reactor pressure vessel, torus-shaped pressure suppression chamber contained a large amount of water, and vent piping connecting the drywell and the water space in the pressure suppression chamber (US NRC, 1980). This vent piping consists of eight main vents, vent header, and about eighty downcomer pipes.

The PUMA facility is utilized as the modeled facility to perform a generic research to understand the relevant phenomena. The PUMA facility is the integral test facility originally built to study the performance of the GE Simplified Boiling Water Reactor (SBWR) safety systems (NRC) (Ishii et al., 1998). The major components of PUMA facility is Reactor Pressure Vessel (RPV), Drywell (DW), Suppression Pool (SP), Gravity Driven Cooling System