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LARGE WATER-HAMMER PRESSURES FOR COLUMN SEPARATION IN PIPELINES

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INTRODUCTION

Experimental evidence of short-duration pressure pulses following the collapse of a vapor cavity at a valve have previously been presented in the literature (Yamaguchi and Ichikawa 1976; Yamaguchi et al. 1977; Martin 1983; Simpson 1986; Simpson and Wylie 1987). This paper investigates the variation of magnitude and shape of short-duration pressure pulses for a simple reservoir-valve system connected by a hypothetical frictionless pipe. Details of the mechanism for the occurrence of a short - duration pressure pulse are presented. The discrete vapor-cavity numerical model is used to analyse the pipe system during column separation events for different initial steady-state velocities. This model has been described in detail in earlier publications (Wylie and Streeter 1983; Simpson and Wylie 1989).

OCCURRENCE OF SHORT-DURATION PRESSURE PULSES

A large pressure resulting from the collapse of a vapor cavity is referred to as a short-duration pressure pulse (Simpson 1986). The time duration of the pressure pulse refers to the $2L/a$ time period for the pipeline of length L, where a is the wave propagation velocity. Thus a short-duration pressure pulse associated with collapse of a vapor cavity lasts for between 0 and $2L/a$ s.

To explore the occurrence of short-duration pressure pulses, a reservoir-pipeline-valve system as shown in Fig. 1 will be considered. The horizontal and frictionless pipeline is 980 m long. The $2L/a$ period for the pipe is 2 s, assuming a = 980 m/s. An initial steady-state velocity of 0.6 m/s is assumed. For an instantaneous valve closure at the downstream end of the pipe, the change in pressure head ΔH due to the change in velocity ΔV of a flowing fluid is given by Joukowsky's law as

$$\Delta H = -\frac{a}{g}\Delta V \tag{1}$$

where $\Delta V = V_f - V_i$; V_f = the fluid velocity after the valve has been moved to the final position; V_i = the initial fluid velocity; and g = gravitational acceleration. For the configuration in Fig. 1, the Joukowsky head rise is 60 m as shown in Fig. 2 for g = 9.80 m/s^2. The plot of the hydraulic grade line (HGL) versus time at the valve was obtained from the discrete vapor-cavity numerical model. An x-t plot of the method of characteristic plane for the transient is shown as part of Fig. 2.

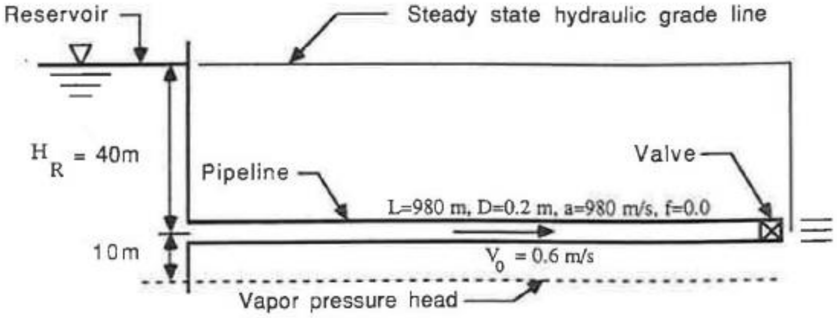

Figure 1. Reservoir-Pipeline-Valve Definition Sketch

An explanation of the physical formation of a short-duration pressure pulse is now given. Upon instantaneous valve closure at 0.2 s (A-B in Fig. 2) a pressure wave travels out from the valve toward the reservoir. The wave reflects from the reservoir and travels back to the valve, arriving at the valve at $2L/a$ s after closure. The pressure at the valve then drops below the initial steady state at 2.2 s and collapses at 4.6 s (E). The time of existence of the cavity is 2.4*L*/*a* s, which is not a multiple of 2*L*/*a* s. When the cavity collapses, a head rise of 90 m from a vapor pressure head to an HGL of 80 m occurs (E-F). The sudden cavity collapse has produced a second waterhammer wave in the pipe in ~ddition to the original valve closure wave. produced a second water-hammer wave in the pipe in addition to the original valve closure wave. The short-duration pressure pulse occurs when the original valve closure wave arrives back at the valve at a time of 6.2 s (GH). The result is a head rise of 100 m to an HGL of 180 m, as shown in Fig. 2. The pressure pulse results from the superposition of the initial valve closure wave and the cavity collapse wave.

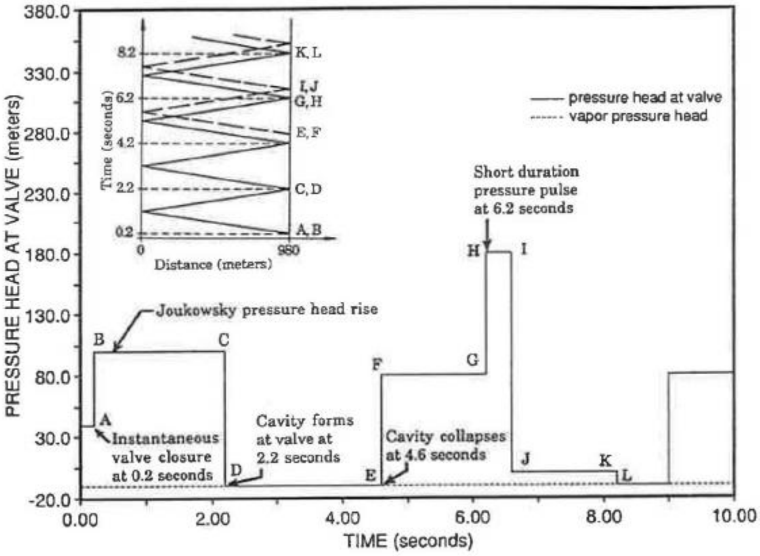

Figure 2. Pressure Head versus Time for Horizontal 980-m Pipe Following Instantaneous Valve Closure ($V_o = 0.6$ m/s)

Fig. 2 demonstrates that the maximum pressure rise following the collapse of a vapor cavity at the valve may exceed the Joukowsky pressure head rise as computed from (1). The short-duration pressure pulse is superimposed on the normal transient pressure trace for a rapid valve closure in a pipeline. It should be emphasized that the occurrence of the maximum pressure rise following the collapse of a vapor cavity does not occur immediately on collapse but is delayed by between 0 and 2*L*/*a* s.

NUMERICAL MODEL PREDICTION OF SHORT-DURATION PRESSURE PULSES

A study of the occurrence of short-duration pressure pulses was made by modeling the system in Fig. 1 using the discrete vapor-cavity numerical model. Column separation occurred only in the form of a localized vapour cavity at the valve. No extended zones of distributed vaporous cavitation occurred along the pipeline during the water-hammer event following instantaneous closure of the downstream valve .

The magnitude and duration of the short-duration pressure pulse varies depending on the initial steady-state conditions of flow. Fig. 3 compares the pressure versus time trace from the discrete vapor-cavity numerical model at the valve for the system shown in Fig. 1. Results for various initial steady-state velocities ranging from 0.5 m/s to 1.1 m/s are shown. For velocities less than 0.5 m/s, no column separation occurs at any location in the pipe. For 0.5 m/s, the pressure drops exactly to vapor pressure at the valve, and no vapor cavity grows there. For initial steady-state velocities greater than 0.5 m/s, a vapor cavity forms at the valve at 2*L*/*a* s after the instantaneous valve closure. As the initial velocity increases, the time of existence of the cavity at the valve increases (Fig. 3).

Narrow, short-duration pressure pulses due to wave superposition (e.g., 0.6 and 1.1 m/s in Fig. 3) occur when the vapor cavity at the valve collapses immediately following the reflection of the valve closure wave at the downstream end valve. Wider short-duration pressure pulses (e.g., 0.9 m/s), on the other hand, occur when the cavity collapses just prior to the reflection of the valve closure wave at the valve. The shorter the time of existence of the cavity at the valve, the larger the magnitude of the short-duration pressure pulse relative to the Joukowsky head rise.

No short-duration pressure pulse occurs for 0.5 m/s or 1.0 m/s, or in fact for any multiple of 0.5 m/s as an initial steady-state velocity. For these cases the cavity collapses at an exact integer multiple of 2*L*/*a* s. The likelihood of a cavity collapsing at exactly the same time as the valve water hammer wave arrives back at the valve is remote. Thus it should be more common to observe situations such as pressure traces shown for 0.6-0.9 m/s in Fig. 3.

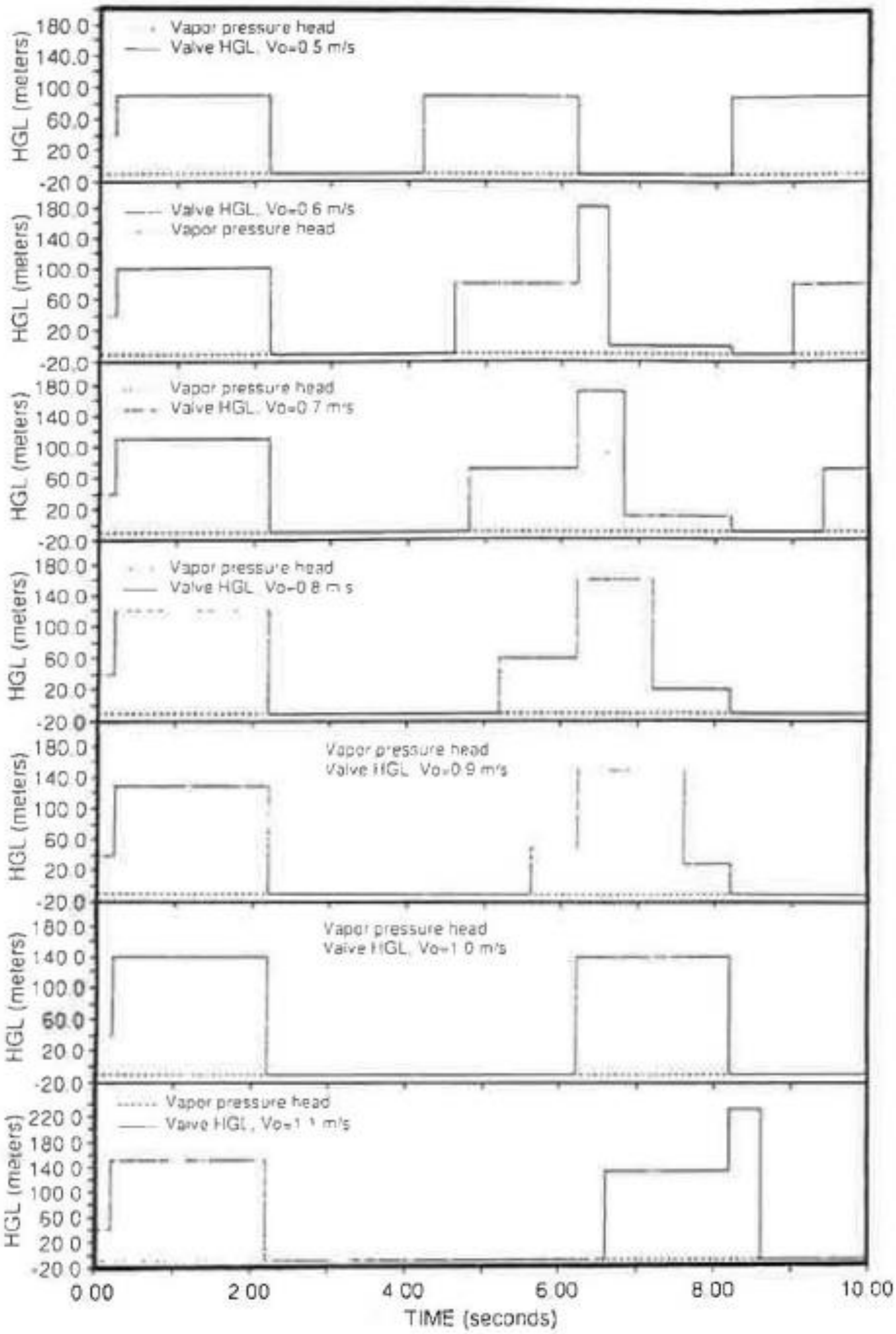

Figure 3. Pressure Head versus Time Plots for Various Initial Steady-State Velocities for Reservoir-Pipe-Valve System

EXPERIMENTAL EVIDENCE OF SHORT-DURATION PRESSURE PULSES

Fig. 4 summarizes some of the experimentally recorded HGL, versus time plots at a downstream valve for an experimental apparatus of a 36.0-m-long, 19.05-mm-diameter pipe at the University of Michigan, Ann Arbor, Michigan (Simpson 1986' Simpson and Wylie 1987). The plots show the variation of magnitude and duration of short-duration pressure pulses for five different initial steady-state velocities. The general variation in shape of the short-duration pulses matches the numerical model results presented in Fig. 3.

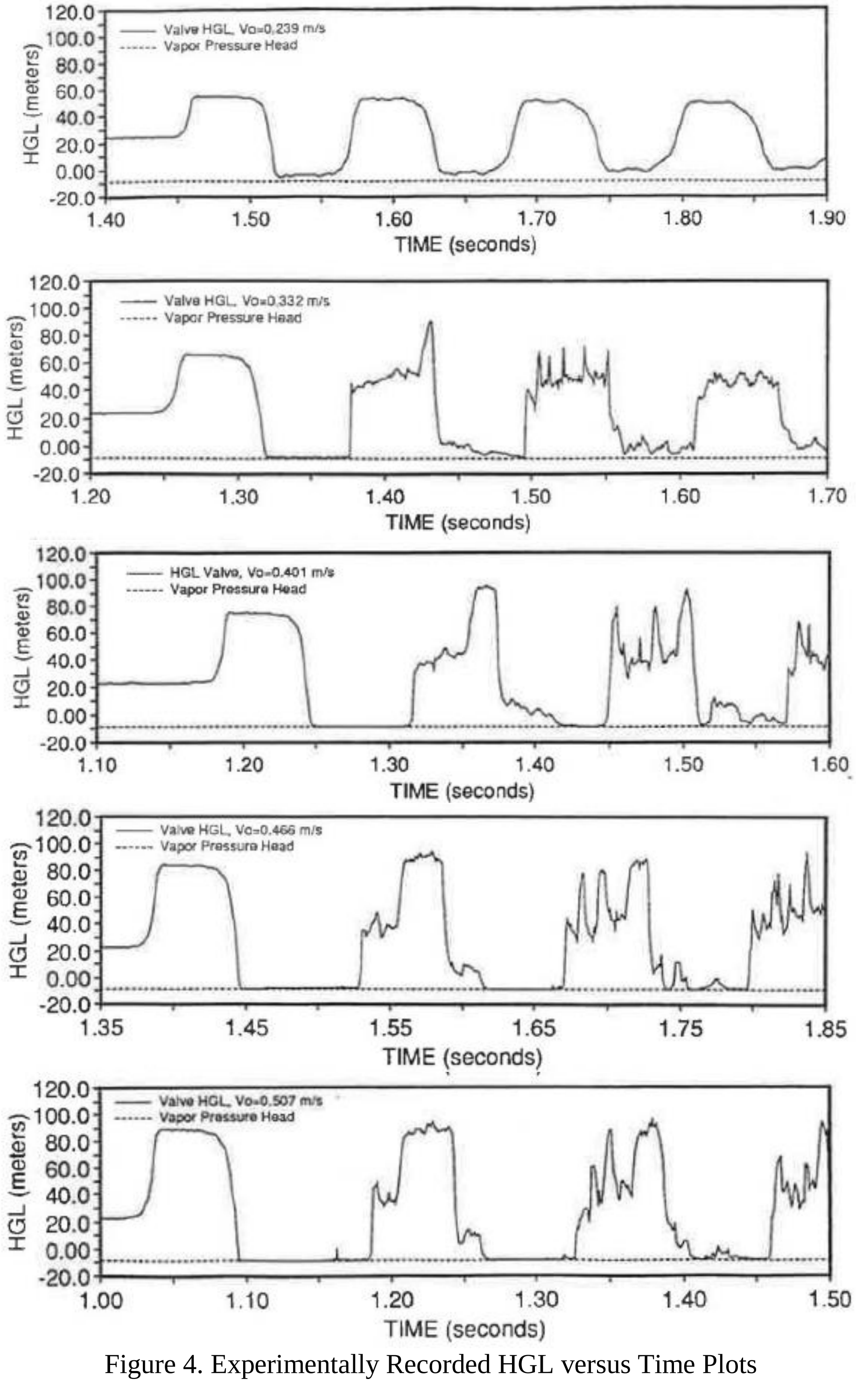

Figure 4. Experimentally Recorded HGL versus Time Plots

CONCLUSIONS

Pressure pulses following vapor-cavity collapse in a pipeline may exceed the Joukowsky valve closure head rise. A series of numerical model and experimentally measured pressure versus time results indicate short-duration pressure pulses may occur following cavity collapse. The magnitude of the pressure pulse depends on superposition of water-hammer waves. The relative timing of the collapse of the vapor cavity at the valve versus the reflection of the valve closure water-hammer waves from the valve is the controlling factor.

ACKNOWLEDGMENT

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APPENDIX II. NOTATION

The following symbols are used in this paper:

a = wave propagation velocity, in m/s;
D = diameter of pipeline, in m;
f = Darcy-Weisbach friction factor;
g = gravitational acceleration, in m/s^2;
H_R = reservoir head, in m;
L = pipeline length, in m;
V_f = final velocity or velocity of valve end of water column just before cavity collapse, in m/s;
V_i = initial velocity, in m/s;
V_o = initial steady-state velocity, in m/s;
ΔH = Joukowsky pressure head rise, in m;
ΔV = change in velocity, in m/s; and
$2L/a$ = pipeline wave return time, in s.