REVIEW OF TWO-PHASE WATER HAMMER

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1 INTRODUCTION

In a thermalhydraulic system like a nuclear power plant, where steam and water mix and are used to transport large amounts of energy, there is a potential to create two-phase water hammer. Large water hammer pressure transients are a threat to piping integrity and represent an important safety concern. Such events may cause unscheduled plant down time.

The objective of this review is to provide a summary of the information on two-phase water hammer available in the open literature with particular emphasis on water hammer occurrences in nuclear power plants. Past reviews concentrated on studies concerned with preventing water hammer. The present review focuses on the fundamental experimental, analytical, and modelling studies. The papers discussed here were chosen from searches covering up to July 1993.

2 WATER HAMMER FUNDAMENTALS

Water hammer is defined as the change in pressure that occurs in a fluid system as a result of a change in the fluid velocity. This pressure change is a result of the conversion of kinetic energy into pressure, which creates compression waves, or the conversion of pressure into kinetic energy, which creates rarefaction waves. Single-phase water hammer is defined as water hammer in which the fluid remains in the liquid state during the entire water hammer process. Two-phase water hammer is often associated with condensation-induced water hammer in which steam pockets collapse. In this review, it is also defined as water hammer which occurs under column separation/cavitation conditions and in air/water systems.

Condensation induced water hammer can cause greater damage than other forms of two-phase water hammer. The condensation rate of steam on liquid surfaces and the pipe walls is a deciding factor in the collapse process of steam pockets. Unfortunately, the detailed mechanisms leading to the experimentally derived condensation rates which have been observed are not clear. As mentioned by Warren [1], available experimental data lies mainly in the low-pressure region. To date, the value of the condensation coefficient is not known for high pressure and high temperature regions. Results inferred from the evaluation of water hammer events indicate that under nuclear reactor conditions the condensation coefficient could be several orders of magnitude greater than at atmospheric conditions [2].

3 WATER HAMMER IN NUCLEAR POWER PLANTS

Although a variety of industries have shown an interest in water hammer, the greatest concern has been shown in the nuclear power generating industry. Here the overriding sensitivity to safety-related issues and economic concerns have led to extensive investigations.

The most extensive effort to date has taken place in the United States. In large part, this concern about water hammer can be traced back to the early 1970's when the number of reported water hammer occurrences in U.S. nuclear power plants was increasing dramatically [3]. This led the United States Nuclear Regulatory Commission (USNRC) to classify water hammer as Unresolved Safety Issue A-1 (USI A-1) and a flurry of activity took place to support its resolution.

A large part of the effort expended to resolve USI A-1 went directly into semi-analytical and statistical examinations in an attempt to decrease the number of water hammer occurrences. An effort was made to

catalogue water hammer events. Detailed analyses and investigations were made to ascertain the reason for these events and suggest operational and design changes to prevent them from occurring in the future, but little effort was made to advance the theory of two-phase water hammer. As a result of these studies, it was discovered that approximately half of the water hammer occurrences resulted from operator error, and half resulted from design deficiencies. It was also found that most of the water hammer occurred when a given plant was relatively new, especially when it was being commissioned.

Water hammer has continued to be a topic of great interest to the nuclear power industry. The bulk of information and research into this phenomenon continues to come from this sector, along with calls for more fundamental research.

4 REVIEWS AND OVERVIEWS

4.1 History

Good historical reviews of the development of water hammer theory and experiments are available in the literature [4–7]. These early papers, although acknowledging the existence of two-phase water hammer, concerned themselves primarily with single-phase water hammer since this was the subject of prime importance at that time.

4.2 United States Nuclear Regulatory Commission

Since the late 1960's and early 1970's two-phase water hammer has received increased attention, particularly in nuclear power plants. The classification of water hammer as USI A-1 led to a number of publications by the USNRC in the 1970's and 1980's that provided broad reviews and overviews of water hammer occurring in U.S. nuclear reactors [8–19].

The earliest reports tend to concentrate on steam generator water hammer [8–10]. One of the most thorough reports was published in 1977 [11]. Commonly referred to as "the Creare report", it examines water hammer occurring in feed-ring type PWR steam generators. Scale model, single-effect experimental results, and results of modelling efforts are also discussed. The water cannon experiments included in this report are still being actively modelled [20]. Other reports published during this time concentrated primarily on a statistical compilation of all significant water hammer events in U.S. nuclear reactors. The 1981 report by Chapman et al. [12] concentrated on a compilation of all known and suspected water hammer events, and the 1982 report by Uffer et al. [13] presented an evaluation of these events. The final summary of this work by Serkiz in 1983 [14] led to the resolution of USI A-1. It also represents a candid overview of the perceived analytical and modelling capabilities available for water hammer at that time.

Since then, several other key reports have been published summarizing the work being done on water hammer. The USNRC report published by Valandani, Uffer and Sexton in 1984 [15] considers the potential dynamic loads on nuclear reactor components as a result of thermalhydraulic transients such as flow induced vibrations and water hammer. The 1988 report by Izenson, Rothe and Wallis [16], concentrates exclusively on two-phase water hammer. This general review attempts to summarize what is known about the types of two-phase water hammer events possible in all parts of nuclear reactors. It also includes an extensive reference section that is not restricted to literature published on U.S. type reactors.

A good summary of available tools for modelling water hammer transients as well as the entire spectrum of experimental, and analytical work performed on water hammer was published under the sponsorship of the USNRC by Watkins and Berry in 1979 [17].

Several USNRC reviews and overviews of water hammer can also be found in the conference literature. A paper given by Serkiz in 1983 [18] summarizes the USNRC position at the time USI A-1 was finally resolved. A paper given by Leeds and Lam in 1987 [19] updates the 1981 and 1982 reports by Chapman et al. [12] and Uffer et al. [13] respectively on recent occurrences of water hammer events in nuclear power stations.

4.3 Electric Power Research Institute

The Electric Power Research Institute (EPRI) has also commissioned a number of detailed studies of water hammer in nuclear reactors. The first signs in the open literature of the EPRI's extensive involvement in the issue of water hammer in nuclear plants came in 1979 when a conference was held dealing exclusively with EPRI water hammer programs [21]. As with the USNRC, this early conference concerned itself primarily with the problems being experienced in steam generators.

An EPRI literature review by de Vries and Simon in 1985 on suction effects on feed-pump performance [22] also includes a section on thermodynamically induced water hammer.

Two EPRI reports on water hammer were published in 1989. Martin and Wiggert produced a report on hydraulic transients in cooling-water systems summarizing an international set of data on the subject [23]. The report includes a literature search, experimental and test data, as well as significant modelling efforts made with several codes to model and explain the investigated phenomena. The second report published in 1989 by Chou and Griffith [24] summarizes a long term effort at the Massachusetts Institute of Technology (MIT) to experimentally investigate two-phase water hammer.

During the years 1987–1992 the EPRI was actively involved in the investigation of water hammer. During this time, five conference papers were published outlining the progress made by the nuclear industry to investigate and minimize the occurrence of two-phase water hammer [25–29]. These conference publications reflect a longstanding effort by a number of investigators and organizations contracted by the EPRI to produce what may be the most comprehensive summary of all aspects of water hammer in the nuclear industry to date [30]. This five-volume report summarizes nuclear plant water hammer experience, the determination of root causes of reported events, the compilation of experimental data on water hammer, the description and assessment of analytic models and computer codes applicable to water hammer assessment, and the development of guidelines for water hammer prevention, diagnosis, and assessment.

4.4 Conference Publications

A number of conference publications have also been written by the people and organizations who have prepared the USNRC and EPRI reports. In particular, the engineering companies Creare, Quadrex, and Stone & Webster, as well as the Bechtel Power Corporation in California have been actively presenting compact summaries of their work in conference publications.

Rothe, who was one of the co-authors of the Creare report for the USNRC [11], co-authored a paper with Wiggert in 1987 [31] on water hammer in nuclear plants which outlines the authors' experience in modelling condensation induced water hammer.

Uffer from Quadrex, an organization responsible for the production of several USNRC reports [13,15], has also published reviews and overviews dealing with two-phase water hammer in nuclear plants [32–35]. These papers provide a good, short overview of the work conducted by the USNRC [32], a summary of the analysis needs for water hammer [34], notes on the steps which can be taken to prevent water hammer [35], as well as a review of possible causes of water hammer in direct contact heater systems [33].

Stone and Webster, an organization responsible for the production of several key reports produced by the EPRI [29,30], has also helped to produce conference papers summarizing the types of two-phase water hammer observed in nuclear reactors, and the potential steps which have, and can be taken to prevent them [36,37].

Finally, a group of authors from Bechtel Power have assembled the framework for a knowledge base which could be used to investigate the susceptibility and root causes for water hammer in a nuclear power station [38]. In doing so, they also provide a compact and tidy summary of the possible water hammer effects in a reactor core spray system. This core spray system is unique to the geometry of certain PWR reactors.

4.5 Theoretical

Summaries and reviews published in conferences and journals of a more academic nature include a paper published by Jones et al. [39] on condensation induced water hammer in steam generators and a critical review by Leaf et al. [40] of various numerical schemes used to model single-phase water hammer.

4.6 United Kingdom and Canada

The above reviews and overviews of water hammer were all produced by organizations and individuals in the United States. Reviews of water hammer have also been made in the UK and in Canada.

In 1980, Wilkinson and Dartnall [41] produced a survey of damaging condensation induced water hammer in British fossil power plants. This survey covered all water hammer events in the previous 15–20 years. It concentrated particularly on thermodynamically induced water hammer, as well as giving a detailed analysis of one particularly damaging incident.

A good overview of the type of water hammer events observed in CANDU reactors can be found in a journal paper by Mikasinovic and Marcucci from Ontario Hydro [42]. This paper compares and contrasts the water hammer events observed in CANDU type reactors with those seen in U.S. PWR and BWR reactors. The results of this investigation show that, with minor exceptions, the water hammer experienced in U.S. and Canadian reactors is similar. The data for this paper were taken from a previously published Ontario Hydro report [43].

Goulding (Ontario Hydro) [44] has also cooperated with several other authors from California-based consulting companies to investigate methods which are used to model water hammer. This paper gives a very brief review of methods in use, and provides some insight into available codes commonly used to model water hammer.

A report similar in scope to the present review and the report prepared by Valandani, Uffer and Sexton for the USNRC in 1984 [15] was prepared by Atlantic Nuclear Services for the Atomic Energy Control Board (AECB) [45]. This report summarizes primarily the condensation induced water hammer experienced by U.S. reactors as published in reports by the USNRC, EPRI, the American Nuclear Society (ANS), and the American Society of Mechanical Engineers (ASME).

4.7 Books

The most comprehensive fundamental summary and discussion of water hammer can be found in the works of Streeter and Wylie [46–51]. This literature includes a journal publication by Streeter [46] comparing numerical methods for the modelling of water hammer, and a journal publication by Streeter and Wylie [47] discussing different methods which can be used to control surges, including surge tanks, accumulators, relief valves and air inlet valves. Streeter's book [51] on fluid mechanics includes an overview of water hammer as part of a chapter on unsteady flow.

By far the most frequently quoted reference for water hammer is Streeter and Wylie's 1967 book "Hydraulic Transients" [48]. Although it deals primarily with single-phase water hammer, it is worth mentioning here as it was instrumental in establishing the groundwork for a quarter century of modelling efforts. It has also helped to establish the method of characteristics as the method of choice for the analysis of this class of water hammer. Several later editions of this book have also been published under the title "Fluid Transients" [49, 50].

The most recent book on water hammer to appear is a large work by Záruba [52]. This work provides a good introduction to the phenomenon of water hammer, but spends most of its time detailing a single-phase water hammer code developed by the author. In a sense it constitutes a user manual for the program.

5 EXPERIMENTAL RESULTS

5.1 Water and Noncondensables

The presence of a noncondensable can be a help or a hindrance to water hammer, depending on its distribution in a piping system. An example of a situation where the presence of noncondensable gas in a pipeline can be responsible for water hammer is shown in the paper by Yu and Francisco [54]. Relatively large pockets of noncondensable gas in the Emergency Core Coolant System (ECCS) in a CANDU reactor resulted in a rapid movement of water in the pipes on poising of the system. The resulting momentum transfer to the pipes caused significant damage to pipe hangars.

Experimental studies tend to concentrate on the beneficial effects of noncondensables. Martin and Padmanabhan [55] have looked at the effect of the introduction of small amounts (up to 1.4%) of air in an entrained or dissolved state in water. Over this range of concentration, the presence of air has a marked effect on the water hammer wave propagation speed and pressure. One of the interesting results of this study shows that the theoretical values for propagation speed tend to be consistently higher than the ones observed experimentally. A discussion of experimental results from a Russian paper by Zubkova [56] also notes the potential mitigating effect on water hammer of homogeneously distributed air in the water.

The presence of noncondensable gases in water and their effect on water hammer has also been investigated experimentally by a group at Kobe in Japan [57]. In this case, both homogeneous as well as inhomogeneous distributions in horizontal pipes have been examined. The results show that both distributions can have a significant effect on water hammer.

Introduction of air in the form of a surge tank can also be used to mitigate water hammer. A discussion of the principles underlying surge tanks can be found in the classical water hammer texts by Streeter and Wylie [48–50]. Bernhart [53] has also experimentally investigated various geometries of surge tanks and their performance.

5.2 Water and Void (Cavitation/Column Separation)

A significant effort has been expended by the research group at Delft University to look into water hammer caused by column separation. Experimental investigations of water column separation which occurs at the downstream face of a valve which has been slammed shut have been examined by this group [58, 59], as well as cavitation generated in a closed pipe which was struck by a solid bar at one end [60], and cavitation that forms at the high points of a pipeline [61].

A Japanese group at Keio University has examined the production of void formed on the downstream face of a slammed valve, as well as at a high point in a pipe [62]. A UK group has looked into the production of vapour column separation just downstream of a restriction located at a high point in a pipe [63].

Bechtel Power Corporation [64], and Millstone Nuclear Power Station [65] have reported the introduction of various methods to prevent void collapse water hammer on pump startup, including the use of vacuum breakers to fill the void with air, a system to keep the downstream side of the pump pressurized, and a special pump startup cycle to fill the void during pump runup.

5.3 Condensation Induced Water Hammer

Condensation induced water hammer represents the major field of experimental water hammer investigation, and the Department of Mechanical Engineering at MIT is one of the most active groups in this area of research. This group has conducted experimental programs to investigate almost all aspects of condensation induced water hammer. Their efforts have been primarily directed towards fundamental experiments to investigate the physics behind condensation induced water hammer, but scale models of reactors have also been investigated.

The largest effort at MIT has gone into the investigation of countercurrent steam/water flow in horizontal or slightly inclined pipes. This is the geometry of the cold-leg in a PWR primary circuit where the ECCS water is introduced. The results of fundamental experiments can be found in papers by Swierzawski and Griffith [66], and Bjorge et al. [67,68]. Scale-model experiments of horizontal steam/water flows can be found in a USNRC report produced by Jackobek and Griffith [69] discussing emergency core cooling of a reactor, and a paper published by Akselrod et al. [70] discussing condensation induced water hammer in steam distribution systems. This work on horizontal or near horizontal pipes with steam/water flow has resulted in a number of analytical and numerical models and correlations to describe the experimental results.

Fundamental experiments on steam/water flow in inclined pipes have also been performed at MIT by Griffith and Silva [71]. This work has resulted in the production of a stability map indicating the effect of pipe inclination on water hammer production.

The horizontal filling of pipes has also been considered by this group. In this case, a region filled with subcooled liquid is separated from a region filled with saturated steam and water. On opening a valve, the subcooled liquid flows into the region filled with saturated steam and water and, under certain conditions, produces a water hammer. These experiments were conducted for various degrees of subcooling and initial subcooled water velocity. The results were shown in the form of stability maps. Experiments have also been conducted in which the region to be filled on valve opening has a slight downward inclination. When the valve is opened, the downward flow of the water helps to fill the region under investigation [24,72,73].

Filling vertical pipes from the top has also been investigated. An apparatus utilizing top filling was used to produce water hammer which was subsequently directed to a piping system used to investigate fluid-structure interactions [74–78]. Fundamental experiments on top filled pipes were also performed to obtain flow regime and stability maps indicating the conditions under which condensation induced water hammer could be expected [24,72].

Vertical upfill, or water cannon experiments were also performed at MIT [24,72]. These investigations also resulted in stability maps. In these experiments, a subcooled water region below and the superheated steam region above are initially separated by a quick acting valve. Prior to the opening of the valve, the pressure on either side of the valve could be controlled. This allows a repeatable set of conditions to be established. On opening the valve the subcooled water enters the region filled with steam. The steam rapidly condenses, drawing in the water, and on hitting the end of the pipe, a water hammer pulse is generated in the system.

Other experiments undertaken by the MIT group include investigations of water hammer generated due to the sudden stopping of a flashing flow [79]. An examination of water hammer created by the flashing of hot water on passing through a restriction in a pipe caused by a partially open valve was also conducted [80]. In this case, a slug of cold water, followed by a slug of hot water passes through a partially open valve. As the hot water passes through the valve, it flashes and the pressure drop across the valve increases, causing the liquid upstream to quickly decelerate. This deceleration causes water hammer.

An overview of the work done at MIT can be found in a USNRC publication [69], and an EPRI report [24], as well as a paper published in *Nuclear Engineering and Design* [72]. Details of this work can also be found in a number of MIT dissertations. The work of this group will be revisited in the analytical section below, since most of their results went into the production of analytical models to predict whether or not a pipe will experience water hammer under steam/water flow.

Fundamental horizontal steam/water condensation induced water hammer experiments include a study by Lee and Bankoff [81]. This paper summarizes a series of experiments in the form of a stability map for two pipe inclinations. An extensive USNRC report on the same subject was produced by Lee [82]. Wang et al. [83] also consider the entrainment of a slug of water at a low point in a pipe by steam. Depending on the size of the slug, and the velocity of the steam flow, a potentially destructive water hammer event can result from the condensation induced acceleration of the water slug.

A significant number of experimental investigations into the creation of condensation induced water hammer in feedwater type steam generators have been performed as part of the USI A-1 investigations initiated by the USNRC. Gonnet et al. [84] used a scale model of the feedwater ring in a steam generator to investigate the conditions under which water hammer can form during horizontal countercurrent steam/water flow in the ring. The results of similar, but much more extensive experimental investigations were presented as part of the Creare report [11].

Experimental investigations on condensation induced water hammer in steam generators have also been conducted by Westinghouse [85]. These studies were undertaken to determine if the newer preheat type steam generators are prone to water hammer. The results indicate there is no cause for concern. The experiments do not point to any evidence suggesting preheat-type steam generators are prone to water hammer.

Investigations of water injection in a horizontal or near horizontal pipe filled with steam [86, 87], or steam injection into a water-filled pipe [88, 89] have also been performed. Water injection into a steam-filled pipe can occur during emergency core coolant injection, and steam injection occurs in suppression pools. In both cases, it is important to know the conditions conducive to condensation induced water hammer. Both types of injection can produce a surprisingly complex array of different behaviours depending on such variables as injection rate, degree of water subcooling and pipe inclination. In all cases only injection into horizontal or nearly horizontal pipes was considered.

The work done on condensation induced water hammer has not been restricted to the use of steam and water. A number of experiments have been performed using Freon as a working fluid, most notably the Japanese groups at Kobe University [90, 91] and Hitachi Ltd. [92]. The efforts at Kobe concentrated on the behaviour of flashing flow upstream of a valve which is slammed shut. The Hitachi experiments considered the opposite phenomenon: flashing flow generated in saturated liquid when a valve is opened.

An interesting form of two-phase water hammer involving Freon was investigated by Jakeman, Smith and Heer [93]. In these experiments, a mixture of liquid Freon and subcooled water was made. This liquid mixture was then dropped into a pool of hot water. The resulting vapour explosion produced a sharp shock wave which travelled through the system as a pressure wave. Although this study was initially meant to study only the vapour explosion, the need to explain the propagation of the pressure wave through water and air/water mixtures led to a study of water hammer.

6 ANALYTICAL RESULTS

The mass, momentum, and energy conservation equations needed to describe the phenomenon of water hammer are complex. As a result, a full analytical solution of the water hammer problem is not normally attempted. Nonetheless, analytical examinations of special cases can lead to new insights into the problem. Analytical solutions can sometimes be derived that can be used to check numerical solutions or clarify experimental results. Nondimensional solutions can give some insight into the physical process and the importance of the various terms involved in the solution. In this section a brief review of some of the more recently published analytical solutions to water hammer problems is presented.

6.1 Water and Noncondensables

Since there is limited mass transfer between phases in air/water flow, efforts to describe single-phase water hammer analytically have often used the assumption that the air/water can be considered a homogeneous mixture. Properties such as wave speed and density relationships are derived for this mixture. Such an effort was made by Akagawa and Fujii [57]. A more detailed analytical examination of the same problem was also published by the same authors [94].

Fanelli [95] and Ewing [96] have considered analytical derivations of the wave speed under water hammer conditions in two-phase mixtures. A more fundamental look at the same problem in nondimensional matrix

form has been considered by Dobran [97]. Additional results on this topic can also be found under the more general heading of pressure wave propagation through two-phase mixtures. For example, Henry [98] discusses pressure wave propagation through annular and mist flows.

Martin [99] has investigated the maximum pressure rise expected when a column of water is accelerated against a pocket of air in a pipeline. The results are presented in non-dimensional form and are used to illustrate a number of situations in which the presence of air entrapped in a pipeline could increase or decrease the peak pressures during water hammer.

Jakeman et al. [93] consider the reflections a pressure wave undergoes as it passes from a single-phase water to a a two-phase air/water mixture region. Amplifications of the pressure wave of up to 3.5 are shown to occur under some conditions.

Finally, Moody [100] has derived a series of analytical expressions to describe the forces on a relief valve when the steady gas discharge fro the valve is interrupted by the arrival of a gas/liquid mixture. It is important to calculate the impact forces generated as a result of such an event to ensure the integrity of the relief valve.

6.2   Water and Void (Cavitation/Column Separation)

The collapse of void cavities and the subsequent generation of water hammer has been the subject of a number of analytical investigations. The results of Tarasevich [101] derive the maximum excess pressures that can be expected on collapse of a void cavity as a function of the initial velocity of the water. Plotted in dimensional and non-dimensional form, the analytical solution is seen to follow experimentally derived data relatively well, but both deviate from the ideal Joukowsky line as the initial velocity of the water increases.

Tanahashi and Kasahara [62] have constructed an analytical void model for comparison with experimental results. The void generated on the downstream side of a slammed valve and at a high point in a pipe has been investigated by these authors.

Youngdahl and Kot [102] developed an analytical model to describe a system in which a disc rupture or valve opening results in the filling of empty pipes in a reactor relief system. The objective in this case was to develop a model to be included in a method of characteristics code. Due to the rapid depressurization of the water upstream, a cavitation model was included.

The research group at Delft has developed a number of analytical models to describe the behaviour of a collapsing void [59, 61, 103, 104]. These models were subsequently included into numerical codes used to model experiments performed by this group.

A paper similar to the one by Jakeman et al. [93] has been written by Timofeev [105] on the reflection of a pressure wave on entering a region of moist vapour. Again, depending on the conditions, large amplifications can be caused in the reflected pressure wave. In a sense, this type of examination represents the most general case of void generated water hammer.

6.3   Condensation Induced Water Hammer

As in the experimental area, the group at MIT has made a significant contribution in this field. Most of these experimental investigations have been accompanied by efforts to summarize and clarify the results using analytical models. Models have been developed for stratified steam/water flows in horizontal and nearly horizontal pipes (Bjorge at al. [67] and Bjorge and Griffith [68]), the collapse of a steam pocket in a vertical pipe filled with subcooled water (Gruel et al. [74, 77, 78], Hurwitz and Huber [75]), and steam/water regions in vertical and horizontal pipes which are suddenly filled with subcooled water (Chou and Griffith [72]). An overall summary of the analytical work done by this group can be found in the EPRI report by Chou and Griffith [24].

The analytical models for condensation induced water hammer under steam water counterflow conditions in a horizontal pipe developed by the MIT group have also been extended by a group at the Korea Advanced Institute of Science and Technology (KAIST) (Chun et al. [106], Chun and Nam [107], and Park and Chun [108]). In these publications, the authors describe improvements to the original work that allow better estimates to be made of the upper and lower bounds of flow conditions where water hammer occurs.

Significant analytical work on the stability of steam-water countercurrent flow in an inclined channel has also been performed by Lee and Bankoff [81], and Lee [82]. This work has led to the derivation of expressions for use in stability maps to delimit the zones where condensation induced water hammer occurs. Details of this work can be found in the USNRC report by Lee [82].

Analytical work on horizontal steam/water countercurrent flow has also been conducted as part of the investigations of condensation induced water hammer in feed-ring type steam generators. In addition to the Creare report [11], analytical work on this subject can also be found in the papers by Warren [109] and Jones et al. [39].

The Japanese research group at Kobe has also conducted analytical examinations of the effects of passing pressure waves through one component, two-phase Freon mixtures [94, 110–112]. In this case, the analytical method involved solving the basic one-dimensional water hammer equations by linearization and iterated Laplace transformation.

Analytical examinations of subcooled water injection into a steam-filled pipe can be found in papers by Aya and Nariai [113] and Aya et al. [87]. This work resulted in the derivation of nondimensional expressions that can be used to plot a stability map for different types of injection behaviours.

The present review of the analytical treatment of water hammer only covers papers and publications concerned directly with water hammer. It is worth noting however that information relevant to the general physical principles involved in water hammer can also be found in studies which concern the modelling of kinematic and pressure waves. For example, the paper on the properties and modelling of kinematic and pressure waves in two-phase flow by Bouré [114] is also relevant to the physics of water hammer pressure waves.

7 NUMERICAL RESULTS

Given the application limits of analytical methods, and the difficulty and expense of performing experiments at reactor-typical conditions, a significant effort has been made to model water hammer numerically. Numerical models can be used to investigate the effects of various potential changes made in a system, or optimize a design. When used in conjunction with an experimental program, pre- and post-test numerical simulations can provide valuable data, potentially saving a significant amount of experimental effort.

7.1 Water and Noncondensables

The numerical modelling of water hammer in systems containing water and noncondensables has typically been handled either by using homogeneous codes accounting for the presence of any noncondensables by dynamic modification of the celerity (pressure wave speed) or by using heterogeneous codes considering the presence of noncondensables as a discrete entity.

Homogeneous models include models based on the method of characteristics and the finite-difference method. Füzy [115] has developed a homogeneous model based on the method of characteristics in which the celerity is modified to account for the presence of air. The influence of air on water hammer, and in particular the potential adsorption or desorption of air from the water is studied. Martin and Padmanabhan [55] have also developed a specialized homogeneous code based on the method of characteristics. Sample calculations are shown to illustrate the ability of the model to simulate the presence of various amounts of dispersed air in the water. Akagawa and Fujii [57] have used the Lax-Wendroff finite-difference method to develop a code to model a valve slam in bubbly systems, and Bhallamundi and Chaudry [116] have made a comparison between

two finite-difference methods (a third order explicit Warmington-Kutler-Lomax scheme and a second-order implicit Beam and Warmington scheme) and experimental transient data in bubbly flows.

Heterogeneous models assembled to model water hammer in the presence of noncondensable gases include a method of characteristics code written by Aktershev and Fedorov [117]. In this paper, a sample calculation is performed to simulate a system containing a surge tank. Wiggert et al. [118] have demonstrated the applicability of a four-point centered implicit scheme to model water hammer in heterogeneous air/water systems.

Large thermalhydraulic network codes using heterogeneous modelling have also been used to simulate water hammer in air-water systems. Chang et al. [119] used PISCES-2D ELK, an explicit finite-difference code capable of performing simulations in Lagrangian or Eulerian coordinates. In this case, modelling was conducted to simulate entrainment of water in S- and U-shaped pipes. Comparisons between 1-D and 2-D simulations show significant differences in the results.

Bouton [120] used TRANSFLUID, a 1-D finite-difference method code developed by Aerospatial that uses the Runge Kutta method and is capable of simulating thermalhydraulic networks. The results of the 1-D TRANSFLUID simulations are compared to results generated using FLOW3D, a 3-D finite-difference code developed by Flow Science Inc. The objective in this case was to simulate the priming of a piping network of a spacecraft with a propellant into a dead-ended pipe, with and without initial gas pressure.

Murray [121] also uses what is described as a large, network-capable code based on the method of characteristics to model water hammer in the presence of noncondensables. The program includes a sophisticated flow regime map, and a number of examples of various simulations that have been successfully performed using the code are given in the paper.

7.2 Water and Void (Cavitation/Column Separation)

Many of the efforts to model the presence of void created by column separation use the method of characteristics to model the single-phase liquid in a pipe, coupled to a special model to account for the appearance of cavitation or column separation. One of the most active efforts of this type, and certainly one of the most advanced in this area are the models developed at the Delft University of Technology and the Delft Hydraulics Laboratory. Over the years, various researchers at these institutions have integrated a number of models into method of characteristics codes and validated them against standardized test data obtained from experiments performed at Delft. Kalkwijk and Kranenburg [59] discuss the implementation of a cavitation model into a method of characteristics code, and include sample calculations using classical valve slam experimental results. Kalkwijk et al. [103] evaluate two models against experimental data: a small bubbles model, and a thin cavity model. Safwat and Polder [58] use a code to simulate a classical valve slam experiment in which void is assumed to form on the downstream face of the valve. Provoost [61] uses a method of characteristics code coupled with three different cavitation models: a bubble flow model, a separated flow model, and a concentrated cavitation model. Comparison of numerical results to experimental results shows the concentrated cavitation model achieves the best results.

Not all of the efforts at Delft have involved the use of the method of characteristics however. Citing some of the difficulties involved in including the equations of state describing cavitating flows into a method of characteristics (MOC) code, Kranenburg [104] developed a finite-difference model using a Lax-Wendroff scheme to examine the effect of gas release during column separation.

Some of the more recent efforts to be reported from Delft include a conference paper by Tijsseling and Lavooij [122]. Here a method of characteristics code that includes the ability to account for fluid-structure interaction as well as column separation was verified against a series of standard benchmark experimental results. Tijsseling and Fan [60] have also used a method of characteristics code including fluid-structure interaction and used a concentrated cavity model to simulate cavitation occurring inside a closed pipe that is struck at one end.

Similar efforts involving the use of the method of characteristics coupled to cavitation models have also been made at the University of Michigan. Tullis et al. [123] have coupled a method of characteristics code to two different column separation models, a lumped air model, and a discrete bubble model, to simulate column separation with air release. Simpson and Wylie [124] have published a discussion of some of the difficulties involved in implementing a discrete cavity model into a method of characteristics model. They discuss problems involving the appearance of non-physical pressure spikes and include some sample calculations to illustrate these difficulties. Martin and Wiggert [125] include a short review of developments in modelling the presence of air and air adsorption/desorption during cavitation and column separation. Their paper presents a comparison of modelling results using a modified method of characteristics code and a four-point finite-difference code to simulate water hammer occurring in power station cooling water systems. In addition to the summary of modelling efforts, the paper also presents a summary of transient tests performed on cooling water systems, and compares simulation results for both codes. Simpson and Wylie [126, 127] discuss the use of the method of characteristics to model cavitation occurring in an upward sloping line upstream of a slammed valve. These papers include a discussion of the formation of vaporous cavitation, and the comparison of two models that can be used to model cavitation in method of characteristics programs: a discrete vapour cavity model, and a combined cavity-distributed cavitation model.

Hurwitz [76] and Gruel et al. [78] at MIT use a method of characteristics code combined with a cavitation model as part of a suite of three codes used to describe the propagation of a water hammer pressure wave through a piping network.

Other numerical models coupling the method of characteristics to cavitation/column separation models have been developed and discussed by various authors. Tanahashi and Kasahara [62] use the method of characteristics coupled with a column separation model to simulate the appearance of column separation on the downstream face of a slammed valve. Suda [128] uses this approach to model classical valve slam and pump seizure problems. Using a method of characteristics program, Ruus et al. [129] have generated a series of graphs to describe maximum pressure increases resulting from water column separation and check valve closure of a simple low head pump discharge line. Finally, Marsden and Fox [63] have created a method of characteristics code with a special column separation mode that does not assume the cavity occupies the entire cross section of the pipe. The results of the simulations compare well to experimental data.

Homogeneous method of characteristics models where the celerity is adjusted to account for the presence of vapour regions have been developed by De Bernardinis [130] and De Almeida [131]. De Bernardinis demonstrates a method of characteristics model of this type considering the column separation that may occur on the downstream side of a slammed valve using a homogeneous void bubble model that accounts for the heat transfer between the bubbles and the liquid. De Almeida considers the more general case in which cavitation can take place anywhere in the pipe.

Finite-difference methods have also been applied to simulate water hammer in the presence of cavitation. Gibson and Levitt [132] have developed a finite-difference code capable of modelling suspended or dissolved gas, laminar and turbulent flow regimes, and cavitation. Chiatti and Ruscitti [133] use a finite-difference method capable of modelling cavitation to simulate a diesel injection system, and Gwinn and Wender [134] used a standard solver package to simulate cavity collapse on startup of a pump into lines where column separation had occurred.

In addition to the custom-made codes described above, large thermalhydraulic network codes capable of simulating column separation and cavitation have also been used to model water hammer. Youngdahl and Kot [102, 135] at Argonne National Laboratories made use of the method of characteristics code PTA to model systems where cavitation may occur. Yih et al. [136] have used RELAP5-FORCE, a specially modified version of RELAP5-MOD1 to model the filling of voided lines in PWR reactors during a loss of coolant accident with loss of outside power. Capozza [137] described an Italian method of characteristics code TRANSID, capable

of performing thermalhydraulic network calculations involving cavitation. A relatively detailed explanation of the code is given as well as a description of a number of the calculations performed using it.

HAMOC, a method of characteristics code capable of simulating column separation is outlined in a report by Johnson [138]. HAMOC was designed to replace the method of characteristics code WHAM. One of the main reasons for developing HAMOC was WHAM's inability to simulate column separation. This report is primarily meant to serve as a programmer's manual for HAMOC, but also includes a sample calculation that is compared against the results of WHAM, and a proprietary Westinghouse TRAPP version of the BLODWN-2 fluid code.

Fleming [139], and Goitom and Bonema [140] make use of LIQT, a method of characteristics code applicable to thermalhydraulic network simulations, to model cavitation and water hammer. Fleming describes the application of LIQT for simulating the cavitating flows occurring in a sewage pumping station in Ancorage, Alaska under loss of power conditions. Goitom and Bonema use LIQT to model Finchaa, a high head hydroelectric power project in Ethiopia to determine potential maximum and minimum pressures in the system.

Williamson [141] described a search conducted to find a code to model the dynamic cavitation process involved in the rapid filling of a voided line. Programs considered were DAPSY (a method of characteristics code), TRAC (a drift flux code), RELAP5 (a finite-difference code), and SOLA-PLOOP (a drift flux code). After some consideration, it was decided to develop the needed capabilities in the SOLA-PLOOP code. The report includes an explanation of the modifications made to the code and the results of simulations.

In summary, the creation of void due to column separation has been modelled using a wide variety of codes including specialized codes written to model a specific experiment or thermalhydraulic network as well as large thermalhydraulic network codes. The majority of codes utilize the method of characteristics to model the sections of pipe containing single-phase liquid, and couple in a special model capable of simulating column separation or cavitation as the need arises.

7.3   Condensation Induced Water Hammer

Condensation induced water hammer is a very complex phenomenon. The simulation of condensation induced water hammer is by far the most difficult to model numerically. Relatively few papers have been written on modelling two-phase water hammer in comparison to simulations of water hammer in air/water systems or under cavitating/column separation conditions.

One of the most commonly used large thermalhydraulic network codes for simulating condensation induced water hammer is RELAP5. This code was developed at the Idaho National Engineering Laboratory (INEL) under the primary sponsorship of the USNRC. It is based on a model for two-phase systems solved by a semi-implicit finite-difference method [142].

So and Pshyk [143] used RELAP5/MOD2 in an attempt to model condensation induced water hammer in the CANDU primary heat transport system. Due to the geometry of the system under investigation and the type of reactor outlet header break case undertaken, condensation induced water hammer pressure spikes were seen to occur in the reactor outlet header under certain conditions, but they were not significant. Sweeney and Griffith [79] at MIT have used RELAP5/MOD3 in an effort to model the water hammer pressure wave created by the sudden stopping of a flashing flow, and RELAP5/MOD3 Version 5m5 was used by Yeung et al. [20] to model the Creare water cannon experiments [11].

Attia and Ruhl [144] have also attempted to model the Creare water cannon experiments [11]. In this case, the authors made use of PISCES 2D-ELK, an explicit finite-difference code capable of performing simulations in Lagrangian or Eulerian coordinates. Attempts were made to model the steam-filled region as a gas and also as an instantaneous void using the models within the code. At best, the peak pressures predicted by the code came to within an order of magnitude of the experimental results.

Travis and Torrey [145] used SOLA-LOOP, a non-equilibrium, drift-flux code capable of simulating two-phase flow in thermalhydraulic networks, to model and analyze three tests performed utilizing a full scale pressurized water reactor facility at the Superheated Steam Reactor Safety Program Project at the Kernforschungszentrum near Frankfurt. The tests involved an investigation of the performance of a check valve and the associated piping following a sudden pipe rupture.

Specialized models have also been used to describe the process causing condensation induced water hammer. Hurwitz [76] and Gruel et al. [78] at MIT have assembled a model that builds on the model originally used in the Creare report [11] to solve for the condensation processes occurring in a vertical water cannon type condensation induced water hammer event. Warren [109] has performed a study of the water slugs that form in the horizontal feedwater pipe of a feed-ring type steam generator. Two codes were developed and compared: a method of characteristics code using a continuum analysis, and a finite-difference (Runge-Kutta) code using a lumped formulation. Wang et al. [83] have performed an analysis of a two-phase water hammer event that occurred during startup testing of a nuclear power plant. Here, a method of characteristics code was used to simulate liquid condensate entrainment by steam in the low point of a steam line to show the most likely cause and mechanisms of the observed water hammer transient.

Finally, a recent study by Wendel and Williams [146] has been undertaken to examine the ability of RELAP5 to predict the pressure-wave propagation that occurs after a pipe break in the advanced neutron source reactor currently being designed at Oak Ridge National Laboratory. Test results show numerical diffusion in RELAP5. However, a detailed convergence study indicates that, given an adequate nodalization, RELAP5 is capable of predicting the amplitude of a water hammer pressure wave caused by an instantaneous pipe break.

In summary, generalized thermalhydraulic network codes are often used to model condensation induced water hammer. A recurring problem invariably commented on by most authors is the inability of these codes to accurately predict condensation induced water hammer. A primary concern is the uncertainty of the mass transfer coefficient between the steam and the subcooled water under dynamic high temperature, high pressure conditions. As a consequence, the simulation results often do not agree well with the experimental results. It should also be noted that efforts are currently underway to qualify TUF (Ontario Hydro) and CATHENA (AECL) as two-phase water hammer codes. Efforts are also being undertaken to validate PTRAN (AECL) for use in water hammer simulations under cavitation/column separation conditions.

8   SUMMARY

In the area of two-phase water hammer, many research studies concentrate on analyses of experimental results and discuss the development of analytical theory. Less effort has been expended to advance the development of comprehensive numerical codes. This is in no small part due to the complexity of the phenomenon itself. Some reasonably successful attempts at modelling have been made, but these generally involved the use of specialized codes developed to model specific experiments. Generalized codes have shown themselves to be somewhat less adept at modelling two-phase water hammer.

The results of this state-of-the-art review indicate that two-phase water hammer is an ongoing topic of concern in nuclear power plants as a safety issue as well as for economic reasons. Numerous studies have been undertaken to examine the causes and effects of two-phase water hammer and the steps that can be taken to prevent it from occurring. A review of the available literature has been performed and the results show these investigations have resulted in a better understanding of the fundamental phenomena involved, but much work remains to be done. Two-phase water hammer is a complex phenomenon, and certain aspects remain unclear in spite of the attention it has received, and the large number of publications written about it in the open literature.

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