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Water hammer with column separation: A historical review

A. Bergant[a], A.R. Simpson[b], A.S. Tijsseling[c,*]

[a]*Litostroj E.I. d.o.o., Litostrojska 40, 1000 Ljubljana, Slovenia*
[b]*School of Civil and Environmental Engineering, University of Adelaide, Adelaide 5005, South Australia*
[c]*Department of Mathematics and Computer Science, Eindhoven University of Technology, P.O. Box 513, 5600 MB Eindhoven, The Netherlands*

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Abstract

Column separation refers to the breaking of liquid columns in fully filled pipelines. This may occur in a water-hammer event when the pressure in a pipeline drops to the vapor pressure at specific locations such as closed ends, high points or knees (changes in pipe slope). The liquid columns are separated by a vapor cavity that grows and diminishes according to the dynamics of the system. The collision of two liquid columns, or of one liquid column with a closed end, may cause a large and nearly instantaneous rise in pressure. This pressure rise travels through the entire pipeline and forms a severe load for hydraulic machinery, individual pipes and supporting structures. The situation is even worse: in one water-hammer event many repetitions of cavity formation and collapse may occur.

This paper reviews water hammer with column separation from the discovery of the phenomenon in the late 19th century, the recognition of its danger in the 1930s, the development of numerical methods in the 1960s and 1970s, to the standard models used in commercial software packages in the late 20th century. A comprehensive survey of laboratory tests and field measurements is given. The review focuses on transient vaporous cavitation. Gaseous cavitation and steam condensation are beyond the scope of the paper.

Keywords: Water hammer; Fluid transients; Column separation; Cavitation; History; Review

1. Introduction

1.1. Water hammer and column separation

Modern hydraulic systems operate over a broad range of operating regimes. Any change of flow velocity in the system induces a change in pressure. The sudden shutdown of a pump or closure of a valve causes fluid transients which may involve large pressure variations, local cavity formation, distributed cavitation (bubble flow), hydraulic and structural vibrations and excessive mass oscillations. In particular, the occurrence of column separation may have a significant impact on subsequent transients in the system.

*Corresponding author. Tel.: +31 40 247 2755; fax: +31 40 244 2489.
E-mail addresses: anton.bergant@litostroj-ei.si (A. Bergant), asimpson@civeng.adelaide.edu.au (A.R. Simpson), a.s.tijsseling@tue.nl (A.S. Tijsseling).

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Nomenclature

Abbreviations in References

ASCE	American Society of Civil Engineers
ASME	American Society of Mechanical Engineers
AWWA	American Water Works Association
BHRA	British Hydromechanics Research Association
BHR	Group British Hydromechanics Research Group
FED	Fluids Engineering Division
IAHR	International Association of Hydraulic Research
IChemE	Institution of Chemical Engineers
IMechE	Institution of Mechanical Engineers
JSCE	Japan Society of Civil Engineers
JSME	Japan Society of Mechanical Engineers
MISI	Moscow Institute of Civil Engineering
PVP	Pressure Vessels and Piping
SMiRT	Structural Mechanics in Reactor Technology

Abbreviations

DGCM	discrete gas cavity model
DVCM	discrete vapor cavity model
FEM	finite element method
FSI	fluid–structure interaction
GIVCM	generalized interface vaporous cavitation model
HGL	hydraulic grade line
MOC	method of characteristics

Scalars

A	cross-sectional pipe area (m^2)
a	pressure wave speed (m/s)
B	constant in water-hammer compatibility equations (s/m^2)
C	constant in water-hammer compatibility equations (m)
D	inner diameter of pipe (m)
E	Young's modulus of pipe wall material (Pa)
e	pipe wall thickness (m)
f	Darcy-Weisbach friction factor
g	gravitational acceleration (m/s^2)
H	(piezometric) head (m)
K	bulk modulus of liquid (Pa)
L	pipe length (m)
l	cavity length (m)
p	gage fluid pressure (Pa)
p^*	absolute fluid pressure (Pa)
Q	discharge (m^3/s)
R	pipeline resistance coefficient (s^2/m^5)
S	cavitation severity index
T	absolute temperature (K)
T_c	valve closure time (s)
T_{cs}	duration of the first column separation (s)
t	time (s)
V	flow velocity (m/s)
$\forall$	volume (m^3)
x	distance along the pipeline (m)

α	void fraction
γ	specific weight (kg/m^2/s^2)
Δ	numerical step size, change in magnitude
θ	pipe slope (rad)
ρ	mass density (kg/m^3)
ψ	numerical weighting factor

Subscripts

A	point in x–t plane
B	point in x–t plane
b	barometric
cs	column separation
f	final
in	inception, initial
j	computational section index
m	mixture
max	maximum
mc	negative (minus) characteristic
P	point P in x–t plane, downstream side of point P
Pu	upstream side of point P
pc	positive (plus) characteristic
q	quasi-steady
RV	reservoir-valve (see Eq. (5))
s	shock
sv	shock-vapor
u	upstream, unsteady
v	vapor
0	initial (steady) state

Column separation is like the breaking of a solid rod or rope—Galilei already described this analogy (Rouse and Ince, 1957, 1963, p. 57)—and the phenomenon can be nicely demonstrated in a simple toy apparatus (Wylie, 1999) that emits light flashes when filled with glycerin (Schmid, 1959; Chakravarty et al., 2004). Large pressures with steep wave fronts may occur when column separations collapse and the practical implications are therefore significant. As an outcome, fluid transients may lead to severe accidents (Jaeger, 1948; Bonin, 1960; Parmakian, 1985; Kottmann, 1989; De Almeida, 1991; Galante and Pointer, 2002). The general policy in hydraulic design involving fluid transients is to avoid column separation.

1.2. Previous reviews

Jaeger et al. (1965), Martin (1973) and Thorley (1976) provided valuable summaries with extensive bibliographies of the historical development of many aspects of water hammer including column separation. Streeter and Wylie, in their three textbooks (Streeter and Wylie, 1967; Wylie and Streeter, 1978a, 1993), give account of previous work on column separation. De Almeida (1987) reviewed the period 1978–1987. Beuthe (1997) gave an extensive general review with emphasis on steam condensation, omitting perhaps the first contribution to this subject by Stromeyer (1901). During the period 1971–1991 an international Working Group of the IAHR carried out a major research effort with respect to column separation in industrial systems. One of the main aims of the Group was the development of computer codes and the validation of these against experimental results. The outcomes of this work have been summarized in an extensive synthesis report (Fanelli, 2000). Current collaborative research in Europe is carried on through Surge-Net. The present paper is a deliverable of the Surge-Net Work Packages 2 (Multiphase Flow) and 4 (Collection of Data).

1.3. Scope and outline of the paper

Cavitation is a broad field of research. This review is confined to the macroscopic aspects of transient vaporous cavitation with focus on the important case of column separation. The aim is to give a historical account, to summarize the state of the art, and to have a list of references as complete as practically possible. Microscopic aspects of cavitation, cavitation erosion, cavitation noise and vibration, and advanced cavitation theory—subjects not considered herein—are covered by Knapp et al. (1970), Hammitt (1980), Trevena (1987), Young (1989), Brennen (1995) and Li (2000). Valuable information may also be obtained from the review by Arndt (1981). The presence of air in water may have a significant impact on fluid transients. Air presence is considered briefly herein, but the focus is on systems with very little air, as these situations will, in most circumstances, result in the highest pressures.

Following this introduction, water hammer and the different types of cavitation (including column separation) are explained in Section 2. Section 3 considers mathematical models and their numerical implementation. Experimental studies of column separation and field measurements are surveyed in Section 4 and Section 5 gives the conclusion to this paper.

2. Water hammer, column separation and cavitation

2.1. Water hammer in a historical context

The conception of the theory of water hammer can, amongst others, be traced to Ménabréa (1858), translated by Anderson (1976), Ménabréa (1862), Michaud (1878), Von Kries (1883), Frizell (1898), Joukowsky (1900), Gibson (1908) and Allievi (1902, 1913). Joukowsky conducted experiments in Moscow in 1897/1898 when he derived his famous law for instantaneous water hammer. This law states that the (piezometric) head rise ΔH resulting from a fast ($T_c < 2L/a$) closure of a downstream valve is given by

$$\Delta H = \frac{aV_0}{g}, \tag{1}$$

in which a is the pressure of wave speed, V_0 the initial flow velocity, g the gravitational acceleration, L the pipe length and T_c the valve closure time. The wave speed is estimated from Korteweg's (1878) formula

$$a = \sqrt{\frac{K/\rho}{1 + (K/E)(D/e)}}, \tag{1a}$$

where K is the bulk modulus, ρ the mass density, E the Young's modulus of the pipe wall material, D the inner diameter of the pipe, and e the wall thickness. The period in a pipe, $2L/a$, is the time for a pressure wave to travel from the valve to a reflection point (e.g. a reservoir) and back. Formula (1) is generally referred to as the *Joukowsky* equation, but Tijsseling and Anderson (2004) pointed out that Von Kries (1883) was actually the first one to derive and validate it.

2.2. Column separation

Column separation can have a devastating effect on a pipeline system. A well-known example is the accident at Oigawa hydropower station in 1950 in Japan (Bonin, 1960). Three workers died. The plant was designed in the early 20th century. A fast valve-closure due to the draining of an oil control system during maintenance caused an extreme high-pressure wave that split the penstock open. The resultant release of water generated a low-pressure wave resulting in substantial cavitation that caused crushing (pipe collapse) of a significant portion of the pipeline due to the external atmospheric pressure load. Jaeger (1948) reviewed a number of the most serious accidents due to water hammer in pressure conduits. Many of the failures described were related to vibration, resonance and auto-oscillation. Two of the failures involved column separation. In one case a governor caused a valve to open suddenly and thus produced a low-pressure wave that resulted in a column separation at a change in the pipe profile. When the liquid columns rejoined, strong pressure rises caused cracking of a concrete section of the penstock. Kottmann (1989) described two accidents related to column separation in which two workers died. List et al. (1999) reported severe damage to the lining of a pump discharge pipeline, finally resulting in leaks. The cause was vapor cavity collapse.

2.3. First observations of sub-atmospheric pressures during water-hammer events

Carpenter (1894) and Carpenter and Barraclough (1894) were the first to record sub-atmospheric pressures in a water-hammer event, as noted by Joukowsky (1900, pp. 3–5). Joukowsky (1900, pp. 31–32) was the first to observe (see Fig. 1) and understand column separation. He explained the events in his experimental main-pipeline-gate system

Fig. 1. Pressure record exhibiting column separation. Horizontal axis: time (each dot indicates half a second). Vertical axis: pressure (Joukowsky pressure of 15.3 bar). The upper horizontal line is the static pressure and the lower horizontal line is the atmospheric pressure. [Adapted from Joukowsky (1900, Fig. 17); also shown by Simin (1904, Fig. 13), and by Moshnin and Timofeeva (1965, Fig. 1)].

literally as follows: "*Starting at the moment of closure of the gate the water in the pipe is continuously being stopped, whereby it is being compressed, the pipe expands and the pressure increases with* Δp. *When this state travels with the celerity a up to the main, the latter transmits back along the pipe the pressure of the main (a little raised due to water hammer in the main itself) and a velocity of the water, which is directed in the direction of the main. This phase first passes the cabins II and III (measuring points), as a result of which the pressure in the indicators (gages) in these cabins falls to the pressure of the main. When however the mentioned phase reaches the gate, this instantaneously causes, since the velocity of the water is directed away from the gate, a decrease of the pressure at the gate. If thereby the velocity V is so large, that according to the theory the reduced pressure would be negative, a break of the water mass will occur. The water column will be separated from the gate, ahead of which a small rarefied void develops. Similar separations can also form in other parts of a liquid column, the parts towards which the reduced pressure propagated.*" and "*The condition, that the water column is separated from the gate, prolongs the duration of the reduced pressure and makes the second impact stronger than the first, because it takes place with the velocity, at which the liquid column speeds into the rarefied void.*" See also Simin (1904, pp. 381–382).

Gibson (1908) performed water-hammer experiments with closure and opening of a downstream valve in a laboratory pipeline apparatus. He indicated that a low-pressure wave initiated gas release. Strowger and Kerr (1926) warned that load rejection could cause a full column-separation in the draft tube of a reaction water turbine. Thorley (1976) attributed the first work on vapor cavities to Hogg and Traill (1926) and Langevin and Boullée (1928). Mostowsky (1929) presented the first theoretical analysis of column separation in an explanation of his laboratory measurements. Billings et al. (1933) presented a paper at the first symposium on water hammer in 1933 in Chicago (Proceedings, 1933) that dealt with "*parting of the water column*". The authors noted that dangerous instantaneous pressure rises often originated in the upper portion of a penstock, when the liquid column parted and rejoined abruptly.

2.4. Vaporous cavitation

Two types of vaporous cavitation in pipelines are distinguished. The magnitude of the void fraction of the vapor within the liquid is the basis for identifying the two types. It is defined as the ratio of the volume of the vapor, $\forall_v$, to the total volume of the liquid/vapor mixture, $\forall_m$:

$$\alpha_v = \frac{\forall_v}{\forall_m}. \tag{2}$$

The symbol α was introduced by Wallis (1969) in his classic textbook on two-phase flow. The two types are: (i) local column-separation (large α, $\alpha \approx 1$) and (ii) distributed vaporous cavitation (small α, $\alpha \approx 0$). In contrast to column separations, distributed vaporous cavitation occurs over an extended length of the pipe. All cavities maintain the vapor pressure of the liquid.

2.4.1. Cavitation inception and tensile stress

The vapor pressure of the liquid is adopted as the cavitation inception pressure in most mathematical models for transient cavitation. However, there are a number of reported experiments with cavitation inception pressures (negative absolute pressure peaks) much lower than the liquid vapor pressure (Lee et al., 1985; Takenaka, 1987; Fan and Tijsseling, 1992; Simpson and Bergant, 1996). Washio et al. (1994) even observed traveling tensile waves (negative absolute pressure waves) in a dead-end branch of a main oil pipe. The magnitude of the negative absolute pressure is the dynamic tensile strength of the liquid. It is determined by the flow conditions and the cavitational properties of liquid and pipe walls. Intense pre-pressurization of the liquid tends to increase its tensile strength.

Plesset (1969), Overton et al. (1984) and Trevena (1984, 1987) give in-depth treatments of tensile stresses in liquids. Recent results have been presented by Williams et al. (1999), Williams and Williams (2000) and Brown and Williams (2000). Tensile stress is a metastable condition for the liquid, which in a transient event is governed by nonequilibrium thermodynamics.

Shinada and Kojima (1987) measured small negative absolute pressures of longer duration in transient cavitation tests. They attributed this to the effect of surface tension, which can be important when the distributed cavitation zone consists of many miniscule bubbles.

2.4.2. *Local large vapor cavities*

After the studies of column separation by Joukowsky (1900) and Mostowsky (1929), it was LeConte (1937) who presented some of the first experimental results for a local liquid column separation. He also proposed an analytical model based on rigid-column analysis. An arbitrary coefficient had to be introduced to provide a match between the analytical and experimental results. Knapp (1939) attributed many failures in the upper portion of a penstock to the pressure rise that resulted from column separation at a "*knee*" in the profile. Previously cited causes for these failures had been described as of "*obscure origin*".

Lupton (1953) presented a summary of the graphical method, with one section devoted to "*separation of water columns*". He introduced the possibility of the formation of an intermediate vapor cavity not located adjacent to a hydraulic device (valve, turbine, etc.) or at a high point and he presented an example that exhibited the sequence of events leading to the formation of such an intermediate cavity. Moores (1953) initiated consideration of the topic in a discussion of Lupton's paper, when he posed a question as to what happened when pressure waves meet. Lupton's reply stated that: "*if the meeting of the waves were negative, and their sum exceeded the absolute head H_0 existing initially, a gap would be formed*". Jordan (1961) developed an analytical method for the computation of the exact locations along a pipeline of intermediate cavities.

O'Neill (1959) noted that most previous graphical studies overlooked the formation of intermediate cavities, which impose an internal boundary condition in the pipe. Experimental results with visualization studies of the growth and decay of intermediate cavities were presented. Sharp (1960, 1965a, b), continuing O'Neill's work, considered the growth and collapse of small vapor cavities produced by a rarefaction wave. An ideal spherical cavity was analyzed theoretically (Sharp, 1965a). Experimental results, which included high-speed photography of single intermediate cavities, were presented. Sharp proposed that another type of cavity also existed "*during the first and succeeding rupture phases for an entirely different reason*". A succession of a small number of cavities at regular intervals was asserted to form moving away from the valve (Sharp, 1965a, 1977). Reversal of the transient flow in the pipeline caused these cavities to collapse and a series of regular pulses resulted when the liquid columns rejoined. This phenomenon appears to be similar to the occurrence of distributed vaporous cavitation as discussed below.

2.4.3. *Distributed small vapor cavities*

The difference between a local column separation and distributed cavitation was first described by Knapp (1937b) in a paper at the second water hammer symposium in New York (Proceedings, 1937), which expanded the work in an earlier reference (Knapp, 1937a). He presented an example in which a pressure drop was produced by a rupture of the pipe just below a shutoff valve. The negative wave traveled up the pipeline unchanged until the wave front intersected the "*zero pressure line*". The liquid between the point of intersection and the downstream reservoir cavitated partially, but column separation did not occur. Reflection of the pressure wave from the reservoir brought the liquid back to its original state (without cavitation). He stated that "*further investigations were necessary to clear up completely such water-hammer conditions with cavitation*". Knapp (1939) further developed the concept of distributed cavitation in a discussion of LeConte's (1937) paper and concluded that this could not be solved by the graphical method.

De Haller and Bédué (1951) presented an analytical treatment of column separation. They suggested that cavities could occur along long sections of pipeline rather than forming a local gap occupying the entire pipe cross-section. Lupton (1953) provided a description of the sequence of events associated with distributed vaporous cavitation in the transmission of a negative wave along an upward sloping frictionless pipe. Bunt (1953) presented findings of a laboratory investigation on column separation at a valve and at high points, where the possibility of the formation of a distributed vaporous cavitation region was recognized.

Jordan (1965) investigated column separation and distributed cavitation in pumping systems with horizontal, upward and downward sloping pipe sections and he studied analytically the effect of hydraulic grade line (HGL) and pipe slope

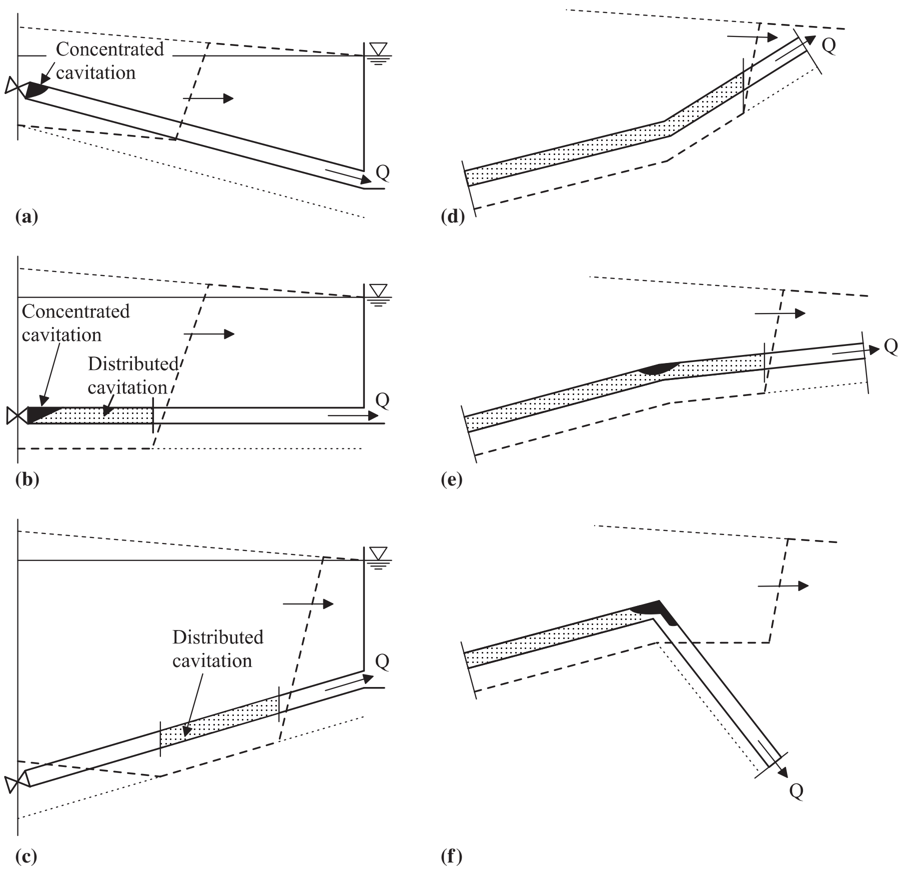

Fig. 2. Dotted lines: vapor head; thin dashed lines: steady state head; dashed lines: unsteady head. (Left) Fast-closing valve generating cavitation in (a) downward sloping pipe, (b) horizontal pipe, and (c) upward sloping pipe. [Adapted from Zielke and Perko (1985, Fig. 3)]. (Right) Cavity formation at a knee with pipe slope (d) increasing, (e) decreasing but still upward, and (f) decreasing to downward [adapted from Zielke and Perko (1985, Fig. 4)].

on the formation of cavitation zones. A cavitation zone may result from the passage of a negative wave traveling in the direction of decreasing steady state pressure. In contrast, if the steady state pressure increases in the direction of wave propagation a vaporous cavitation zone cannot occur (Zielke and Perko, 1985; Simpson, 1986; Simpson and Wylie, 1989). This is portrayed in Fig. 2.

2.5. *Gaseous cavitation*

Many papers have addressed the effects of free gas, dissolved gas and gas release on transients in liquid-filled pipelines (Swaffield, 1969–1970, 1972a, b; Enever, 1972; Kranenburg, 1974b; Martin and Padmanabhan, 1975; Sundquist, 1977; Wiggert and Sundquist, 1979; Wylie, 1980; Baasiri and Tullis, 1983; Chaudhry et al., 1990; Hadj-Taieb and Lili, 1998, 1999, 2000, 2001; Kessal and Amaouche, 2001). One of the main features of liquids is their capability of absorbing a certain amount of gas with which they come into contact through a free surface. In contrast to rupture and vaporization, which takes only a few microseconds, gas release is a diffusive process, which takes several seconds (in water at room temperature). Gas absorption is much slower than gas release (order of minutes) (Zielke et al., 1989). Dissolved gas is an important consideration in sewage water lines, aviation fuel and oil lines. Gas comes out of solution when the pressure drops. It may be assumed that released gas stays in cavities and does not immediately redissolve following a rise in pressure. Kobori et al. (1955), Pearsall (1965) and Raiteri and Siccardi (1975) showed that the presence of free gas reduces the wave speed and, according to Eq. (1), the transient pressure variations.

2.6. Short-duration pressure peaks following cavity collapse

Short-duration pressure peaks *exceeding* the Joukowsky value given by Eq. (1) may occur after cavity collapse. The phenomenon is explained for a frictionless reservoir-pipe-valve system, Fig. 3(a). Instantaneous valve closure causes a head *rise* $\Delta H = (a/g)V_0$. The head rise travels towards the reservoir, where it reflects negatively, and returns at the closed valve at time $2L/a$. Fig. 3(b) shows the pattern of propagation and reflection of pressure waves in the distance–time plane. Fig. 3(c) shows the heads at the valve calculated with a water-hammer model with (thick solid line) and without (thin solid line) a cavity forming at the valve. The liquid flows in the reverse direction (towards the reservoir) at time $2L/a$. Complete stoppage of the flow at the valve now requires a head *drop* of $(a/g)V_0$ relative to H_0. This head drop (thin solid line in Fig. 3(c)) would result in a head less than the vapor head (horizontal dashed line in Fig. 3(c)). When the head is not allowed to drop below the vapor head (thick solid line in Fig. 3(c)), the reverse velocity at the valve is not reduced to zero at time $2L/a$, but to (Mostowsky, 1929, Fig. 7(b) herein with $\Delta H_{in} = H_0 + H_b$)

$$V_0 - \Delta V_{vc} = V_0 - \frac{g\Delta H_{in}}{a}, \tag{3}$$

where

$$\Delta H_{in} = H_0 + H_b - p_v^*/\gamma, \quad \Delta H_{in} < \Delta H \tag{3a}$$

is the head drop (relative to H_0) which starts vaporization. Here, H_0 is the steady state head at the valve, H_b the barometric head, p_v^* the absolute vapor pressure at temperature T, and $\gamma = \rho g$ the specific weight of the liquid. Now, at the closed valve, the flow is towards the reservoir, the liquid detaches from the solid and a cavity begins to grow. The cavity acts as a fixed-head boundary condition for the pressure waves. At each successive time interval ($4L/a$, $6L/a$, etc.) a pressure wave reflects off the vapor cavity and the *reverse* liquid velocity decreases by an amount of $2\Delta V_{vc}$. At a certain time this velocity changes direction, the cavity then begins to shrink and it finally collapses at point A in Fig. 3(b) and (c). The head directly caused by the cavity collapse is less than the head $H_0 + \Delta H$ generated by valve closure, but the maximum head (larger than Joukowsky pressure head rise!) occurs, in this example, at a time of about $6L/a$ (point B in Fig. 3(b) and (c)) in the form of a short-duration peak. If the cavity collapse would have taken place exactly at the arrival of a pressure wave front, at times that are multiples of $2L/a$, then a short-duration peak would not have occurred.

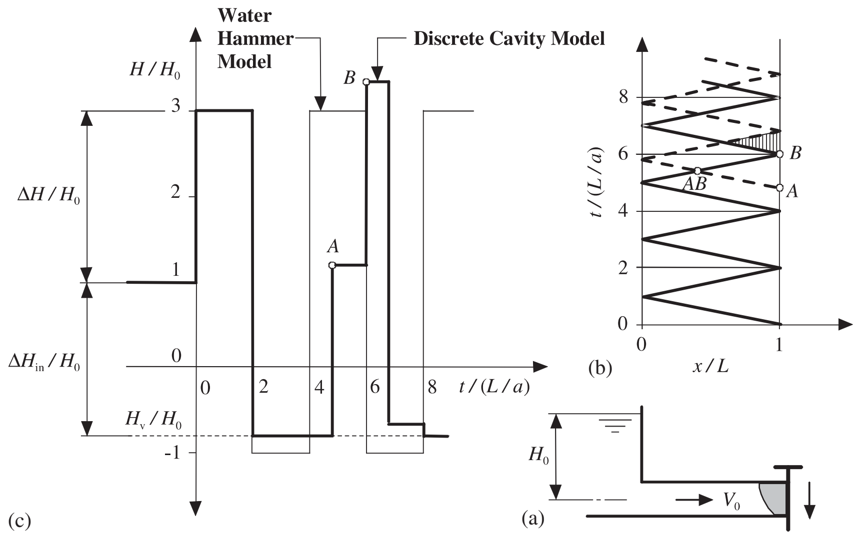

Fig. 3. Formation of a short-duration pressure peak. (a) Reservoir-pipe-valve system. (b) Wave paths in distance-time plane. (c) Piezometric-head history at valve.

In a similar consideration, Wylie and Streeter (1993, pp. 192–196) showed that the time of existence of the first vapor cavity approximately is

$$T_{cs} = \frac{2a}{g\Delta H_{in}} V_0 \frac{L}{a} = \frac{\Delta H}{\Delta H_{in}} \frac{2L}{a}, \tag{4}$$

thus confirming the formula found by Mostowsky (1929) and shown in Fig. 7(a) herein.

Angus (1935, 1937) presented one example in which the collision of a liquid column with a closed valve resulted in a short-duration pressure peak of large magnitude. The duration of the pressure peak was about one-tenth of a $2L/a$ period. Pressure traces measured by Binnie and Thackrah (1951) indicated the existence of a short-duration pressure peak, which exceeded the "main shock pressure". The authors attributed the higher pressures to the existence of additional pressure waves caused by reflections from bends, sockets and other discontinuities in the pipeline. Their analysis was based on rigid-column theory and on water-hammer theory. Some of O'Neill's (1959) analytical examples exhibited short-duration pressure peaks, but his experimental pressure records did not. Gayed and Kamel (1959) clearly explained the occurrence of short-duration peaks and they claimed their appearance in one of the measurements (Fig. 11(a) in their paper). Heath's (1962) graphical-method water-hammer analysis predicted short-duration pressure peaks, but these were not apparent in his experimental results. Sharp (1960) published in Nature an example with short-duration pressure peaks and intermediate cavities.

Walsh (1964) and Li and Walsh (1964) estimated the maximum possible pressure rise following the collapse of the first cavity at an upstream valve as

$$\Delta H_{\max} = \frac{a}{g}|V_f| + 2H_{RV}, \tag{5}$$

where V_f is the velocity of the liquid column at the valve just before cavity collapse and H_{RV} the difference of reservoir head and vapor head at the valve. Walsh (1964) presented results for a number of experimental runs, a couple of which possibly show short-duration pressure peaks. The time of existence of the first cavity was quite long with respect to $2L/a$. The velocity V_f was estimated from experimental results using Eq. (5). Equations similar to Eq. (5) were presented by Moshnin (1961), Moshnin and Timofeeva (1965), De Almeida (1983), Simpson and Wylie (1985) and Wylie and Streeter (1993, p. 194 with $\Delta H_{\max} = \Delta H + 2\Delta H_{in}$) for the case of instantaneous closure of upstream and downstream valves, where $\Delta H_{\max}$ can be more than two times the Joukowsky value (1). The situation can even be worse when intermediate cavities form (Sharp, 1960). Kottmann (1989) used rigid-column theory to show that the collapse of a midpoint cavity caused pressure rises of three times Joukowsky. Yamaguchi and Ichikawa (1976) and Yamaguchi et al. (1977) presented oscilloscope traces of experimental results exhibiting what appear to be the first results in the literature that clearly show short-duration pressure peaks. Tarasevich (1980) considered column separation at an upstream valve. He predicted maximum pressures as a function of initial flow velocity. His analysis—based on rigid column theory—was confirmed by the experiments of Smirnov and Zubov (1972).

Martin's (1983) measurements concerned limited cavitation where the time of existence of the cavity at the valve is relatively short. The experimental results showed that the maximum pressure may exceed the Joukowsky pressure rise in the form of a short-duration pressure peak as shown in Fig. 4(a). Unfortunately, the reservoir pressure was rising during the experiment because the tank was too small (Martin, 1989). The measured reservoir pressure shown in Fig. 4(b) was thought to be typical for all experimental runs.

Kojima et al. (1984) presented a mathematical model for predicting both the pressure rise associated with cavity collapse and the duration of the column separation. Their experimental results exhibited short-duration pressure peaks. Simpson (1986) showed a range of short-duration pressure peaks measured in a reservoir—upward sloping pipeline—valve system. Due to the upward slope of the pipe, the vapor cavity was confined to be adjacent to the valve with no distributed cavitation along the pipe (at least until the collapse of the first vapor cavity).

2.7. Severity of cavitation

Martin (1983) inferred the severity of cavitation from the duration, T_{cs}, of the first, mostly largest, column separation at the valve. He introduced the cavitation severity index $S = T_{cs}a/(2L)$, which according to Eq. (4) is equivalent with $S = \Delta H/\Delta H_{in}$. Paredes et al. (1987), Carmona et al. (1987, 1988) and Anderson et al. (1991) proposed a somewhat different index. Bergant and Simpson (1999a) made a classification based on maximum heads (shown in Fig. 5) whether or not exceeding the Joukowsky value (Eq. (1)). The steepness of wave fronts is another important parameter in the assessment of dynamic loads on pipe systems and their supporting structures.

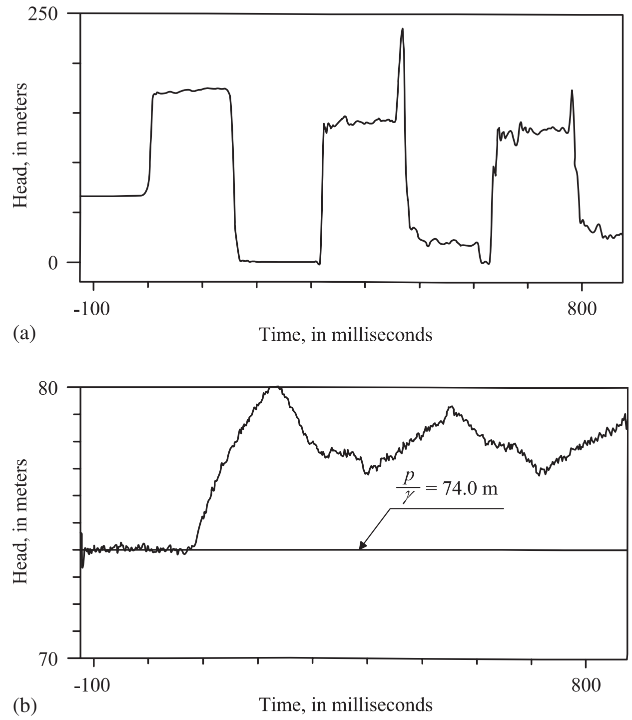

Fig. 4. Experimental result showing short-duration pressure peaks [adapted from Martin (1983, 1989)]. Absolute HGL variation with time, (a) at valve, and (b) in reservoir.

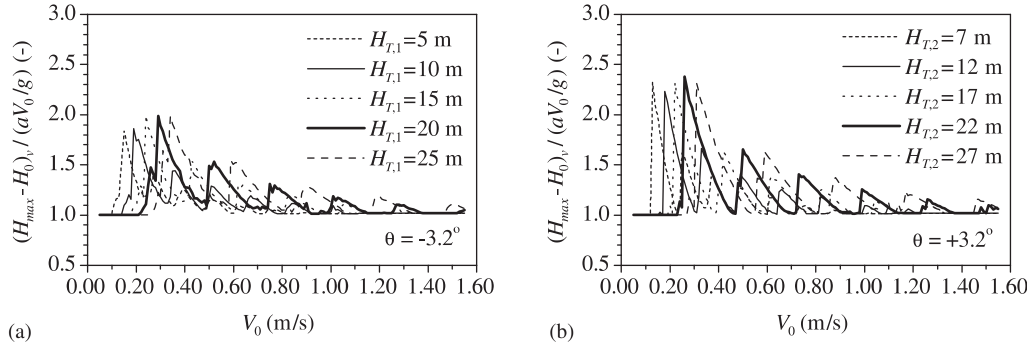

Fig. 5. Computed maximum head at valve as function of initial velocity for varying reservoir-head [adapted from Bergant and Simpson (1999a)]: (a) downward sloping pipe, (b) upward sloping pipe.

3. Mathematical models and numerical methods

A comprehensive investigation of column separation and cavitation in pipe systems was not possible until the 1960s [see Hager (2001)] due to the unavailability of computers. Most studies used graphical and arithmetic procedures originally set forth by Gibson (1919–1920), Schnyder (1932) [see Hager (2001)], Angus (1935), Bergeron (1935, 1950), Stepanoff (1949) and Parmakian (1955). The first computer-oriented procedures for the treatment and analysis of water hammer include work by Thibessard (1961), Lai (1961), Streeter and Lai (1962), Streeter (1963, 1964, 1965), Van De Riet (1964), Vreugdenhil (1964) and Contractor (1965). The first computer models for column separation were developed by Thibessard (1961) at Liège in Belgium, Streeter and Wylie (1967), Baltzer (1967a, b) and Weyler (1969) at the University of Michigan, and Vreugdenhil (1964) and Siemons (1967) at Delft in The Netherlands.

3.1. Water-hammer equations

The water-hammer equations are applied when the pressure is above vapor pressure. They comprise the continuity equation and the equation of motion:

$$\frac{\partial H}{\partial t} + V\frac{\partial H}{\partial x} - V\sin\theta + \frac{a^2}{g}\frac{\partial V}{\partial x} = 0, \tag{6}$$

$$g\frac{\partial H}{\partial x} + \frac{\partial V}{\partial t} + V\frac{\partial V}{\partial x} + \frac{fV|V|}{2D} = 0, \tag{7}$$

where H is the piezometric head (HGL), t the time, V the flow velocity, x the distance along the pipeline, θ the pipe slope, a the pressure wave speed, g the gravitational acceleration, f the Darcy-Weisbach friction factor [its history is nicely described by Brown (2002)] and D the inner diameter of the pipe. For most engineering applications, the convective terms $V(\partial H/\partial x)$, $V(\partial V/\partial x)$ and $V\sin\theta$ are very small compared to the other terms and therefore neglected. Streeter and Wylie's (1967) classic textbook led the world to the method of characteristics (MOC) as *the* numerical method to solve Eqs. (6) and (7) on a digital computer. The MOC uses the compatibility relations that are valid along the positive (C^+: $\Delta x/\Delta t = a$) and negative (C^-: $\Delta x/\Delta t = -a$) characteristic lines. These are for the $x-t$ grid shown in Fig. 6,

$$H_P = C_{pc} - B_{pc}Q_{Pu} + R_{pc}Q_{Pu}|Q_A|, \tag{8}$$

$$H_P = C_{mc} + B_{mc}Q_P + R_{mc}Q_P|Q_B|, \tag{9}$$

where C_{pc}, B_{pc} and R_{pc} are constants for the positive or *p*lus *c*haracteristic (*pc*), and C_{mc}, B_{mc} and R_{mc} are constants for the negative or *m*inus *c*haracteristic (*mc*). In anticipation of discrete cavity models, the discharge may be discontinuous with up- and downstream values Q_{Pu} and Q_P, respectively. In finite-difference form Eqs. (8) and (9) for the computational section P with index j become

$$H_j^t - H_{j-1}^{t-\Delta t} + \frac{a}{gA}\{(Q_u)_j^t - Q_{j-1}^{t-\Delta t}\} + \frac{f\Delta x}{2gDA^2}(Q_u)_j^t\left|Q_{j-1}^{t-\Delta t}\right| = 0, \tag{10}$$

$$H_j^t - H_{j+1}^{t-\Delta t} - \frac{a}{gA}\{Q_j^t - (Q_u)_{j+1}^{t-\Delta t}\} - \frac{f\Delta x}{2gDA^2}Q_j^t\left|(Q_u)_{j+1}^{t-\Delta t}\right| = 0, \tag{11}$$

where Δx is the reach length and Δt is the time step as indicated in Fig. 6.

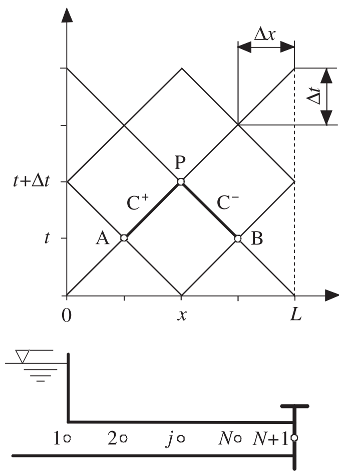

Fig. 6. The method of characteristics ($\Delta x = a\Delta t$) staggered grid for a reservoir-pipe-valve system.

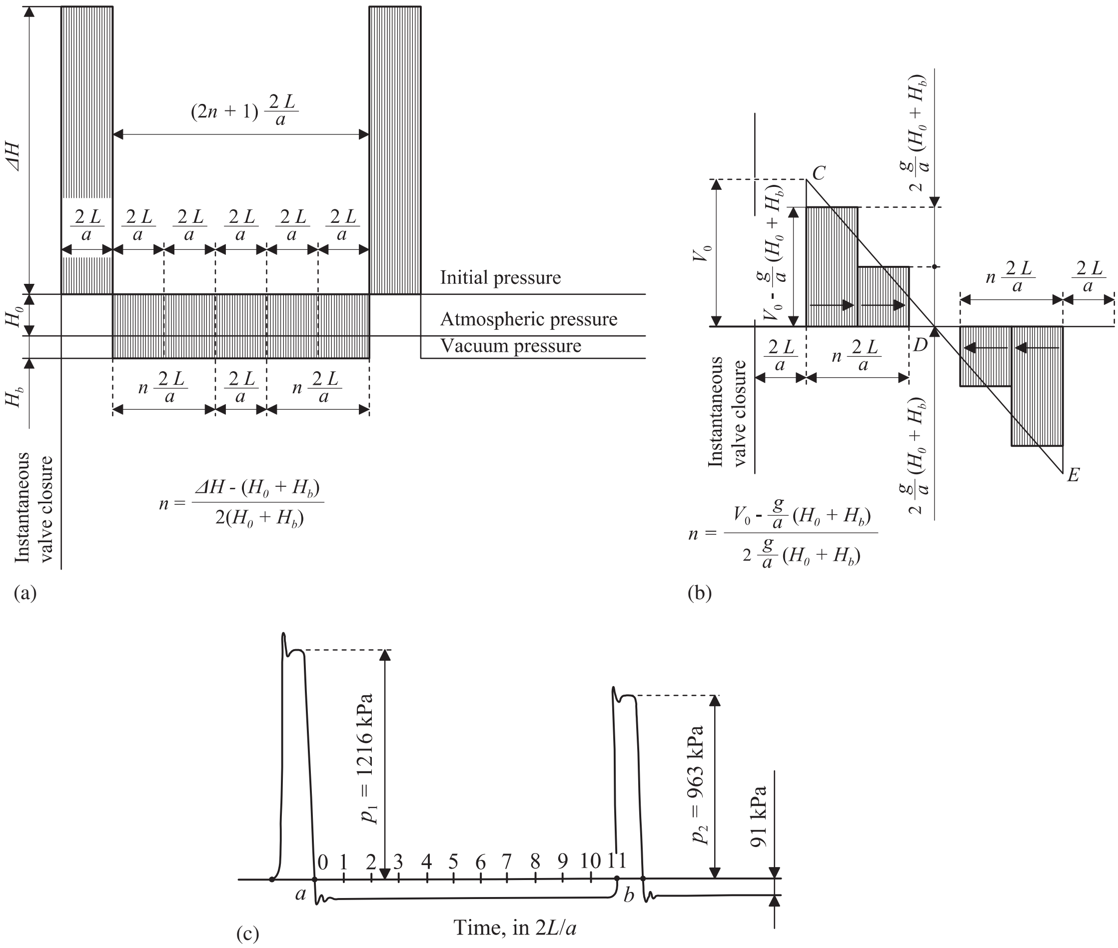

Fig. 7. Theoretical and experimental analysis of column separation in a reservoir-pipe-valve system. (a) Theoretical pressure as function of time [adapted from Mostowsky (1929, Fig. 7)]. (b) Theoretical flow velocity as function of time [adapted from Mostowsky (1929, Fig. 8)]. (c) Experimental pressure as function of dimensionless time [adapted from Mostowsky (1929, Fig. 16)].

3.2. Discrete single-cavity models

Single-cavity numerical models deal with local column separations as described in Section 2.4.2. A single cavity is allowed to form either at a closed end, at a high point or at a change in pipe slope. All graphical solutions of water hammer employ this modeling approach. Rigid column theory has also been used to compute the behavior of systems with single cavities.

Mostowsky (1929) analyzed column separation at a downstream valve. Fig. 7(a) shows the pressure–time diagram for a frictionless pipe where the duration T_{cs} of the column separation is an integer multiple of the wave travel time $2L/a$. This figure is a confirmation of Eq. (4). Fig. 7(b) is the corresponding velocity–time diagram that determines the time of separation. Mostowsky (1929) performed measurements in a 29.5 m long, 2 inch diameter pipe. The measured pressure history in Fig. 7(c) shows that, unlike Fig. 7(a), the second pressure rise is lower than the first one, and the measured number of 11-times $2L/a$ is not the 12-times predicted by Eq. (4). Mostowsky (1929), attributing these discrepancies to friction, performed a rigid-column analysis with a quadratic friction law. He found closed-form solutions, for example a formula relating the effective friction coefficient to p_1 and p_2 (these are indicated in Fig. 7(c)), and an improved formula for T_{cs} giving a value of 10.6-times $2L/a$, which is in close agreement with the experiment.

Angus (1935, 1937) included a single vapor cavity at a boundary in the graphical method (Fig. 8). For a pump failure on a discharge line, the possibility was investigated of a cavity forming on the pipe side of a check valve near the pump.

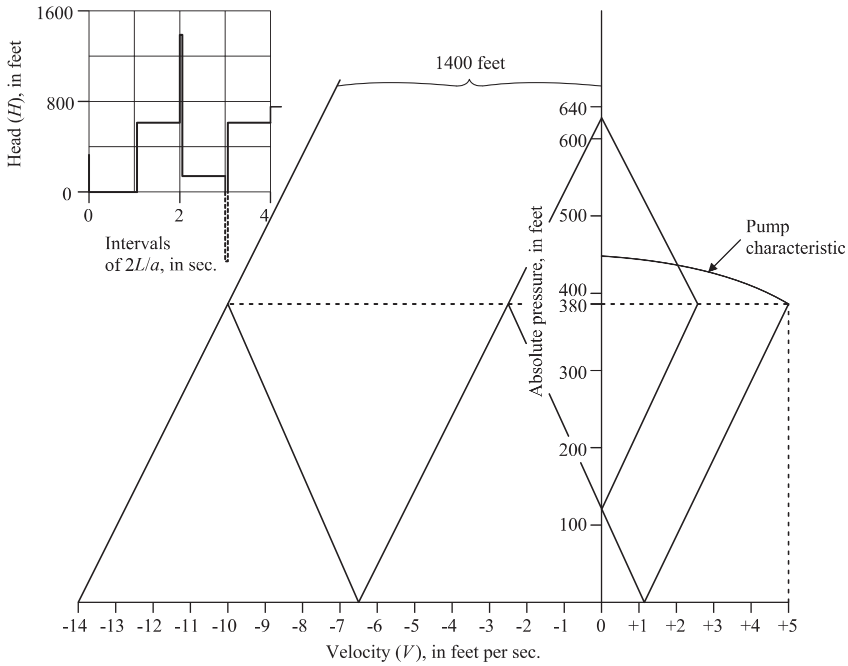

Fig. 8. Graphical method [adapted from Angus (1937, Fig. 20)].

After the cavity formed and the liquid column returned to the closed valve, the pressure rise was found to be about "*four times*" the normal value, because of a large short-duration pressure peak of the type discussed in Section 2.6.

Bergeron's (1939, 1950) treatment of column separation is similar to that of Angus (1935). He indicates that the underpressure in a cavity is not the "*barometric vacuum*", but rather the vapor pressure at the temperature of the liquid. He neglects the influence of gravity on the shape of the liquid–vapor interface. In his application of the graphical method, friction was lumped at the upstream end by using an orifice. A number of cycles of successive formation and collapse of a column separation were considered. Friction loss resulted in damping and the mean value of head rise decreased with every cycle, as did the size of the cavity.

Gayed and Kamel's (1959) analysis included variable-length rigid-column theory and water-hammer theory with noninstantaneous excitation. Kephart and Davis (1961) used rigid-column theory to determine the magnitude of the pressure rise when liquid columns rejoined in pump discharge lines equipped with check valves at the pump outlet. This method served as a preliminary design technique. Escande (1962) included cavities and lumped nonlinear friction in his graphical calculations. Ruus et al. (1984) performed an extensive numerical study of column separation located at a high point.

3.3. Discrete multiple-cavity models

3.3.1. The discrete vapor cavity model (DVCM)

The discrete (concentrated, lumped) vapor cavity model (DVCM) is the most commonly used model for column separation and distributed cavitation at the present time. It is easily implemented within standard water-hammer software and it reproduces many of the physical features of column-separation events. Wylie and Streeter (1978a, 1993) have described the DVCM in detail and they provided a FORTRAN computer code for its implementation. We will use their notation.

Cavities are allowed to form at any of the computational sections (grid points) if the pressure is computed to be below the vapor pressure. Vapor cavities are thus confined to computational sections as sketched in Fig. 9 and pure liquid with a constant pressure wave speed is assumed in between. The absolute pressure in a cavity is set equal to the vapor pressure:

$$p^* = p_v^*. \tag{12}$$

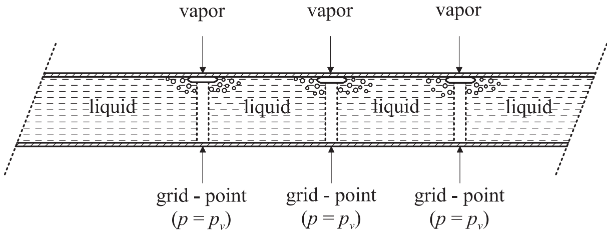

Fig. 9. Definition sketch for discrete vapor cavity model (adapted from Tijsseling, 1993, Fig. 4.9).

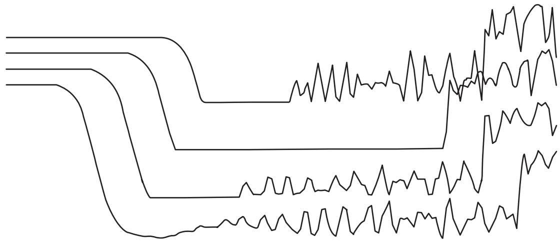

Fig. 10. Numerical oscillations in DVCM results [adapted from De Vries (1972, Fig. 42)]. Pressure-head histories at different positions after pump shutdown.

The upstream and downstream discharges Q_{Pu} and Q_{P} at a cavity are computed from the compatibility relations (8) and (9). The cavity volume $\forall$ follows then from

$$\frac{\mathrm{d}\forall}{\mathrm{d}t} = Q_{\mathrm{P}} - Q_{\mathrm{Pu}} \quad \text{or} \quad \forall = \int_{t_{in}}^{t} (Q_{\mathrm{P}} - Q_{\mathrm{Pu}})\,\mathrm{d}t. \tag{13}$$

The numerical integration of Eq. (13) in the MOC with staggered grid (Fig. 6) is usually given by

$$\forall^t = \forall^{t-2\Delta t} + \{\psi(Q_{\mathrm{P}}^t - Q_{\mathrm{Pu}}^t) + (1-\psi)(Q_{\mathrm{P}}^{t-2\Delta t} - Q_{\mathrm{Pu}}^{t-2\Delta t})\}2\Delta t \tag{14}$$

in which $\forall^t$ and $\forall^{t-2\Delta t}$ are the volumes at the current time and at $2\Delta t$ earlier, and ψ is a numerical weighting factor. If the cavity volume becomes zero or negative, the cavity disappears and the computation returns to the standard water-hammer procedure. Provoost (1976) used a cavity closure condition that exactly satisfies the mass balance.

Although the DVCM was correctly formulated by Thibessard (1961), Vreugdenhil (1964), Streeter (1969) and Tanahashi and Kasahara (1969), these investigators did not apply the model to regions of distributed cavitation. This was done by De Vries (1972, 1973, 1974) when he simulated the experiments performed by Vreugdenhil et al. (1972) and Kloosterman et al. (1973). De Vries (1972) was the first to report on numerical oscillations induced by the condensation of a region of distributed cavitation (Fig. 10). To suppress these oscillations he added small amounts of free gas to the discrete cavities. In fact he then used the discrete free gas cavity model developed by Brown (1968), but with nonzero vapor pressure. This model is described in Section 3.3.2.

Evans and Sage (1983) had confidence in the DVCM and used it for the water-hammer analysis of a 110 km long gravity line of 0.9–1.6 m diameter. Bergant and Simpson (1999b) incorporated cavitation inception with negative absolute pressure (tensile stress) in the DVCM. Numerical and experimental results, both with negative pressure spikes, were compared. The negative pressure spike at cavitation inception did not significantly affect the results.

3.3.2. *The discrete gas cavity model (DGCM)*

The discrete gas cavity model (DGCM) is similar to the DVCM, with a quantity of free air assumed to be concentrated at each computational section. The pressure in a cavity satisfies the ideal gas law:

$$(p^* - p_v^*)\forall = (p_0^* - p_v^*)\forall_0 = \text{constant}, \tag{15}$$

where the free gas is assumed to behave isothermally, which is valid for tiny bubbles. Large bubbles and column separations tend to behave adiabatically. The only difference with the DVCM is in the $\forall - p^*$ curve as shown in Fig. 11,

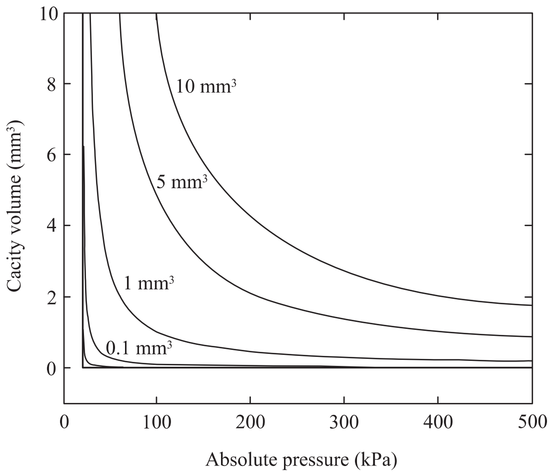

Fig. 11. p^*–$\forall$ curves for DVCM ("L-shaped" solid line, $\forall_0 = 0\,\mathrm{mm}^3$) and DGCM (thin solid lines, $\forall_0 = 0.01\,\mathrm{mm}^3$, $\forall_0 = 0.1\,\mathrm{mm}^3$, $\forall_0 = 1\,\mathrm{mm}^3$, $\forall_0 = 5\,\mathrm{mm}^3$, $\forall_0 = 10\,\mathrm{mm}^3$) with $p_0{}^* = 1$ bar and $p_v{}^* = 0.2$ bar. The value of $p_v{}^*$ (water at 60 °C) is chosen large to show its influence.

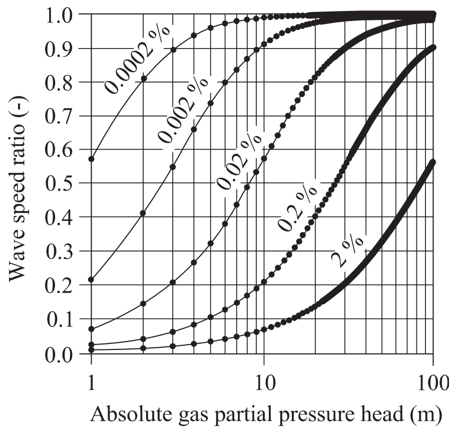

Fig. 12. Wave-speed ratios [adapted from Liou (2000, Fig. 5)]. Dots: numerical (DGCM) wave speed/gas-free wave-speed. Lines: theoretical mixture wave-speed/gas-free wave-speed.

which also tells us that the DVCM is a limit case of the DGCM. The DGCM exhibits dispersion of rarefaction waves and steepening of compressive waves and thus allows shock fronts to form.

Brown (1968) presented the first attempt at describing column separation with the effects of entrained air. Entrained air was assumed to be evenly distributed in concentrated pockets at equal distances along the pipeline. The presence of air decreased the overall pressure wave speed. A pressure–volume ideal-gas relation was assumed to describe the behavior of the concentrated air pockets, whose locations were assumed to be permanent with no change due to the prevailing direction of flow. The presence of entrained air was neglected above a certain head, where the solution reverted back to normal water-hammer computations. After Brown (1968), this model was further developed by De Vries (1973), Provoost (1976), Provoost and Wylie (1981) and Wylie (1984).

In a rigorous mathematical treatise of the DGCM, applying Von Neumann analysis to a linearized set of equations, Liou (1999, 2000) nicely showed that the numerical wave speed converges to the theoretical (physical) one (see Fig. 12). He thus explained why the DCGM exhibits nonlinear variable wave-speed features.

The DGCM model was successfully used by Enever (1972), Tullis et al. (1976), Aga et al. (1980), Ewing (1980), Suda (1990) and Barbero and Ciaponi (1991). Ewing (1980) discussed various damping mechanisms in liquid–gas mixtures. Capozza (1986) applied the method to condenser cooling circuits. Wylie (1992) and Wylie and Streeter (1993, pp. 188–192, 202–205) compared DGCM results with analytical results, with bubbly flow experimental data from Akagawa and Fujii (1987) and with experimental column-separation data from Simpson (1986).

3.3.3. Features and limitations of discrete cavity models

When the absolute pressure reaches the vapor pressure, cavities or bubbles will develop in the liquid. In discrete cavity models (like DVCM and DGCM) the cavities are concentrated at the grid points. Between the grid points pure liquid is assumed for which the basic water-hammer equations remain valid. This means that the pressure wave speed a is maintained (and convective terms neglected) between grid points in distributed cavitation regions. However, in bubble flow the actual pressure wave speed is very low and pressure-dependent. These matters are implicit in the model (Liou, 1999, 2000). Complete and clear descriptions of discrete cavity models are given by Wylie (1984) and Zielke and Perko (1985).

In discrete cavity models the cavities do not move. This is consistent with the acoustic approximation: since the overall time scale is acoustic (water hammer), the displacements of vapor bubbles are small. However, Vreugdenhil (1964) took into account, within the DVCM, the motion of liquid–vapor boundaries.

The maximum length, $l = \forall/A$, of a cavity must be small compared to the spatial mesh size. Simpson and Bergant (1994a) recommended

$$\frac{l}{\Delta x} < 0.1. \tag{16}$$

For distributed cavitation regions, condition (16) is mostly fulfilled. If not, the discrete cavity model is not valid and the application of models for two-phase plug flow, slug flow or open-channel flow should be considered. For column separations, condition (16) may sometimes be violated, which is acceptable in the opinion of the authors, since column separation is a local phenomenon, and only a few grid points are concerned. However, care should be taken when $l/\Delta x$ becomes larger than 1. In that case liquid–vapor boundaries moving from grid point to grid point should be explicitly modeled.

From a physical *microscopic* point of view the *macroscopic* DVCM is not correct; a two-phase flow (Wallis, 1969) approach would be better. However, during vaporous cavitation, Eq. (12) is physically a strong condition, if there is no free gas or gas release involved. Furthermore, the continuity equation, that is the mass balance, is satisfied throughout. Note that the mass of vapor has been neglected, just as the influence of radial pipe displacements on the cavity volume.

The DVCM is a relatively simple model, which is able to cover the essential phenomena in transient cavitation. It fits in with the standard MOC approach, so that it can be used in general water-hammer computer-codes. Its main deficiency is in the numerical oscillations and unrealistic spikes appearing in the calculated pressure histories, when regions of distributed cavitation occur (De Vries, 1972; Bergant and Simpson, 1999a). One way of partly suppressing the oscillations and spikes is by assuming small amounts of initial free gas in the grid points (De Vries, 1973; Provoost, 1976; Wylie, 1984; Zielke and Perko, 1985; Simpson, 1986; Barbero and Ciaponi, 1991; Bergant, 1992; Simpson and Bergant, 1994a). Condition (12) is then replaced by Eq. (15), so that DVCM becomes DGCM. The recommended free gas void fractions to be used are of the order of 10^{-7} at standard atmospheric conditions. The numerical integration of Eq. (15) may also affect the amount of oscillations and spikes (Provoost and Wylie, 1981; Simpson and Wylie, 1985; Simpson and Bergant, 1994a; Liou 1999, 2000). The application of a numerical filter may be considered (Vliegenthart, 1970; Kranenburg, 1974a). Discrete cavity models are able to predict accurately the maximum pressures in a system, but they are usually poor in the prediction of the timing of repeated cavity formation and collapse. The inclusion of unsteady friction (Section 3.8) might help in this respect.

3.4. Shallow-water flow models

Shallow-water (open-channel) modeling provided the first real attempt at a more realistic description of cavitating flow. Bubbles were assumed to form, rise quickly and agglomerate into a single long thin cavity, when the pressure reached the vapor pressure.

Li (1962, 1963) and Li and Walsh (1964) presented a study of the mechanics of pipe flow following a column separation at an upstream closing valve. Spreading of the vapor–liquid interface was described by shallow-water theory with two quasi-linear partial differential equations. The study revealed that the spreading of the surface may be neglected in computing the pressure resulting from the cavity collapse. Rigid-column theory was used for the liquid, which required the assumption that the time of existence of the cavity is long compared to $2L/a$.

Baltzer (1967a, b) used a shallow-water flow model to calculate the shape, movement and collapse of a vapor cavity formed at the upstream side of a valve. A detailed description was presented of the sequence of events. This is illustrated in Fig. 13.

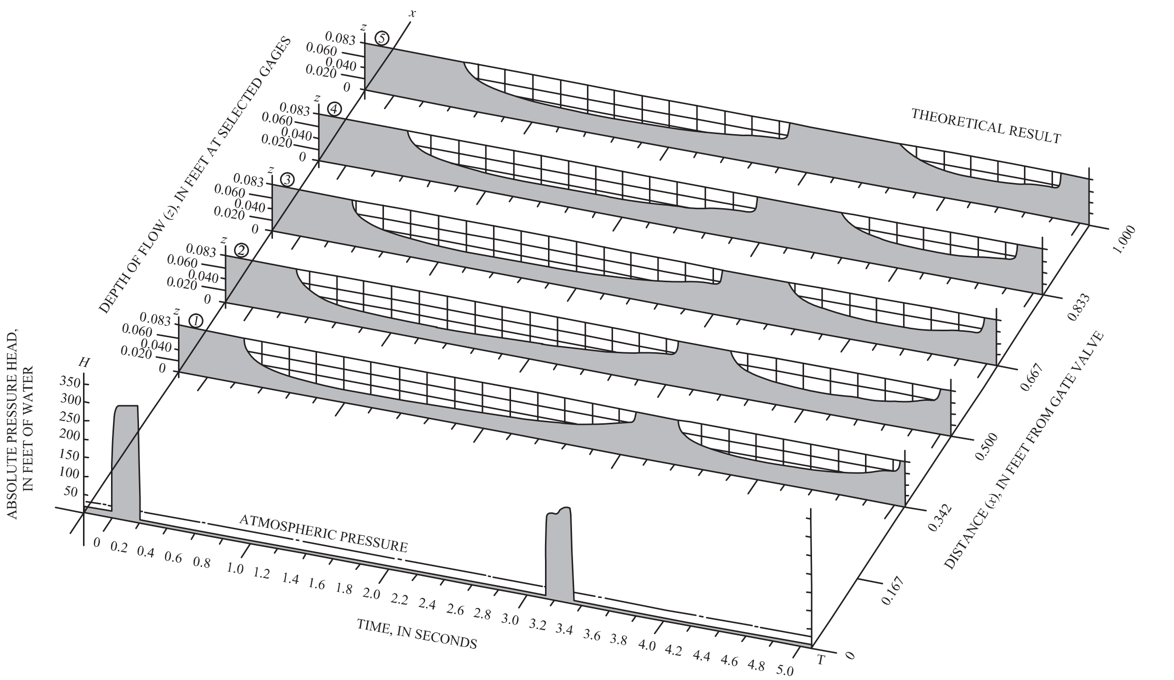

Fig. 13. Simulated transient pressures at gate valve and concurrent, free-surface profiles of vapor cavity (adapted from Baltzer, 1967b, Fig. 4).

Siemons (1966, 1967) assumed that the thickness of the cavity layer was small in comparison to the diameter of the pipe. He stressed that the rise in pressure at cavity collapse would not be great. Kalkwijk and Kranenburg (1971) noted that Siemons' results did not maintain a mass balance at the boundary of the cavity and therefore they questioned the validity of his conclusion concerning the generation of high pressures. The transition from the water-hammer region to the cavitating region is one of the major problems in the shallow-water approach. For this reason, Kranenburg (1974a) concluded that the description of cavitating flow and column separation by shallow-water theory did not seem attractive. Another problem was the appearance of gravity waves. Furthermore, the model is physically incorrect for vertical pipes.

Marsden and Fox (1976) used a similar approach to cavitation as that taken by Baltzer (1967a, b). High pressures were not predicted by their model and the authors concluded that uneconomic overdesign of pipelines resulted if the cavity collapse was computed by normal techniques. Fox and McGarry (1983) presented a variant of the discrete cavity model with a cavity assumed to occupy the upper portion of the pipe and to be spread over a Δx length. Thermodynamic effects were included, but the authors concluded that their influence was insignificant if the vapor pressure of the liquid was small.

3.5. Two-phase flow models

Kalkwijk and Kranenburg (1971, 1973) presented two theoretical "*bubble flow*" approaches to describe distributed vaporous cavitation in a horizontal pipeline. The first approach was entirely based on the dynamic behavior of gas bubbles. The method failed at the point where the radii of the bubbles exceeded a critical value. At this size the bubbles became unstable and the MOC characteristic lines became imaginary. The incorporation of added liquid mass might solve this problem (Geurst, 1985; Thorley and Wiggert, 1985; Gale and Tiselj, 2003). The second approach distinguished between regions with and without cavitation. Different systems of equations held for the water-hammer and the vaporous-cavitation regions (Kranenburg, 1972). The pressure wave speed in the cavitation region, relative to the fluid particles, is reduced to zero, because the pressure in such a region is constant at vapor pressure. Analytical expressions were developed for the velocity and void fraction in horizontal vaporous zones. When a cavitation region stopped growing, a shock formed at the transition from the water-hammer to the vaporous region, which penetrated into the cavitation region.

Kranenburg (1972, 1974b) developed a simplified one-dimensional mathematical model, referred to as the ''*simplified bubble flow*'' model. The slope of the pipe and the influence of gas release were both considered (see also Section 3.7). Kranenburg (1974a) found that there was considerable difficulty in using the MOC due to the pressure dependence of the wave speed as a result of free gas. He asserted that discontinuities or shocks between the water-hammer and vaporous region should be fitted in the continuous solution only for simple cases. To simplify his modeling approach, the bubble flow regime was assumed for the whole pipe, even for the water-hammer regions. A modified surface-tension term was used to achieve this simplification. This model did not show explicit transitions between the water-hammer and vaporous cavitation regions. Kranenburg (1972) used a Lax-Wendroff two-step numerical scheme despite the occurrence of shock waves. An artificial viscosity was used to suppress the numerical instability that spread the developing shock front over a number of grid points. Column separation was explicitly taken into account at mesh points where it was expected to occur. Wylie and Streeter (1978b, 1993) developed a similar case-specific analytic model involving vaporous cavitation.

3.5.1. *Two-phase flow equations for distributed vaporous cavitation*

The two-phase equations describing a vaporous cavitation region are the following equations of continuity and motion (Streeter, 1983; Bergant and Simpson, 1992; Wylie and Streeter, 1993):

$$\frac{\partial \alpha_v}{\partial t} + V_m \frac{\partial \alpha_v}{\partial x} - \frac{\partial V_m}{\partial x} = 0, \tag{17}$$

$$\frac{\partial V_m}{\partial t} + V_m \frac{\partial V_m}{\partial x} + g \sin\theta + \frac{f V_m |V_m|}{2D} = 0, \tag{18}$$

where α_v is the void fraction of vapor and V_m the mixture velocity. The pressure is assumed constant at vapor pressure, so that only gravitational and friction forces act. The two equations are valid for small void fractions ($\alpha_v < < 1$) and up to a temperature of about 330 K (Hatwin et al., 1970), so that thermodynamic effects are not important. The conventional Darcy-Weisbach friction factor f for fully liquid flow is assumed in Eq. (18), because the effect of bubbles on friction loss can be ignored for small void fractions (Griffith, 1987).

The solution of Eq. (18) for V_m depends on the pipe slope being upward, downward or horizontal and it depends on the velocity of the liquid–vapor mixture at the time of cavitation inception. Assuming that V_m is a uniform velocity—independent of x—in each individual cavitation zone, the different results of integration for V_m can be found in Streeter (1983), Bergant (1992), and Bergant and Simpson (1999a).

3.5.2. *Shock equations for the condensation of distributed vaporous cavitation*

A vaporous cavitation region expands in size due to a propagating low-pressure wave. Eventually, the cavitation region stops expanding and condensation starts. The movement of the interface (shock-wave front) separating the one-phase (liquid) and the two-phase (liquid–vapor mixture) fluids is described by shock equations. Isothermal conditions across the interface of infinitesimal width are assumed (Campbell and Pitcher, 1958). The shock equations are (Bergant, 1992; Bergant and Simpson, 1992):

$$a_s \left[\frac{g}{a^2} (H_s - H_{sv}) + \alpha_v \right] - (V - V_m) = 0, \tag{19}$$

$$g(H_s - H_{sv}) + (V - V_m)(V - V_m - a_s) = 0, \tag{20}$$

where a_s is the shock-wave speed, H_s the head on the liquid side of the wave front and H_{sv} the head on the cavitation side of the wave front. Relations (19) and (20) couple the water-hammer Eqs. (6) and (7) and the two-phase flow Eqs. (17) and (18).

3.6. *Interface models*

This type of model combines discrete cavities with two-phase flows. Flow regions with different characteristics (that is: water hammer, distributed vaporous cavitation, end cavities and intermediate cavities) are modeled separately, while the region interfaces are tracked. Kranenburg (1974b) modeled column separation at a valve in combination with the description of vaporous cavitation regions using his ''bubble flow'' model. The model was applied to the inclined-pipe experiments of Baltzer (1967a, b).

Streeter (1983) was the first to develop a combined analysis for modeling column separations at high points and a number of distributed vaporous cavitation regions, while retaining the shock-fitting approach to explicitly compute the locations of transitions between water-hammer and vaporous-cavitation regions. Gas release was not considered, thereby removing the problem associated with the variable wave speed due to the presence of free gas. The model was applicable to pipes at any angle with the horizontal. Many separate cavitation zones could be modeled, as well as their collapse and reforming. The equations developed for the vaporous regions were for various combinations of slope and initial velocity at cavity inception. A computational section became vaporous once a pressure less than the vapor pressure had been computed from the water-hammer MOC. A time-line interpolation was used to estimate the first occurrence of vapor at a computational section. The development by Streeter (1983) also considered the formation of discrete vapor cavities. It was asserted that a discrete cavity may only form if the angle with the horizontal between two adjacent pipe sections decreased in the downstream direction, such as at a high point. If vapor pressure occurred at such a section, a column separation was assumed to form. For all other pipe slope conditions a distributed cavitation region was assumed. This approach did not account for the possibility of intermediate cavities due to the interaction of two low-pressure waves.

Bergant (1992) and Bergant and Simpson (1992) extended a standard DVCM with vaporous cavitation zones, shock waves and various types of discrete cavities. The model, referred to as a generalized interface vaporous cavitation model (GIVCM), handles a number of pipeline configurations (sloping and horizontal) and various interactions between water-hammer regions, vaporous-cavitation regions, and intermediate and boundary column-separations. For example, Fig. 14 shows a typical sequence of transient events in a horizontal pipe including growth and collapse of a discrete cavity, propagation of a vaporous cavitation zone and two shock-wave fronts. In essence, the GIVCM algorithm maintains the same basic structure as the DVCM and it is therefore simpler than previous interface models (Simpson, 1986). A loop for the shock treatment at appropriate computational sections was added to the basic DVCM loop and a module for combined discrete-cavity and distributed-cavitation computation was incorporated. Flags to control the correct physical behavior of various phase interactions and to identify possible new interactions strengthened the algorithm.

3.7. Modeling of gas release

Dijkman (1968) and Dijkman and Vreugdenhil (1969) extended Siemons' (1967) shallow-water flow model by considering gas release into a single cavity at a high point. The pressure rise, after compression of the cavity incorporating released gas, was concluded to be less serious than for the vapor-only case. Gas flow equations were solved in combination with the shallow-water equations. The MOC was applied to solve the resulting fourth-order hyperbolic system. The authors concluded that it was uncertain how the collapse pressures may be computed and suggested an approach of attempting to prevent the occurrence of cavitation.

Kranenburg (1974a) presented an extensive work on the effect of free gas and gas release on cavitation in pipelines. Gas release in the vaporous region was concluded to cause damping of the pressure peaks caused by the collapses of

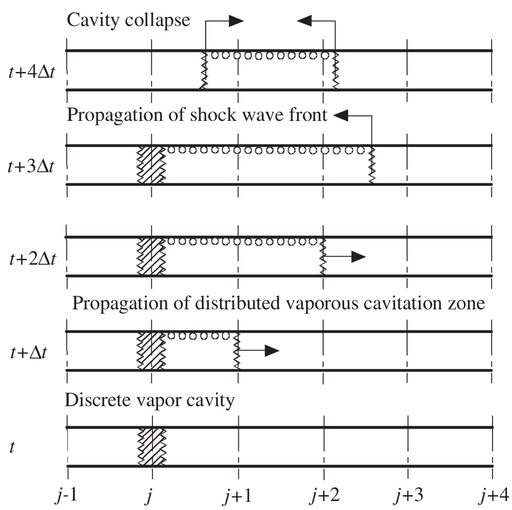

Fig. 14. Cavitation and shock formation in a horizontal pipe [adapted from Bergant and Simpson (1992)].

column separations. To support this contention, a hydrodynamic energy balance was computed for a column separation in a reservoir/horizontal-pipeline/valve system. Contributions to the energy balance included elastic energy of the liquid and pipe wall, elastic energy of the free gas, work done at the reservoir, dissipation caused by shock waves, and dissipation caused by wall friction. The elastic energy of the free gas was small compared with the dissipation terms. This explained the relatively small influence of gas release at the column separation void. There was only slight damping due to wall friction. The conclusion was drawn that the marked energy loss may be attributed to the dissipation at the shock-wave fronts due to heat-transfer and viscosity effects. In summary, Kranenburg (1974b) concluded that the inclusion of gas release had no effect when only cavitating flow occurred, whereas the influence was considerable when column separation occurred in combination with cavitating flow. Gas release in the cavitating flow region adjacent to a column separation diminished the duration of subsequent separations and thus the maximum pressures upon collapse. Barbero and Ciaponi (1991) examined the influence of initial free gas and gas release in their calculations.

3.8. *Modeling of friction*

In horizontal regions of distributed cavitation the pressure is constant and the flow accelerations are governed by friction forces only, see Eq. (18). Therefore, an accurate modeling of friction is a prerequisite. To do so, the friction factor f used in Eqs. (7) and (18) can be expressed as the sum of a quasi-steady part f_q and an unsteady part f_u (Zielke, 1968; Vardy, 1980; Vardy and Brown, 2000, 2003, 2004; Bergant et al., 2001). In this way a number of unsteady friction models have been incorporated in standard discrete cavity models (Safwat et al., 1986; Dudlik, 1999; Axworthy and Chabot, 2004).

Shuy and Apelt (1983) performed numerical analyses with five different friction models (steady, quasi-steady and the three unsteady friction models developed by Carstens and Roller (1959), Trikha (1975) and Hino et al. (1977)) that had been incorporated into a standard DVCM. The authors studied 'slow' transients in two long pipelines (2.3 and 9 km). For the case of pure water-hammer they found only small differences in the results of the five models, but for the case with column-separation large discrepancies occurred.

Brunone and Greco (1990), Golia and Greco (1990) and Brunone et al. (1991) used the DVCM in combination with Golia's (1990) unsteady friction model. Numerical results were compared with results of measurements of rapid water-hammer and column separation. Significant discrepancies between experiment and theory were found for all runs when using a quasi-steady friction term. Results obtained with Golia's friction model showed an improved agreement between the computed and measured results. However, the agreement was better for the water-hammer case than for the column-separation case.

Kojima et al. (1984) developed a "*gas non-bubbly flow*" model using unsteady pipe friction that accurately predicted their experimental results. The influence of unsteady laminar friction was studied. Bergant and Simpson (1994a) investigated the performance of the quasi-steady and three distinct types of unsteady friction models, namely those of Zielke (1968), Hino et al. (1977) and Brunone et al. (1991). The Zielke and the Brunone et al. unsteady friction models gave the best fit with experimental data for the case of pure water-hammer. Bughazem and Anderson (1996, 2000) extended an earlier DVCM study by Anderson and Arfaie (1991) with Brunone's unsteady friction model and found excellent agreement between theory and experiment. Shu (2003b) extended a two-phase flow model with Zielke's (1968) friction model.

3.9. *Alternative methods for modeling column separation*

3.9.1. *Jordan algebraic method*

Jordan (1965, 1975) developed an analytical method for the treatment of distributed vaporous cavitation zones. He asserted that pressure waves cannot propagate through an established mixture of liquid and vapor and that therefore the Schnyder–Bergeron graphical method could not be used in this region. Jordan developed equations for distributed vaporous cavitation and for the penetration of liquid columns into cavitating regions. He thus calculated the duration of cavitation. Tarasevich (1975, 1997) developed a similar analytical method.

3.9.2. *Finite element method*

Howlett (1971) modeled the liquid contained within a pipe system by means of solid beams without bending stiffness in a finite element (FEM) solution procedure. Watt et al. (1980), Bach and Spangenberg (1990), Jović (1995) and Shu (2003a) applied the FEM to the classical water-hammer equations. Giesecke (1981) used the FEM and mentioned the discrete cavity model, but did not show any results. Axisa and Gibert (1982) and Schwirian (1982, 1984) employed the DVCM within the context of the FEM; gaps were allowed to form between the axial beam elements simulating the liquid as shown in Fig. 15. They compared numerical results obtained with and without cavitation.

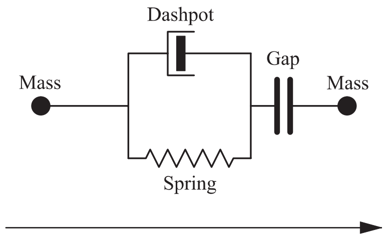

Fig. 15. DVCM in FEM context [adapted from Schwirian (1984, Fig. 4)]. Dynamic element with gap, which allows the formation of a cavity.

3.9.3. Other methods

Mansour (1996) used the DVCM in combination with a special finite-difference scheme for the water-hammer equations. Fanelli (2000) presented unsteady pipe flow equations for a simple condenser cooling water system, including variable wave speed and friction losses due to the presence of gas bubbles, and equations for column separation. In addition, a number of boundary conditions were fully described, representing pumps, valves, condensers, siphons, surge tanks and nonreturn valves.

3.10. A comparison of models

De Vries et al. (1971), Kalkwijk et al. (1972), Vreugdenhil et al. (1972) and Provoost (1976) compared Siemons' (1966, 1967) shallow-water flow model with Kalkwijk and Kranenburg's (1971, 1973) "*bubble flow*" model. Experimental results were presented for a horizontal 1450 m test circuit. The construction of some large water supply pipelines in The Netherlands prompted these studies. Allowing the occurrence of pipeline cavitation was considered as an alternative to expensive water-hammer control devices such as surge tanks, air vessels and flywheels. The authors concluded that the results obtained from both computer programs exhibited adequate agreement with the experimental results for the horizontal test circuit. Provoost (1976) found that the shallow-water model did not reproduce the field measurements for a pipeline system with two high points and the "*simplified bubble model*" of Kranenburg (1972, 1974b) was not suited to describe column separations at high points. As a result, the DGCM was used by De Vries (1973) and Provoost (1976).

Simpson (1986), Bergant (1992) and Bergant and Simpson (1999a) compared numerical results from discrete vapor (DVCM), discrete gas (DGCM) and (generalized) interface vaporous cavitation models (GIVCM) with results of measurements. The principal source of discrepancies between the computed and measured results was found to originate from the method of physical description of distributed vaporous cavitation. Simpson and Bergant (1994a) and Bergant and Simpson (1994b) compared a number of cavitation models. They found that within the MOC the staggered grid is preferred above the rectangular grid, which actually comprises two independent staggered grids that may cause chessboard instability.

Miwa et al. (1990) validated numerical results from the DVCM, the DGCM and a variable wave-speed model with consideration of gas release against experimental data. Dudlik (1999) and Dudlik et al. (2003) compared the results of commercial codes with new experimental data. Dudlik et al. (2000) compared the DVCM with a three-phase model that allowed for the calculation of sudden changes of gas content in the liquid. Shu (2003b) compared the DVCM with a two-phase model and with experimental data from Sanada et al. (1990).

4. Laboratory experiments and field tests

In all the experiments described in this section, unless otherwise stated, water hammer and column separation are initiated by the rapid closure of a valve and the test liquid is water.

4.1. Visualization of cavity formation

Escande and Nougaro (1953) reported an early flow visualization study. They conducted column-separation experiments in a laboratory apparatus comprised of a 25 m long horizontal pipeline of 200 mm internal diameter. A transparent section was positioned next to the valve for flow visualization using a high-speed camera. A large vapor cavity was observed following the closure of the valve. Bunt (1953), Smirnov (1954), Kamel (1954) and Blind (1956) made similar observations; they presented photographs exhibiting the shape of the cavity at the valve during its growth and collapse. The vapor–liquid interface sloped gently over quite a long distance.

Duc (1959) investigated column separation, for three different piping configurations at a high point, due to the shutdown of pumps in a 1 km long discharge line at a field installation. A clear piece of plexiglas pipe at the high point allowed a sequence of photographs to be taken, which exhibited the changes in the cavity during a column separation. These tests contradicted the generally accepted supposition of a complete separation of the liquid columns at an elevated point. Liquid remained at the separation point until return-flow filled the void. O'Neill (1959) also concluded from a photographic study that intermediate cavities did not form over the entire pipe cross section, as ideally assumed in the theory; most cavities appeared in the upper portion of the cross section only.

Li and Walsh (1964), Baltzer (1967b) and Safwat (1972a) presented photographs of a discrete cavity at the downstream side of a closing valve. The appearance of tiny bubbles was observed across the whole cross-section, which extended along a large portion of the pipe. Tanahashi and Kasahara (1970) studied photographically the formation and collapse of a discrete cavity at the high point of a pumping system. Nonoshita et al. (1991, 1992, 1999) presented photographs of column separation in a laboratory draft tube of a water turbine following wicket gates closure. They studied the effect of the draft tube inlet swirl on column-separation events. The swirl flow generated gas release and subsequent attenuation of maximum pressures following cavity collapse. Bergant (1992) and Bergant and Simpson (1996) presented photographs of column separation in a sloping pipeline. A discrete vapor cavity and a distributed vaporous cavitation zone were observed following rapid valve closure. Dudlik et al. (1997, 1999) and Dudlik (1999) presented photographs of column separation in a 230 m long test rig with complex pipe geometry.

Swaffield (1969–1970) and Kojima et al. (1984) employed photography to visualize column separation in liquids other than water (kerosene, mineral oil). Differences in the column-separation mechanism for different liquids were not observed.

Yang et al. (1996) and Adam et al. (1998) used a 100 Hz nonintrusive electrical-capacitance tomography technique to observe cross-sectional images from changes in fluid capacitance in a 32 m long pipeline of 42 mm diameter. Cavities forming at the top of the pipe were of approximately circular cross-section rather than having a horizontal lower surface. Jaworek and Krupa (2004) developed a similar technique, but working at 80 MHz. Dudlik et al. (1997, 1999) and Dudlik (1999) used the 1 kHz "*wire-mesh*" visualization technique developed by Prasser et al. (1998, 2001) which is based on the fluid conductivity. The flow-disturbing intrusive effect of such a device was studied by Wangjiraniran et al. (2003).

Tabei et al. (2003) added small amounts of the noble gases xenon and argon to initially degassed water to provoke light emission at bubble collapse. In this way, they were able to accurately determine the speed of a shock wave entering a region of bubbly flow. Their theoretical study showed that local temperatures up to 7000 K may occur when small bubbles collapse. Su et al. (2003) observed the strongest light signals when water with xenon was cooled to near its freezing point. Chakravarty et al. (2004) conducted tests with many different liquids. They found the best cavitation sonoluminescence in liquids with a low vapor pressure and a moderately high viscosity. Mechanical energy could be converted into visible light with an efficiency as high as 1%.

4.2. Laboratory experiments with column separation

At the end of 19th century Joukowsky (1900) conducted water-hammer and column-separation experiments in Aleksejew's water supply system in Moscow. He had three pipelines of lengths and diameters $\{(L, D) = ((320, 51); (320, 102); (325, 152))$ (m, mm)$\}$, each with a downstream valve, connected to the main supply pipeline of diameter 610 mm. Pressure records were taken at the valve and along the pipeline. Joukowsky was the first to qualitatively explain the phenomenon of column separation (see Section 2.3).

Langevin and Boullée (1928)—as presented in Bergeron (1950)—were probably the first persons using piezoelectric pressure transducers for the measurement of column separation. Their record shown in Fig. 16 is typical for all later measurements. Mostowsky's (1929) measurement in a 30 m long, 51 mm diameter pipe is shown in Fig. 7(c).

Binnie and Thackrah (1951) tested a pipeline with an automatic air-inlet valve. When the air-valve was removed, a series of violent impacts took place due to cavity formation and collapse. Maximum recorded pressures were actually somewhat greater than the theoretical estimates. Lupton (1953), in discussing Binnie and Thackrah's (1951) paper, did not agree with the use of air valves because of the unpredictably high pressures that may result from the presence of air in a pipeline. Gayed and Kamel (1959) showed pressure histories obtained in a 2.6 m long pipe for different initial flow velocities.

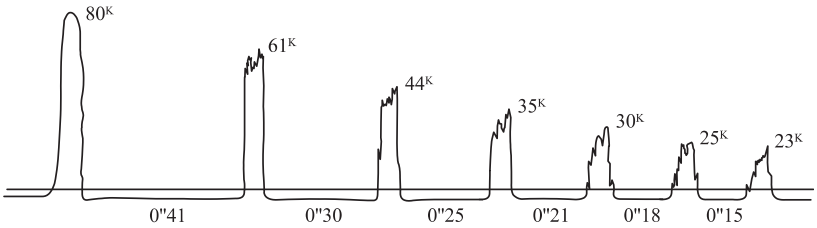

Fig. 16. Typical pressure history for repeated column separation and collapse [adapted from Bergeron (1950, Fig. 56)].

Carstens and Hagler (1964, 1966) considered water hammer in a pipeline transporting phosphate-ore slurry. Results were presented from both a laboratory model and a theoretical analysis that described the column-separation phenomenon. Jordan (1965) investigated column separation and distributed vaporous cavitation in a laboratory apparatus comprising a 202 m long upward-sloping pipeline of 52 mm diameter.

Baltzer (1967a, b) found that the measured pressure rises in a coiled-pipe apparatus were appreciably smaller than those predicted by his shallow-water flow model. Tanahashi and Kasahara (1970) presented a comparison of experimental and analytical results of water hammer with column separations at the valve and at the pipe midpoint. Raiteri and Siccardi's (1970) experimental records were later on used by De Bernardinis et al. (1975) to validate their mathematical models.

Safwat (1972a–c), Safwat and De Kluyver (1972) and Safwat and Van Den Polder (1973) performed measurements in 40–46 m long horizontal plexiglas pipelines of 90 mm diameter with and without a condenser. Vreugdenhil et al. (1972) conducted tests in a 1450 m long horizontal pipeline of 100 mm diameter to which Provoost (1976) added two high points. Piga and Sambiago (1974) tested in a laboratory cooling water system with lengths 25–30 m and diameter 100 mm, and Thorley and Chohan (1976) in a horizontal pipe of length 16 m and diameter 38 mm.

Krivchenko et al. (1975) presented results of column-separation measurements in a draft tube of the Kaplan turbine test rig at MISI, Moscow. A large cavity formed after rapid closure of the wicket gates. Column separation first occurred in the space between the guide vanes and the runner, the cavity then grew into the draft tube inlet cone. A large pressure peak occurred after cavity collapse. The authors provided measurements of the pressures under the turbine head cover and at the draft tube inlet, as well as measurements of the axial hydraulic force acting on the turbine runner. Nonoshita et al. (1991, 1992, 1999) performed similar experimental tests.

Katz and Chai (1978) carried out experiments in 0.3 m long tubes of 5 or 6 mm diameter with 2 ms valve closures. They showed one diagram of column-separation duration as a function of initial velocity (ranging from 1 to 20 m/s). This is the only paper (known to the authors) describing a beneficial use of column separation, namely as feedback mechanism in liquid oscillators that can be used for industrial cleaning. Their theory, based on rigid-column theory, included the effect of gas release.

Kot and Youngdahl (1978a, b) gave a clear explanation of the DVCM and they used experiments in a 9 m long closed tube for its validation. Aga et al. (1980) measured cavitating oil flow in a 250 m long, 90 mm diameter, test rig. Van De Sande and Belde (1981) tested in a U-tube of 9 m length and 45 mm diameter. Graze and Horlacher (1983) built two horizontal test rigs (120 and 86 m, and diameters of 82 and 200 mm, respectively). The authors stressed the importance of using adequate pressure transducers and recording equipment to avoid unrealistic pressure spikes, which is discussed in Section 4.6. Gottlieb et al. (1981) recorded extremely high pressure peaks immediately upon the collapse of vapor cavities. These could be unrealistic because of the type of pressure transducer used.

Fox and McGarry (1983) developed a test rig for the study of pressure transients in pipelines carrying volatile liquids (18 m length, 55 mm diameter). Martin (1983) tested in a coiled tube (102 m length, 13 mm diameter). He presented experimental results (Fig. 4) with limited, moderate and severe cavitation, the severity being defined in Section 2.7. Golia and Greco (1990) found excellent agreement between DVCM computations and Martin's (1983) experimental data. Borga and De Almeida (1985) tested in a horizontal pipeline of 105 m length and studied the influence of an in-line nonreturn valve on reducing the pressure pulses.

Simpson (1986) studied the short-duration pressure peaks explained in Section 2.6. Measurements were done for eight levels of cavitation severity. The test rig consisted of a 36 m long upward-sloping pipeline of 19 mm diameter connecting two reservoirs. The difference in elevation between the reservoirs was 1 m.

Paredes et al. (1987) and Carmona et al. (1987) constructed a 1460 m long and 104 mm diameter horizontal pipeline. The IAHR working group (Fanelli, 2000) has a data base with 13 experimental records of the laboratory tests by Paredes et al. (1987) with different initial flow velocities (0.35–0.82 m/s) and static heads (16–80 m). Barbero and Ciaponi (1991) reported on 23 experiments performed in a 500 m long, 110 mm diameter, test circuit. Anderson et al.

(1991) and Anderson and Arfaie (1991) discussed several aspects of the DVCM and they showed results of laboratory measurements for three levels of cavitation severity.

The laboratory apparatus of Shinada and Kojima (1987, 1989, 1995) was a small-scale physical model of a hydraulic press. The oil-filled test pipe was 5 m long with a diameter of 19 mm. The test results were compared with the results of a single vapor-cavity model that included laminar unsteady friction and a dynamic equation of motion for the valve. Miwa et al. (1990) performed column separation tests in a 500 m long steel pipeline of 0.10 m diameter. Pressures were recorded at seven positions along the pipeline.

Tijsseling and Fan (1991a, b, 1992) carried out measurements in a 4.5 m long, 52 mm diameter, closed pipe. Transients were generated through the impact of a solid steel rod at one end of the pipe, which led to very steep wave fronts (pressure rises in microseconds). Two complications encountered in the conventional reservoir-pipe-valve system were absent: the initial steady state pressure gradient and the nonlinear valve closure. The water was stored under pressure in a closed container so that the amount of free gas was negligible. Because of the time scale of the experiment (in milliseconds) there was no gas release and negligible wall friction. The experiment isolated vaporous cavitation (in combination with fluid–structure interaction, FSI), the severity of which was regulated by the static pressure of the water and the impact velocity of the rod. The experimental results were used to validate the DVCM. Sayir and Hausler (1991) also performed cavitation experiments in a closed tube. The tube was made of transparent PVC, 20 m long and 110 mm in diameter.

Bergant (1992), Bergant and Simpson (1995) and Simpson and Bergant (1996) performed a series of tests in an adjustable experimental apparatus comprising a 37 m long pipeline of 22 mm diameter and sloping at about 5%. The following quantities were varied: initial flow velocity, heads in the tanks, and position (downstream end, midpoint, upstream end) and closure time of the valve. Repeat tests and uncertainty analyses were performed. The results and documentation of all 116 measurements can be obtained through the School of Civil and Environmental Engineering at the University of Adelaide.

It is difficult to directly measure flow rates in transient flows. Washio et al. (1996) developed a procedure to accurately deduce flow rates in transient laminar flow from two adjacent pressure transducers. The procedure is based on frequency-dependent friction theory (Zielke, 1968) and relies on a specially constructed differential amplifier. The method was shown to work very well for oil column-separation in the test rig of Washio et al. (1994). The typical changes of flow rates during column separation and rejoining were successfully measured for the first time (Fig. 17).

Mitosek (1997, 1998, 2000) made cavitation measurements in plastic pipes. He recorded extremely high pressure peaks that might be attributed to the strain-gage type pressure transducers used (see Section 4.6). Greenshields and Leevers (2000) studied the brittle fracture behavior of plastic pipes. Their laboratory apparatus consisted of a closed vertically falling pipe where column separation occurred at the tapered bottom end. Surge and cavity collapse were able to fracture pipes with an initial defect.

Nakagawa and Takenaka (1995), Lai et al. (2000) and Gale and Tiselj (2003) carried out tests with initial vapor voids of different air content. Nakagawa and Takenaka (1995) created an initial void by cooling down hot liquid in a closed

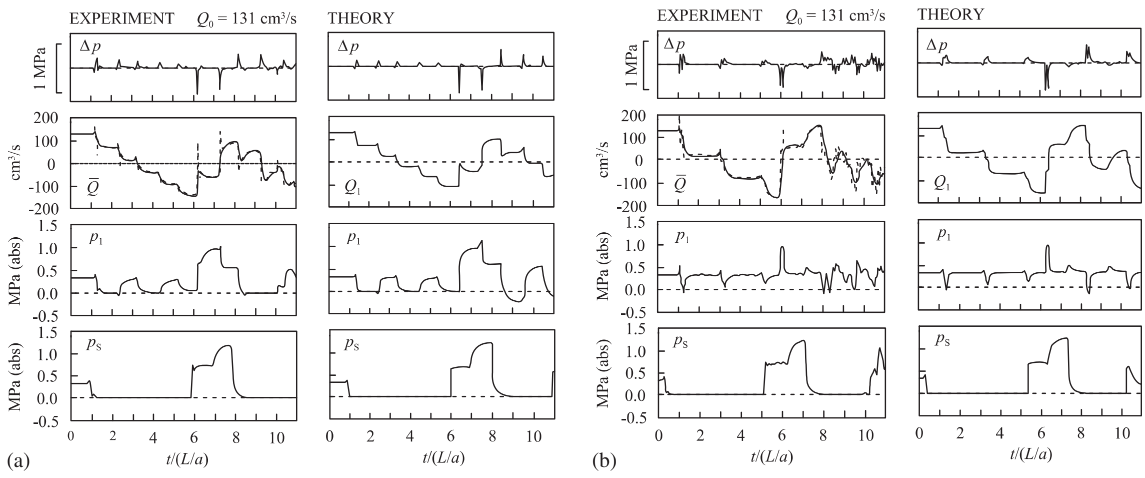

Fig. 17. Measured (first and third column) and calculated (second and fourth column) results in column-separation experiment. The second row depicts flow rates [adapted from Washio et al. (1996, Fig. 8)].

pipe. Lai et al. (2000) performed tests in a pipeline with one vertical branch. Deaerated water was the test liquid. The test results were used to validate their DGCM code, which had a polytropic gas law, but no gas release mechanism.

4.3. Laboratory experiments with gas release

Keller and Zielke (1976) measured free gas variations subsequent to a rapid drop in pressure in a 32 m long pipe with a diameter of 125 mm that was connected to a cavitation tunnel. Wiggert and Sundquist (1979) conducted experiments using 129 and 295 m long coiled-tube apparatuses with a diameter of 25 mm. They investigated gas release during transients at different initial gas concentrations. The effects of gas release, cavitation nuclei and turbulence were studied. Martin (1981) used a plexiglas pipe apparatus (length 32 m, diameter 26 mm) where the water was saturated with injected air.

Kazama (1983) performed experiments with water–methanol mixtures. A test-section of 2 m length contained an initial cavity of vapor and foam at its vertical closed end. Sudden valve opening created a pressure wave collapsing the cavity. The pressure at one location and the volume of remaining air were measured.

Shinada (1994) studied experimentally and theoretically column separation with gas release. In a 2.5 m long, 19 mm diameter pipe he tested with saturated and deaerated oil. He measured air content, surface tension and diffusion rate. On the basis of experimental results, the proposed bubble-diffusion model allowed for gas release only at the column separation.

4.4. Laboratory experiments with fluid–structure interaction

The repeated collapse of column separations and the almost instantaneous pressure rises associated with them (see Fig. 16) form a severe load for pipelines and their supporting structures. Structural vibration is likely to occur. Fluid-induced structural motion, structure-induced fluid motion and the underlying coupling mechanisms are commonly referred to as FSI. Most of the experimental researchers mentioned herein prevented unwanted FSI effects by rigidly anchoring their pipes. Fan and Tijsseling (1992), however, focused on the simultaneous occurrence of cavitation and FSI. They performed experiments in a closed pipe, the vibrating ends of which interacted with transient column-separations. They observed distributed vaporous cavitation caused by a stress wave in the pipe wall. Tijsseling et al. (1996) investigated experimentally and theoretically column separation in an unrestrained one-elbow pipe system. Tijsseling and Vardy (2006) presented cavitation tests in an unrestrained one-branch system. Review papers by Tijsseling (1996) and Wiggert and Tijsseling (2001) provide information on combined cavitation/FSI models and on FSI in general.

4.5. Field tests

Apelt (1956) measured pressures in the field for water hammer in pump discharge lines that undergo liquid column separation. His investigations verified that water-hammer theory may be applied with confidence, but that it could not account for the phenomenon of column separation. Richards (1956) also presented some field test data for pumping plants. He contended that it was virtually impossible to analytically analyze such systems. O'Brien (1956) took issue with this point and cited some extensive calculations that involved six or seven separate column-separations. Whiteman and Pearsall (1962) conducted field tests at a pumping station on reflux-valve characteristics and pressure rises after pump shutdown. Heavy flywheels were used to lengthen the rundown time, thereby preventing column separation. Duc (1959, 1965) measured column separation in a field installation. In addition to recording pressure peaks due to the rejoining of liquid columns, the phenomena were observed visually. The results exhibited some narrow high-pressure peaks of short duration. These may have resulted from the type of pressure gage being used (see discussion in Section 4.6).

Brown (1968) presented field measurements of transients in two pump discharge lines with distinct "*knees*" in their profiles. The pressures measured in the field were greater than those predicted by the graphical method in the design stage. This was attributed to the presence of free and dissolved air in the liquid. He noted that the presence of air may result in large pressure surges and higher reverse speeds of pumps due to the prolonging of column separation.

De Vries (1975a, b) carried out measurements in a thermal power plant cooling water system (pipeline at the upstream end of the condenser: length of 76 m and diameter of 1.8 m; pipeline at the downstream end of the condenser: length of 182 m and diameter of 1.8 m). Provoost (1976) conducted an investigation of a 28 km long pipeline with a diameter of 1.8 m. The pipeline was carefully deaerated before each test. Six cases of pump shutdown were presented. Sharp (1977) presented field measurements in a 12 km long, 250 mm diameter, pipeline. Siccardi (1979) presented a comprehensive summary of measurements and computations of water hammer and column separation in a cooling water system at La Casella thermal power plant (pipeline at the upstream end of the condenser: length of 440 m and diameter of 2 m; pipeline at the downstream end of the condenser: length of 234 m and diameter of 1.6 m). The data base of the IAHR working group (Fanelli, 2000) contains data measured in the La Casella power plant; Daco and Meregalli (1981) provided 25 experimental records of pump start-up and pump power-failure at different operating conditions.

De Almeida and Hipolito (1981), Jolas (1981), Enever (1983) and Yow et al. (1985) conducted extensive tests in the cooling water systems of thermal and nuclear power stations. Wang and Locher (1991) found surprisingly good agreement between simulations and field data obtained in a 47 km long cross-country pipeline with a diameter of 0.84 m. Axworthy and Chabot (2004) took measurements in a 0.25 m diameter sewage main consisting of 720 m of ductile-iron pipes and 915 m of PVC pipes.

4.6. Selection of pressure transducers

Care must be taken in the selection (and way of mounting) of pressure transducers to be used in cavitation measurements. Pressure transducers may easily be damaged during cavitation tests, because the nearby explosions and implosions of small bubbles are too severe a load (Chen and Israelachvili, 1991; Broos, 1993, p. 13). The natural frequency of the pressure transducer must be high compared to the frequencies in the measured signal. It is noted that exploding and imploding cavitation bubbles may lead to pressure signals with a frequency spectrum up to 1 MHz (Oldenziel and Teijema, 1976, p. 14). Graze and Horlacher (1983) and Simpson and Bergant (1991, 1994b) reported unrealistic pressure spikes and oscillations for inductive and strain-gage type pressure transducers and attributed these to the fact that the natural frequency of the transducer was too low. Borga and De Almeida (1985) concluded that the pressure transducer should be a sophisticated low-inertia instrument. Sayir and Hausler (1991) had problems with a too low natural frequency of piezoelectric transducers. Le et al. (1989, p. 3) developed their own special transducers with a natural frequency of 1.7 MHz to overcome this problem. Arndt et al. (1995) described how to make your own pressure transducer. Mitosek (1997, 1998, 2000) found unrealistically high-pressure peaks with strain-gage type pressure transducers. Greenshields and Leevers (2000) discussed the frequencies in measured signals in relation to the natural frequencies of pipe-wall and piezoelectric pressure transducer, noting that the latter are reduced by added liquid mass.

5. Conclusion

During the 20th century there was considerable research conducted into water hammer with column separation. This report attempts to span all of the significant research that has been carried out during this period. The occurrence of low pressures and associated column separation during water-hammer events has been a concern for much of the 20th century in the design of pipe systems for distribution and cooling. The closure of a valve or shutdown of a pump may cause pressures so low that the liquid will cavitate. The collapse of vapor cavities and rejoinder of water columns can generate—nearly instantaneously—extremely large pressure that may cause significant damage or ultimately failure of the pipe system.

As early as 1900, Joukowsky had identified the physical occurrence of column separation. The 1930s produced the first mathematical models of vapor cavity formation and collapse based on the graphical method. The identification of the various physical attributes of column separation occurred in the mid-20th century (distributed or vaporous cavitation in the 1930s; intermediate vapor cavities in the 1950s). These both led to a better physical understanding of the process of column separation and ultimately laid out the groundwork for the development of computer-based numerical models. The 1960s saw the development of the first computer models of column separation within the framework of the method-of-characteristics solution of the water-hammer equations. A variety of alternative numerical models were developed from the late 1960s to the early 1990s. The most significant models that have been developed include: the DVCM, the DGCM and the generalized interface vapor cavity model (GIVCM). The first two are the easiest to implement. The DVCM is the most popular model used in currently available commercial computer codes for water hammer analysis. Advanced two-phase flow models are still under development.

Numerous experimental studies have been carried out during the 20th century. These have benefited from the technological advances in measuring equipment (the introduction of the piezoelectric pressure transducer in the late 1920s was a milestone) and from the development of novel flow visualization technologies in the 1990s including high-speed video imaging, electrical-capacitance tomography and wire-mesh sensors.

From all the validation tests presented in the literature it may be concluded that, despite its simplicity, the DVCM reproduces the essential features of transient cavitation. The versatility of the model has been demonstrated by the variety of pipe systems used in the tests. The major deficiency of the model is the appearance of nonphysical oscillations in the results. The DGCM is better in this respect and therefore recommended in developing and revising industrial engineering water-hammer computer codes. The interface models give reliable results, but they still are quite complicated for general use.

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