Experimental Investigation of Transients Caused by Rapid Valve Opening

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ABSTRACT

Effective transient analysis requires more than a facility with the basic physics of the transient flow and the computational machinery that allows a degree of quantitative prediction. Rather, analysts must have something more: they must have a "feeling" or "sense" of what conditions lead to extreme, difficult or pathological behaviour. Without this design sense, analysts are left effectively blind, forced to grasp in the dark among a myriad of possibilities for those conditions or events that truly govern design and for those means that would be effective to counteract transient loading. This paper serves as a reminder that is not only velocity changes that can be decisive in design, but that pressure alone, and its sudden loss, represents a degree of risk. In the particular case study reported here, a pressurized and static length of plastic pipe is subject to a rapid opening at one end; the resulting dramatic transient, which is obviously in no way hinted at by the initially zero velocity, is reasonably severe and generates a decompression wave that in turn leads to cavitation at the dead-end and subsequent cavity collapse, as well as to an impressive acoustic signal. Such a depressurization event may at least be a partial explanation of why transient failures in large systems have sometimes been progressive (one failure leading to a cluster of failures) and severe under low flow/high pressure conditions within some supply and distribution systems.

INTRODUCTION

Perhaps one of the things that best characterizes transient phenomena is their ability to surprise both the novice and the experienced analyst. Transient events are by their very nature often rapid and sudden, able to arise at almost any time and for a system in almost any state, and triggering a host of important (but sometimes obscure) consequences. This makes the processes of acquiring intuition about design and controlling events a long and arduous one. Yet intuition is often invaluable, since intuition saves time during the design process through a sure-handed convergence to the key variables; it reduces numerical searches by giving the analyst the ability to see through what details are merely extraneous to what are essential; it helps operators avoid mistakes during service by allowing them to take appropriate and safe actions; and it aids forensic studies by helping one assign and divide responsibilities and possible blame in a fair, reasonable and appropriate way. In fact, even attempts at automatic identification procedures (e.g., Jung et al., 2007, 2007, 2008 and 2009) require a restricted search space to be practical.

Perhaps one of the most reliable and tested rules-of-thumb for the transient analyst is that attention should always be given to the most severe changes in velocity. Velocity changes (whether slow or fast) invariably invoke pressure changes, but when the velocity changes are rapid they can map one-to-one with pressure changes. The constant of proportionality in such a relation is dictated by the well-known (and often large) water hammer wave speed via the Joukowski relation (Boulos et al., 2006). This leads to one conventional set of transient considerations, as well as to the resulting rules associated with velocity control during, say, filling or routine pump or valve operations.

But there at least one important transient case for which a preoccupation with velocity will never find or identify. This is the transient associated with a rapid depressurization event, particularly in a closed system (i.e., one lacking a sustaining source of fluid). In this case, the depressurization might arise by design, as when a drain valve is opened, or by accident, as when a pipe suddenly ruptures or when a confining valve is accidentally and abruptly opened. It is this transient event associated with the rapid opening of a valve that this paper is concerned; the primary part of the exploration is experimental.

EXPERIMENTAL SYSTEM

The specific scenario in easily visualized: imaging that when doing maintenance of a pressurised pipe branch, as a possible preliminarily action for emptying the line, the supply is often first disconnected by closing an upstream isolation valve. After this, the downstream valve is possibly opened to depressurize the system, sometime with little regard to transient pressures. Laboratory tests carried out at the Water Engineering Laboratory (WEL) of the University of Perugia, Italy have shown that the execution of such a manoeuvre – particularly when it is fast – can give rise to unexpectedly severe water column separation phenomena. The subsequent collapse of water cavities is characterized by possibly devastating implosions as well as by overpressures that can easily be larger than the hydrostatic value.

The test pipe in the Perugia rig is high density polyethylene one with a length equal to 164 m and nominal diameter DN110 (Fig. 1). During tests simultaneous measurements of pressure p at some selected locations as well as sound pressure level δ were executed in order to give inform the investigation. Specifically pressure was measured at sections N and M – approximately 29.7 m and 70.6 m downstream the inlet valve, respectively – and at the end section EV, just upstream the operated valve (a ball valve with DN50). The pressure level of the acoustic signal was recorded at section N since the results of a preliminary numerical model showed that in that was the part of the pipe at which the most severe water column separation phenomena took place.

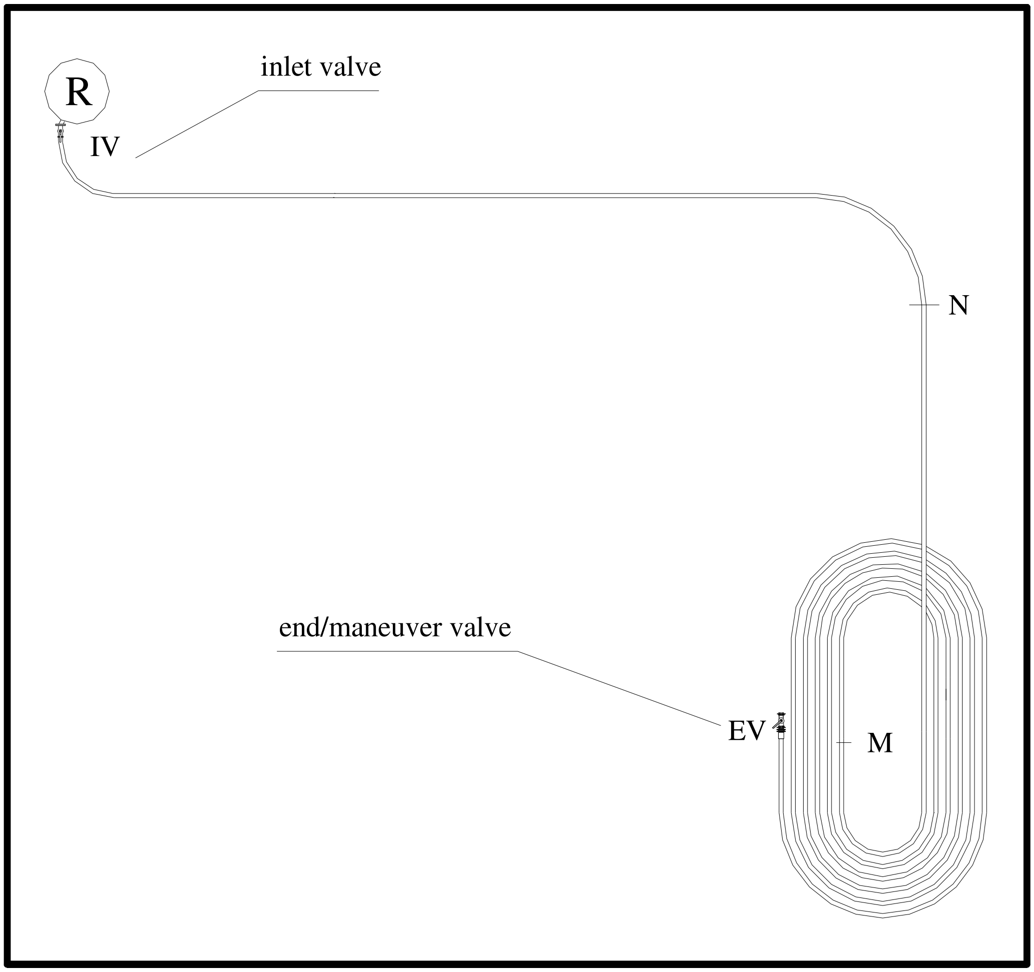

Figure 1. Experimental setup.

Several tests were executed with different values of the initial pressure p_s as well as different conditions at the inlet of the pipe (Table 1, where γ = fluid specific weight). Unfortunately the nature of this document does not allow the authors to convey the sense of the sound signal, which is characterized by a sharp and rapidly propagating “crack”, almost like first breaking a nut.

Test (#)	Inlet valve (IV) status	p_s/γ (m)
1	open	22.1
2	close	22.1
3	close	38.6
4	close	54.5

Table 1. Characteristics of the laboratory tests.

Specifically for a given value of the initial pressure (p_s/γ = 22.1 m) the opening of the end valve was executed with the inlet valve IV open (test # 1) or closed (test #2). The phenomenon was distinctly different in the two cases: with the inlet valve open pressure traces are characterized by a fast decrease with a regular oscillations around the steady state value (Figs. 2a and 2b). Furthermore the time behaviour of the sound pressure level is almost constant with no obvious peaks (Fig 2c). By contrast, when during the transient the supply is curtailed (i.e., when the inlet valve in Fig. 3 is closed), significant pressure rises occur at sections M and N and water column separation occurs (Figs. 3a and 3b). To pressure peaks correspond pressure sound level peaks due to the collapse of vapour cavities during the transient (Fig. 3c).

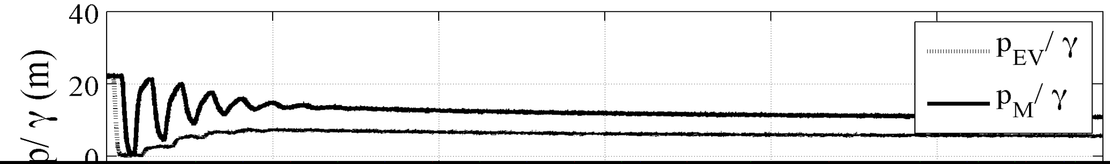

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Figure 2. Test # 1 – pressure signal, p/γ, at sections: a) EV (dashed line) and M (solid line); b) N; c) time history of sound pressure level, δ, at section N.

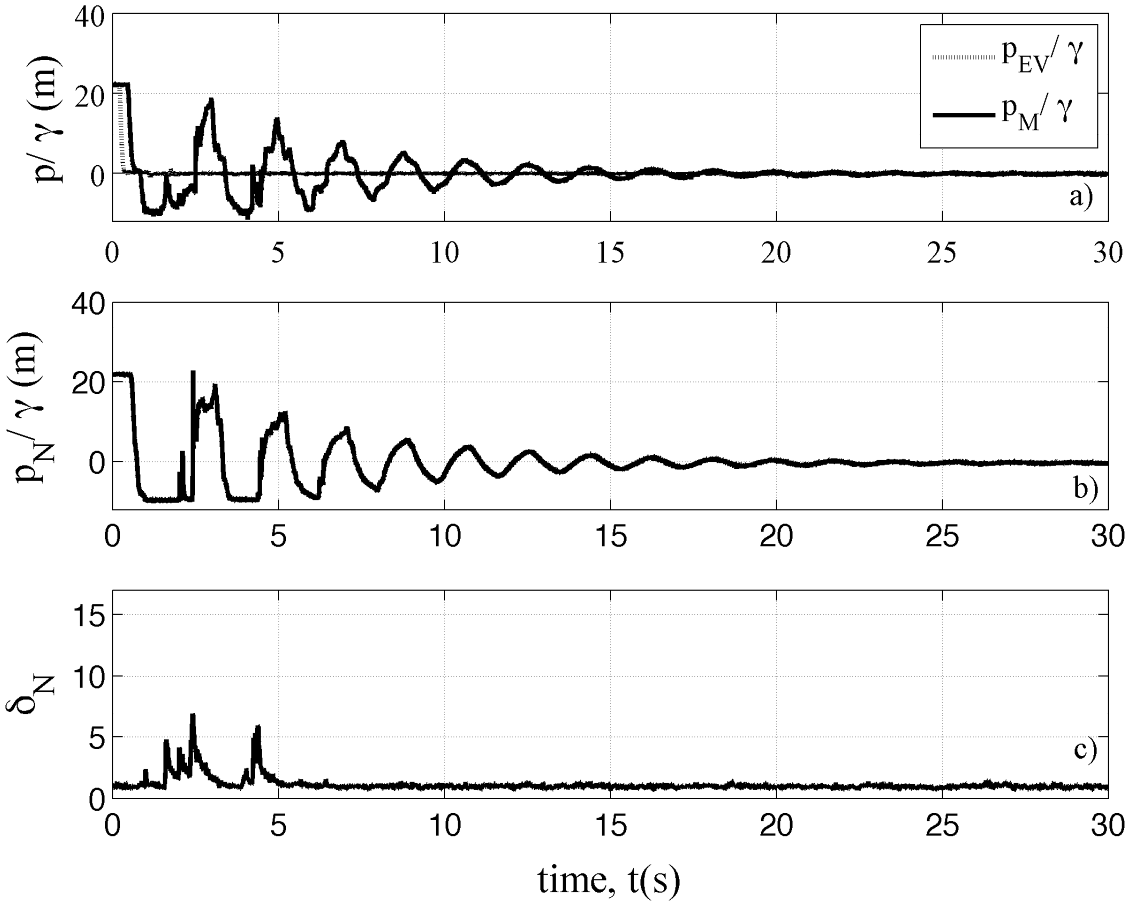

Figure 3. Test # 2 – pressure signal, p/γ, at sections: a) EV (dashed line) and M (solid line); b) N; c) time history of sound pressure level, δ, at section N.

With the initial pressure is increased – an action that one might simplistically assume would increase the resistance of the system to negative pressures – the pressure peaks increase with progressively more short period fluctuations (Figs. 4b and 5b). The same behaviour can be noted in δ traces (Fig. 4c).

Clearly, as a deeper reflection on the Joukowski relation would imply, the flow of transient information is a continuous interchange of pressure and velocity information, and it is often unimportant which change initiates the event. Thus, whenever systems are present under elevated pressure relative to the local environment, there is a non-trivial opportunity for a depressurization event to trigger a destructive transient sequence. This is particularly true for systems with high pressure that are otherwise confined (without an external flow source) since a check or dead end tends to double the pressure drop associated with the primary pressure wave.

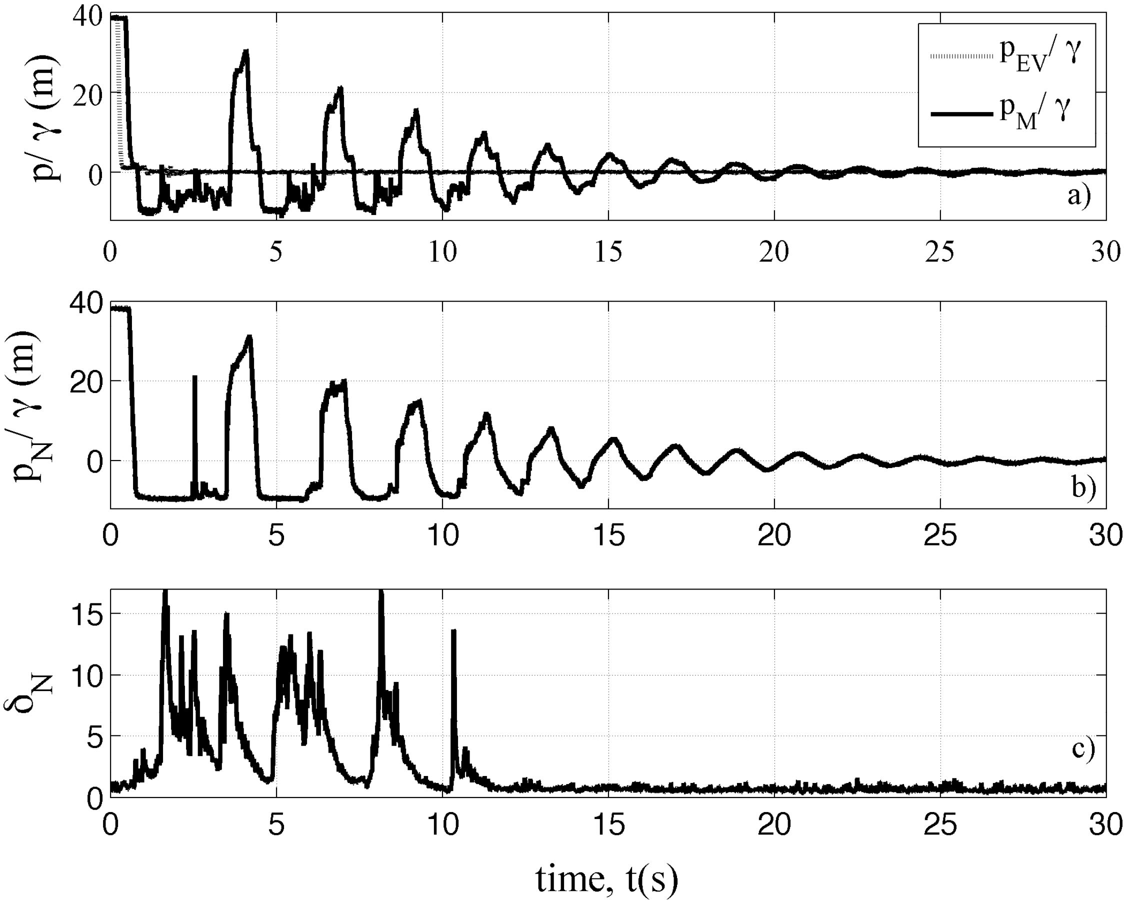

Figure 4. Test # 3 – pressure signal, p/γ, at sections: a) EV (dashed line) and M (solid line); b) N; c) time history of sound pressure level, δ, at section N.

According to numerical model results (space limitations preclude their full treatment here) water column separation is more severe the closer the section to the inlet (e.g. Figs 5a and b). Moreover, due to the increase of the percentage of air in water as the air comes out of solution, the value of the wave speed decreases and, as a consequence, the characteristic time of the pipe increases (Figs. 3, 4, and 5).

What is interesting and important is that the water column separation does not represent a simple conversion of pressure energy (due to strain and confinement effects) to kinetic energy and back. If this were the case, the magnitude of the resulting pressure signals would be bound by the initial pressure. But these traces show, and as the literature supports (e.g., Marin, 1983 or Kranemburg, 1974) the extreme values of the pressure during the transient event may frequently exceed $p_{s.}$ This is obvious in Figs. 5b and should be born in mind if static systems are maintained in a pressurized condition, as they frequently are. Phase change may effective permit and concentration of focusing effect of transient pressure waves.

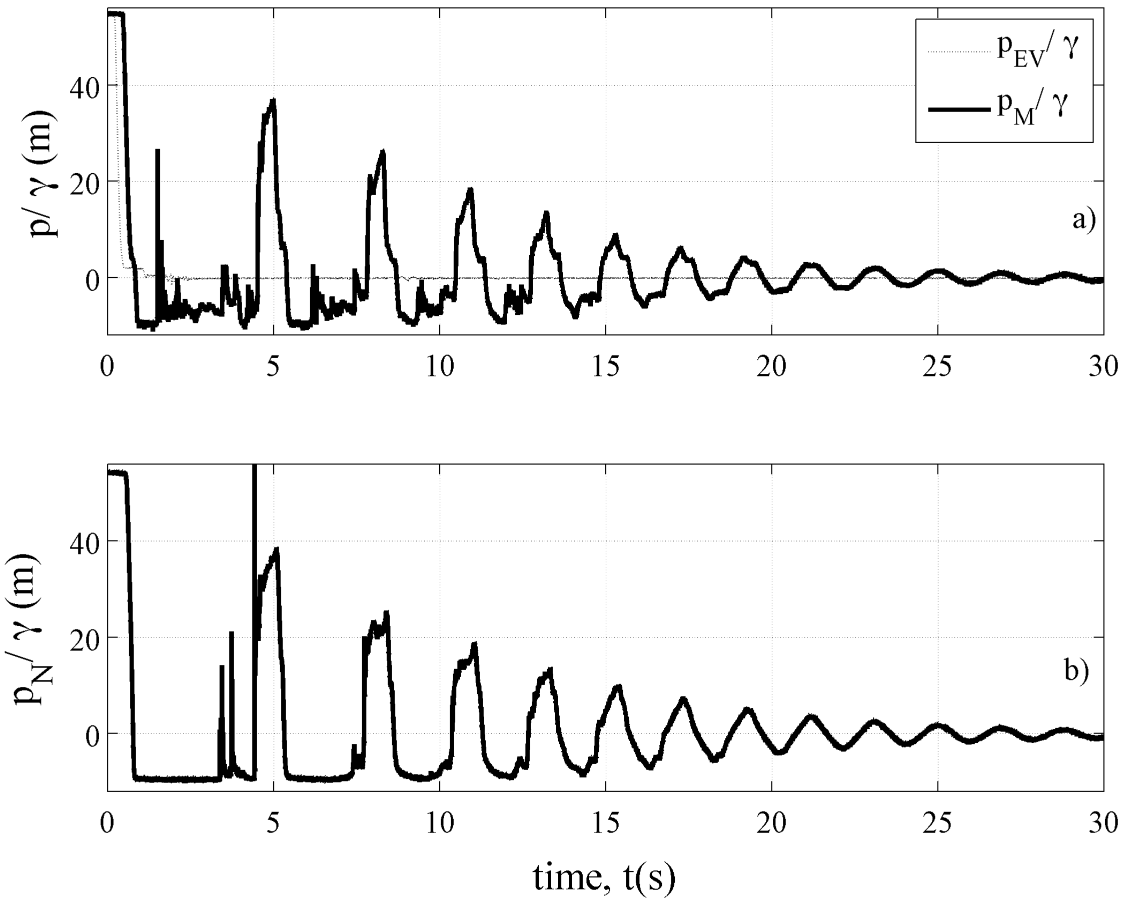

Figure 5. Test # 4 – pressure signal, *p*/γ, at sections: a) EV (dashed line) and M (solid line); b) N.

CONCLUSIONS

Transient analyst must quickly and implicitly recognize conditions that lead to severe or dangerous events. To the obvious and legitimate concern for rapid velocity changes, one must add the presence of pressure itself, particularly in isolated systems. The resulting transient analysis can be important, dramatic, and possibly destructive. This reality may well explain the reality of why pipe failure events can cluster, particularly during low flow conditions such as during night time supply. Closing a valve against a moving flow always represent a transient concern, but it is just as possible for an opening even in an otherwise static system, even if the opening were associated with a pipe break, to create a severe and important transient event that might indeed have other consequences.

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