Nuclear Engineering and Design 261 (2013) 165–173

Contents lists available at SciVerse ScienceDirect

Nuclear Engineering and Design

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

Water hammer characteristics of integral pressurized water reactor primary loop

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HIGHLIGHTS

- Water hammer models developed for IPWR primary loop using MOC.
- Good agreement between the developed code and the experiment.
- The good agreement between WAHAP and Flowmaster can validate the equations in WAHAP.
- The primary loop of IPWR suffers from slight water hammer impact.

ARTICLE INFO

Article history:
Received 21 July 2012
Received in revised form 2 March 2013
Accepted 10 March 2013

Keywords:
Water hammer
Integral pressurized water reactor
Method of characteristic
Experimental verification
Flowmaster

ABSTRACT

The present work discussed the single-phase water hammer phenomenon, which was caused by the four-pump-alternate startup in an integral pressurized water reactor (IPWR). A new code named water hammer program (WAHAP) was developed independently based on the method of characteristic to simulate hydraulic transients in the primary system of IPWR and its components such as reactor core, once-through steam generators (OTSG), the main coolant pumps and so on. Experimental validation for the correctness of the equations and models in WAHAP was carried out and the models fit the experimental data well. Some important variables were monitored including transient volume flow rates, opening angle of valve disc and pressure drop in valves. The water hammer commercial software Flowmaster V7 was also employed to compare with WAHAP and the good agreement can validate the equations in WAHAP. The transient results indicated that the primary loop of IPWR suffers from slight water hammer impact under pump switching conditions.

1. Introduction

Water hammer is a kind of shock wave, which is caused by a sudden pressure change within the compressible liquid and pipes. It is harmful to all kinds of pressure pipelines and happens frequently, causing valve failure, pipe leak, flow passage components damage and so on. Water hammer is one of the important factors that threaten the safety of nuclear power plant. For example, in pressurized water reactor (PWR), violent thermo-hydraulic transients in the primer loop may cause pipe rupture which may induce loss of coolant accident (LOCA) and lead to reactor shutdown. In 1973, a severe water hammer accident happened in American Indian Point 2 nuclear power plant, which caused the containment thermal deformation and main feed water pipe breakage as large as 45.7 cm at the penetrating place through the containment (Liu, 1987). In China, the pipe line has vibrated voilently and led to alarm signals for many times since Daya Bay and Ling-ao nuclear power plants were put into operation, which can even cause the condensate extraction pump to shut down (Zhang and Zhu, 2008). Therefore, water hammer phenomenon in nuclear power plants has drawn much attention for nuclear power plant safety and economic issues in recent years.

In nuclear power plants, water hammer transients can be caused by both two phase flow and single phase flow transients. Two-phase water hammer is often associated with condensation-induced phenomenon, which may cause greater damage than single-phase water hammer (Beuthe, 1997). Two-phase water hammer often appears in nuclear power plant and has been investigated by many researchers (Barna et al., 2010; Barten et al., 2008; Beuthe, 1997; Prica et al., 2008). However, the detail mechanisms of the condensation-induced water hammer have not been fully understood. Much attention has been drawn to single-phase water hammer phenomenon. Some sophisticated algorithms are developed and applied to specific single phase flow systems.

Water hammer prediction is mainly carried out by the analysis method, the graphic method (Allievi, 1925), and the numerical method in the early stage. The classical water-hammer equations are a set of hyperbolic equations, which are acquired by the

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http://dx.doi.org/10.1016/j.nucengdes.2013.03.038

Nomenclature

a	sound velocity (m/s)
A	flow area (m^2)
D	pipe diameter (m)
f	friction factor
g	acceleration of gravity (m/s^2)
H	pressure head (m)
I	rotational inertia of the valve disc. (kg m)
K	effective elastic modulus (Pa)
m	the dimensionless form of the axial torque
n	the dimensionless form of the rotational speed
Nr	the rated rotational speed
Q	volume flow rate (m^3/s)
t	time (s)
Ve	the container volume (m^3)
V	fluid velocity (m/s)
w	the angular velocity (rad/s)
x	length (m)
θ	pipe inclination angle (°)
β	valve opening angle(°)
τ	the dimensionless opening

dimensionless method (Ghidaoui et al., 2005). The solving procedure of the analysis method is very complicated. The analysis method is used to solve the basic simplified equations and only applied to simple pipe networks when the loss of water head is neglected. The graphic method is very complex in drawing and not accurate enough. The development of computer technologies makes the numerical method of water hammer simulation in complex pipe networks become possible.

In recent years, the numerical method is widely used in water hammer phenomenon study and almost replaced the analysis method and the graphic method. The main numerical methods to simulate water hammer events include method of characteristic (Wylie and Streeter, 1993), the finite volume Method (Zhao and Ghidaoui, 2004), the finite element method (Kochupillail et al., 2005), Wavelet-Galerkin (Sattar et al., 2009), the fluid structure interaction, and so on. Among those methods the method of characteristic (MOC) is the most popular one, and Afshar and Rohani (2008) even developed a different MOC procedure IMOC. Some research indicates that MOC fits experimental data well (Liu et al., 2005). Ghidaoui et al. (2005) investigated eleven available water hammer commercial software packages, and found that in eight of them the method of characteristic was applied.

Flowmaster is one of the most well-known virtual thermo-fluid modeling software to simulate water hammer. It can analyze fluid flow and pressure surge through complex piping networks. Flowmaster has been widely used in water hammer calculation in nuclear system in recent years (Marcinkiewicz et al., 2008; Zhang et al., 2012). Lee analyzed hydrodynamic characteristics of auxiliary feed water system in PWR using Flowmaster and showed a good agreement between the simulation and the measurements (Lee et al., 2011).

There are many factors which lead to water hammer in PWR. Such as power failure, reactor normal shutdown and startup, pump shutoff and startup, pump blockage, valve closure, open and instability, pipe rupture, rapid condensation, transient void. Generally speaking, normal startup and shut-off operation could not lead to excessive water hammer pressure, but sudden power failure of the pump and accidental pump shutoff often lead to severe water hammer. In order to evaluate the safety situation of IPWR, the method of characteristic is employed in the present work to predict water hammer in primary loop during pump startup, pump power failure and pump switch processes.

2. Structure of the primary loop

The primary system arrangement of the present IPWR is shown in Fig. 1, the primary coolant water at 15.5 MPa flows from the pumps to the downcomer, then travels downwards to the lower plenum and enters the reactor core. The coolant picks up heat and exits into upper plenum. Heated primary fluid exchanges energy with the secondary fluid in steam generator and finally returns to the pump. In both WAHAP and Flowmaster, simplified models of the primary loop and its components are developed. And the schematic diagram of the models in WAHAP is displayed in Fig. 2. The arrows demonstrate the flow direction. Container A refers to the chamber at the outlet of the steam generator primary side, respectively. The symbols (1)–(2) refer to the simplified pipelines of the OTSG. Pipe 1 with restrictive device refers to the core passage. Pipe 2 and pipe 3 present the core bottom plate and the downcomer. Pipe 4 with restrictive device is heat exchange tubes in steam generator and pipes 7, 8, 12, and 13 with restrictive devices refer to the pipelines adjacent to the pumps outlet. The length of the pipes in demonstrated in Table 1

The structure of the four pumps in parallel is designed in case of pump failure. Four eccentric butterfly valves are installed in the pump outlet to prevent reverse flow. When pump starts, shut down or valve closes, water hammer may happen. The valve structure and the definition of the opening angle are illustrated in Fig. 3. The valve disc has an natural opening angle of about 70° in the gravitational field. The opening angle is more then 90° when the valve closes.

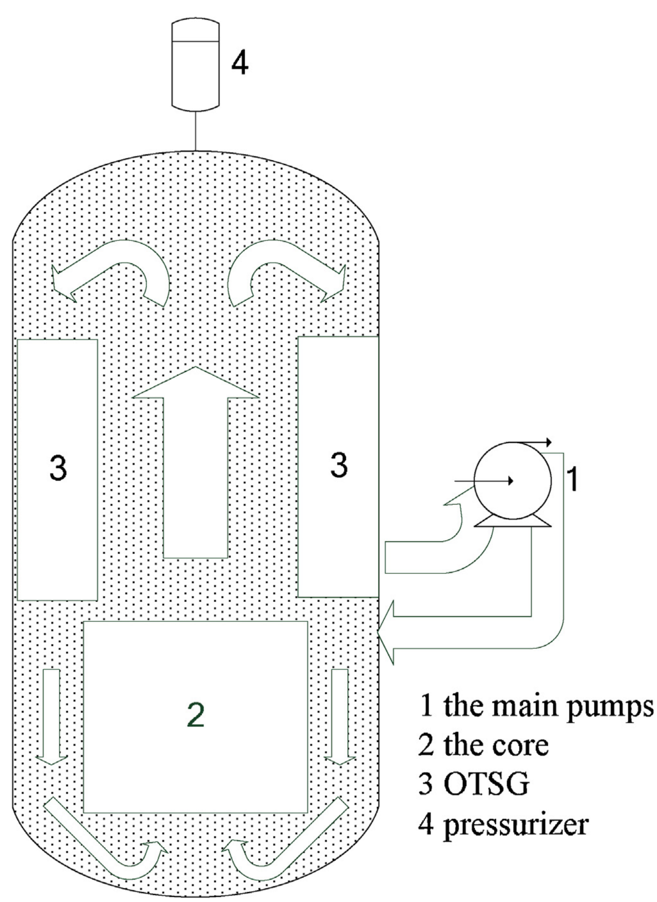

Fig. 1. The primary system arrangement of the IPWR.