CHAPTER 1

INTRODUCTION

1.1. Background

Transient flow in a piping system is a transition of flow from one steady flow to another and occurs as a result of the abrupt changes in the normal operating condition like closing or opening of the valve, starting or stopping of pumps. Such abrupt changes create pressure waves of significant magnitude. The propagation and reflection of these pressure waves are referred to as hydraulic transients or water hammer (WH). Classical one-dimensional water hammer equations were commonly used to model transient flow (Chaudhry, 1979; Chaudhry and Hussaini, 1985; Hadj-Taıeb and Lili, 2000; Greyvenstein, 2002; Mitosek and Szymkiewicz, 2012; Amara et al., 2013; Shimada and Vardy, 2013; Seck et al., 2017; Martins et al., 2017). Though these equations correctly predicted the first pressure peak, the experimental results always show sudden damping of pressure wave contrasting the numerical results obtained from classical WH analysis (Araya and Chaudhry, 1997; Brunone et al., 2000; Mitosek and Szymkiewicz, 2012; Amara et al., 2013; Monajitha et al., 2014; Shimada and Vardy, 2013; Seck et al., 2017; Martins et al., 2017). Many researchers investigated the reasons for this deviation and identified a few factors such as fluid friction, nature of network demand, unsteady friction, leaks in pipes and elasticity of pipe material (Araya and Chaudhry, 1997; Vitkovsky et al., 2000; Brunone et al., 2000; Mitosek and Szymkiewicz, 2012; Amara et al., 2013; Monajitha et al., 2014; Shimada and Vardy, 2013; Seck et al., 2017; Martins et al., 2017) as the reasons.

The interaction between the pipe material and the fluid (Fluid structure interaction) is a physical phenomenon which does not have full representation in the classical water hammer theory. This lack of representation of fluid-structure interaction in the conventional water hammer model could be one of the possible reasons for having the deviation in the damping of pressure between that observed in experimental measurements and that from the model. Fluid induced structural motion, structure induced fluid motion, and the underlying coupling mechanisms are commonly referred to as Fluid-Structure Interaction (FSI). In conventional water hammer analysis, the elasticity of pipe is incorporated into the propagation speed of pressure waves; and the pipe inertia and axial pipe motion are generally not taken into account. These simplifications are acceptable for rigidly anchored pipe system. However, for less restrained systems, fluid structure interaction is more significant (Heinsbroek and Tijsseling, 1994; Ferras et al., 2016a). Three liquid-pipe interaction mechanisms were generally used to model the FSI, and these are friction coupling, Poisson coupling and Junction coupling (Wiggert et al., 1987; Lavooij and Tijsseling, 1991). The Friction coupling represents the mutual friction between the liquid and the pipe. The Poisson coupling relates the pressures in the liquid to the axial (longitudinal) stresses in the pipe through the radial contraction or expansion of the pipe wall. The Junction coupling applies at specific points in a pipe system such as unrestrained valves, bends and tees.

Water hammer waves cause pressure rise/drop alternatively in the piping system. When low pressure goes below the vapour pressure of the fluid, the system is subjected to cavitation. The cavitation is the formation, growth and collapse of vapour bubbles in a flowing fluid when the pressure drops below its vapour pressure. Research area on cavitation is vast and includes gaseous cavitation, vaporous cavitation and column separation. Simpson and Bergant (1994a) summarized the previous experimental investigations in the field of water hammer with column separation. Generally, the pressure caused by water hammer with cavitation is significantly higher than that consequent to water hammer alone. Hence, investigations considering the effect of cavitation on piping system also become essential.

1.2. The relevance of the Topic

The study on fluid structure interaction in liquid-filled pipe system dates back to the nineteenth century; the fundamental theoretical basis for FSI in straight liquid-filled pipes was proposed by Skalak (1954). In classical water hammer theory, an equivalent bulk modulus K^* was initially included to represent the effect of pipe material and the thickness of the pipe. Later, different structural parameters were included in the WH analysis. Accordingly, several mathematical models are available in the literature to represent FSI in WH analysis. During a transient flow event in a fluid-filled piping system, the generated pressure wave propagates in the fluid and induces the axial, flexural, rotational, radial and torsional actions in the piping system. Even though many researchers included FSI in their study, most of them coupled the axial motion equations of the pipe alone, with the fluid equations, in the analysis (four-equation model) (Lavooij and Tijsseling, 1991; Li et al., 2003; Ferras et al., 2017). The researchers who used all the aforementioned actions in the form of the fourteen-equation model (Wiggert et al., 1987; Mittal and Tezduyar,1995; Heinsbroek,1997) including the lateral and torsional equations, considered these one dimensional (1-D) equations as uncoupled with the other four equations. Moreover, the interaction of all the equations is coupled at the junctions only.

The load imparted on the piping system during the process of water hammer and cavitation is transferred to the support mechanisms such as anchors, thrusts, and blocks. Limited investigations have been carried out to study how the forces consequent to water hammer and cavitation are transmitted from the piping system to the pipe anchors and support mechanism and vice versa. Similarly, the studies seeking the influence of the support condition/ anchoring system on the transient cavitating flow are limited. Most of the investigations on FSI in piping system (Vardy and Fan, 1986; Heinsbroek and Tijsseling, 1994; Ferras et al., 2017) ignored the effect of cavitation in their theoretical work and made arrangements for avoiding cavitation in their experimental works. Vardy and Fan (1986 and 1989) carried out tests on FSI without cavitation on four different pipe systems in a test rig built in the Hydraulics Laboratory, University of Dundee (UK). Tijsseling and Fan (1991, 1992 and 1994) carried out experiments in the same experimental setup by considering cavitation. They carried out the experiments in a horizontal pipe, pipe with elbow and T pipe. All the tests were conducted in closed pipes suspended freely in a horizontal plane, thus avoiding the effect of support conditions and the transients were generated by the impact of solid steel rod on one of the pipe ends. Heinsbroek and Tijsseling (1994) conducted an experimental investigation on the effect of support rigidity on conventional water hammer analysis. Experimental set up consists of seven straight pipes connected by six 90^o bends suspended by steel cables and supported by springs at the bends. This experiment has limited practical application owing to its deviation from the practical system. Ferras et al. (2017) developed a 1-D FSI solver for a modified form of 4-equation model, capable of describing the resistance to movement of anchor blocks and its effect on the transient pressure wave propagation in straight pipelines. However, the effect of fixed anchors on the transient cavitating flow has not been explored so far. Moreover cavitation is not considered in the experiments conducted by Heinsbroek and Tijsseling (1994) and Ferras et al. (2017).

1.3. The motivation for the Research Work

Several cases of steel and concrete penstock failure have been reported (Adamkowski, 2001). Adamkowski (2001) reported that a penstock failure in the Oigawa Power station, Japan in 1950 caused by water hammer as a result of the sudden closure of a butterfly valve. A detailed study of penstock failure in Lapino Power plant in December 1997 by Adamkowski (2001) revealed that the leading cause of failure was the excessive pressure rise due to water hammer. Moreover, the increase in pressure caused by water hammer in a piping system and its damping behviour can be influenced by the anchoring conditions of the piping system. Hence, the study of FSI is also vital in piping systems of nuclear reactors where the collapse of the system may lead to radiation which is the most hazardous situation. Such studies are significant in chemical industries also where failure creates environmental issues.

Disruption of water supply is a common issue in Kerala, which is attributed by the pipe bursting because of water hammer and cavitation. The transient analysis with FSI can be utilized to assess the risk of failure of the existing pipes under different working conditions. Besides, the induced vibrations during transient flow in a liquid-filled piping system are also a crucial area to be investigated as it affects the pipe connections, fittings and flow regulating instruments. Hence, FSI analysis plays a critical role in the understanding of the acceleration of the piping system under dynamic loads and can be used as an aid to reduce the vibration of the piping system.

1.4. Objectives of the Research Work

The lack of representation of fluid-structure interaction in the classical water hammer theory could be one of the possible reasons for the inability in predicting the damping of pressure accurately. In FSI, there is an interface surface which is common for both the fluid and the solid domain. The governing equations of both the fluid and the solid must be satisfied at this interface. Similarly, fluid and solid boundary conditions must also be satisfied at this interface. A set of coupling conditions, which initiates the transfer of data between the fluid and solid domain, accomplishes this compatibility. During the transient condition in the fluid-filled piping system, the pressure waves propagate in the fluid and induce the axial, flexural, rotational, radial and torsion actions in the piping system. Even though many researchers included FSI in their study, most of them coupled the axial motion equations of the pipe alone, with the fluid equations, in the analysis. The researchers who used the fourteen equation model, including the lateral and torsion equations, considered these 1-D equations as uncoupled with the other four equations. The interaction of all the equations is coupled at the junctions only. The studies which incorporate two-way coupling of the structural and fluid system in the FSI analysis in 3-D were not yet addressed in full respect for a practical problem. Moreover, the study of FSI in a practical problem, considering the prominent physical features of the problem, is not present in the literature.

Moreover, most of the experimental investigations on transient flow reported in the literature neglected cavitation and made arrangements to avoid cavitation during experiments. The studies with cavitation and FSI were conducted on suspended pipe systems, with closed pipes suspended freely in a horizontal plane, so that the effect of supporting conditions could be excluded. Limited experiments have been reported so far considering water hammer with cavitation incorporating the impact of fixed anchors. Hence, the effect of fixed anchors attached to the piping system on transient cavitating flow characteristics, in a reservoir-pipe-valve system is selected as the area of the present experimental investigation. The objectives of the present study are fixed accordingly as

1. To assess the effect of valve closure time, flow velocity, material property and number of fixed anchors on transient cavitating flow through a pipe by conducting experiments in a reservoir-pipe-valve system.
2. To simulate the transient flow for evaluating the effect of FSI on the damping of pressure wave.
3. To examine the effect of number of fixed supports on transient flow through pipes by numerical simulation.

1.5. Organization of the Thesis

The thesis work comprising six chapters altogether as described below

- The introduction (Chapter 1) provides an overview of transient flow, cavitation and fluid structure interaction and the importance of modelling transient flow with fluid structure interaction. The scope and objective of work are also given at the end of this chapter.
- The literature review (Chapter 2) provides historical background and overview of essential concepts related to the present research area. It is divided into four subsections, viz., water hammer, cavitation, computational fluid dynamics, and fluid structure interaction. The theoretical and experimental researches carried out in the area are included in this chapter.
- Chapter 3 - materials and methods have four main parts. The first part provides the governing equations of fluid dynamics, structural dynamics and cavitation. The numerical methods used for the solution of concerned governing equations are given in the second part. The third part describes the numerical implementation procedure using the software. The last part includes the experimental setup and details of the experiment conducted as a part of the current study.
- In chapter 4, the results and discussions of the current experimental investigation are presented. The experimental results are presented as the influence of different variables adopted for the study, on transient flow characteristics.
- In chapter 5, the results and discussions of the numerical investigation are presented. This chapter has two main parts. The first part is the investigation on the effect of FSI on the wave damping of pressure. The second part includes the particulars of numerical modelling of the current experimental study to determine the influence of several fixed anchors on transient flow characteristics.
- Summary and conclusion of the research are presented in chapter 6.

1.6. Summary

This chapter gives an introduction about the transient cavitating flow and its significance in practical situations. It also describes the basic principles of Fluid Structure Interaction. Further, it details the scope and objectives of the present study and the thesis outline.