Progress in Nuclear Energy 93 (2016) 418–430

Contents lists available at ScienceDirect

Progress in Nuclear Energy

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

An investigation on flashing instability induced water hammer in an open natural circulation system

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ARTICLE INFO

Article history:
Received 24 March 2016
Received in revised form
7 September 2016
Accepted 18 September 2016

Keywords:
Water hammer
Flashing instability
Experimental investigation
Numerical analysis

ABSTRACT

The flashing instability induced water hammer phenomenon (FIIWH) is firstly found in an open natural circulation experimental facility, which is used to study the thermalhydraulics characteristic of natural circulation style PCS. The primary mechanism of the FIIWH is that, the periodic movement of flashing front in the upwards channel leads to the periodic violent changes of the local pressure and temperature at the underpart of upwards channel. However, the pressure change rate is more rapid than temperature, which causes the alternately transforms of water from superheated and subcooled at the underpart of upwards channel, and results in the periodic violent evaporation and steam condensation process there. Among them, the rapid condensation causes the sudden acceleration and collision of water columns and forms a transient high pressure peak i.e. the FIIWH. Besides, the horizontal tube at the underpart of upwards channel (pipeline structure) also makes an essential effect on the FIIWH.

Furthermore, the influence factors on the region and intensity of FIIWH, e.g. the heating tube outlet temperature, inlet subcooling, loop structure and non-condensable gas in water are experimental studied in detail. The initial and terminal conditions of the FIIWH are also found out by experiments. And the contour map describing the scope and intensity of the FIIWH are drawn in this paper.

Finally, a simplified numerical model is carried out to simulate the pressure peak of the FIIWH. The simulation result shows a good agreement with the experimental result on the low inlet subcooling conditions, while it has a disparity with the experiment result on the high inlet subcooling conditions. And the deviation reason and improvement orientation of the model are analyzed in this paper.

1. Introduction

The Fukushima-Daiichi accident caused the extensive concerns of the nuclear safety again (Wang et al., 2016), and after that various researches were carried out to improve the safety of the nuclear reactor, and one of which is Passive containment cooling system (PCS). PCS is an essential facility of advanced pressurized water reactor (APWR). It can remove the heat in containment under the accident conditions without external power, and control the temperature and pressure of mixture steam in containment in a safe range. The layouts of PCS closely depend on the styles of containment. For the AP1000, the steel containment shell itself is used as the huge air-cooled heat exchanger of PCS (Zhao and Chen, 2014), the mixture steam in containment condensate at the internal face of containment, and the released heat is took away by the air flow outside the containment by convection heat transfer process. For HPR1000, which adopt the double-wall dry-concrete containment promoted by European Utilities Requirements (EUR), in consideration of the poor heat transfer characteristics of dry-concrete, a natural circulation-style PCS is built extra (Guo et al., 2014). The schematic diagram of this kind PCS is shown in Fig. 1.

The PCS of HPR1000 has 12 sets of natural circulation loop with the height of 23 m, which distribute uniformly across circumference of containment. Each set of the natural circulation loop consists of an internal heat exchanger, an external elevated water tank and connecting pipings. The mixture steam in containment condensate at the surface of internal heat exchanger, and the released heat is transferred to the external environment by the open natural circulation system. In addition, the pipings of the PCS need penetrate the thick double-wall of containment, and bypass the complicated equipments and systems in containment, which

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http://dx.doi.org/10.1016/j.pnucene.2016.09.015
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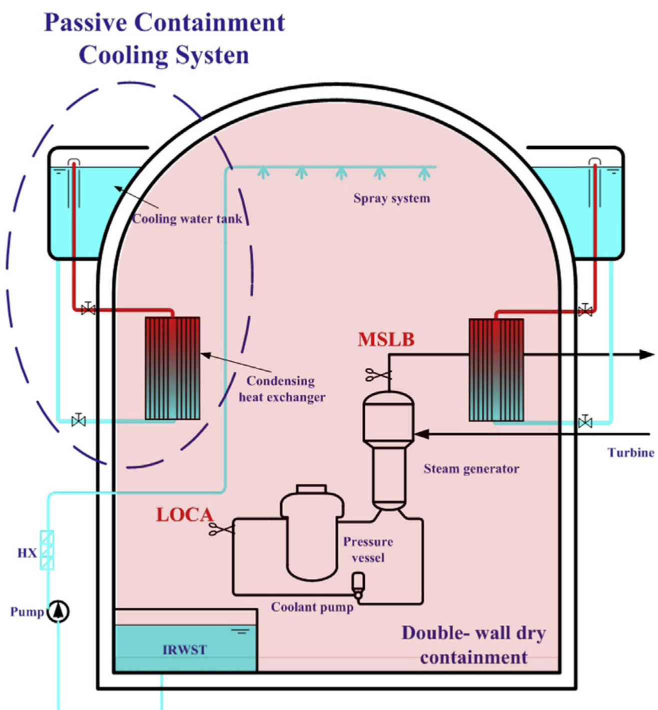

Fig. 1. Sketch of the passive containment cooling system.

makes its pipeline structure in engineering is relatively circuitous and usually have relatively long horizontal tubes.

To investigate the thermodynamic characteristics of open natural circulation system which has a relatively long horizontal tube in the riser, an experimental facility was built. During the experiments, the flashing instability induced water hammer (FIIWH) phenomenon was observed in the horizontal tube. The reciprocating movement of flashing front in the riser of natural circulation when flashing instability occurs leads to the periodic changes of local pressure in the horizontal tube, which results in the periodic vaporization and steam condensation there. Thereinto, the steam condensation process results in the sudden acceleration of water column at both ends of steam slug in the opposite directions, then the liquid columns impact onto each other and cause the transient high-pressure pulses which may cause the seriously damage of loop strictures.

The water hammer phenomenon has been widely investigated by previous researchers, and it can be divided into two kinds, namely the valve-induced water hammer (VIWH) and the condensation induced water hammer (CIWH). The VIWH is usually induced by the rapid changes in the velocity of a flowing fluid, which lead to the simultaneous pressure changes propagated from the point of velocity change with local sound velocity of fluid into the pipe system, and cause violent shocks of the loop structures, such as pipe walls, bends and fittings (Tian et al., 2008); and the CIWH is usually caused by the intensive condensation when vapor and subcooled liquid come into contact. The vapor transition to liquid state results in a substantial fluid volume reduction, which causes a rapid pressure drop of vapor phase. The pressure difference between vapor and the water leads to the sudden acceleration of liquid columns and their impact onto an obstacle, such as a valve, a closed end of the pipe or another liquid column. A pressure pulse at the moment of the liquid column impact and a generated pressure wave propagation might have a potential for the serious damage of loop structure (Milivojevic et al., 2014). It was reported that the CIWH occurred in various industrial thermalhydraulic systems, such as in the feed water system and in the steam generator of power plant (Serkiz, 1983; de Vries and Simon, 1985; Beuthe, 1997); in the district heating system (Kirsner, 1999) and in the ammonia refrigeration system (Martin, 2009), and it causes pressure peaks of tens of bars or even higher than hundred bars in those engineering system. Moreover, previous experimental and numerical researches were conducted to investigate the characteristics and mechanism of the CIWH in the lab. Gruel et al. (1981) investigated the steam bubble collapse process in a vertical pipe between the lower stagnant hot water column and the upper downward accelerating column of cold water, and they observed the liquid column as a rigid body and derived a simple mechanical model for the prediction of water column velocity and pressure impulse at the moment of impact. Zaltsgendler et al. (1996) investigated CIWH in a vertical pipe initially filled with steam and fed with cold water by a quick opening valve at the bottom. The CIWH in the counter current flow of subcooled water and steam in the horizontal and slightly inclined pipes was investigated by Chun and Yu (2000). Also the CIWH caused by the cold water inflow into the horizontal pipe filled with steam was experimented and numerically simulated by Barna et al. (2010), the simulations were performed by the WAHA3 code based on a transient one-dimensional two-fluid model. Milivojevic et al. (2014) developed a one-fluid model for the prediction of pressure surges during the CIWH. It is shown that the reliable predication of pressure surges strongly depends on the calculation of the condensation rate, transient friction and the water-steam interface tracking. Due to the lack of CIWH condensation model, a new approach of MOC is derived to calculate the model. The simulation results show relatively good agreements with the experiment results.

The FIIWH phenomenon studied in this paper is actually a kind of special CIWH process, which occurs in an open natural circulation and induced by the flashing instability. The flow characteristic of open natural circulation and the mechanism of flashing instability were investigated in the previous literature extensively (Kyung and Lee, 1996; Inada et al., 2000; Su et al., 2002, 2001; Guo et al., 2005; Yang, 2014; Shi et al., 2015, 2016). However in their experiments, the FIIWH did not occur for some reasons. Moreover, the FIIWH process indeed has a potential to occur in the open natural circulation-style PCS system. Hence, the mechanism and occurrence region of FIIWH should be figured out for avoiding it. To achieve those purpose, an experimental investigation on the FIIWH was carried out in this paper, Moreover, a simple numerical work was also raised to simulate the peak of pressure oscillation induced by the FIIWH.

2. Experimental apparatus and methods

2.1. Experimental apparatus

The experimental apparatus (as Fig. 2 shows) consists of a mixed steam supply system, an open natural circulation system and a measurement and data acquisition system.

The mixed steam supply system is the heat source of open natural circulation. It includes a boiler, an air compressor, an experiment vessel and a condensate tank. The saturation steam generated by the boiler and the air provided by the compressor mix together, then injected into the experiment vessel to simulate the gas environment in containment under accident conditions. The high-temperature mixture in the experiment vessel condenses at the heating tube surface, and the released heat is carried off by natural circulation. The condensate is collected by the condensate tank and discharged to drainage.

The open natural circulation system contains a stainless steel heating tube, a cooling water tank and the connecting pipings. The