# Discussion of "Effect of Boundary on Water Hammer Wave Attenuation and Shape" by Huade Cao, Ioan Nistor, and Magdi Mohareb

Arris S. Tijsseling

Associate Professor, Dept. of Mathematics and Computer Science, Eindhoven Univ. of Technology, P.O. Box 513, 5600 MB Eindhoven, Netherlands. Email: a.s.tijsseling@tue.nl

https://doi.org/10.1061/(ASCE)HY.1943-7900.0001701

The authors consider pressure waves in pipes and they propose a new model for reflections at reservoirs. Their study suggests that local energy dissipation at a reservoir is nonnegligible and needs to be included as an additional damping mechanism in water-hammer models. My main concern is that the additional damping/dispersion perceived by the authors cannot be attributable to reflection delays. A second concern is that the new model is validated against experimental data (pressures measured either at a closed valve or at a distance 1,500$D$ downstream of the reservoir, where $D$ is the pipe's diameter) in which all possible damping mechanisms are mixed. It is impossible to distinguish between the different mechanisms and—in addition—there is experimental error and uncertainty. A better—or at least easier—approach would be to compare with theory and/or computational fluid dynamics (CFD) to study the physics of wave reflection at reservoirs. For this reason, numerical simulations based on acoustics theory are presented here. The test problem, which may serve as a benchmark, consists of a large reservoir excited by and interacting with a pressure wavefront in a pipe. As usual, it all boils down to scales of length (of pipe, of reservoir, of wave, of wavefront, of turbulence, of diameter of pipe, of penetration depth) and time (of wave return, of pressure increase, of turbulence, of frequency of excitation). In particular, pressure increase time (relative to $D/a$, where $a$ is wave speed) is shown to be an important parameter that has not been varied by the authors.

## Numerical Simulations

Vardy and Tijsseling (2020) coupled one-dimensional *axial* wave equations in the pipe to one-dimensional *spherical* wave equations in the reservoir and solved these using a special form of the method of characteristics. They considered wave propagation in air where real shocks can occur in pipes due to the self-steepening of wavefronts. For the present discussion, we simulated water and used input data similar to those in the authors' paper: $D = 20$ mm, $a = a_f = 1{,}400$ m/s, $\rho = 1{,}000$ kg/m$^3$, and $L$ is sufficiently large. To isolate the reflection process, we have a stationary initial situation, no friction, and the same speed of sound in pipe and reservoir. A suddenly applied flow at the remote end of the pipe (with velocity $V_0 = -1$ m/s) creates a pressure wave of magnitude 1.4 MPa (according to Joukowsky) traveling toward the reservoir (Fig. 1). This wave reflects at the interface between the pipe and the reservoir, which is modeled in a manner that ensures continuity of pressure and flowrate.

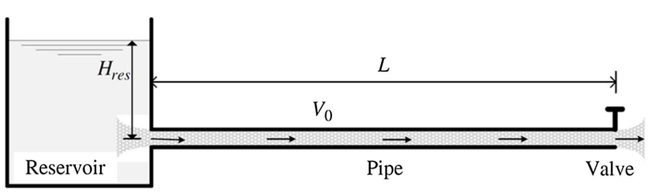


**Fig. 1.** Schematic of the reservoir-pipe-valve system. (Reprinted from the original paper, © ASCE.)

Figs. 2 and 3 show the results obtained for a nearly instantaneous (step) pressure increase and velocity decrease arriving at the reservoir [Figs. 2(a and b)]. As the authors conjecture, the process of reflection of the wavefront at the reservoir is not instantaneous, but gradual. As a consequence, after reflection, the wavefront is spread over a distance of about 60 mm—i.e., about 3$D$ [Figs. 2(c and d)]—where the nondelayed classical water-hammer reflection is given as a reference. Fig. 3 shows the transient pressures and velocities in the reservoir during the same period. At any particular radial distance, the pressure increases suddenly and then decays gradually; that is, the induced disturbance is pulse-like, not a sustained increase, even though the rate of flow from the pipe remains constant after reflection. The amplitude of the radially propagating pulse decreases with increasing distance because of spherical expansion. The interface between the pipe and the spherical domain experiences a pressure peak of 1.2 MPa, which almost fully decays within a time span of 0.05 ms, after which initial reservoir gauge pressure (zero herein) prevails. In the same time span, the flow from the end of the pipe jumps to a velocity of 2 m/s, which is the magnitude predicted by fundamental water-hammer theory. During the 0.05-ms interval, the total distance moved by fluid particles traveling at 2 m/s is 0.1 mm, which is about 0.5% of the pipe diameter. This is more than a thousand times shorter than the jet lengths discussed by the authors.

Figs. 4 and 5 show the corresponding results for a steep but non-instantaneous (i.e., ramp-like) initial wavefront. For clarity, the ramp is a linear increase in pressure. The increase time is $2D/a$ so the ramp length is $2D = 40$ mm [Figs. 4(a and b)]. After reflection, the ramp length has increased to about 80 mm—i.e., to about 4$D$ [Figs. 4(c and d)]. The consequences of the delays induced by the reflection process are strongest at the beginning and end of the reflection sequence. The maximum steepness of the reflected ramp (roughly midway along its length in this instance) does not differ greatly from the steepness of the incident ramp. Fig. 5 shows the decaying transient pressures and velocities in the reservoir. It is seen that the pressure peak is less than half the peak produced by the step wavefront. The pressure near the pipe entrance is sustained above reservoir pressure (zero herein) for a longer period (about 0.1 ms) than for the step wavefront, but at a much lower pressure. This behavior is very well known in acoustic circles. It is a manifestation of the fact that the amplitudes of the disturbances in the external flow field (i.e., the reservoir) depend (to the first order) on *rates of change* of flows from the pipe, not on their *amplitudes*.

Figs. 6 and 7 show the results obtained for a less steep ramp wavefront, with an increase time of $10D/a$ such that the ramp

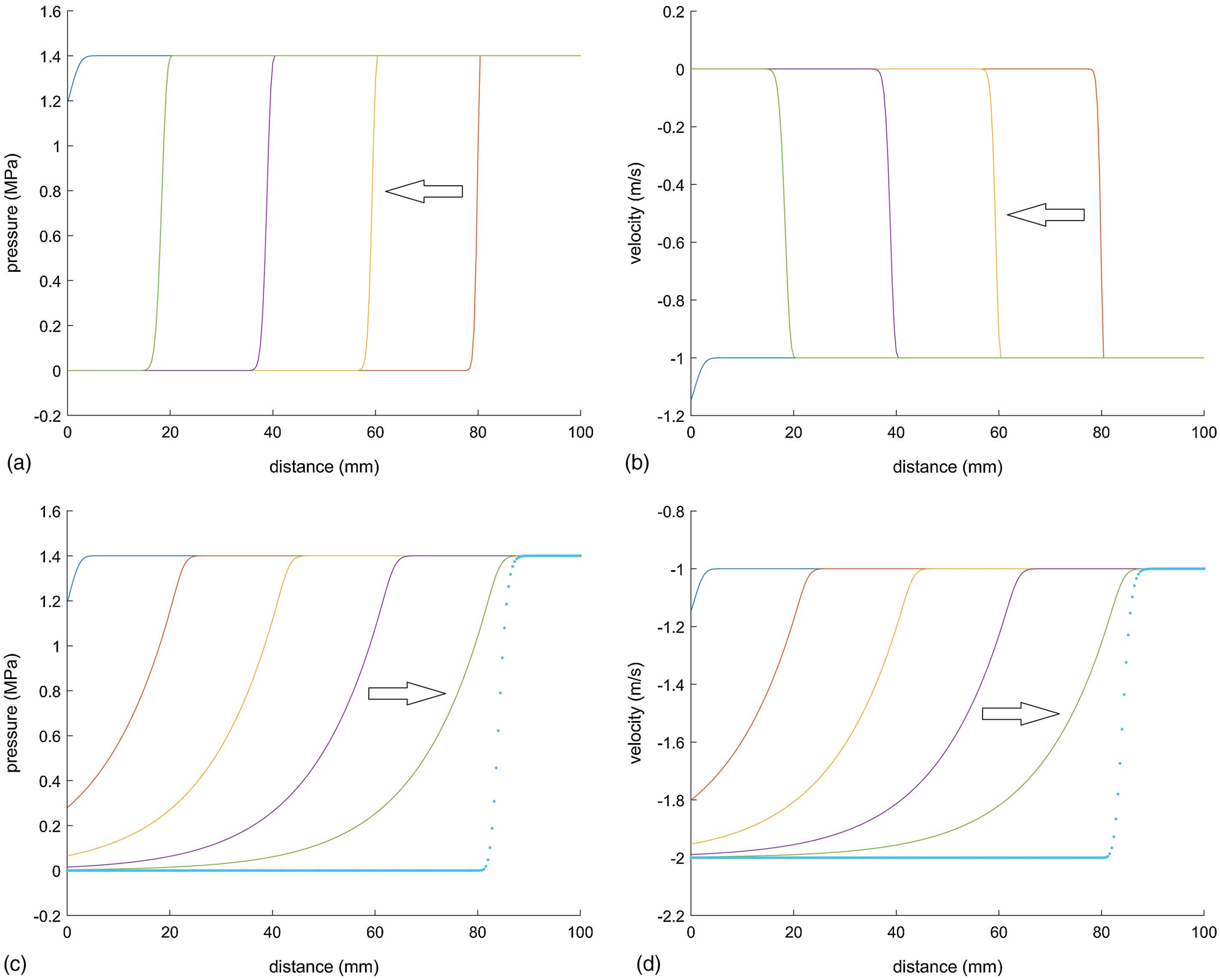


**Fig. 2.** Step wavefront. Pressures and velocities in the pipe at different times (with 0.015-ms interval) for (a) incident pressure wave; (b) incident velocity wave; (c) pressure wave reflected at reservoir; and (d) velocity wave reflected at reservoir (dotted curve = classical water-hammer).

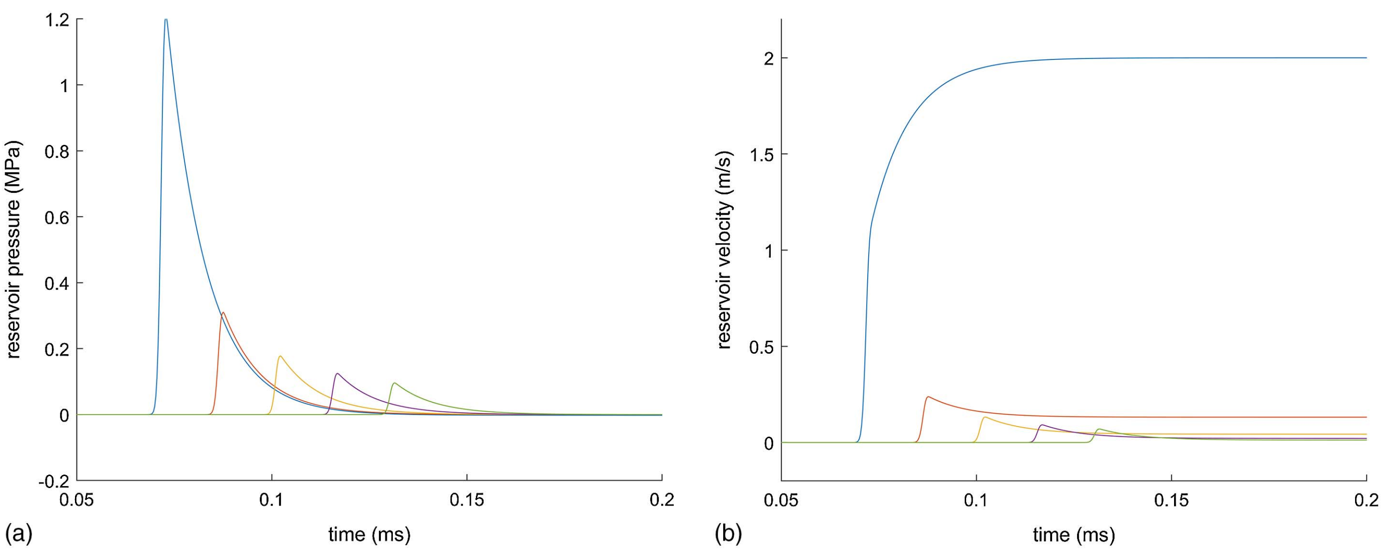


**Fig. 3.** Step wavefront. (a) Pressures; and (b) velocities at pipe entrance; and at distances $D$, $2D$, $3D$, and $4D$ into the reservoir.

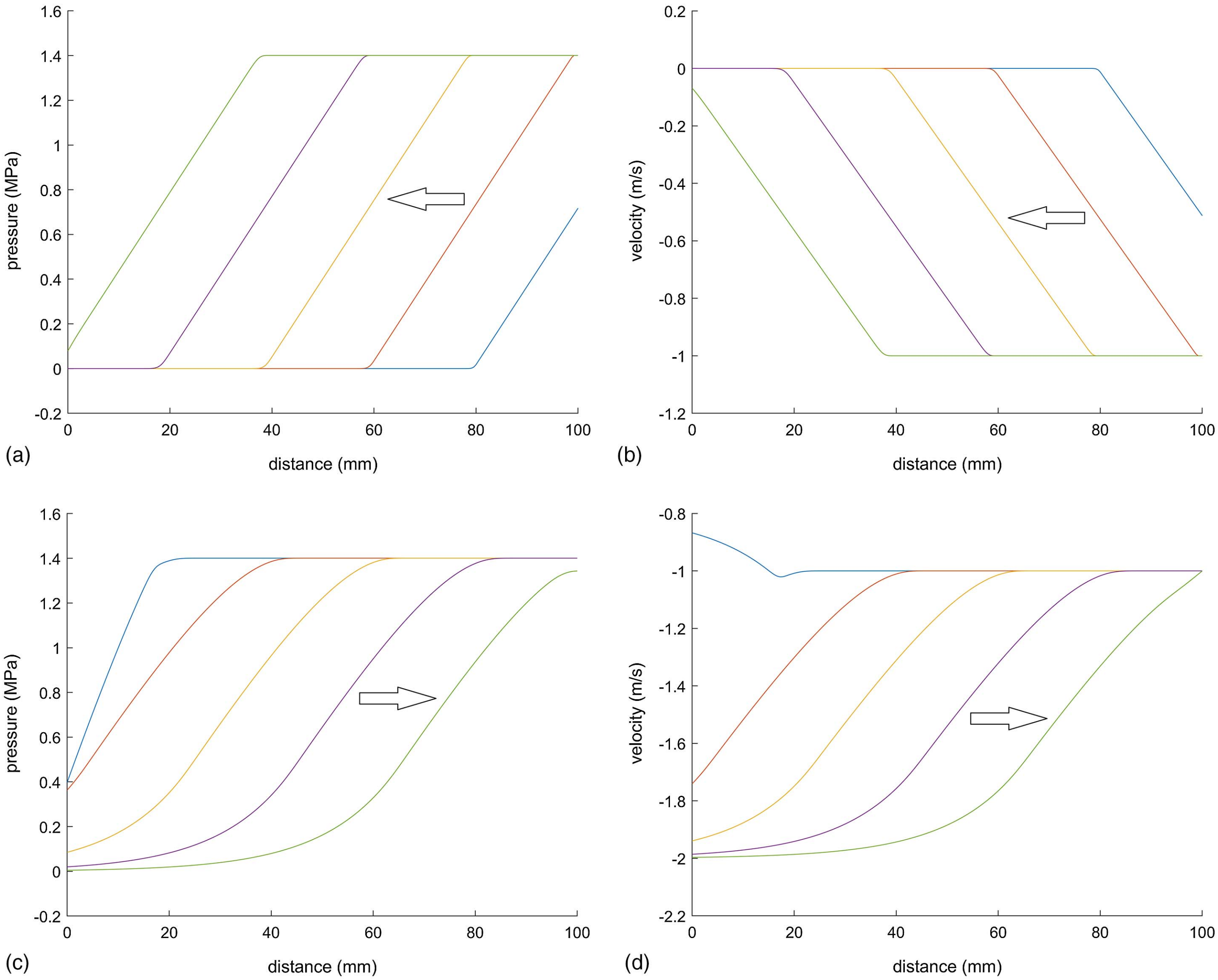


**Fig. 4.** Ramp wavefront ($2D$). Pressures and velocities in the pipe at different times (with 0.015 ms interval) for (a) incident pressure wave; (b) incident velocity wave; (c) pressure wave reflected at reservoir; and (d) velocity wave reflected at reservoir.

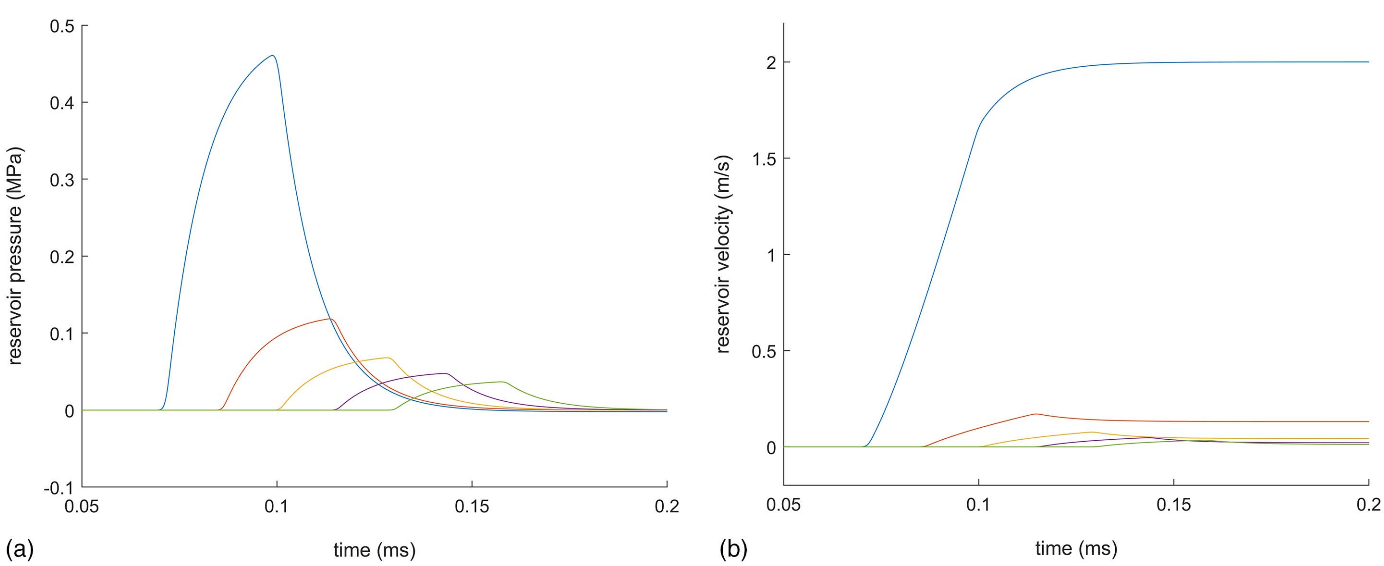


**Fig. 5.** Ramp wavefront ($2D$). (a) Pressures; and (b) velocities at pipe entrance; and at distances $D$, $2D$, $3D$, and $4D$ into the reservoir.

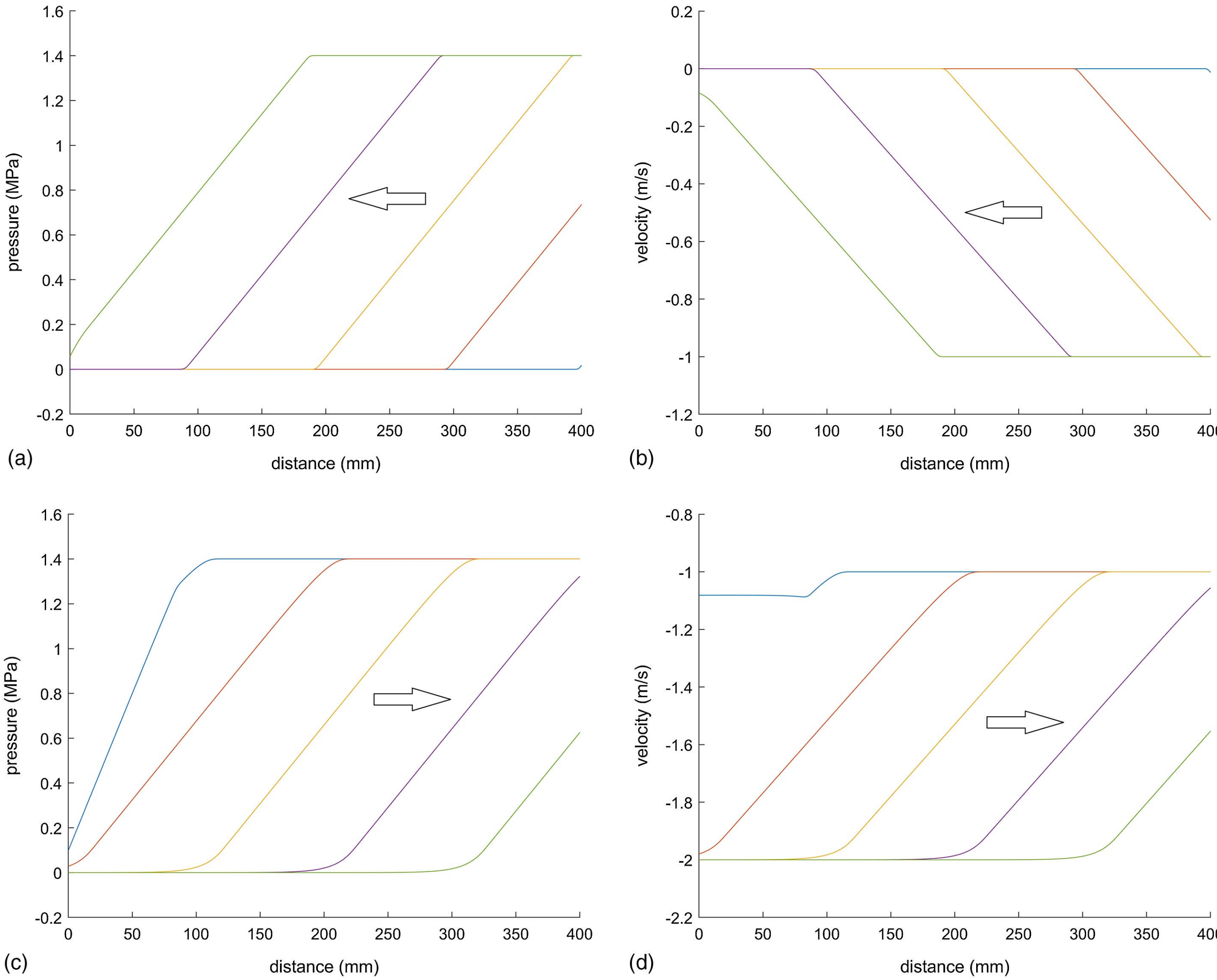


**Fig. 6.** Ramp wavefront (10$D$). Pressures and velocities in the pipe at different times (with 0.073 ms interval) for (a) incident pressure wave; (b) incident velocity wave; (c) pressure wave reflected at reservoir; and (d) velocity wave reflected at reservoir.

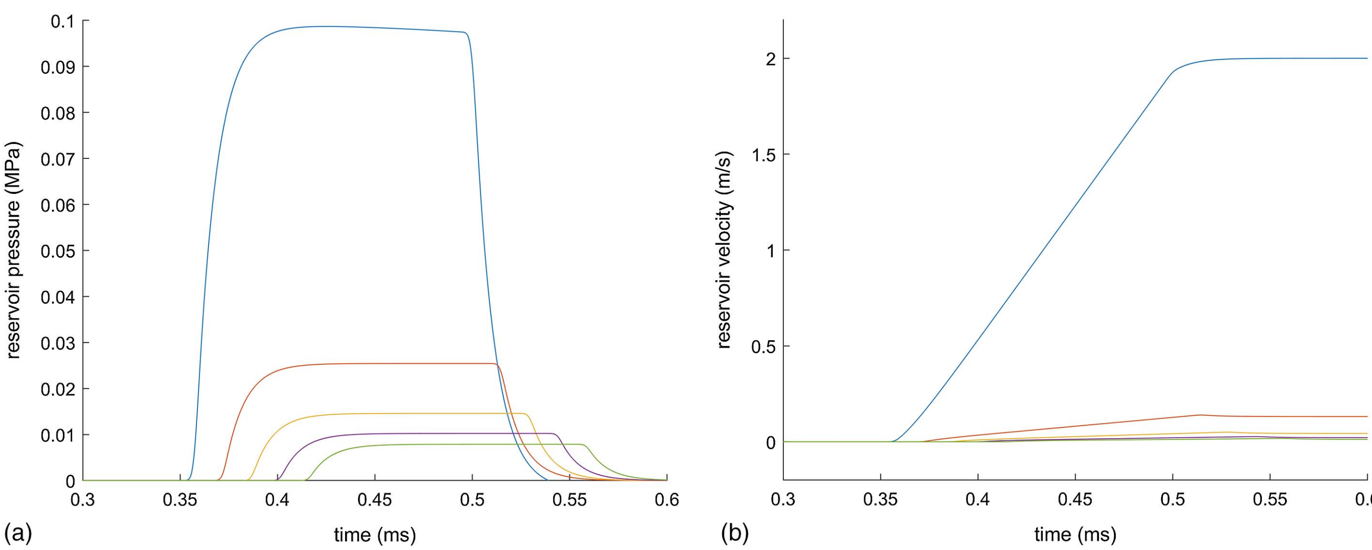


**Fig. 7.** Ramp wavefront (10$D$). (a) Pressures; and (b) velocities at pipe entrance; and at distances $D$, 2$D$, 3$D$, and 4$D$ into the reservoir.

length is $10D = 200$ mm. Fig. 6 shows that the wave's ramp length (i.e. steepness) is almost unaffected by the reflection from the reservoir: it remains about 200 mm. That is, in common with the shorter ramp, the delays in the reflection process have greatest influence at the toe and heel of the ramp and very little influence in the intermediate region. Accordingly, they cannot be the cause of the additional wavefront distortion that the authors are attempting to explain in the original paper. Fig. 7 shows the decaying transient pressures and velocities in the reservoir. The velocity increases approximately linearly to a sustained maximum—i.e., it mirrors the shape of the incident wavefront. In contrast, the pressure increases to a maximum that remains almost constant for most of the duration of the pulse. To first-order accuracy, it is responding to acceleration, not velocity; that is why the maximum is so much smaller than for the shorter ramp and it is also why it decays to zero after the reflection has occurred.

All of the cases illustrated here are for wavefronts that are much steeper than those that reach the reservoir in the examples the authors consider (because of experimental valve closure times). Accordingly, the sustained increases in pressure that will exist at the pipe entrance in their cases will be even smaller than those in Fig. 7. This has important implications for the model of the jet that they propose as well as for the reflection process itself.

## Jet Model

Although not strictly necessary for the purposes of the main thrust of this contribution to the discussion, the discusser would like to raise a few points about the authors' description of the behavior of jets. The jet is assumed to develop after the reservoir acoustics—as described previously—has died out (i.e., after 0.1 to 0.2 ms). It is important to consider things within the context of the available time scales. One time scale is related to $L/a$; this is the one that is of relevance to water-hammer effects. Another time scale is related to $D/a$; this is the one that is of relevance to wave reflections at boundaries. A third is the pressure increase time.

The most common way to model a reservoir is to treat it as a location of constant pressure exactly at the entrance of the pipe. Sometimes the reflection point of constant pressure is taken somewhere inside the reservoir, thus effectively extending the pipe length $L$ by $\delta L$ to account for added mass and/or elasticity effects. The authors have elaborated on the latter.

To ease the discussion and focus on the outflow at the reservoir, all possible friction and damping mechanisms are ignored in the following description. Instantaneous closure of the valve in a reservoir-pipe-valve system yields (at time $L/a$, where $a$ is the wave speed in the pipe) a stagnant compressed liquid column at Joukowsky pressure. If the pressure at the pipe entrance is regarded as constant (at the hydrostatic reservoir pressure), then for the next $2L/a$ period there will be a convective counterflow from the pipe into the reservoir with velocity $V_0$ (the initial flow velocity before valve closure). Following the authors' model, this will produce a jet of maximum length $\ell = 2LV_0/a$ (for the special case that the jet has the shape of the pipe). For the jet to be slender, $\ell/D = 2\mathsf{Ma}L/D$ should not be too small, with $\mathsf{Ma} = V_0/a$. For the authors' data in Table 1 of the original paper, $\ell/D$ has the value 9 and one might assume the forming of a jet. However, for Bergant's experiment (Table 3 of the original paper) $\ell/D$ is smaller than 1 and it is difficult to regard this as the aspect ratio of a conventional jet.

If the liquid in the reservoir is treated as incompressible (because of its free surface) (the wave speed in the reservoir $a_f = \infty$) and the connected pipeline is long enough, then a convective jet of conical shape may be assumed (Fig. 2 of the original paper), the (front) velocity of which decreases with time and distance into the reservoir. The conjectured jet is to be regarded as a rigid column, having mass but no elasticity. However, in the discusser's model, there is no net force for long-enough time to drive the jet because the pressure pulse at the pipe entrance has died out. Such a net force must come from convective—as opposed to acoustic—mechanisms, that is, pressures scaling with $\rho V^2$ instead of $\rho a V$. Convective pressures are ignored in the authors' model, which is understood to hold for a sudden expansion and, if the jet is reversible, also for a sudden contraction, although jet reversal (different in- and outflow behavior, i.e., hysteresis), vena contracta, and kinetic and entrance (or exit) losses [quasi-steady $(1 + K)V^2/g$ head term] have not been considered. Like the maximum jet length $\ell$, the ignored convective terms in the water-hammer equations scale with $\mathsf{Ma}$, and they will possibly have a similar (to the proposed end effect), if not larger, influence on the pressure waves in the pipe.

## Conclusions

The discusser agrees with the authors that there is not a well-defined reflection point or area.

The reservoir is inherently incapable of sustaining elevated pressures at the pipe entrance for anywhere near as long as the authors' model requires.

After reflection, a step wavefront is spread over a distance of only about three pipe diameters. Other wavefronts will increase in length by about three pipe diameters, but this will usually be undetectable in comparison with their lengths.

The amplitude of the resulting pressure pulse radiating into the reservoir is negligible after traveling, say, 10 pipe diameters into the reservoir.

The authors' conjectured influence of a jet on the reflection process is inconsistent with physics because its time scales are much greater than those involved in the true reflection process of pressure wavefronts. A jet could have time to develop when a pipeline is sufficiently long, but it would do so long after the reflection has occurred.

## Acknowledgments

The numerical simulations were carried out by emeritus professor Alan E. Vardy of the University of Dundee in Scotland, United Kingdom. The software used is ThermoTun, which simulates pressures, velocities, and temperatures in rail tunnels and stations. It models changes in these parameters due to train movements and the operation of fans. It is particularly well suited to simulating wave effects caused by high-speed trains including sonic booms emanating from tunnel portals.

## References

Vardy, A. E., and A. S. Tijsseling. 2020. "Method of characteristics for transient, spherical flows." *Appl. Math. Modell.* 77 (3): 810–828. https://doi.org/10.1016/j.apm.2019.07.037.