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Numerical research on water hammer phenomenon of parallel pump-valve system by coupling FLUENT with RELAP5

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ABSTRACT

Water hammer caused by system devices closing or opening are important factors that threat the safety of nuclear reactors. A coupling scheme is proposed to analyze water hammer in a designed parallel pump-valve system. The developed FLUENT/RELAP5 makes it possible to obtain three-dimensional (3-D) flow field of the key area with lower computer resource than traditional computational fluid dynamic (CFD) analysis. The coupled code can reflect many sophisticated phenomena which system code ignores. In the developed coupling scheme, RELAP5 is compiled as a Dynamic Link Library (DLL). The compiled library is invoked as a subroutine at every time step by FLUENT. A testing case has been proposed to verify the implementation of the coupling scheme. Testing results prove the implementation of the coupling scheme successful and coupled results reliable. During the period of valve close, the coupled code predicts considerably well over movement of the valve element by the moving grid method. During the period of pumps start, three shock waves occur, and the mechanical loading oscillates continuously after 12 s. Moreover, the coupled results are compared with the standalone RELAP5 results. Contrast analysis represents that the coupled FLUENT/RELAP5 has the potential to obtain credible transient numerical results. The predicted 3-D transient characteristics directly reflect the generated pressure surges and forces in the designed pump-valve system, which is a fundamental guide for mitigating the threat of water hammer.

1. Introduction

Water hammer is an important factor that affects the safety of nuclear reactors. Thermal-hydraulic transients induce multi-phase water hammer to cause pipeline system serious deformations or even breakup. In 1973, a water hammer accident happened in American Indian Point 2 nuclear power plant due to generated pressure wave, causing main feed water pipe breakup (Zuo et al., 2013). The generated high pressure wave would produce a surge of positive reactivity in the core resulting in a rapid increase of power by collapsing the vapor bubbles (Ivanov et al., 2007). Moreover, large and rapid local pressure changes will propagate along the hydraulic system at the speed of sound (Frizell, 1898), and the propagated pressure surge can affect the mechanical integrity of a system. For example, the expansion pressure wave that a loss of coolant accident (LOCA) forms propagates from the break to the vessel, inducing important loads on the vessel internals (Engel, 1994). Thus, water hammer is an enormous threat to safety of the loop system.

The conception of the theory of water hammer can be traced to Ménabréa, translated by Anderson (Anderson, 1976). In theory, water hammer is mainly divided into three kinds: the mixture of water and non-condensable gas induced water hammer, the column separation induced water hammer and the steam condensation induced water hammer (CIWH) (Beuthe, 1997). The latter two kinds appear more frequently than the first kind, and condensation-induced water hammer could cause greater damage than that induced by column separation. However, the mechanisms of CIWH are relatively complicated and could not be predicted correctly with many well-known two-phase flow-codes like RELAP5 and TRAC (Carlson and Rouhani, 2003). Though WAHA3 has a quick condensation model, which is the only model capable to simulate CIWH phenomena, the simulation results always show additional pressure peaks (Barna et al., 2010). Thus, much experimental research has been carried out to study the mechanism of sophisticated CIWH phenomena.

The column separation refers to the breaking of liquid columns and cavitation. The local cavitation commonly occurs when system devices close or open suddenly in the fluid flow system. This

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Nomenclature

α	Inclination angle of pipeline	K	The elasticity modulus of liquid bulk (Pa)
Δl	Length of a shock wave (m)	c	The coefficient of pipe support
a	The propagation speed ($m{\cdot}s^{-1}$)	E	The elasticity modulus of pipe material (Pa)
ρ	Density of fluid ($kg{\cdot}m^{-3}$)	δ	The thickness of pipe wall (m)
A	Cross section area of a pipe (m^2)	D_e	The internal diameter of a pipe (m)
υ	Fluid velocity ($m{\cdot}s^{-1}$)	F	Water hammer loading (N)
Δt	An infinitesimal time interval (s)	Δp	The variation of fluid pressure (Pa)
$\Delta\rho$	The variation of fluid density ($kg{\cdot}m^{-3}$)	SNJ	Single-Junction Component of RELAP5 code
ΔA	The variation of area (m^2)	CIWH	Condensation induced water hammer
$\Delta\upsilon$	The instantaneous variation of fluid velocity ($m{\cdot}s^{-1}$)		

process usually involves large pressure variations and structural vibrations. Due to the liquid column parting and rejoining abruptly, dangerous instantaneous pressure rise originates. The propagation of pressure waves can induce immediate large loads on the pressure boundaries and on their structural supports. This dynamic wave flow happens frequently and causes mechanical failure of a device easily. It can have a devastating effect on a pipeline system. Moreover, the indirect effects through the fully coupled dynamics of a nuclear power plant during a system transient can also be a matter of safety concern.

Column separation induced water hammer research methods mainly include experimental research method, analysis method, numerical method, and graphic method (Allievi, 1925). During the 20th century, considerable research was conducted in water hammer with column separation. Jordan investigated column separation and distributed cavitation in pumping systems with horizontal, upward and downward sloping pipe sections (Jordan, 1965). Pump startup process produces a rapid change of mass flow rate in pipeline leading to column separation induced water hammer.

In nuclear system, water hammer generated by pump startup or valve close could cause column separation induced water hammer phenomena. With the development of computer technology and computational fluid dynamics, the numerical method is widely used in the water hammer study in recent years, including the finite element formulation (Kochupillai et al., 2005) and Riemann solvers for simulations by Godunov method (Guinot, 2000). Two-phase flow codes like RELAP5 (Feng et al., 2016), TRAC (Boyack et al., 1985) and CATHARE (Barre and Bernard, 1990) are feasible to solve safety analysis of nuclear reactors. Barten et al. compared TRACE results with the analytical solutions and found out that TRACE results were very good for the 1-D cases with respect to the pressure maxima and a small difference was only obtained in the wave speed. (Barten et al., 2008). RELAP5 is commonly used to predict the hydraulic loading without considering dynamic interaction between the fluid and the pipeline construction in Sweden (Marcinkiewicz et al., 2008). However, standalone RELAP5 analysis could be not accurate enough when dynamic interaction is taken into account. Traditional system codes still remain some problems in predicting transient characteristics of water hammer phenomena. Thus, a new designed coupling scheme is proposed in this paper. The column separation induced water hammer is investigated with coupling CFD and RELAP5 in this paper.

RELAP5 is known to be one of the best 1-D thermal-hydraulic system codes, which is used to model the pump and pipe components with a desired degree of physical modeling (Wang et al., 2012). As we all know, the valve model in RELAP5 is kind of brief and can't reflect the 3-D flow field of check valve. Check valve is the key part in water hammer process, and the 3-D transient characteristics are very important parameters. CFD codes are capable of calculating much more detailed flow field predictions through the use of more detailed physical models (Aumiller et al., 2001). Thus, check valve is modeled by FLUENT in coupled analysis.

The coupled code system performs a domain decomposition of the complete problem to allow each program to solve a piece of the problem (Aumiller et al., 2002). The best known example of coupled codes is the COBRA/TRAC code (Thurgood and Guidotti, 1983). The coupling of RELAP5/MOD3 and CONTAIN is a successful coupling example (Smith, 1995). Coupling the system code with other codes is regarded as a functionality extension of the system code in the present study. The use of coupling scheme makes it probable to obtain the 3-D flow field of key area without burdening the user with unreasonable run times and complex physical simulation. In particular, FLUENT is explicitly linked with the improved RELAP5, which bring up a multi-scale program. In this paper, the coupled FLUENT/RELAP5 is developed for the calculation of dynamic loadings on two pump system caused by fluid transients without burdening the user with unreasonable run times.

2. Physical model and theory

2.1. Structure of the physical model

The parallel pump-valve system is chosen as the research object. Two valves are installed in the pump outlet. Water hammer happens when pumps start, shut down or valve close. A brief schematic diagram of parallel pump-valve system is displayed in Fig. 1.

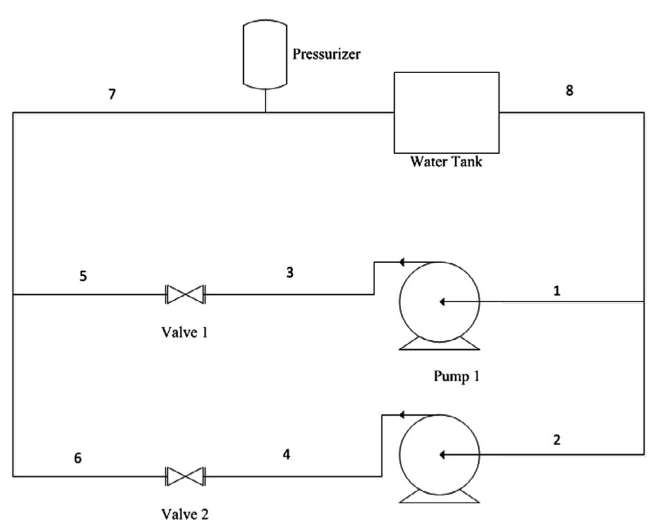

Fig. 1. Brief schematic diagram of parallel pump-valve system.