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HYDRAULIC TRANSIENTS AND NEGATIVE PRESSURES – CONSEQUENCES AND RISKS

BY BRYAN KARNEY

Orderly, steady, liquid flows in closed conduit systems can be disrupted in a variety of routine ways. Two crucial disruptions are overviewed here, one arising through the introduction of unsteadiness associated with changes in the system's boundary conditions (typically adjustments to operating conditions at pumps, valves and tanks) and the other by inducing or introducing a second phase, a gas or vapor, into the flow. This article briefly overviews the often-problematic but invariably fascinating nature of these transient water-air or water-vapor flows.

Introduction

Pressurized pipe systems, whether carrying treated water or untreated wastewater, are required to meet a variety of technical requirements, ranging from achieving sufficient hydraulic capacity, to delivering water undegraded in chemical and biological quality, to being economically viable, to having sufficient structural strength to withstand both internal and external loadings. One of the perhaps surprising (and sometimes overlooked) implications of these basic performance constraints is that the pipeline needs to breathe well – that is, that all lines need to limit cavitation and to permit and control the movement of air into and out of the line as the line responds to a range of operational requirements.

The steady-state flow of liquid water in a pressurized conduit system is typically expressed physically in a kind of stately cadence – as the flow progresses downstream, mechanical energy is transmitted farther along the line but is also gradually converted into thermal form. Even for turbulent flow, this progression in a single-phase system generally sees the total mechanical energy of the flow diminishing downstream, even while experiencing many local variations in the component velocity, elevation, and pressure heads. But even though these three-component heads do change, they do so quite predictably in response to obvious local changes induced by things like undulations in the pipeline profile or local changes in the flow's cross-sectional area. Significant adjustments in mechanical energy sometimes occur too, as for instance when a flow passes through a pump or turbine.

But transient or unsteady conditions disrupt this orderly progression, creating sudden local changes in flow and pressure that are subsequently propagated throughout the connected system via coupled acoustic pressure and velocity waves. As much as the overall system response can be dramatic, usually associated with some initiating cause followed by the system's sometimes complex response, what happens within any individual pipe is fundamentally more limited. Under steady flow, the inflow and outflow of water to a pipe segment must be equal, since an imbalance in flow rates would imply an accumulation or depletion of matter over time, and thus a violation in the steady assumption. But under unsteady flow conditions, a pipe segment can experience any combination of only four primary events: the inflow rate can increase or decrease and/or the outflow rate can increase or decrease, with each change initiating a propagating pressure/velocity wave.

With one of these pairs – namely, either an increase in inflow or a decrease in outflow – a transient increase in the mass contained in that pipe will occur, and thus the pressure within the segment will necessarily rise due to the mobilization of a tiny (but significant) compressibility effect. Either or both of these induced changes causes a transient pressure increase and a so-called positive wave to be initiated at the location of the imbalance. These positive-pressure transient waves increase other things too, such as inducing stresses or movement in the pipe wall or its supports, and thus leading to an increased chance of a pipe burst or other component failure. This sequence of consequences is indeed at the heart of the conventional concerns with water hammer.

But the opposite imbalance can lead to other less-well appreciated issues. Thus, if, for any reason, either the flow into a pipe section is decreased, or the outflow increased, the

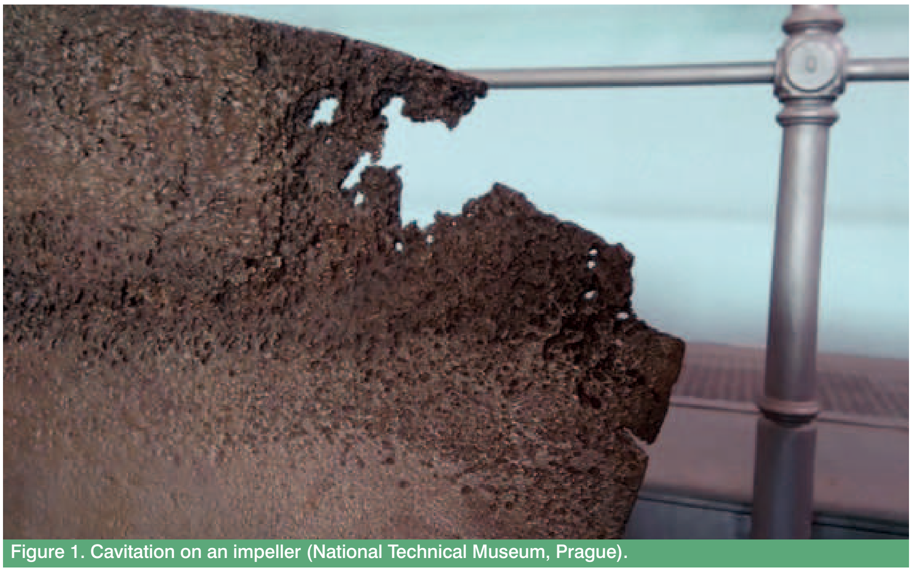
Figure 1. Cavitation on an impeller (National Technical Museum, Prague).

pressure in the segment quickly drops, sometimes to values below atmospheric, or possibly even to the vapor pressure. Such pressure drops tend to either induce a phase change in the flow or to draw foreign material into the pipe (whether air or water, possibly along with dissolved substances or entrained solids) through any available cracks or openings.

What is significant as well is that the generic system adjustments that generate negative pressure events are associated with quite routine operational actions. Any or all of the following can lead to a transient negative pressure event, from the failure or trip of a supply pump, to simply closing an upstream valve, to rapidly opening a downstream valve, or having to suddenly satisfy a water demand from the pipe, to draining a line, or to the pipe experiencing a burst event. The design and operation challenges associated with this pressure drop often create many hazardous operational conditions as well as those associated with induced phase changes. Indeed, phase changes, or related air and water ingresses, tend to make pipeline operation and design more unpredictable, more asymmetric, more prone to failure, and generally more pathological, than a quick or uninformed appraisal might indicate [1]. It is to these phase-change-inducing transient events that the remainder of this short article is addressed.

Causes and consequences of negative pressures

Transient imbalances are a notable cause of negative pressures, but not the only one. Even steady state influences and Bernoulli effects can induce negative pressures and phase changes. Any of the following conditions can be problematic in this sense: high elevations such as associated with an elevated pipe profile or siphon structures; flow restrictions such as those associated with partially closed valves or blockages; high velocities in combination with large surface roughness or abrupt changes in the flow direction; or large secondary flows such as those associated with the vortex action and secondary flow of pumps or turbines. Any of these common causes are capable of creating sufficiently low local pressures to induce cavitation, or perhaps to induce air or gas release such as freeing ammonia from solution in certain sewer systems. Any transient event (associated with the local flow imbalances just described) can greatly exacerbate those conditions, superimposing an additional complexity on an already complicated phenomenon.

Few hydraulic engineers will need a reminder of how damaging local cavity creation and collapse can be. When a fluid cavitates, a vapor pocket is formed in the flow, a condition that is almost invariably unstable since higher pressures follow low values, either in space or in time. Thus, cavitation in the suction of a pump (induced by vortex action) evolves into vapor collapse as the outward flowing fluid moves the vapor cavities into the outer reaches of the impeller, while cavitation bubbles generated in the throat of a valve (induced by high local velocities) are swept into regions of higher pressures downstream. The collapse of these cavities is often so violent that extremely high pressures, high temperatures, and even high velocities frequently result [2]. Figure 1, taken at the National Technical Museum in Prague, shows the typical outcome of an impeller having been exposed to a strongly cavitating flow. The material near a repeated cavity collapse is first fatigued and then effectively "eaten away" by a process that is so irresistible that no known material can withstand its attack indefinitely.


Figure 2. Complexity of nucleation visualized by dew on grass.

The low-pressure conditions that can occur at the highpoints in a pipeline profile, or in the eye of a pump, or in the throat of a valve, can also be generated by the transient imbalances referred to earlier. But it is the conjunction of multiple causes that often creates the greatest challenge to system designers and operators. Thus, for example, a pump trip can generate a negative pressure wave that might be tolerable to the pump but interacts with a high point in the pipe profile to create negative pressures and potentially cavitation. The cavitation can sometimes be so extensive as to effectively split the flow into two segments in an event called water column separation, a phenomenon extensively reported on in the classic water hammer literature. To limit the cavitation risks, air-vacuum valves are often placed at high points to limit the pressure drop to less-negative valves, but at the cost of admitting air into the line, and effectively substituting one two-phase flow challenge (water and vapor) with another (water and air). As is the case so often with cavitation, the most damaging consequence is not the formation of these air or vapor cavities, but their collapse, a transient event that has frequently damaged not only air valves but also their adjoining conveyance system [1], [2].

Before considering air-related transient events in slightly more detail, it is useful to briefly mention an interesting and sometimes forgotten reality about cavitation: the transition between liquid and vapor states is not automatic as soon as saturation pressures are reached. In fact, this transition is greatly facilitated by the presence of nucleation sites, sites that are often associated with small particles or nucleation sites in the flow and give a kind of hint or nudge to the flow about where to focus or concentrate the phase change. The complexity and randomness of this nucleation process can be visually appreciated by a close inspection of almost any vegetated surface after a dewfall. As Figure 2 indicates, both the size and distribution of the resulting condensation droplets are highly variable. This complexity of this distribution is present whenever phase change occurs, though usually, the results are much more difficult to visualize than when dew on the grass. However, in most commercial pipeline applications many nucleation sites are presented and the transition between phases is not unduly inhibited.

Of course, cavitation is not the only possible consequence of negative pressures. Negative pressures can in some cases can lead to the release gases, many of which are corrosive, or can induce the pipe wall to buckle, with often grave structural and hydraulic consequences. Negative pressures can also induce ingress into the pipe from the surrounding soil or water, creating a water quality threat in potable water systems. Moreover, negative pressures can draw larger quantities of air into the pipeline, creating an air pocket that can pinch the flow, increase hydraulic losses, generate air removal issues, and possibly intermittent and pulsatile action in the flow.

The complication of air in a water line – its presence, admission and expulsion

The devices that help to facilitate this air exchange are the set of a line's air valves (which let air out), vacuum valves (to let air in), and combination air valves (which permit a two-way air flow). For simplicity, all these roles are collected here under the general term of "air exchange valves". The process of design for these devices generally involves choosing the valve manufacturers, selecting the kind and number of valves, selecting the location and specific mounting of each valve, and sizing all their exchange orifices of each valve. One of the great challenges of selecting an appropriate set of air valves for a given pipeline system is that the function of these valves must generally cover a broad range of requirements, and there is actually remarkably few data about the long-term performance of these valves over the range of environments commonly encountered in pressurized pipeline work. Several publications by Ramezani and others highlight these challenges [5], [6].

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Before considering air valves in slightly more detail, it is worthwhile emphasizing that merely the presence of air can be problematic. When, say, an air pocket is present, not only are buoyancy forces mobilized but the compressibility of the line is increased, a fact that can allow the fluid to accelerate in ways that would not be possible if only liquid were present [7], [8], [9]. Figure 3 shows a typical case where a line containing an air pocket is rapidly pressurized; in this plot, VF represents the void fraction occupied with air, a measure of the system's capacity to allow acceleration as the air is compressed. Since the original pocket is not under significant pressure, its density is low and it can be compressed with only a moderate change in pressure. This allows source water to accelerate to high velocities before compressing the air sufficiently to provide the pressures needed to decelerate and eventually arrest the water's forward motion. In general, rapidly pressurizing spaces containing air pockets can have dramatic and sometimes even explosive consequences.

The roles that air exchange valves have to perform are quite varied, ranging from allowing air to be removed during line filling operations to allowing air to re-enter the line when it is drained. But they also extend to what amounts to temporary or transient local filling and draining operations under water hammer or surge conditions, such as the pressure waves induced by power failure to a pump or the rapid closure of a valve. That is, if the local pressure drops below atmospheric conditions, a suitably-sized vacuum valve should open to admit air to maintain pressures, and then this admitted air should be safely discharged at a controlled rate when internal pressures again rise above atmospheric values. Finally, air valves need to remove the small amount of air that can evolve or be present in the line even under otherwise steady conditions. What makes these roles particularly problematic is that the sizing and location choices for the different design conditions can be in conflict, and it is not always easy to know how to achieve a suitable compromise, let alone to know how frequently their action is called for in practice.
A hint of this air-induced complexity is providing by considering the simple act of filling a line with not untypical profile. Figure 4 shows a case where a line with a V-shaped elevation profile is being filled. Intuitively one might expect little problem with negative pressures since the line is filled from a water source at a higher elevation than any point on the pipeline itself. However, there is roughly a

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Figure 3. Pressure and velocity during air pocked compression after pressurization. [4]

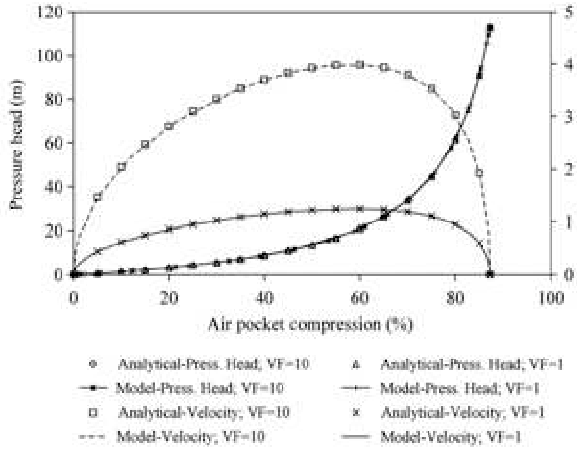

Figure 4. Air or vapor pocket growth and collapse due to line filling in a V-shaped profile. [3]