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Numerical study on effects of check valve closure flow conditions on pressure surges in pumping station with air entrainment

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SUMMARY

This paper proposes a numerical procedure to better compute the characteristics of pressure surges when check valves close under different flow conditions in a pumping station. Studies have shown that the effects of check valve closure on the pressure transients are predominantly dependent on the magnitude and gradient of the flow velocities immediately downstream of the check valve at the instant of valve closure. Through the present study, it was noted that the transient flow velocities near the check valve of a fluid system are also dependent on the characteristics of the air entrained into the fluid system. An improved numerical computational procedure for the fluid system with air entrainment under different transient conditions downstream of the check valve is also proposed in this paper. With a fluid system operating within the critical range of air entrainment values, the present analysis showed that there is a possibility of 'high pressure surges' when the check valves were closed at flow rates other than the positive flow conditions. This phenomenon was confirmed through field observations. This study thus concludes that a detailed numerical transient analysis of the fluid system, with various assumed amounts of entrained air, is necessary whenever there is the possibility of air entrainment into the fluid system, and that the flow conditions at the instant of check valve closure need to be modelled. Copyright © 2001 John Wiley & Sons, Ltd.

KEY WORDS: air entrainment; check valve closure characteristics; pressure surges; pumping system

1. INTRODUCTION

Different types of check valve [1–8] possess very different flow characteristics under transient conditions. It is assumed here that for a given geometry of the swing-type check valve (Figure 1), the valve opening during steady state is determined by the steady state flow rate V_0. The higher the steady state flow rate, the larger is the valve opening and the longer it takes the moving elements of the check valve body to close completely when the flow reverses. The fluid

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velocity gradient $\mathrm{d}v/\mathrm{d}t$ is assumed to play an important part in the dynamic phenomena during valve closure. If the fluid system flow rate decrease is gradual (e.g. using an appropriately sized flywheel), with a longer time period for the first flow reversal (i.e. flow reversal time, $\Delta t1$ in Figure 1(b)), valve slamming and high-pressure surges can generally be minimized with an appropriate manner of valve closure. Making the above assumptions, the present analysis considered a fluid system with air entrainment ε and studied numerically the latter's effect on the manner of flow behaviour near the valve during closure. From the available literature on dynamic valve closure characteristics [2–4,7,8], it is observed that the rate of decrease for a given flow rate is approximately linear over the interval during which the flow rate starts to decrease and eventually reverses. This physical observation is implemented in the present numerical calculation procedure to better determine the suitability of a check valve type for a given pumping system. Sharp [9] also mentioned that when selecting check valves to be installed into a pumping system, numerical simulation of the transient characteristics should be carried out for different check valve flow conditions. Previous numerical studies [10–14] have shown that the presence of air pockets in the pipeline can severely exacerbate the transient pressure peaks which might arise during pump shut-down.

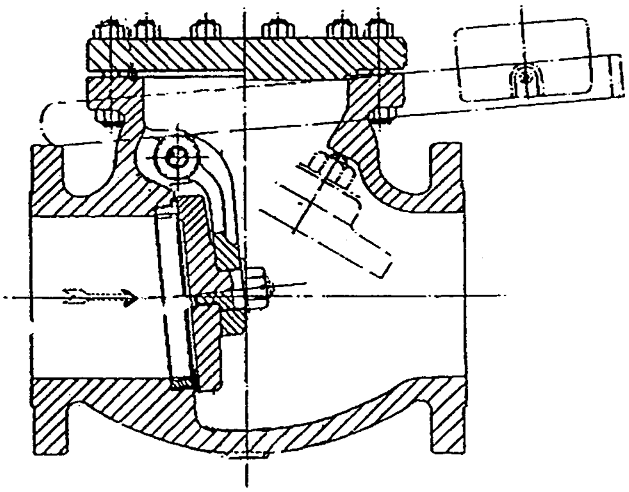
2. DYNAMIC CHECK VALVE RESPONSES

When a significant decrease in the flow rate is encountered in the pump during pump rundown, the check valve will be initiated to close. At this instant V_0^{k+1} and its rate of decrease $(\mathrm{d}V/\mathrm{d}t)$ are computed together with the C^- characteristic line at $i=0$ for all subsequent time levels. In the case when the flow characteristics during check valve closure are known, the flywheel or pump set inertia can be sized such that the pump continues delivery for a period longer than the check valve closure time. When a reverse flow occurs at the check valve (Figure 1(b)), the latter responds according to the experimentally obtained dynamic characteristics of the check valves [8]. The characteristics of the flow through the check valve are numerically modelled here as

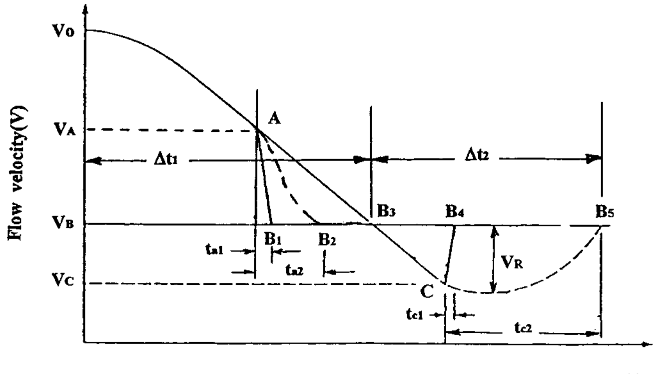
$$V_\mathrm{R}/V_0 = D_1 + D_2(A^*) + D_3(A^*)^2 + D_4(A^*)^3 \tag{1}$$

where $A^* = |\mathrm{d}V/\mathrm{d}t|/[(V_0)^2/D]$ is the reverse flow deceleration parameter through the check valve, V_0 is the steady state flow velocity, $\mathrm{d}V/\mathrm{d}t$ is the reverse flow velocity gradient, D is the check valve nominal diameter, D_1, D_2 and D_3 are the characteristic parameters of the type of check valve and D_4 is the characteristic parameter of the check valve due the effect of air entrainment.

While the valve is closing (point B3, Figure 1(b)), the fluid has reverse velocity V_R flowing through the valve. The valve position is controlled by the flow and valve dynamics and closure occur after some back flow is established. Figure 1(b) shows some possible velocity time history for various valve closures following the removal of the driving force in the system, such as pump stoppage, pump power failure, etc. Paths AB_1 and AB_2 represent respectively undampened and dampened check valve closure with forward flow velocities; point B3 represents check valve closure at zero flow velocity; paths CB_4 and CB_5 represent undampened



(a) Swing type check valve



(b) Model of flow at check valve closure

Figure 1. A numierical model of check valve closure velocities.

and dampened check valve closure when the flow has reversed through the check valve respectively.

Check valves serve to prevent the reversal of flow in a pumping system. If, however, a reversal of flow occurs in a very short time, the valve may close after the flow has already been reversed. Depending on the type of check valve used, a sudden decrease in the reversal of flow will occur (Figure 1(b), path CB_4), possibly resulting in unallowable pressure variations and slamming of the valve. To theoretically predict whether slamming of a check valve is to be expected, data under dynamic conditions of the valve have to be known. In most cases these data are not known. In a recent study carried out by Lee [14], it was shown that the possibility of a check valve slamming, however, may be estimated through a numerically predicated 'flow reversal time' t_R. Prototype valve tests showed that the variation in the fluid velocity gradient $|\mathrm{d}V/\mathrm{d}V|$ with time is of decisive importance when considering the valve slamming problem. Obviously, the shorter the time of transient flow reversal from pump trip (Figure 1(b), $\Delta t1$), the more likely it is that valve slamming will occur. This again depends on the type of check valve used. Nozzle-type of recoil check valves tend to have a better dynamic response than the conventional swing-type check valves. It is thus important to know the 'flow characteristics' of the system near the check valve during pump trip so that, at the design stage of a hydraulic project, it is possible to predict whether the chosen type of check valve will satisfy the design specifications of the pumping system.

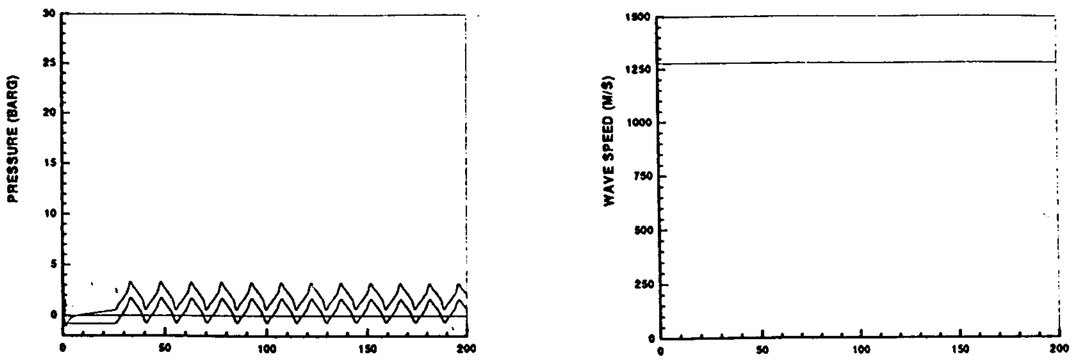
3. RESULTS AND DISCUSSION

The typical pipeline profile of a pumping station with air entrainment (ε) used previously by Lee [11–14] is also used this study. The pressure transients resulting from a simultaneous pump trip of all pumps are monitored at the two locations A and B. A is the immediate downstream location of the check valve. Location B is at the peak of the pipeline profile. In this study, the check valves have been selected such that each will close at a different flow velocity during a pump trip. The resulting pressure transients are analysed to study the effect of check valve closure on pressure surges for a pumping system.

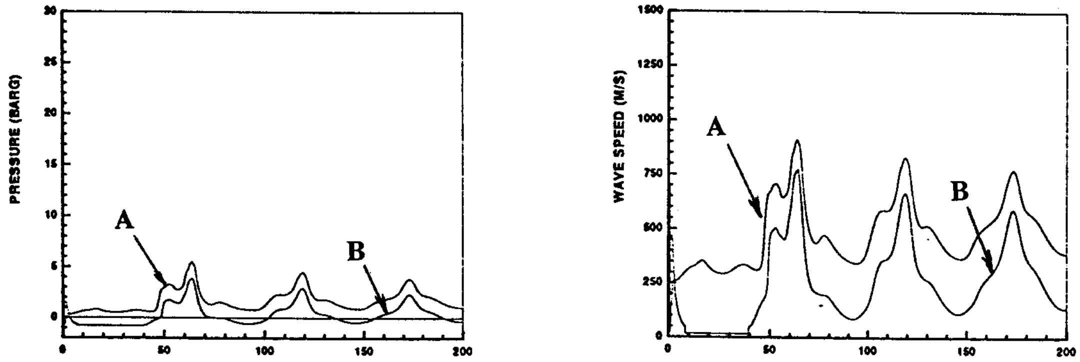
Figure 2 shows the typical pressure transients at the lowest point A (maximum pressure) and the peak point B (minimum pressure) of the pipeline contour with check valve closure at different forward flow velocities (i.e. $V_A = kV_0$, where k is a positive number between 0.0 and 1.0). The pressure surges observed are not very severe at all air entrainment levels. Figure 3 shows the typical pressure transients at the corresponding points of A and B along the pipeline when the undampened check valve closes with a reverse flow velocity (path CB_4, Figure 1(b), with $V_C = -kV_R$, where k is a positive number between 0.0 and 1.0). The transient pressures are observed to be very extreme. The highest pressure surge observed in this study occurs at the peak reverse flow velocity (V_R in Figure 1(b)), while the pressure surges were relatively low for positive or near zero flow velocity through the check valve when the check valve closed.

Typically, when the check valve closes at a reverse flow velocity, a pressure surge will be generated, which increases when the magnitude of the reverse velocity at the time of valve closure increases. At a high reverse flow velocity, the associated energy in the flow increases. When the check valve suddenly closes, this huge amount of energy is released when the flow undergoes a sudden deceleration (negative $\mathrm{d}V/\mathrm{d}t$) to zero velocity almost instantaneously. This explains why the most severe pressure peak occurs when the check valve closes rapidly at the highest reverse flow velocity. When the check valve closes at a forward flow velocity, a downsurge will be generated. However, after the initial downsurge, the pressure transient recovers quickly to that of the pressure transient where the check valve closes at zero velocity.

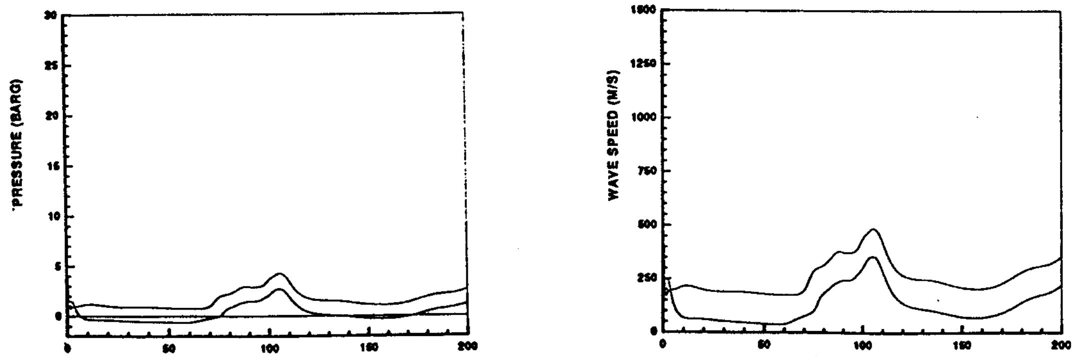
(a) Pressure transients **(b) Wave speed transients**



(i) $\varepsilon=0.0000$

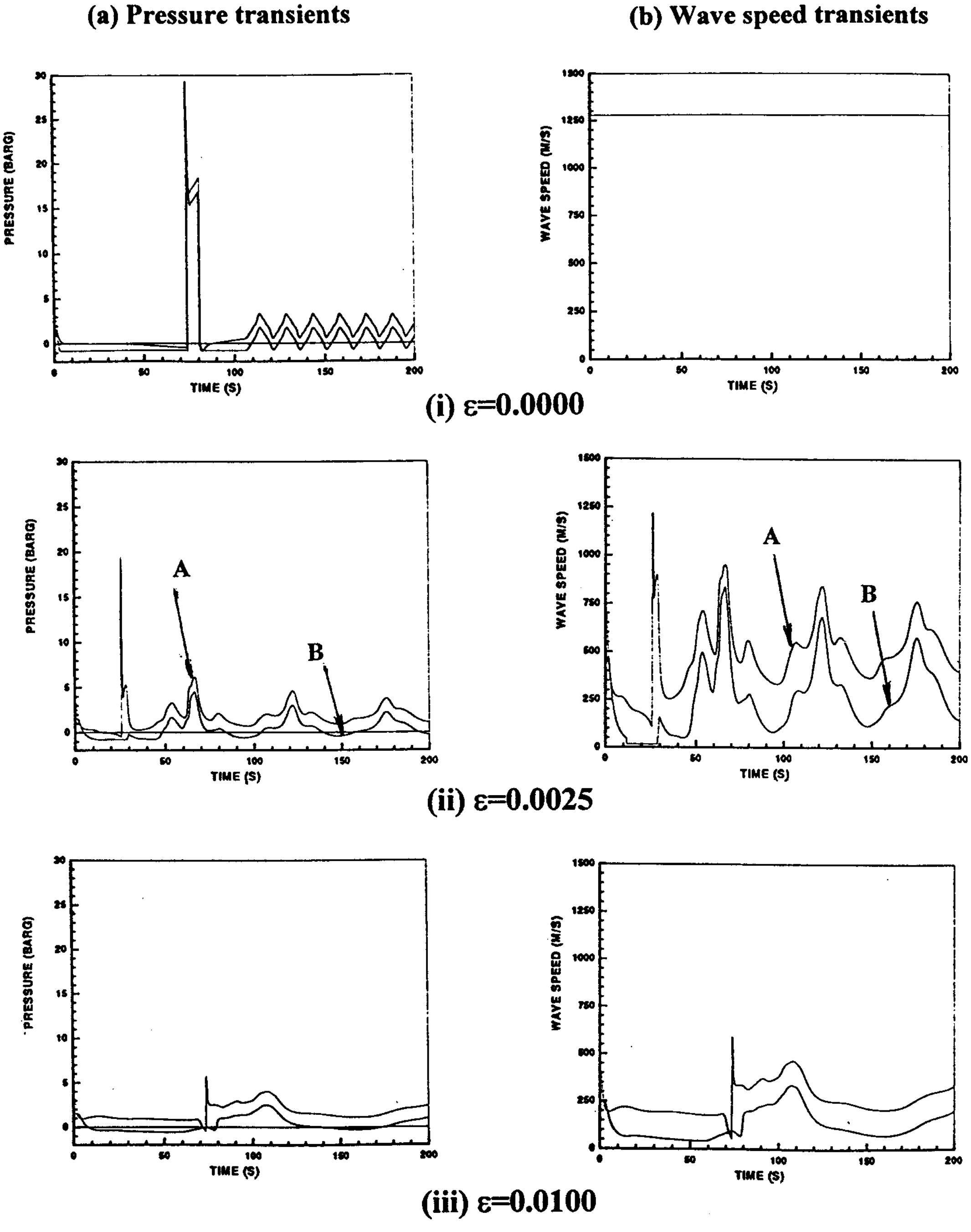


(ii) $\varepsilon=0.0025$



(iii) $\varepsilon=0.0100$

Figure 2. Pressure and wave speed transients for check valve closure at flow velocity V_A.



(i) ε=0.0000

(ii) ε=0.0025

(iii) ε=0.0100

Figure 3. Pressure and wave speed transients for check valve closure at flow velocity V_R.

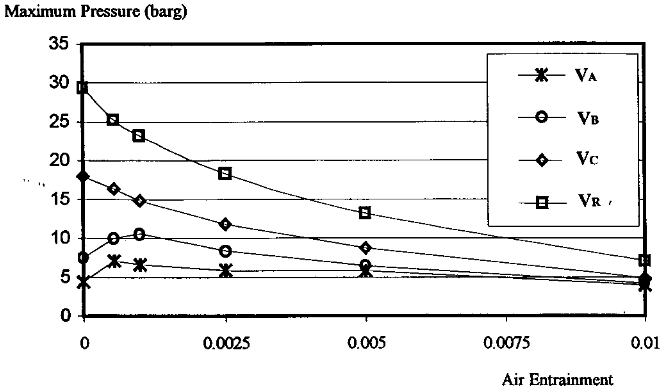


Figure 4. Effects of air entrainment on pumping system maximum pressure.

The above numerical model provides useful information on the effects of air entrainment on the maximum pressure within a given pumping system. Figure 4 shows that the maximum pressure along the pipeline is also dependent on the air entrainment level. Maximum transient pressure may not necessarily always occur at a particular air entrainment level. They can occur within an intermediate critical range of air entrainment values. This range of critical air entrainment values can only be obtained through numerical experiment for a given pumping system.

In general, when designing a pumping system, it is thus recommended that check valves be selected such that they will close at near zero flow velocity. Since in reality this is difficult to achieve, the selected check valve should at least be able to close when the flow still has a little forward velocity. For a system in which a high flow deceleration may occur, a quick closing check valve should thus be selected.

4. CONCLUSIONS

A numerical model was proposed to investigate the effects of check valve closure at different flow conditions on pressure surges during a pumping trip. The study showed that severe pressure surges occurs when check valve closes with a reverse flow velocity at a steep velocity gradient. When the check valve closes at with a forward velocity, the pressure transients are similar to those that occur at zero velocity, except for an initial downsurge. Numerical studies also showed that by modelling the effects of air entrainment into the computation of wave speed for a fluid system, reasonable predictions of transient pressures with proper phasing and attenuation of pressure peaks can be obtained when the check valve closed.

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APPENDIX A. NOMENCLATURE

a	wave speed
D	mean diameter of pipe
i	node point at $x_i = (i-1)\Delta x$
P	pressure inside pipe
Q	fluid flow rate
V	flow velocity
V_0	steady state flow velocity of fluid system
V_{C}	flow velocity during check valve closure
V_{R}	reverse velocity during check valve closure
X	distance along pipeline

Greek letters

ε	fraction of air in liquid
ε_0	fraction of free gas in liquid at atmospheric pressure
ε_{g}	fraction of dissolved gas in liquid
τ	valve closure function

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