Cavitation inception in pipeline column separation

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CAVITATION INCEPTION IN PIPELINE COLUMN SEPARATION

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ABSTRACT
This paper investigates the influence of the magnitude of cavitation inception pressure on column separation phenomena. During column separation in pipelines, resulting from water hammer events, the pressure can drop below the vapour pressure of the fluid. Experimental results from two configurations of a reservoir-pipeline-valve-reservoir system apparatus are presented. "Negative" pressure spikes below the level of vapour pressure head for the fluid were recorded in both these experimental runs. Cavitation inception with a "negative" pressure was incorporated into a numerical model of column separation referred to as the discrete vapour cavity model (DVCM). The numerical model can reproduce the behaviour when an appropriate negative pressure value for cavitation inception is incorporated into the DVCM. The local negative pressure spike at cavitation inception does not significantly affect the column separation phenomena. Inclusion of the occurrence of this phenomena into the DVCM numerical model does not improve the numerical results.

KEYWORDS
water hammer, column separation, cavitation inception, discrete vapour cavity model, experimental apparatus, pipeline

INTRODUCTION
Water hammer in pipelines results in column separation when the pressure drops to the liquid vapour pressure assuming a negligible amount of free and released gas is present in the liquid (Wylie and Streeter 1993). Column separation occurs either as a localised vapour cavity at a boundary and along the pipe (large void fraction) or as distributed vaporous cavitation zone which may extend over long sections of the pipe (void fraction close to zero).
Liquid vapour pressure is accepted as the cavitation inception pressure in standard column separation numerical models (Wylie and Streeter 1993). There are a number of column separation experiments with cavitation inception pressures much lower than the liquid vapour pressure (Lee et al. 1985; Takenaka 1987; Fan and Tijsseling 1992; Simpson and Bergant 1996). The liquid pressure should drop to the pressure which excites a "critical" number of active nucleation sites for cavitation inception (Brennen 1995). The magnitude of the negative pressure is governed by cavitational properties of the liquid and pipe walls. The number and size of nuclei are increased once the cavitation has been induced.
The objective of this paper is to investigate the influence of "negative" pressure on column separation phenomena. Cavitation inception with "negative" pressure is incorporated into a numerical model referred to as the discrete vapour cavity model

(DVCM). Numerical results are compared with results of two distinct experimental runs in a sloping pipeline laboratory apparatus. The first case represents closure of a downstream end valve in an upward sloping pipe; the second case is the closure of an upstream end valve in a downward sloping pipe.

DISCRETE VAPOUR CAVITY MODEL DESCRIPTION

The discrete vapour cavity model (DVCM) for pipelines is a single component two-phase flow model assuming constant wave speed for liquid between computational sections. When the pressure at a computational section drops below the vapour pressure of the liquid, it is set to the vapor pressure. A vapour cavity, assumed to occupy the whole cross-section, is formed. The standard water hammer solution is no longer valid at the section. When the cavity collapses at a section, the one phase liquid is re-established.

The standard numerical algorithm for the DVCM allows vapour cavities to form at computing sections in the method of characteristics (Wylie and Streeter 1993). In this paper the staggered grid of the specified time intervals is applied to the integrated water hammer compatibility equations. The friction term in the water hammer compatibility equations is integrated by parts (Wylie and Streeter 1993) using an assumed constant steady-state friction factor (Bergant and Simpson 1994).

The growth and subsequent decay of the vapour cavity is calculated from the two compatibility equations and the integrated continuity equation for the vapour cavity volume $\forall$ (Wylie 1984):

$$\forall_{t+2\Delta t} = \forall_t + [(1-\psi)(Q_t - Q_{u,t}) + \psi(Q_{t+2\Delta t} - Q_{u,t+2\Delta t})]2\Delta t \qquad (1)$$

in which Q = downstream discharge, Q_u = upstream discharge, Δt = time step and ψ = weighting factor. The weighting factor ψ can take on values between 0.5 and 1.

The DVCM model may generate unrealistic pressure spikes following multi-cavity collapse in a distributed vaporous cavitation zone. The distributed vaporous cavitation zone occurs in an extended region of the pipe when a rarefaction wave progressively drops the pressure to the liquid vapour pressure. The DVCM gives reasonably accurate results when the number of reaches is restricted (the ratio of maximum cavity size should be below 10%) and sensitivity analysis to input parameters is performed (Simpson and Bergant 1994).

Cavitation inception in the DVCM is controlled by the flags which detect the onset of cavitation. The standrad liquid vapour pressure is replaced by a cavitation inception pressure (less than vpour pressure) at selected computational sections (at the valve or along the pipeline) and selected discrete cavity openings (first, second, etc.). The standard DVCM computation is resumed in the next time step.

WATER HAMMER AND COLUMN SEPARATION EXPERIMENTAL APPARATUS

A sophisticated apparatus for investigating water hammer and column separation events in pipelines has been designed and constructed (Bergant and Simpson 1995). The apparatus comprises a straight 37.23 m (U_x = ±0.01 m) long sloping copper pipe of 22.1 mm (U_x = ±0.1 mm) internal diameter and 1.63 mm (U_x = ±0.05 mm) wall thickness connecting two pressurised tanks (Fig. 1). The uncertainty in a measurement U_x is expressed as a root-sum-square combination of bias and precision errors (Coleman and Steele 1989). The pipe slope is constant at 5.45 % (U_x = ±0.01 %) or 1 (vertical) to 18.3 (horizontal).

A specified pressure in each of the tanks ($H_{T,1}$ and $H_{T,2}$) is controlled by a computerised pressure control system (U_x = ±0.3 %). The water flows from a tank with a higher set pressure (emptying-tank) to a tank with a lower set pressure (filling-tank). The net water volume in both tanks and the capacity of air compressor limit the maximum steady state velocity to 1.5 m/s and maximum operating pressure (pressure head) in each tank to 400 kPa (40 m).
Transient events in the apparatus are initiated by rapid closure of the ball valve. Fast closure of the valve is carried out either by a torsional spring actuator (closure time (t_c) may be set from 5 to 10 milliseconds) or manually by hand. The actuator provides a constant and repeatable valve closure time.
Five pressure transducers (H_v, $H_{q,1}$, H_{mp}, $H_{q,2}$ and H_r; U_x = ±0.7 % for the piezoelectric type transducers) are located at equidistant points along the pipeline including as close as possible to the end points (Fig. 1). The water temperature in Tank 1 (T_w; U_x = ±0.5 °C) is continuously monitored and the valve position during closure is measured using optical sensors (U_x = ±0.0001 s for the valve closing time).

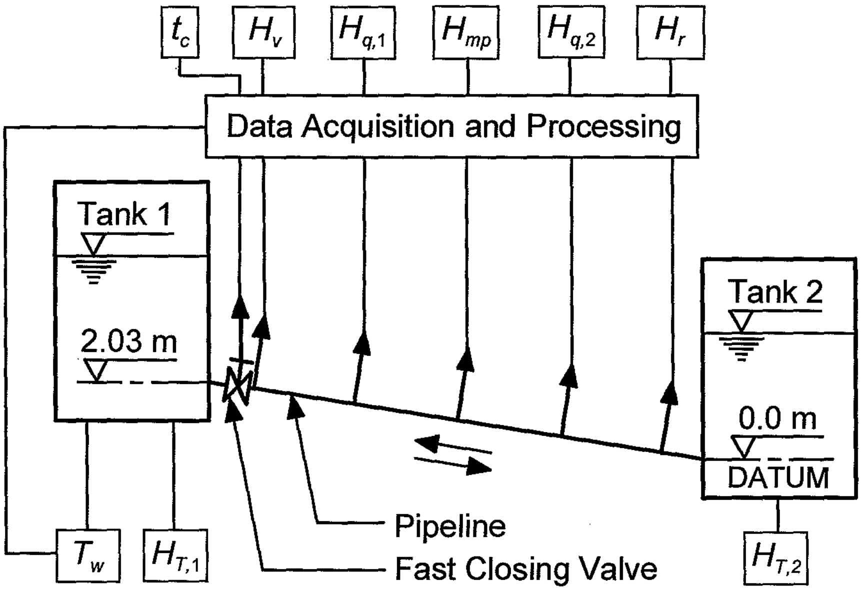

Fig. 1 Experimental apparatus layout

Each experiment using the experimental apparatus consists of two phases. First an initial steady state velocity condition (U_x = ±1 % for the volumetric method) is established. Second a transient event is initiated by a rapid closure of the valve. The wave propagation velocity (U_x = ±0.1 %) is obtained from the measured time for a water hammer wave to travel between the closed valve and the quarter point nearest to the valve.

NUMERICAL AND EXPERIMENTAL RESULTS

Numerical and measured results of two distinct experimental runs are compared in order to investigate cavitation inception phenomena in pipeline column separation. The first case represents closure of a downstream end valve in an upward sloping pipe; the second case is the closure of an upstream end valve in a downward sloping pipe (Fig. 1). The flow conditions for the two cases were (Simpson and Bergant 1996): initial flow

velocity $V_0 = 1.50$ m/s, static head in an upstream end tank (Tank 2 in Case 1, Tank 1 in Case 2) $H_T = 32.$ m, valve closure time $t_c = 0.009$ s, water temperature $T_w = 15.5\,^{\circ}$C and wave speed $a = 1319.$ ms^{-1}; the numerical parameters for each DVCM computational run were: number of reaches $N = 16$ and weighting factor $\psi = 1.0$.
Measured and computed piezometric heads for the two cases are compared at the valve (H_v) and at the midpoint (H_{mp}). The results of measurements at the two quarter points ($H_{q,1}$ and $H_{q,2}$) show similar behaviour as the results at the midpoint. The head adjacent to the Tank 2 (H_r) is the reservoir head.

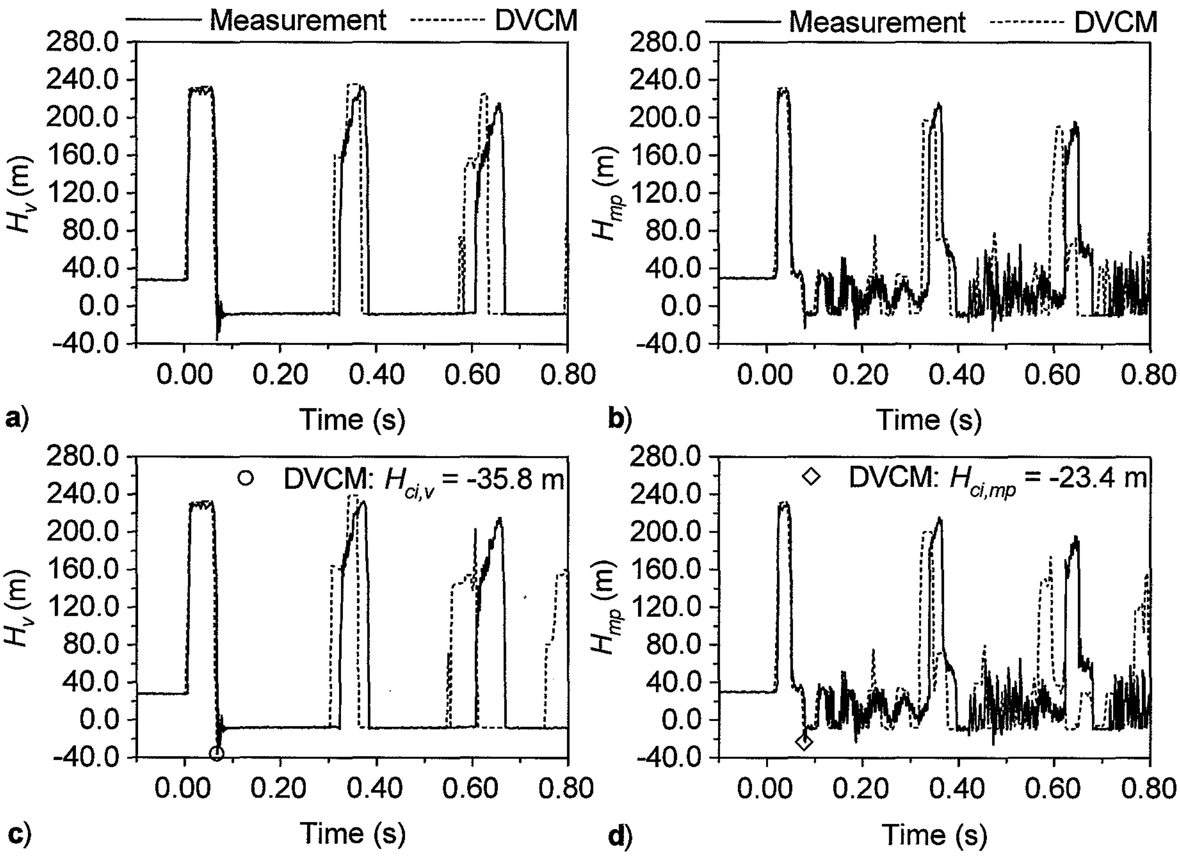

Fig. 2 Comparison of H_v (at fast closing valve) and H_{mp} (at midpoint) for Case 1 (upward sloping pipe, valve at downstream end)

Fig. 2 shows experimental and two sets of numerical results for Case 1. Experimental results exhibit "negative" pressure spikes. The first column separation at the valve and at the midpoint occurs at a pressure head which is much less than the liquid vapour pressure head. After a few milliseconds the pressure head rises to the liquid vapour pressure head. Transient cavitation increases the number of active nucleation sites. Subsequent column separations at the valve do not exhibit pressures below the liquid vapour pressure. There are two additional "negative" pressure spikes at the midpoint. The negative pressure spikes may be contributed to by the significant pre-pressurisation of the liquid in the pipeline after valve closure (water hammer wave) and at some points after condensation of distributed cavitation zones (shock waves) along the pipe. The DVCM results with a cavitation inception pressure head (H_{ci}) set to the vapour pressure head (H_{vap}) are shown in Figs. 2a and 2b. There is a good agreement between the computed and measured maximum heads (important data for a pipeline design engineer). Timing for DVCM results is slightly faster than for measured results.

Setting the cavitation inception pressure head at the first cavity opening at the valve and at all 15 computational sections along the pipeline to the experimentally predicted "negative" pressure spikes (H_{ci} = -2$L(x)$/3-11; 0 < $L(x)$ ≤ L = 37.23 m; at fast closing valve: $L(x)$ = L, $H_{ci,v}$ = -35.8 m) leads to faster transients altering the magnitude and shape of pressure traces (Figs. 2c and 2d) in comparison to the standard DVCM results (Figs. 2a and 2b).

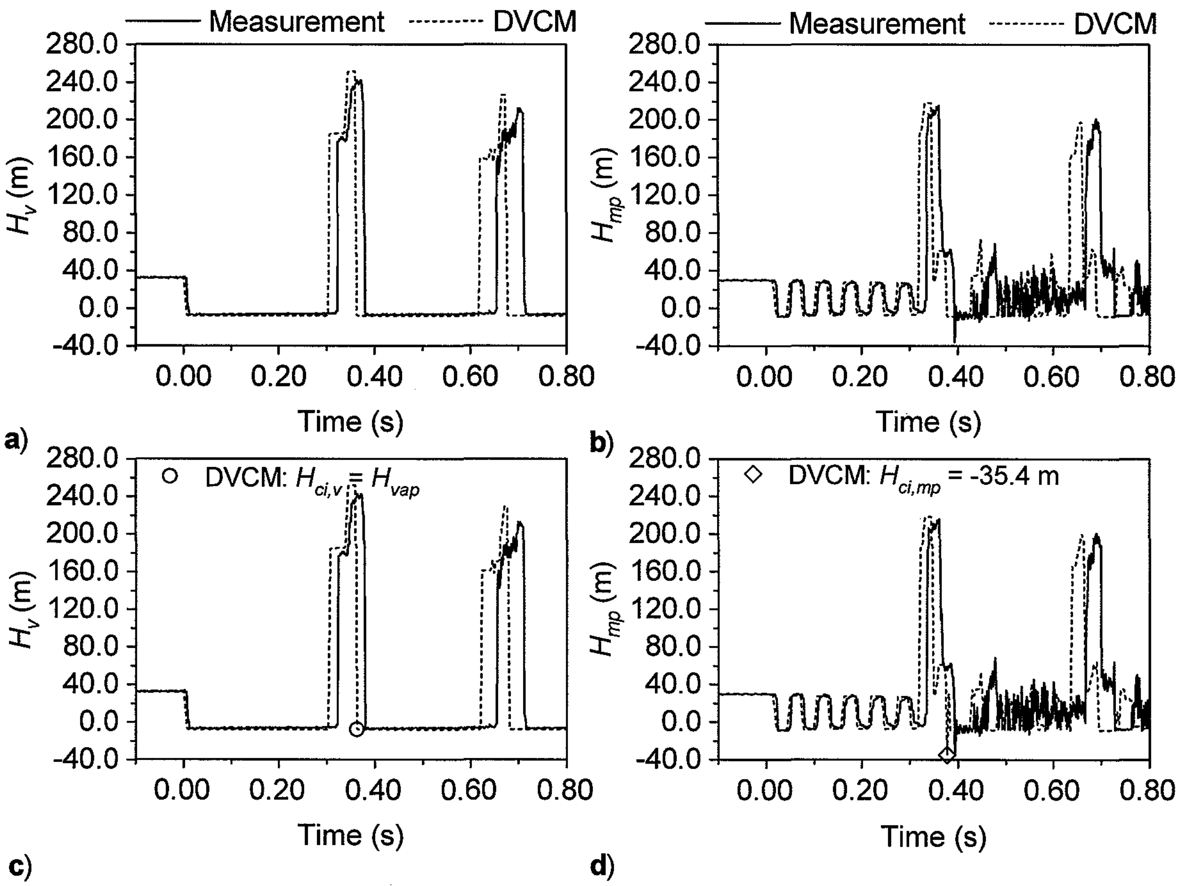

Fig. 3 Comparison of H_v (at fast closing valve) and H_{mp} (at midpoint) for Case 2 (downward sloping pipe, valve at upstream end)

Measured and numerical computational results for Case 2 are depicted in Fig. 3. The experimental results clearly show the effect of de- and pre-pressurisation on cavitation inception. Fast closure of the upstream end valve generates a rarefaction wave dropping the pressure to the liquid vapour pressure at the valve and along the pipe. The pressure never drops below the vapour pressure at the valve (sufficient number of active nucleation sites). A negative pressure spike at the midpoint is generated after the first large pre-pressurisation of the liquid following the collapse of a large cavity at the valve. Reservoir (shock) waves along the pipeline during existence of the first cavity at the valve never compress small vapour bubbles along the pipe above the initial steady state pressure. The DVCM results with a cavitation inception pressure head (H_{ci}) set to the liquid vapour pressure head (H_{vap}) (Figs. 3a and 3b) show a similar behaviour as respective DVCM results for the Case 1 (Figs. 2a and 2b). Setting the cavitation inception pressure heads at all 15 computational sections along the pipeline to experimentally predicted "negative" pressure spikes after the first cavity collapse at the valve (H_{ci} = -2(L-$L(x)$)/3-23; 0 < $L(x)$ < L = 37.23 m; at the valve: $L(x)$ = 0) results in slightly slower transients (Figs. 3c and 3d) in comparison to the standard DVCM results (Figs. 3a and 3b). The magnitude and shape of the two computed pressure traces are somewhat similar.

Comparison between the results of measurements and the two sets of computed results for the Case 1 and Case 2 shows an adverse effect of a "negative" pressure spike introduced in the DVCM at the valve for the Case 1 (formation of a large cavity in pre-pressurised liquid). Inclusion of experimentally predicted negative pressure spikes along the pipeline has a minor effect on the computational results (formation of distributed vaporous cavitation zone). Results of further numerical analyses with pressure spikes along the pipe well below the experimentally predicted ones exhibit similar adverse effects as the results for the Case 1. In addition, comparison of DVCM results with cavitation inception pressure set to the liquid vapour pressure shows the same degree of agreement for the Case 1 experiment with large "negative" pressure spikes at the first cavitation inception (Figs. 2a and 2b) and for the Case 2 results with vapour pressure at first cavitation inception (Figs. 3a and 3b).

CONCLUSIONS

The influence of the magnitude of cavitation inception pressure on column separation phenomena has been investigated. The cavitation inception pressure may drop below the liquid vapour pressure in the case of intense pre-pressurisation of the liquid. Cavitation inception with "negative" pressure was incorporated into the discrete vapour cavity (DVCM) numerical model. Numerical and measured results of two distinct experimental runs with "negative" pressure spikes were compared. The local "negative" pressure spike at cavitation inception does not significantly affect the column separation phenomena. Inclusion of "negative" spikes into the DVCM does not improve numerical results.

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