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In-line Check Valves for Water Hammer Control

Bryan W. Karney[1] and Angus R. Simpson[2]

Abstract

This study systematically explores the relatively neglected surge protection strategy of installing an in-line check valve at an intermediate point within a pipeline. The in-line check valve is selected to isolate part of the system from a high-pressure source of fluid subsequent to a low-pressure water hammer event, in this way greatly reducing or eliminating any return surge. A typical application involving a pipeline with an isolated high point within its profile is numerically investigated. The low pressure transient event first opens an air-vacuum valve at the line's high point. However, the violent expulsion and collapse of this air cavity is thereafter avoided, and thus the resulting water hammer pressures dramatically reduced, by an in-line check valve installed between the high point and the downstream reservoir. The effectiveness of the surge protection is shown to depend on hydraulics and topology of the line (particularly the position of the high point), on the position of the check valve, and on both the hydraulic and mechanical properties of the check valve. Although the check valve only protects the lower (normally upstream) portion of the line from the return surge, the transient response of the remainder of the line can sometimes be improved through installing either a bypass around the check valve or by perforating the check valve's working element. The role and function of any pressure-relieving function at the valve is also numerically investigated and is shown to be a compromise between upstream and downstream protection.

Key words: water hammer, transients, surge protection devices, check valve, pipeline design, column rejoinder

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INTRODUCTION

Water hammer events can cause serious problems in pressure pipelines systems and networks. When the rate of flow is rapidly changed, the often-substantial kinetic energy associated with the flowing water can be rapidly converted into strain energy in the fluid and the pipe wall, thereby causing either abnormally high or low system pressures or stresses. Since such water hammer pressures are quite capable of contaminating the flow, breaking the pipe and damaging hydraulic equipment, it is not surprising that many protective strategies have been proposed. Control approaches run the gamut from simple avoidance or mitigation strategies, such as an appropriate selection of pipe diameter, material, wall thickness, to imposing operational constraints. Protection measures also include the installation of sophisticated (and often expensive) specialized devices including surge tanks, one-way feed tanks, air chambers and a host of automatic control valves.

The use of a check valve is ubiquitous as a protection strategy on the discharge side of pumps, but it is not this application that is considered here. Rather, the current study systematically explores the relatively neglected protection strategy of using an in-line check valve well removed from the usual source of fluid. The specific goals of the study are three-fold: (i) to bring this simple and yet often effective surge protection strategy to the attention of practicing engineers, (ii) to present both the strengths and drawbacks of an in-line check valve as a high-pressure surge protection strategy, and (iii) to provide guidance about when in-line check valves are most beneficially employed in pipe systems, and when they should be avoided.

Traditional Check Valve Applications and Concerns

A review of the conventional water hammer literature demonstrates that check valves at pumping stations are a powerful, economical and universally appreciated surge protection strategy (e.g., Parmakian 1955, Chaudhry 1987, Thorley 1991, Wylie and Streeter 1993). In fact, check valves installed at the outlet of individual units are used to protect the vast majority of pumping systems. The check valve is intended to close automatically after the pump is shut down, whether the trip occurs by design or accident. Traditionally, an ideal check valve was expected to be highly responsive to the flow, closing immediately and fully at the instant the flow reverses. In this way, the check valve not only inhibits draining of the line (Thorley 1989, Mahgerefteh et al. 2000), but it can significantly improve the system's dynamic response both to the original power failure event and to any "restart" surges that might occur when the system is brought back on line.

These traditional benefits are so great that only for exceptionally large pumping stations, for which the cost of check valves are prohibitively high, is consideration ever given to avoiding check valves at supply pumps. Yet even in large installations the check valve is only rarely omitted, except perhaps when the static head is small and the consequences of flow reversal at the pump are easily counteracted by other means. Probably the only common applications meeting these criteria are supply pumps for either low-head cooling water systems or fluid transfer pumps in treatment applications. Yet, as interesting and important as pumping station applications are, they are not the primary issue here.

Another set of long-standing concerns in previous check valve studies has been the detailed prediction and control of the valve's hydraulic response. In such studies it is explicitly acknowledged that real valves are neither inertia-less nor frictionless, as was sometimes naively assumed, and that instantaneous closure on flow reversal is often a fantasy. In this context the critical issue of modeling the valve's dynamic response has received considerable attention. Numerous authors (e.g., Thorley 1991, Chaudhry 1987, Li and Liou 2003, Sugiyama et al. 2003) have explored the key issues of valve torque and inertia, of viscous and mechanical damping, and of the valve's structural/hydraulic response to flow. The pioneering work of Provoost (1980) and Thorley (1989) is significant while the recent work of Li and Liou (2003) represents a particularly thorough illustration of the modeling challenges. The valve's "slam" behavior is particularly crucial if there is an energy source, such as an air chamber of a still operating pump, near to the pump station (Purcell 1997). If there is a delay in the valve's response, so that a substantial reverse flow is established before the valve closes, sometimes destructive surge forces and pressures can be created (Sugiyama et al. 2003). Yet, other than a quick sensitivity study to the issue of delay closure, these important issues are also considered beyond the scope of the work presented in this paper.

Rather than a consideration of these conventional issues, the goal here is to investigate the role of an in-line check valve, possibly installed well removed from the pump station. This kind of check valve application is used to isolate a portion of a line from reverse flows originating from a high head source of water. More specifically, the installation has the goal of blocking or severely restricting the passage of high-energy water back to a low pressure region, and thus limiting the return surge or column rejoinder following a de-pressurization event. Although this kind of check valve application has been mentioned in passing in the literature (Webb 1981), it has received little systematic attention.

The dynamics of a system employing an inline check valve are introduced here through a study of a typical pipeline configuration. Specifically, the transient is introduced through either the failure of an upstream pump or the closure of an upstream valve in a simple system with an intermediate high-point.

SURGE PROTECTION WITH IN-LINE CHECK VALVE

The essence of an in-line check valve as a surge protection measure is elegant in its simplicity: it is to limit return surge by controlling or avoiding cavity collapse (column rejoinder) along the profile. Despite this simplicity, many questions still arise. Under what circumstances is this protection strategy likely to be most effective? How effective is it in controlling upsurge? Are their circumstances under which this approach is dangerous and thus should be avoided? In order to answer such practical questions, it is helpful to first review the sequence of events that an in-line check-valve system is designed to target or interrupt.

Test System. The test system is idealized to focus attention on the primary hydraulic variables relating to the selection of the in-line check valve. Thus, the profile is assumed to rise locally to an intermediate high point that is the prescribed site of column separation (Figure 1). The rise of the pipeline profile as it approaches the high point is accentuated in Figure 1 to highlight the assumption that water column separation is only modeled at the highpoint itself and not along the profile. Although such a profile is certainly unrealistic in many applications, so in fact is the severity of the initiating transient event. This is, in many applications the inertia of the pump, the wave velocity of the pipeline, or the initial velocity in the system will combine to create a less steep sloped transient event, and the associated profile assumptions can be relaxed as a consequence.

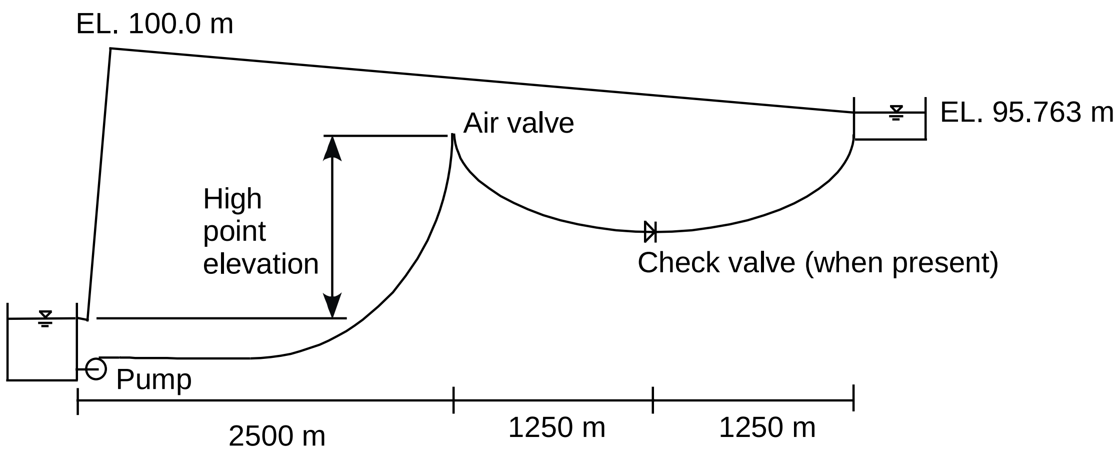

Figure 1. Schematic of pipeline case study system

The upstream steady state head at the supply end of the system is held at 100 m for all numerical results in this study. Water is discharged into a downstream reservoir (the “discharge reservoir”) maintained at an elevation consistent with an assumed velocity, taking into account all head losses due to friction. Since during transient events, the flow may temporarily reverse, perhaps making “upstream” and “downstream” designations confusing, the initial flow direction is used here to permanently define these orientations.

The Hazen-Williams headloss equation is used and an assumed C factor of 120 is applied to all pipes. The wave speed in each pipe has been set to 1250 m/s, a value typical of rigid pipe materials such as concrete, steel or ductile iron. The distance from the source reservoir to the high point is 2500 m, so that the return travel time (2L/a) for a water hammer wave in the system as a whole is 8 s. The distanced from the high point to the check valve (if present) is 1250 m, as is the distance from the candidate check valve location to the discharge reservoir. Thus, if an in-line check valve is present, the system is divided into three setions; if the check valve is absent, the system is split by the high point into two equal lengths. In all cases, either a supply check valve (if the upstream is viewed as a pumping station) or a rapidly closing valve is assumed at the source location.

The exact location of the in-line check valve is not critical and it could be located at any convenient and economically-attractive position between the high point and the downstream reservoir. A promising location, since it protects the maximum length of line, is adjacent to the (normally) downstream reservoir. In this paper, the "¾ point" from the source is selected because it helps to make visible the sometimes interesting response of the system between the check valve and the discharge reservoir. To better appreciate the benefits of the inline check valve, the transient response of the system both with and without the in-line check valve is described.

Transient Event. The simulated transient is created by a rapid stoppage of the system inflow. More precisely, the discharge at the upstream end is linearly reduced to zero in 1 s. This event reasonably mimics both the power failure of a pump of small inertia and the rapid closure of an upstream valve. Although the equivalence between a rapidly closing valve and a failing pump is not exact, it is a reasonable mimic for the small-inertia pumps so typical of modern practice. Indeed, if the closure of the pump's check valve is rapid compared to the wave return period, the sole difference between the two events is the shape of the leading edge of the wave front. As a rapid shut-off is assumed here, the upstream boundary is representative of either a failing pump or a rapidly closing source valve, a simplification that avoids having to provide a detailed specification of the upstream boundary condition.

The transient initiation event causes a rapid reduction of inflow into the pipe system, thus creating a low-pressure wave that propagates from the source. In the test system, the diameter of each pipe has been set at 1.128 m, a convenient choice in that the resulting cross-section area is 1 m^2, thus making discharges numerically equal to velocities. The initial velocity is taken as exactly 1 m/s; the associated downstream reservoir level consistent with this flow is 95.763 m, with negligible local losses (e.g., about 1 cm) at the source and terminal reservoirs and at the in-line check valve, if present. As mentioned, water column separation is only simulated at the high point in the system; thus, no consideration is given to distributed water column separation along the pipe's length.

Response of Test System

An excellent discussion of the theory and application of transient events in a pipeline system is available in standard references (Parmakian 1955, Chaudhry 1987, Thorley 1991, Wylie and Streeter 1993). However, as all effective protection approaches depend on strategic intervention in the evolution of hydraulic events, a brief physical description of the transient event is useful.

Due to the sudden stoppage of inflow the magnitude of the initial downsurge may sometimes be sufficiently large to cause widespread cavitation in the pipeline; even if less extreme, the vacuum valve at the high point may open and admit air. This combination air-vacuum valve is assumed here to be large enough to generate little resistance to the admission or escape of air. To consider a system without an air valve at the high point, the same representation can be used for the growth of a discrete vapor cavity at a suitable distance vertically above the assumed air valve position.

Returning to the transient event, a low-pressure wave originating at the source propagates along the pipe system until it reaches the downstream discharge reservoir. As this wave is transmitted, various characteristics, such as changes in pipe diameter or frictional effects, can alter its shape or magnitude. Although many effects are minor, this is seldom true for the air-vacuum. In fact, an air vacuum valve is specifically designed to alter propagation of a low-pressure wave by locally maintaining the hydraulic gradeline at roughly the elevation of its air-admission orifice. As is shown in more detail later, the action of the air valve has important implications for the overall system response.

Whether modified significantly or not, the low-pressure wave makes its way to the discharge reservoir, where a wave reflection occurs. The primary wave converts the discharge reservoir into a source of water, permitting reversal of flow in the line so that the discharge reservoir partly replenishes the water lost during the passage of the original low-pressure wave. This return surge and reverse flow progressively re-establishes the reservoir head within the system. The return flow is established at a rate commensurate with the difference in elevation between the high point and the downstream discharge reservoir and to a value reflecting the hydraulic capacity of this pipe segment.

Overall, what makes the transient response of the test system so interesting (and so non-linear) is the interaction between the various devices and components. It is the initial difference between the upstream and downstream heads along with the system hydraulic capacity that establishes the initial flow in the pipe. The value of the initial flow together with the pipe's wavespeed in turn establishes the magnitude of the initial downsurge. The low pressure wave interacts with the pipe profile to determine the amount of air that is admitted at the high point, which in turn establishes the boundary conditions for the refilling phase. The flow that reverses into the pipeline itself is partly established by the hydraulic capacity of the pipe connecting the high point to the downstream discharge reservoir. Thus, all components of the system ─ including its diameter, length, material, friction, profile and initial conditions ─ influence the system's transient response. Given all this, the numerical results presented here must be seen as both provisional and anecdotal.

Air Valve Issues and Assumptions

Although the adopted simplifying assumptions facilitate numerical exploration, none of them have a decisive impact on the primary goal of this study. Nevertheless, in the simulation results to follow, the assumption of a large air-vacuum valve at the high point is in one sense conservative. The amount of air admitted and expelled is obviously larger than would be expected from a smaller valve. Thus, the return surge will not be cushioned by an air pocket at the high point, as might be expected with a properly functioning (and, in fairness, more appropriately sized) air valve. Proper selection of air valve properties is generally an important part of a comprehensive surge protection strategy.

In the current study this conservatism is justified on three grounds:

(i) Air valves do not always function as designed, whether due to poor maintenance or some other reason, so that the assumed behavior may in fact be quite representative of a poorly functioning system;

(ii) The air valve condition effectively mimics vaporous cavitation at the high point at an appropriately adjusted high point elevation; thus, this approach allows a simple comparison of the system with and without air valve protection.

(iii) Finally, the purpose of the comparison is not primarily to present realistic pressures, nor to furnish a design chart to be used in lieu of a more serious computer simulation study. The goal is rather to indicate how the sometimes dramatic benefit when the return-surge portion of the air cavity growth cycle is prevented from occurring by the in-line check valve. In fact, one key point is this: when an in-line valve is present, the response of the system typically becomes less sensitive to the size and proper functioning of operating air-vacuum valves.

Role of the In-Line Check Valve. Having discussed the unprotected system, it is easier to comprehend the changes evoked by an in-line check valve. Certainly the in-line check valve has no benefit for the events immediately following the upstream flow stoppage; the initial downsurge will still initiate a low-pressure wave which will still interact with system as it propagates. However, once the low-pressure wave reaches the discharge reservoir, the situation has the potential to evolve quite differently, although the low-pressure signal will still cause the flow to reverse at the discharge reservoir. Yet, as soon as the first front of the reversing flow is experienced at the check valve, this valve will close, preventing the further propagation of this wave of increased pressure. As a direct result, the air or vapor cavity that has formed at the high point will continue to exist and will not be purged by the returning fluid and the associated pre-pressurization of the pipeline.

In this light, a warning relating to pump system re-start is needed. Following a power failure or valve closure event, the original flow should only be re-established under highly controlled conditions, so as to slowly remove any perched air or vapor from the system. The usual operational challenge during start-up is often to avoid an uncontrolled air discharge at any point in the profile. Thus, interestingly, the restart problem could lead to greater problems in a system protected by the in-line check valve and this reality requires explicit consideration during design.

On shutdown or pump failure, the fact that the check valve blocks the return flow from the discharge reservoir following reflection of the water hammer wave is one of its key benefits. Because of its presence, the air (or vapor) cavity at the high point will collapse slowly if at all. Thus the water hammer wave that can be so dramatically and destructively created as last of the air is eliminated from the high point will not occur. The impact of this change on system dynamics can sometimes be significant, and is now explored.

SIMULATION RESULTS

This study compares the responses of a limited set of variations on the test systems, including ones with and without an in-line check valves, and considering the role of a possible perforation or perforations in the check valve working element. As will become clear, the perforation, which is designed to reduce the pressures associated with check valve slam, change the balance of head rise between the portion of the line upstream and downstream of the check valve. We specifically consider the effect of varying the elevation of the assumed high point of water column separation in a system both with and without a check valve. The maximum HGL during a transient in the pipeline system has been systematically determined for various elevations of the high point.

In this section, simulation results are generated using a digital computer program called TransAM based on the method of characteristics (McInnis, Karney, and Axworthy, 2001). The program is based on formulations provided in standard texts (Chaudhry 1987, Wylie and Streeter 1993) and papers (e.g., Karney and McInnis 1992). As no specific contribution are made in this paper to the numerical simulation of transient flow, and as this material is found in standard texts, detailed equations and explanations are not provided.

The Unprotected System

For the system without the in-line check valve, the maximum HGL elevation values are shown in Table 1 (column 2) and plotted in Figure 2 (top curve). As the elevation of the high point increases, the maximum HGL elevations decreases up to an high point elevation of 30 m, then increases to a high point of 50 m and then decreases again. Recall that the initial downsurge, the growth and collapse of the air cavity at the high point, and the interaction of the two events control the dynamics of the system's response. The severity of this interaction is strongly influenced by the timing of the collapse and how this collapse interacts with ongoing transient events. If the elevation of the high point were to be gradually raised, the system would experience varying degrees of destructive or constructive interference form the various water hammer waves. These complicated and non-intuitive interactions account for the non-linear shape of the response curve in Figure 2.

Table 1. Maximum HGL values during the transient events

Elevation of the high point (m)	Maximum HGL without in-line check valve (m)	Maximum HGL with in-line check valve (m)	Reduction in maximum HGL (m)
-5	361.7	171.6	190
1	343.4	159.8	184
5	331.5	151.9	180
10	312.9	141.9	171
20	277.6	122.2	155
30	239.4	102.4	137
40	306.0	110.7	195
50	397.2	130.3	267
60	352.8	148.6	204
70	320.8	168.3	152
80	236.9	188.1	49
90	218.3	207.8	10
100	226.0	226.1	0

The maximum HGL profile along the pipe is shown in Figure 3 for a high point elevation of 50 m. Note that in this case the maximum pressure of 397 m is considerably higher than the Joukowsky pressure rise (100 m + 127.4 = 227.4 m) due to the additive nature of the superimposing waves as they reflect back and forth. The maximum pressure is uniformly high along the entire pipeline.

In contrast to the unprotected system, the maximum HGL in the system once an in-line check valve has been installed at the ¾ point along the pipeline is shown in Figure 2. The maximum HGL elevation values are significantly lower than those corresponding to the no in-line check valve case. Note that not only are the maximum pressures sometimes reduced to a small fraction of the value of the unprotected system, but the curve is smoother and more regular as well. One of the additional benefits of the in-line system is a more uniform response surface.

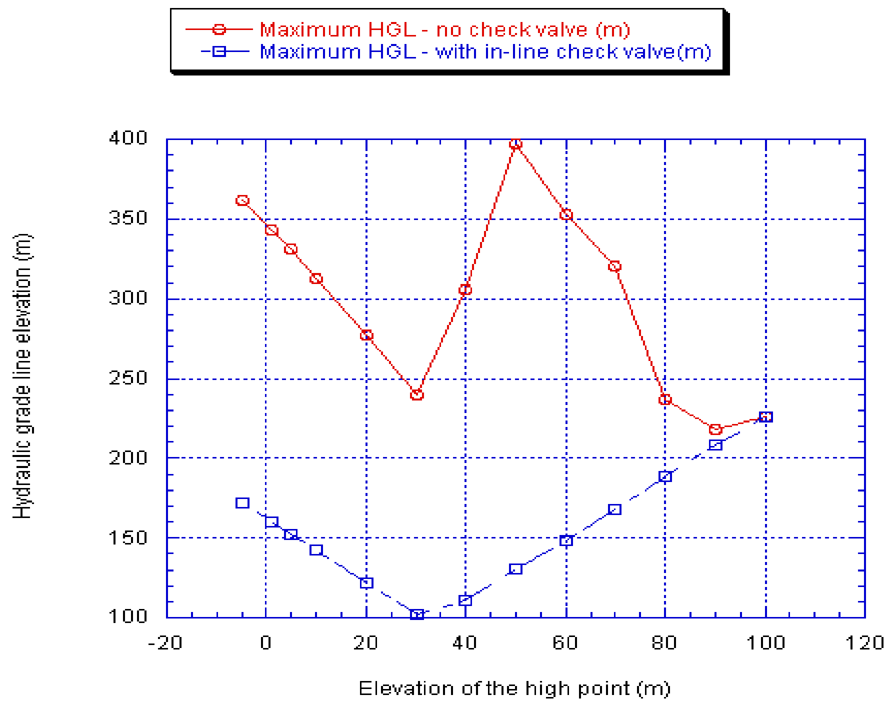

Figure 2. Variation of maximum HGL as the elevation of the high point changes

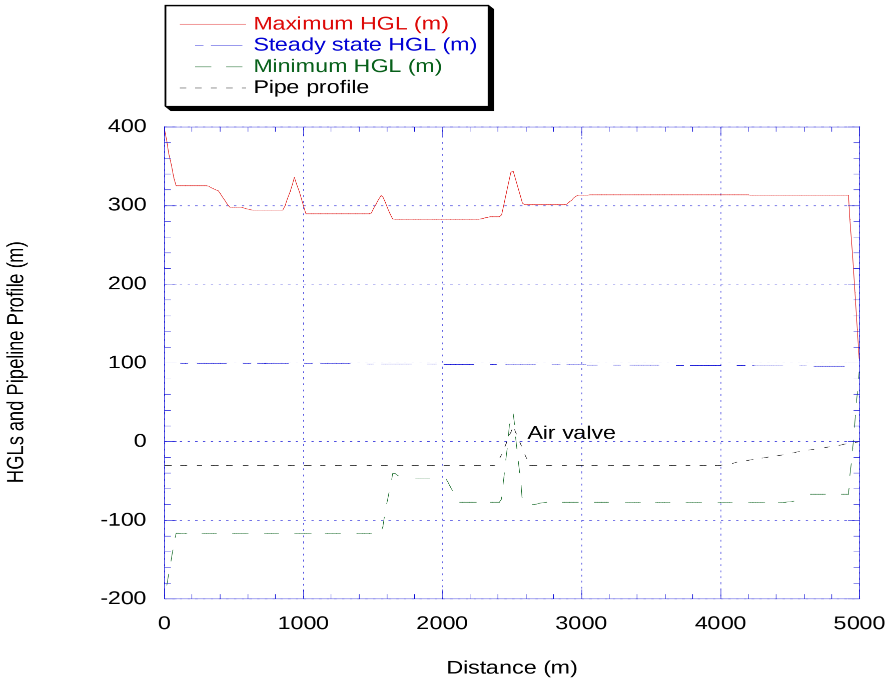

Figure 3. HGL profile for high point elevation of 50 m and no in-line check valve

System Response with In-Line Check Valve

It is interesting to note that as the high point elevation gradually rises to the elevation of the terminal reservoir, the driving head for the reverse flow is progressively eliminated. Thus, there is no dramatic cavity collapse in these systems, whether or not there is an in-line check valve present. Thus, as expected, the two curves in Figure 2 gradually converge as the 100 m elevation is approached.

The maximum HGL for the high point at the midpoint and an elevation of 20 m is shown in Figure 4. The maximum pressure of 122 m is considerably lower than the value of 278 m for the case of no check valve. Another important feature of Figure 4 is that the high pressures are now confined only to the pipeline section downstream of the in-line check valve.

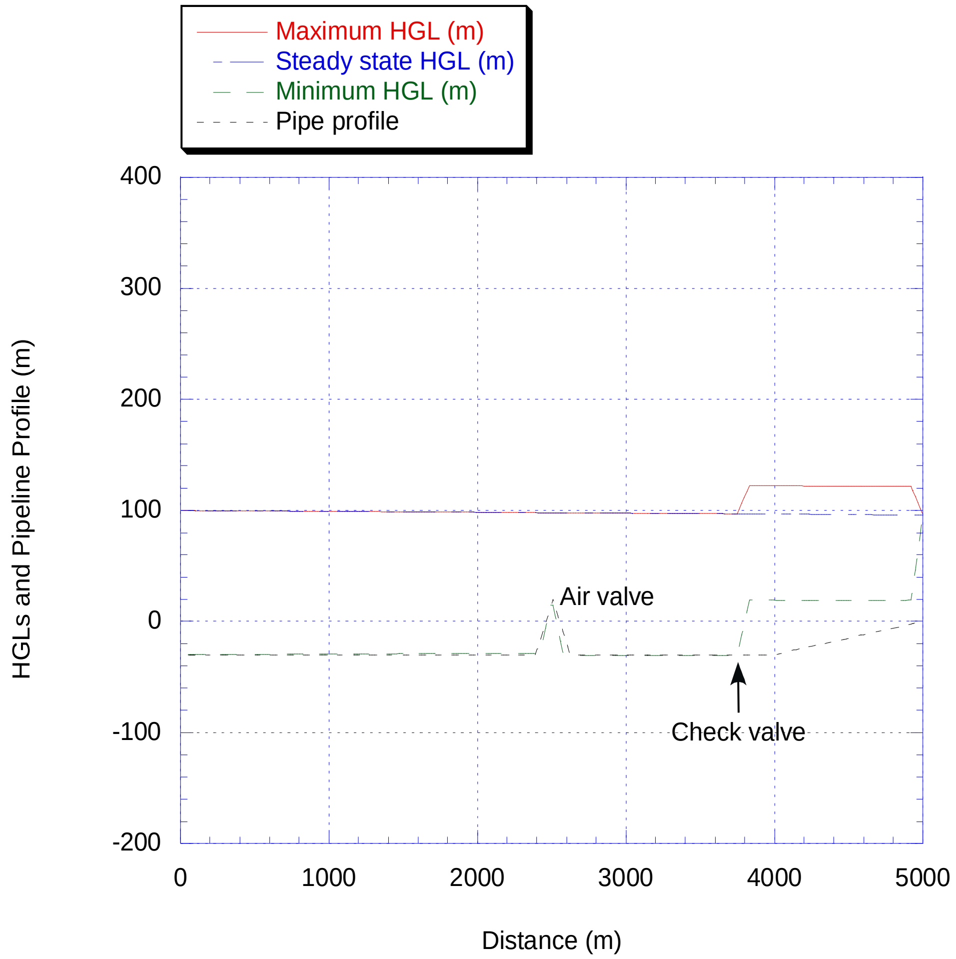

Figure 4. HGL profile for high point at 20 m with an in-line check valve.

Upstream of the check valve, the HGL does not exceed the steady state HGL during the transient event. Interestingly though, when the high point is raised a little higher to an elevation to 60 m, the maximum HGL is altered and becomes as shown in Figure 5. For this case the pressure rise is no longer confined to the pipeline downstream of the in-line check valve. Upstream of the air valve the transient pressures exceed the steady state pressures with a maximum value of 149 m (compared with a value of 353 m for the case of no in-line valve). In this case, the dynamics of the column of water near the highpoint is still sufficient to cause significant water hammer in the line. One implication of this is that the considerations involved in both adopting and locating an in-line check valve can be complex and involved, and are not always well resolved by a snap decision or *a priori* policy.

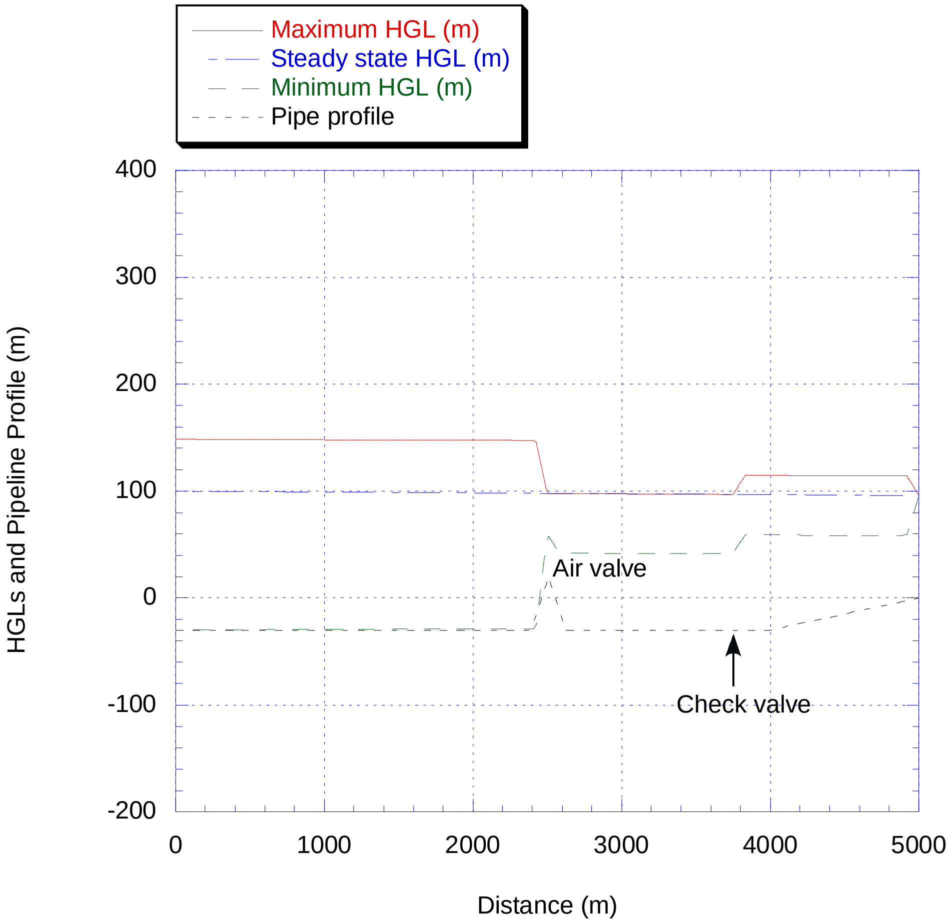

Figure 5. HGL profile for high point at 60 m with an in-line check valve.

Perforated Check Valves

In a case like this last one, there is a considerable pressure rise even though the in-line check valve system is installed. Certainly it may be possible to further reduce this peak pressure by adding other surge protection measures into the system, possibly including additional in-line check valves. Although these options are not explored here, there is one protection strategy that arises so naturally that it is worth some discussion. This is the installation of slow closing "perforations" in the check valve element, as is sometimes done by least one manufacturer (Red Valve).

The motivation behind the perforating or pressure-relieved check valve is easily appreciated through examination of Figures 3 or 4. When using the in-line valve, the normally upstream portion of the line, between the check valve and the discharge reservoir, still experiences considerable transient upsurge, while the remainder of the line is protected from the return surge. By partially limiting or blocking the action of the check valve, either through by-passing the valve with a smaller diameter parallel line or by perforating the valve itself with a relief-valve-like opening, a portion of the high pressure fluid can be passed back to the relatively lower pressure side, thus bringing the two sides into closer hydraulic communication, and limiting the upsurge on the downstream side.

The impact of this action is summarized in Figure 6 which shows the maximum pressure in the line as the effective size of the perforations increases. In general, as the hydraulic connection between the two parts of the system improve (i.e., as the valve loss coefficient increases), the response rapidly approaches the same value of head that would be experienced if the in-line check valve were not present at all. In this plot, the quantitative measure of the check valve's reverse flow capacity is evaluated by its discharge coefficient *Es*, numerically equal to the discharge through the valve divided by the square root of the pressure head difference across the valve's element. Note that the implication of this reverse flow through (or around) the valve is that the lower portion of the line progressively experiences more of the transmitted surge as the valve transmits more flow. Thus, the high pressure on one side is relieved to the lower pressure on the other side, thus bringing the two portions closer to equality. There is clearly a compromise or trade-off involved here, since too large a by-passed flow effectively nullifies the benefits of the in-line check valve. These issues can be discussed with reference to two actual applications.

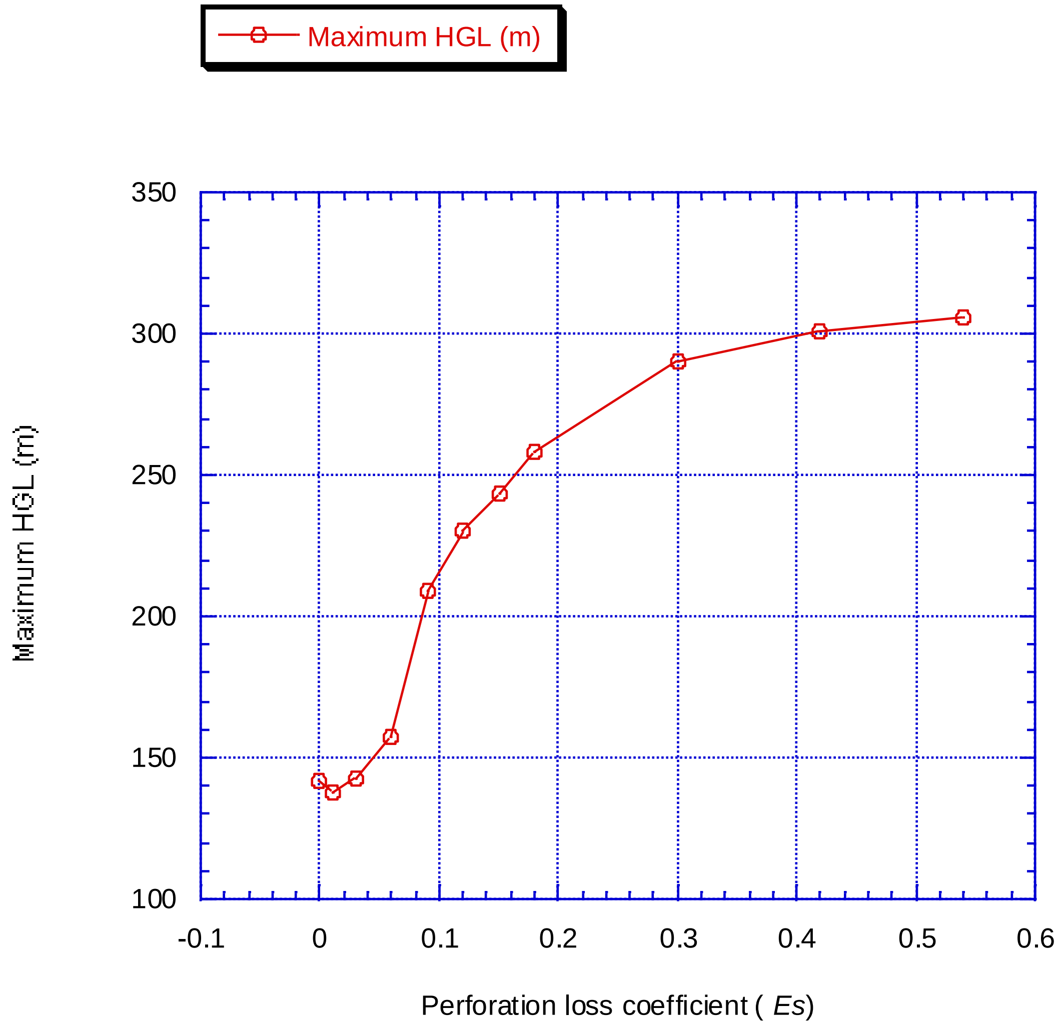

Figure 6. Variation of maximum transient HGL as size of perforations in the in-line check valve increase; high point at 10 m elevation, check valve at ¾ point.

Practical Applications

It is impossible to do justice here to many practical issues relating to surge protection. Numerous local and site conditions determine what range of surge protection strategies, and what combinations of specific attributes, are both physically and economically viable. Practical approaches need to consider the possibility of surge mitigation at the upstream source, say by using air chambers, surge tanks or pump flywheels, to reduce the initial downsurge to tolerable values. Moreover, a range of properly sized, located and maintained relief or control valves could improve the transient response, as could suitable air-vacuum valves. However, trying to be comprehensive in the current discussion would sidetrack us from the central issue of the use in-line check valves. Yet, two applications are worthwhile considering briefly, one of which raises secondary conditions that ultimately precluded the use of an in-line check valve, and another in which in-line check valves permitted a long-term and economical surge solution.

The first illustration relates to a situation where an in-line check valves had been excluded because of ineffective control of reverse flow. This situation arose on a pipeline system in Calgary, in western Canada. The profile of this delivery line, the severity of column rejoinder, and the expense of low pressure control all appeared to make an in-line check valve an attractive and economical surge protection choice. In this case, there was an ideal location for the valve along a moderately sized transmission main feeding to a terminal reservoir; in other words, the system was much as has been assumed thus far in this paper. Simulations of the transmission main were encouraging in that the positive pressure over much of the lower (normally upstream) portion of the line were considerably reduced when the in-line valve was first simulated. Based on these early indications of success, a more detailed numerical model was created, a model that naturally included more of the distribution system feeding off from the transmission main. The interesting aspect of this more detailed model was that it clearly showed that there was more than enough hydraulic capacity in the distribution grid to effective by-pass the check valve obstruction, thus effectively voiding the valve's effectiveness. So in this case, the in-line check valve did too little to obstruct the return flow, and the in-line valve approach had to be abandoned.

In 1996, Urban System Ltd. designed and installed an 11.1 km long primary water supply line for the City of Fort St. John in northern British Columbia. The line was unusual in that the total static head over its length was 320 m, with almost 60% (190 meters) of the elevation gain taking place over a steeply rising 600 m central section. Special concerns taken into consideration included potential pump failure and resulting transient pressures. Pipe materials chosen were 4.5 km of 500 mm welded steel, 2.4 km of 500 mm ductile iron, 3.8 km of 450 mm PVC and 400 m of 900 PVC pipe. The pump station was commissioned in the Fall of 1997 and consisted of three 500 HP variable speed pumps to produce 200 L/s at a rated pressure of 600 psi. In this case, the chief transient concern did not arise from the primary downsurge caused by power failure, but from the return surge generated by the unusually high discharge head. In this case, an in-line check valve was selected and installed to prevent backflow and column collapse following power failure. This protection system has been in effective service for almost a decade, during which the system has experienced a number of complete emergency power failures and transient events without and noted complications.

Guidelines on the Use of In-Line Check Valves

If in-line check valves are to be used to maximum advantage, their evaluation must always be holistic, taking into account all the key features of the hydraulic and operational nature of the candidate system, and the range of other surge protection strategies that might be employed A few special considerations are collected here as issues requiring special attention.

1. If any surge protection strategy is to be used to advantage, the mechanical and hydraulic mechanisms must be carefully maintained. This means that not only does the valve have to be sited where maintenance is convenient, effort and care are required to ensure that the valve is maintained in good working order. A check valve that "freezes" in an open or partially open position, and then possibly slams shut once enough reverse flow is developed, can have devastating consequences in a system (Thorley 1989).

2. One of the complications in the use of in-line air valves is that the air at the high point, such as at the air valve location in this study, is not removed during the normal course of the transient. The implication is that this remaining air must be carefully and intentionally removed under controlled conditions when the system is brought back on line. Thus, pump restart must be well designed and patiently controlled in all systems, but particularly those involving in-line check valves.

3. There are a great many other "unconventional" check valve applications that sometimes deserve special consideration. These should be investigated with creativity and diligence, for the solutions achieved can be quite elegant. For

example, it is sometimes possible to tie-in to reservoirs, to attach to operating devices, or to interconnect lines using a check valve in ways that are often overlooked, but often surprisingly beneficial. While somewhat presumptuous to give the advice to a system designer to be creative, there are sometimes great benefits to an open-minded exploration of the feasible region.

CONCLUSIONS

An important and straightforward application of an in-line check valve is to install it downstream of an intermediate high-point on a rising pumping line. Specific benefits arise from the arrangement following loss of power at a supply pumping station. Specifically, following a power failure event, the low pressure wave originating from the failed pump is prone to induce column separation at high points along the pipe profile. Installation of an appropriate in-line check valve can effectively isolate the point of separation from a high-energy water source, and can thus dramatically limit the surge pressures caused by column rejoinder.

The possible use of the in-line check valves is system dependent and tied-into many specific features of the system, ranging from initial flows, length and diameter of line, initiating transient, event, profile of the line, location of any special features like high points in the line, having suitable candidate location for the installation of the check valve, and having a suitable management that will ensure the valve receives regular and appropriate maintenance. However, when appropriate conditions are met, an in-line check valve can be a hydraulically effective and economically attractive way of controlling transient pressures in a rising pipeline system.

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