Water hammer and Pathogen Intrusion Studies on 24x7 Water Distribution Systems

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Abstract

One of the main goals of 24x7 water supply systems is to provide safe and protected drinking water to the consumers at sufficient pressures. While most continuous water supply systems strive to maintain uninterrupted positive pressures throughout the distribution system, certain abnormal events, such as pump trip resulting from power failure, may generate extreme low or negative pressures in the distribution systems. Ignoring such events amounts to compromising the main goal of 24x7 water supply systems as the low pressure events can potentially result in intrusion of pathogens into the distribution system and the associated public health problems. This paper discusses the importance of water hammer analysis of drinking water distribution systems, describes the tools for transient modeling of large distribution systems, and presents an example illustrating the intrusion potential and ways to mitigate the public health risks arising from low pressure problems.

Introduction

It is quite evident that most water utilities in India are moving towards supplying drinking water 24x7. There are innumerable advantages of supplying water 24x7 instead of the current practice of intermittent supply. One such advantage is the maintenance of positive pressures in the entire distribution system which in turn helps prevent cross contamination of treated water within the distribution system. Low or negative pressures associated with intermittent water supply are the major causes for cross contamination of treated water. Contamination of treated water is critical public healths issue that the continuous water supply schemes are expected to resolve. Prevention of cross contamination by way of maintaining high positive pressures throughout the distribution is an expensive task as it enhances the leakage and other unaccounted water usages. However, this is a worthwhile task as the ultimate goal of continuous water supply schemes is to provide water to the consumers 24x7 at acceptable quality to prevent drinking water related public health issues. The importance and ways/means of controlling microbes in drinking water systems (including source water, treatment plants, disinfection and the associated secondary effects) have been discussed extensively in a recent ASCE task committee report (ASCE 2005).

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Most water utilities in the USA are required to maintain a positive pressure of 30psi (about 2 bars) under normal operating conditions during the peak diurnal demand periods. Similar minimum pressure criteria are followed by most water utilities in the developed world. There may be guidelines for minimum pressure requirements during abnormal operations of water supply systems such as use of water for fire protection etc. In USA, most water supply systems that were designed to provide water for fighting fires are required to maintain a minimum of 20psi (about 1.4 bars) while providing water for fire protection through hydrants. Such criteria have been drawn from decades of collective experience from water supply systems providing potable water to the public 24x7.

Despite such efforts to maintain significant positive pressures under normal operating conditions as well as under fire fighting conditions, at least one of the US water utilities has recorded decease outbreaks in certain regions within their water supply boundaries. (Gullick 2004). Thorough investigations have ruled out the breach of treatment facilities and the associated contamination (pathogens) path into the distribution system. Later investigations have led to the conclusion that the pathogen intrusion has taken place within the distribution system and not from the treatment plants. This is despite the fact that the water utilities have maintained the minimum required pressures under normal operating conditions and there were no fire fighting incidents immediately before the outbreak of deceases. This has lead to the hypothesis that the contamination must have occurred during a transient (water hammer) event resulting from simultaneous tripping of all operating pumps following a power failure condition. Though it was a common practice by the US water utilities to declare a “boil water” advisory to the consumers when there is a major power failure event affecting most pumps in the distribution system, it was not until this event that formal association of pathogen intrusion was tied to the water hammer events within the distribution systems.

This and other related incidents have sparked interest in pathogen intrusion studies on distribution system arising from water hammer events. Gullick et. al. (2004a, 2004b) has documented multiple occurrences of low and negative pressures in drinking water distribution systems following transient generating events such as power failure scenario. In the paper titled “The Potential for Health Risks from Intrusion of Contaminants into the Distribution System from Pressure Transients (LeChevallier, et al, 2002) studies were done to determine if soil / water samples from areas around a water main could contain any type of contaminant that could be harmful to customers. The contaminants studied and identified were both chemical and biological in nature. Research initiatives from USEPA (United States Environmental Protection Agency) and the AWWRF (American Water Works Research Foundation) have led to major developments in modeling pathogen intrusion. The two senior authors of this paper were instrumental in developing these models in association with the top water utilities in the US as part of the joint research initiatives by USEPA and AWWRF.
Pathogen Intrusion Models

Although water hammer analysis of “rising main” systems and other simple branching networks has been quite common and widely practiced around the world, the transient modeling of large distribution systems was inconceivable for most water utilities and engineering consultants specializing in water hammer studies. Because of this reason, there was no documented evidence of transient modeling of large scale systems (network models comprising >1000 pipe elements), until recently.

There are two distinct numerical approaches, namely Eulerian approach and Lagrangian approach, for solving transient analysis problems in pipeline systems (Wood et. al 2005a). The traditional numerically and computationally intensive “Method of Characteristics” is based on the Eulerian approach. The other much more intuitive method called “Wave Characteristics Method” is based on the Lagrangian approach (Wood et al, 1966; Boulos et al, 2005). Although both methods produce identical results, the Wave characteristic method requires orders of magnitude fewer computations the same accurate results (Wood et. al 2005b). Because of its computational advantage without compromising on the accuracy of results, the wave characteristics method was employed by the AWWRF studies to complete the daunting task of modeling potential for pathogen intrusion and mitigation studies for 15 different models serving large water utilities.

Once a powerful transient modeling engine has been identified, the modeling of potential for pathogen intrusion boils down to representing reverse leakage at pipe joints (and other cracks or breaks) in the piping system arising from low or negative pressures generated by the transient event such as pump trip. One of the simplest models is to estimate the leakage in the distribution system, calculate a leakage constant based on this uniformly distributed leakage and assign the leakage constant to each junction node in the distribution system. Utilize this leakage constant to estimate the reverse flow into the piping system during the transient event. For example, if we assume that 5% of the supplied water Q goes as leakage then calculate the leakage constant $K_i$ at any node i using:

$$K_i = 0.05(Q/N) / (P_i - P_{ex})^{0.5}$$

where $N$ is the total number of nodes in the distribution system, $P_i$ is the steady state pressure at node i and $P_{ex}$ is the initial external pressure (usually atmospheric pressure).

Figure 1 shows the steady state pressures for an example water distribution system while the pumps are working at rated conditions. Under normal operating conditions, the lowest pressure in the distribution system was around 54psi (about 3.75 bars), well above the normally required 30psi minimum pressure. Figure 2 shows the pressures at different locations when the pumps are off and water is being fed by the elevated storage tanks. The pressures in the system continued to be higher than the required minimum values of 30 psi. Figure 3 shows a pressure variation graph at pump discharge associated with a normal pump shutdown event where the pump speed gets ramped down smoothly.
Clearly, a normal shutdown event is not expected to generate any low pressure conditions in the distribution system.

Figure 4 shows the pressure variation graph following a pump trip event resulting from power failure where all operating pumps get tripped at the same time. Pressure at the pump discharge drops below zero and reach cavitation conditions indicating a serious low pressure problems in the distribution system. Equation 1 in the reverse order may be used to calculate the associated intrusion potential at each node. The propagation of the intruded material may then be tracked using water quality models such as EPANET. In most cases, the negative pressures of such magnitude are not acceptable and appropriate measures should be taken to prevent such low pressures during unexpected transient events such as simultaneous tripping of all operating pumps. One way of protecting the distribution systems from such undue low pressures is by placing an appropriately sized surge tank at pump discharge. Figure 5 compares the pressure variation at pump discharge with and without a bladder vessel (a closed surge tank that does not require compressors thereby eliminating the associated operational maintenance problems). Clearly, a bladder vessel was able to mitigate the low pressure problems to the degree that they do not pose pathogen intrusion and the associated public health risks. In large 24x7 water distributions systems, a judicial use of good quality air/vacuum valves and appropriately placed small bladder vessels will relieve most low pressure problems.

Figure 1. Steady state pressures for the example water distribution system when the pumps are operating at rated conditions.
Figure 2. Steady state pressures for the example water distribution system when the pumps are off and the elevated storage tanks feed the system.

Figure 3. Pressure variation at pump discharge during normal controlled pump shutdown event.
Figure 4. Pressure variation at pump discharge during a pump trip event caused by power failure.

Figure 5. Pressure variation at pump discharge with and without a bladder tank protection during a pump trip event caused by power failure.
Conclusions

The paper describes the importance of water hammer analysis of drinking water distribution systems in an effort to understand the pathogen intrusion potential resulting from abnormal events as such simultaneous tripping of all operating pumps. The example presented illustrates the differences between pressure conditions under normal steady state operation, controlled pump shutdown event, and abnormal pump trip event. The example also illustrates the effect of adding a simple bladder vessel in mitigating the low pressure problems and associated public health risks.

References