Guidelines for Transient Analysis in Water Transmission and Distribution Systems

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Additional information is available at the end of the chapter

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1. Introduction

Despite the addition of chlorine and potential flooding damage, drinking water is not generally considered a hazardous commodity nor an overwhelming cost. Therefore, considerable water losses are tolerated by water companies throughout the world. However, more extreme variations in dry and wet periods induced by climate change will demand more sustainable water resource management. Transient phenomena ("transients") in water supply systems (WSS), including transmission and distribution systems, contribute to the occurrence of leaks. Transients are caused by the normal variation in drinking water demand patterns that trigger pump operations and valve manipulations. Other transients are categorised as incidental or emergency operations. These include events like a pumping station power failure or an accidental pipe rupture by external forces. A number of excellent books on fluid transients have been written (Tullis 1989; Streeter and Wylie 1993; Thorley 2004), which focus on the physical phenomena, anti-surge devices and numerical modelling. However, there is still a need for practical guidance on the hydraulic analysis of municipal water systems in order to reduce or counteract the adverse effects of transient pressures. The need for guidelines on pressure transients is not only due to its positive effect on water losses, but also by the contribution to safe, cost-effective and energy-saving operation of water distribution systems. This chapter addresses the gap of practical guidance on the analysis of pressure transients in municipal water systems.

All existing design guidelines for pipeline systems aim for a final design that reliably resists all "reasonably possible" combinations of loads. System strength (or resistance) must sufficiently exceed the effect of system loads. The strength and load evaluation may be based on the more traditional allowable stress approach or on the more novel reliability-based limit state design. Both approaches and all standards lack a methodology to account for dynamic hydraulic loads (i.e., pressure transients) (Pothof 1999; Pothof and McNulty 2001). Most of the current standards simply state that dynamic internal pressures should not exceed the design pressure with a certain factor, duration and occurrence frequency. The Dutch standard NEN 3650 (Requirements for pipeline systems) includes an appendix that provides some guidance on pressure transients (NEN 2012).

One of the earliest serious contributions to this topic was the significant compilation of Pejovic and Boldy (1992). This work not only considered transient issues such as parameter sensitivity and data requirements, but usefully classified a range of loading conditions that accounted for important differences between normal, emergency and catastrophic cases, and the variation in risk and damage that could be tolerated under these different states.

Boulos *et al*. (2005) introduced a flow chart for surge design in WSS. The authors address a number of consequences of hydraulic transients, including maximum pressure, vacuum conditions, cavitation, vibrations and risk of contamination. They proposed three potential solutions in case the transient analysis revealed unacceptable incidental pressures:

1. Modification of transient event, such as slower valve closure or a flywheel;
2. Modification of the system, including other pipe material, other pipe routing, etc.; and
3. Application of anti-surge devices.

Boulos *et al*. list eight devices and summarise their principal operation. They do not provide an overview of the scenarios that should be included in a pressure transient analysis. Jung and Karney (2009) have recognised that an *a priori* defined design load does not necessarily result in the worst-case transient loading. Only in very simple systems can the most critical parameter combination can be defined *a priori* (Table 4). In reality, selecting appropriate boundary conditions and parameters is difficult. Further, the search for the worst case scenario, considering the dynamic behaviour in a WSS, is itself a challenging task due to the complicated nonlinear interactions among system components and variables. Jung and Karney (2009) have extended the flow chart of Boulos *et al*. (2005), taking into account a search for the worst-case scenario (Figure 1). They propose to apply optimisation tools to find the worst-case loading and a feasible set of surge protection devices.

Automatic control systems have become common practice in WSS. Since WSS are spatially distributed, local control systems may continue in normal operating mode, after a power failure has occurred somewhere else in the system. The control systems may have a positive or negative effect on the propagation of hydraulic transients. On the other hand, the distributed nature of WSS and the presence of control systems may be exploited to counteract the negative effects of emergency scenarios. Therefore, existing guidelines on the design of WSS must be updated on a regular basis in order to take these developments into account.

Typical design criteria for drinking water and wastewater pipeline systems are listed in section 2. Section 3 presents a systematic approach to the surge analysis of water systems. This approach focuses on guidelines for practitioners. The key steps in the approach include the following: preconditions for the surge analysis; surge analysis of emergency scenarios without provisions; sizing of anti-surge provisions and design of emergency

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controls; evaluation of normal operations and design of control systems. The approach has been applied successfully by Both Deltares (formerly Delft Hydraulics) and HydraTek and Associates Inc. in numerous large water transmission schemes worldwide. Especially the integrated design of surge provisions and control systems has many benefits for a safe, cost-effective and energy-efficient operation of the water pipeline system. Section 4 summarises the key points of this paper.

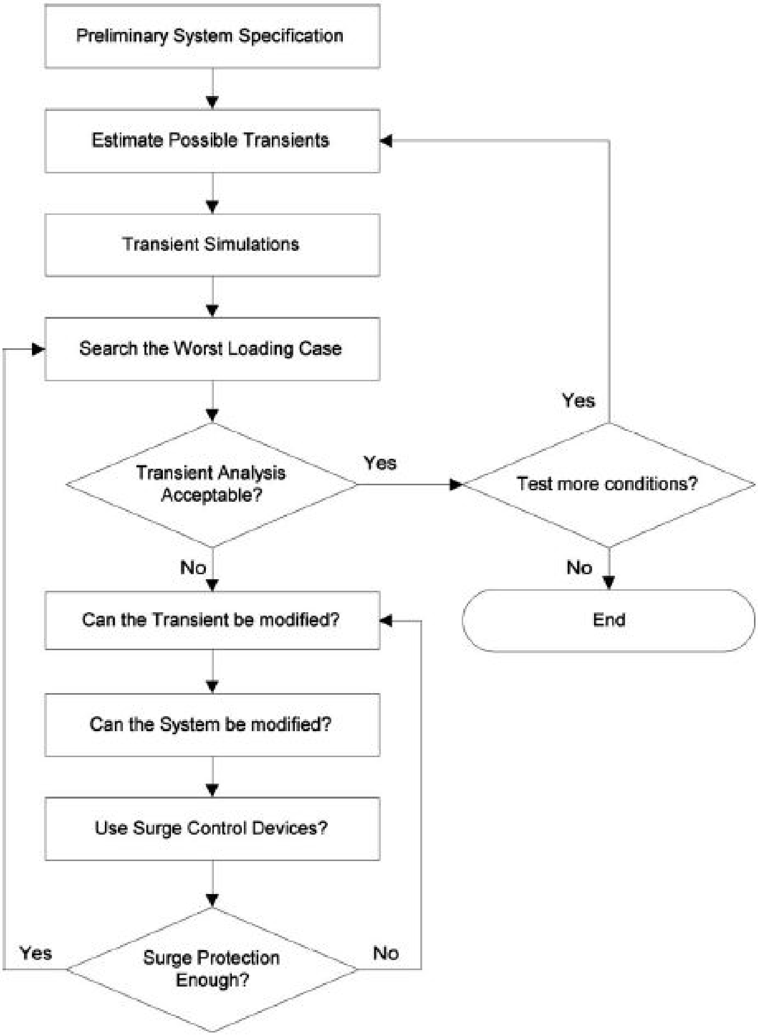


Figure 1. Pressure Transient design (Jung and Karney 2009).

2. Pressure transient evaluation criteria for water pipelines

In any transient evaluation, pressure is the most important evaluation variable, but certainly not the only one. Component-specific criteria must be taken into account as well, such as a minimum fluid level in air vessels, maximum air pressure during air release from an air valve or the maximum fluid deceleration through an undamped check valve.

The maximum and minimum allowable pressure is directly related to the pressure rating of the components. Thin-walled steel and plastic pipes are susceptible to buckling at a combination of external pressure and minimum internal pressure.

The design pressure for continuous operation is normally equal to the pressure rating of the system. During transient events or emergency operation, the system pressure may exceed the design pressure up to a certain factor of the design pressure. Table 1 provides an overview of maximum allowable incidental pressure (MAIP) in different national and international codes and standards.

Code	Maximum Incidental Pressure Factor [-]
DVGW W303:1994 (German guideline)	1.00
ASME B31.4 (1992), IS 328, BS 8010, ISO CD 16708:2000	1.10
NEN 3650-1:2012	1.15
BS 806	1.20
Italian ministerial publication	1.25 – 1.50

Table 1. Overview of maximum allowable incidental pressures (MAIP) in international standards, expressed as a factor of the nominal pressure class.

The minimum allowable pressure is rarely explicitly addressed in existing standards. The commonly accepted minimum incidental pressure in drinking water distribution systems is atmospheric pressure or the maximum groundwater pressure necessary to avoid intrusion at small leaks. If the water is not for direct consumption, negative pressures down to full vacuum may be allowed if the pipe strength is sufficient to withstand this condition, although tolerance to such conditions varies with jurisdiction. Full vacuum and cavitation can be admitted under the condition that the cavity implosion is admissible. Computer codes that are validated for cavity implosion must be used to determine the implosion shock. The maximum allowable shock pressure is 50% of the design pressure. This criterion is based on the following reasoning: The pipeline (including supports) is considered a single-mass-spring system for which a simplified structural dynamics analysis can be carried out. The ratio of the dynamic response (i.e., pipe wall stress) to the static response is called the dynamic load factor (DLF). The dynamic load factor of a mass-spring system is equal to 2. It is therefore recommended that a maximum shock pressure of no more than 50% of the design pressure be allowed. This criterion may be relaxed if a more complete Fluid-Structure-Interaction (FSI) simulation is performed for critical above-ground pipe sections.

3. Systematic approach to pressure transient analysis

The flow chart in Figure 2 integrates the design of anti-surge devices and distributed control systems. It is emphasised that a surge analysis is strongly recommended upon each modification to an existing system. The systematic approach also applies to existing systems.

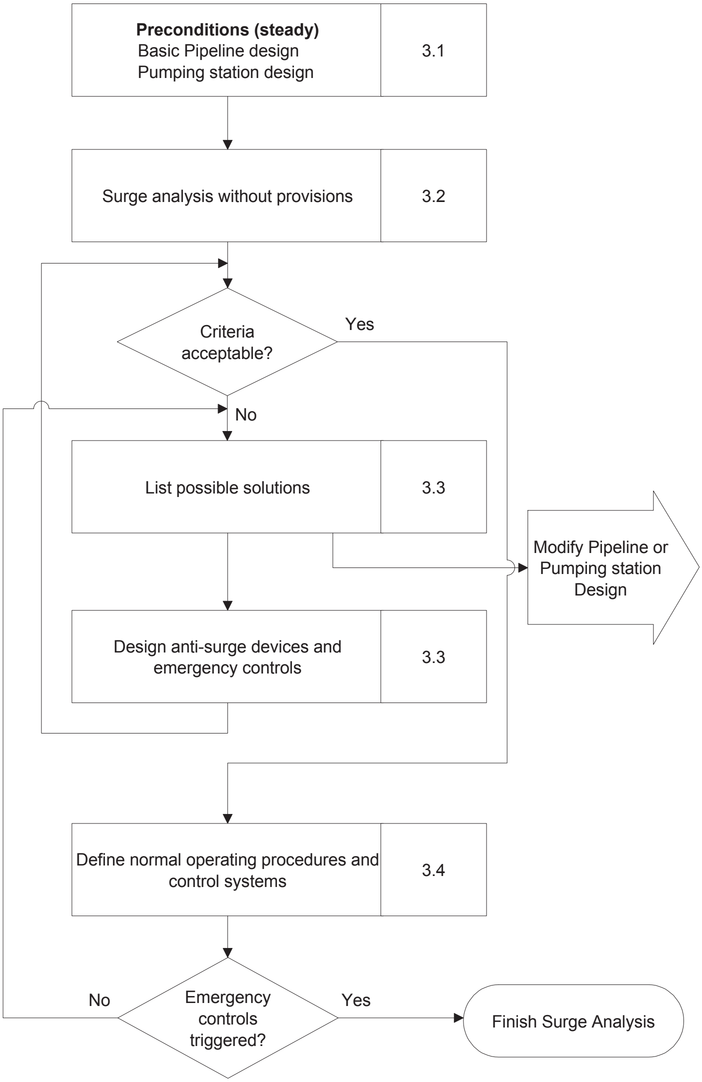


Figure 2. Integrated design for pressure transients and controls.

Because system components are tightly coupled, detailed economic analysis can be a complex undertaking, However, the net present value of anti-surge equipment may rise to 25% of the total costs of a particular system. Therefore, the systematic approach to the pressure transient analysis is preferably included in a life cycle cost optimisation of the water system, because savings on investment costs may lead to operation and maintenance costs that exceed the net present value of the investment savings.

3.1. Necessary information for a pressure transient analysis

The phenomenon of pressure transients, surge or water hammer is defined as the simultaneous occurrence of a pressure and velocity changes in a closed conduit. Water hammer may occur in both long and short pipes. The larger and faster the change of velocity, the larger the pressure changes will be. In this case, 'fast' is not an absolutely term, but can only be used relative to the pipe period, that is, relative to the pipe’s internal communications. The most important parameters for the magnitude of transient pressures are:

- Velocity change in time, Δv (m/s) (or possibly the pressure equivalent)
- Acoustic wave speed, c (m/s)
- Pipe period, T (s)
- Joukowsky pressure, Δp (Pa)
- Elevation profile

The acoustic wave speed c is the celerity at which pressure waves travel through pressurised pipes. The wave speed accounts for both fluid compressibility and pipe stiffness: the more elastic the pipe, the lower the wave speed. In fact, all phenomena that create internal storage contribute to a reduction of wave speed. Since air is much more compressible than water, air bubbles reduce the wave speed considerably, but this is the primary positive effect of air in pipelines. The negative consequences of air in water pipelines, particularly in permitting or generating large velocity changes, can greatly exceed this positive effect in mitigating certain transient changes; thus, as an excellent precaution, free or mobile air must generally be avoided in water systems whenever possible and cost-effective. The maximum acoustic wave speed in an excavated water tunnel through rocks is 1430 m/s and drops to approximately 1250 m/s in steel, 1000 m/s in concrete and ductile iron, 600 m/s in GRP, 400 m/s in PVC and about 200 m/s in PE pipes.

$$c = \frac{1}{\sqrt{\rho\left(\frac{C_1 D}{eE} + \frac{1}{K}\right)}} \tag{1}$$

where:

c = Acoustic wave speed (m/s)

E = Young's modulus of pipe material (N/m^2)

K = Bulk modulus of fluid (N/m^2)

ϱ = Fluid density (kg/m^3)

D = Pipe diameter (m)

e = Wall thickness (m) and

C_1 = Constant depending on the pipe anchorage (order 1).

The acoustic wave speed in water pipelines is shown in Figure 3.

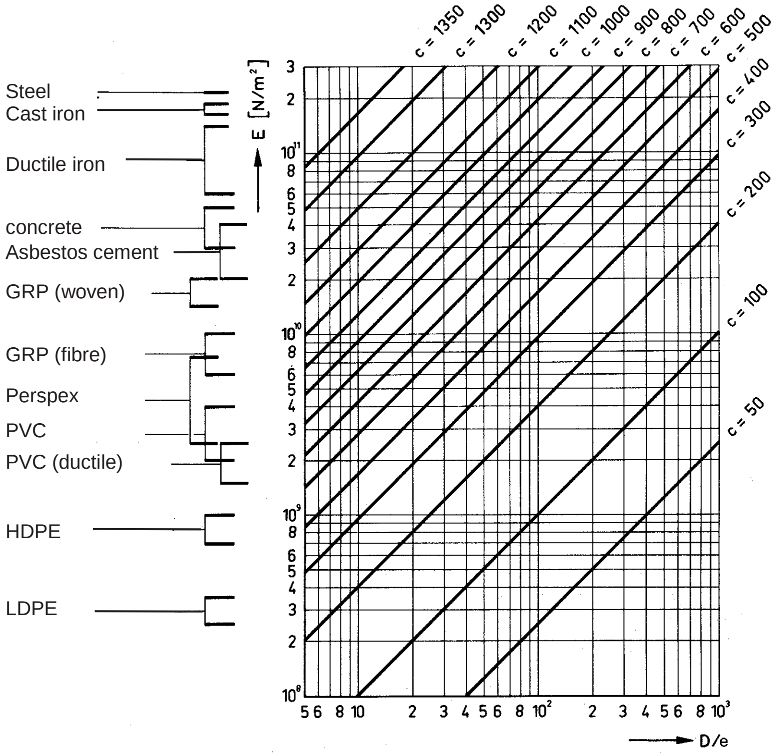


Figure 3. Graph of acoustic wave speed in water pipelines in relation to pipe material (E) and wall thickness (D/e).

The pipe period T [s] is defined as the time required for a pressure wave to travel from its source of origin through the system and back to its source. For a single pipeline with length L:

$$T = 2L/c \tag{2}$$

This parameter defines the natural time scale for velocity and pressure adjustments in the system.

Only after the pipe period the pressure wave will start to interact with other pressure waves from the boundary condition, such as a tripping pump or a valve closure. Any velocity change Δv within the pipe period will result in a certain "practical maximum" pressure, the so-called Joukowsky pressure, Δp.

$$\Delta p = \pm \rho \cdot c \cdot \Delta v \tag{3}$$

A slightly more conservative assessment of the maximum transient pressure includes the steady friction head loss $\Delta p_s = \rho g \Delta H_s$.

$$\Delta p = \pm \left(\rho \cdot c \cdot \Delta v + \rho g \Delta H_s \right) \tag{4}$$

All these parameters follow directly from the basic design. The maximum rate of change in velocity is determined by the run-down time of a pump or a valve closure speed. The pump run-down time is influenced by the polar moment of inertia of the pump impeller, the gear box and motor. The full stroke closure time of valves may be increased in order to reduce the rate of velocity change.

Pressure waves reflect on variations of cross-sectional area (T-junctions, diameter changes, etc.) and variation of pipe material. All these parameters must be included in a hydraulic model.

Finally, the elevation profile is an important input, because extreme pressures typically occur at its minimum and maximum positions.

3.2. Emergency scenarios without anti-surge provisions

A pressure transient analysis or surge analysis includes a number of simulations of emergency scenarios, normal operations maintenance procedures. The emergency scenarios may include:

- Complete pump trip
- Single pump trip to determine check valve requirements
- Unintended valve closure; and
- Emergency shut-down procedures.

A pump trip without anti-surge provisions causes a negative pressure wave traveling into the WSS. If the downstream boundary is a tank farm or large distribution network, then the reflected pressure wave is an overpressure wave. If the check valves have closed within the pipe period, then the positive pressure reflects on the closed check valves by doubling the positive pressure wave (Figure 4). In this way, the maximum allowable pressure may be exceeded during a pump trip scenario.

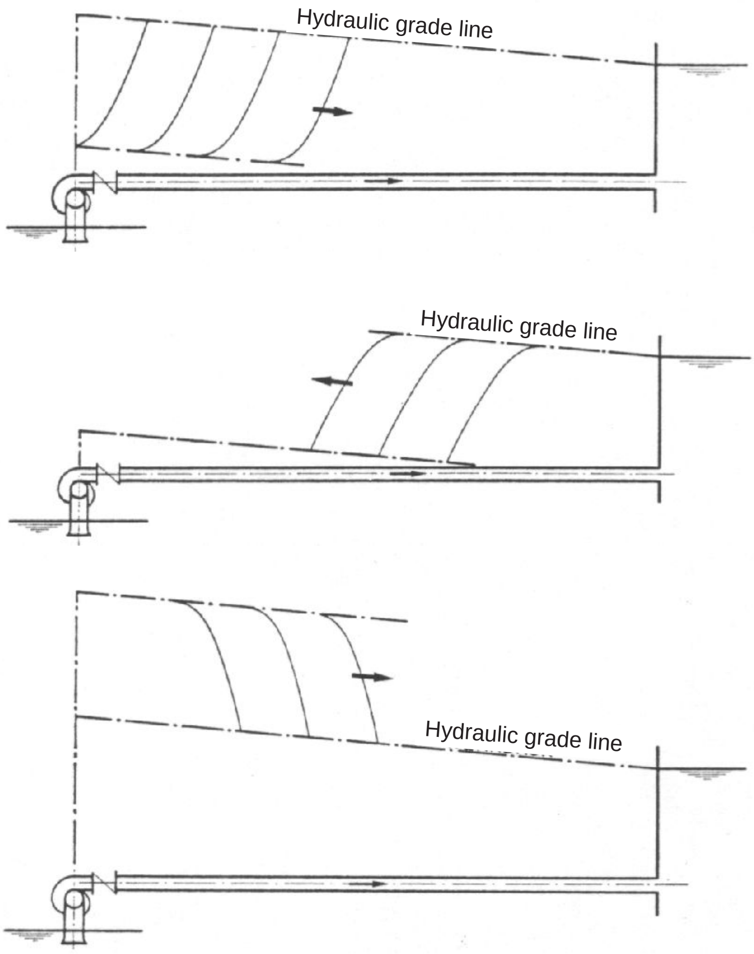
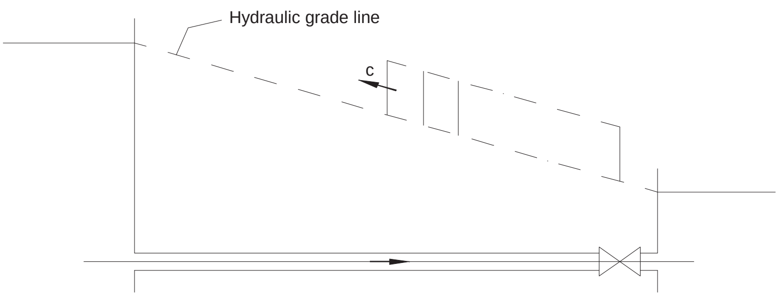
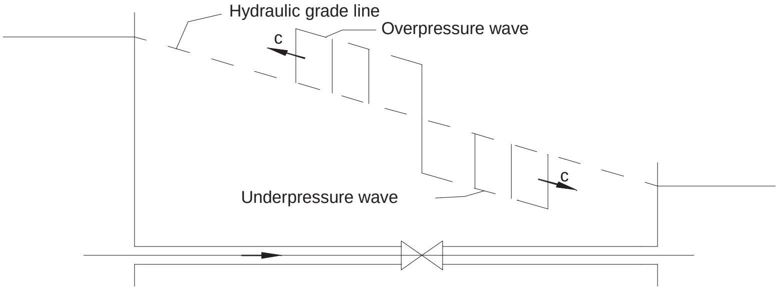


Figure 4. Pressure wave propagation following a pump trip

Check valves will generally close after pump trip. The transient closure of a check valve is driven by the fluid deceleration through the check valve. If the fluid decelerates quickly, an undamped check valve will slam in reverse flow. Fast-closing undamped check valves, like a nozzle- or piston-type check valve, are designed to close at a very small return velocity in order to minimize the shock pressure. Ball check valves are relatively slow, so that their application is limited to situations with small fluid decelerations.



Valve downstream



Valve half-way

Figure 5. Pressure wave propagation following valve closure

Emergency closure of a line valve creates a positive pressure wave upstream and negative pressure wave downstream of the valve. Although the total closure time may well exceed the characteristic pipe period, the effective closure may still occur within one pipe period, so that the Joukowsky pressure shock may still occur. The effective closure is typically only 20% of the full stroke closure time, because the valve starts dominating the total head loss when the valve position is less than 20% open (e.g., Figure 6). If a measured capacity curve of the valve is used, simulation software will deliver a reliable evolution of the discharge and transient pressures in the WSS.

Figure 6 shows an example of a butterfly valve at the end of a 10 km supply line (wave speed is 1000 m/s). A linear closure in 5 pipe periods (100 s) shows that the pressure rises only during the last 30% of the valve closure. Therefore the pressure rise is almost equal to the Joukowsky pressure. A two-stage closure, with a valve stroke from 100% to 30% open in 1 pipe period (20 s), shows a more gradual pressure rise during the closing procedure and a lower peak pressure.

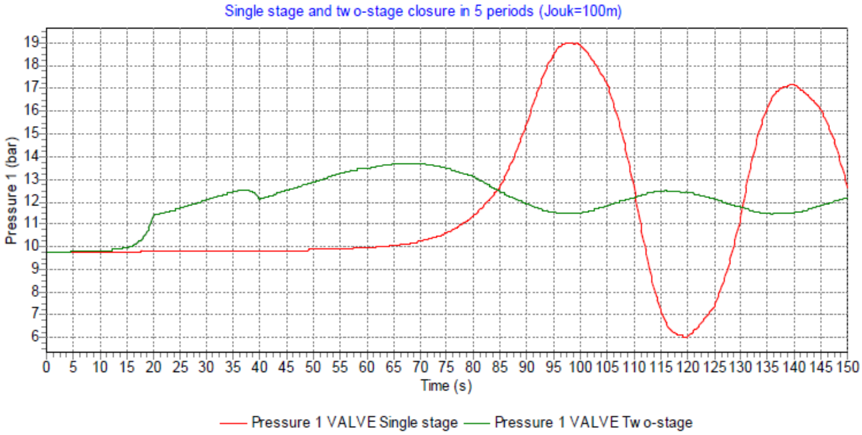


Figure 6. Single and two-stage valve in 5 pipe periods (100 s)

In general, for each scenario multiple simulations must be carried out to determine the extreme pressures and other hydraulic criteria. Scenario variations may include flow distributions, availability of signal transfer (wireless or fiber-optic cable) for the control system and parameter variations. For example, the minimum pressure upon full pump trip will be reached in a single pipeline, if the maximum wall roughness value is used. If an air vessel is used as an anti-surge device, the minimum wall roughness and isothermal expansion must be applied to determine the minimum water level in the air vessel. Adiabatic pocket expansion in air vessels must be applied for other scenarios. The selection of input parameters so that the extreme hydraulic criterion values are computed is called a conservative modeling approach (Pothof and McNulty 2001). The proper combination of input parameters can be determined *a priori* for simple (single pipeline) systems only. Table 4 provides some guidance on the conservative modeling approach.

In more realistic situations a sensitivity analysis is required to determine the worst case loading. A more recent development for complex systems is to combine transient solvers with optimization algorithms to find the worst case loading condition and the appropriate protection against it (Jung and Karney 2009).

In most cases, the emergency scenarios result in inadmissible transient pressures. Possible solutions include modifications to the system or transient event (e.g., slower valve closure), anti-surge devices, emergency controls, or a combination of the above. The solutions will be discussed in more detail in the next section.

3.3. Design of anti-surge devices and emergency controls

In order to mitigate inadmissible transient pressures, hydraulic design engineers have four different management options at their disposal:

1. System modifications (diameter, pipe material, elevation profile, etc.);
2. Moderation of the transient initiation event;
3. Emergency control procedures; and/or
4. Anti-surge devices.

3.3.1. System modifications

Measure 1 is only feasible in an early stage. A preliminary surge analysis may identify cost-effective measures for the surge protection that cannot later be incorporated. If, for example, inadmissible pressures occur at a local high point that seem difficult to mitigate, the pipe routing may be changed to avoid the high point. Alternatively, the pipe may be drilled through a slope to lower the maximum elevation.

Selection of a more flexible pipe material reduces the acoustic wave speed. Larger diameters reduce the velocities and velocity changes, but the residence time increases, which may render this option infeasible due to quality concerns.

A cost-benefit analysis is recommended to evaluate the feasibility of these kinds of options.

3.3.2. Moderating the transient initiation event

A reduction of the rate of velocity change will reduce the transient pressure amplitude. A variable speed drive or soft start/stop functionality may be effective measures for normal operations, but their effect is negligible in case of a power failure. A flywheel increases the polar moment of inertia and thereby slows down the pump trip response. It should be verified that the pump motor is capable of handling the large inertia of the flywheel during pump start scenarios. Experience shows that a flywheel is not a cost-effective option for pumps that need to start and stop frequently.

If inadmissible pressures are caused by valve manipulations, the valve closure time must be increased. The velocity reduction by a closing valve is not only influenced by the valve characteristic, but also by the system. The valve resistance must dominate the total system resistance before the discharge is significantly reduced. Therefore, the effective valve closure time is typically 20% to 30% of the total closure time. A two-stage closure, or the utilization of a smaller valve in parallel, may permit a rapid initial stage and very slow final stage as an effective strategy for an emergency shut down scenario. The effective valve closure must be spread over multiple pipe periods to obtain a significant reduction of the peak pressure. Existing books on fluid transient provide more detail on efficient valve stroking (Tullis 1989; Streeter and Wylie 1993; Thorley 2004).

3.3.3. Emergency control procedures

Since WSS are spatially distributed, the power supply of valves and pumps in different parts of the system is delivered by a nearly-independent power supply. Therefore, local control systems may continue operating normally, after a power failure has occurred somewhere else in the network. The control systems may have a positive or negative effect on the propagation of hydraulic transients. The distributed nature of WSS and the presence of control systems may be exploited to counteract the negative effects of emergency scenarios.

If a centralised control system is available, valves may start closing or other pumps may ramp up as soon as a pump trip is detected. Even without a centralised control system, emergency control rules may be developed to detect power failures. These emergency control rules should be defined in such a way that false triggers are avoided during normal operations. An example of an emergency control rule is: *ESD valve closure is initiated if the discharge drops by more than 10% of the design discharge and the upstream pressure falls by at least 0.5 bar within 60 seconds.*

3.3.4. Anti-surge devices

The above-described measures may be combined with one or more of the following anti-surge devices in municipal water systems.

Devices, affecting velocity change in time	Pressure limiting devices
Surge vessel	By-pass check valve
Flywheel	Pressure relief valve
Surge tower	Combination air/vacuum valves
	Feed tank

Table 2. Summary of anti-surge devices

An important distinction is made in Table 2 between anti-surge devices that directly affect the rate of change in velocity and anti-surge devices that are activated at a certain condition. The anti-surge devices in the first category immediately affect the system response; they have an overall impact on system behaviour. The pressure-limiting devices generally have a local impact. Table 3 lists possible measures when certain performance criteria are violated.

The surge vessel is an effective (though relatively expensive) measure to protect the system downstream of the surge vessel against excessive transients. However, the hydraulic loads in the sub-system between suction tanks and the surge vessel will increase with the installation of a surge vessel. Special attention must be paid to the check valve requirements, because the fluid deceleration may lead to check valve slam and consequent damage. These local effects, caused by the installation of a surge vessel, should always be investigated in a detailed hydraulic model of the subsystem between tanks and surge vessels. This model may also reveal inadmissible pressures or anchor forces in the suction lines and headers, especially in systems with long suction lines (> 500 m). A sometimes-effective measure to reduce the local transients in the pumping station is to install the surge vessels at a certain distance from the pumping station.

Operation	Criterion Violation	Improvement
pump trip	low pressure	bypass pipe, flywheel larger pipe diameter air vessel, accumulator surge tower, surge vessel, feed tank air valve(s) at low pressure points in the system other pipe material with lower Young’s modulus
pump trip	high pressure	air vessel with check valve and throttled by-pass
pump trip	reverse flow in pump	increase (check) valve closure rate by choosing an appropriate fast-closing check valve (e.g. nozzle type)
pump trip	rate of fluid deceleration through check valve (high pressure due to valve closure)	apply spring to reduce check valve closing time apply spring or counter weight with damper to increase check valve closing time and allow return flow
valve closure	high pressure (upstream)	air vessel slower valve closure pressure relief valve or damper at high pressure points higher pressure rating
valve closure	low pressure (downstream)	air vessel slower valve closure air valves at low pressure points
valve throttling	pressure instability	use multiple valves adjust control settings
drainage, filling	entrapped air	use air valves prevent drainage on shut-down

Table 3. Possible mitigating measures in case of violation of one or more performance criteria

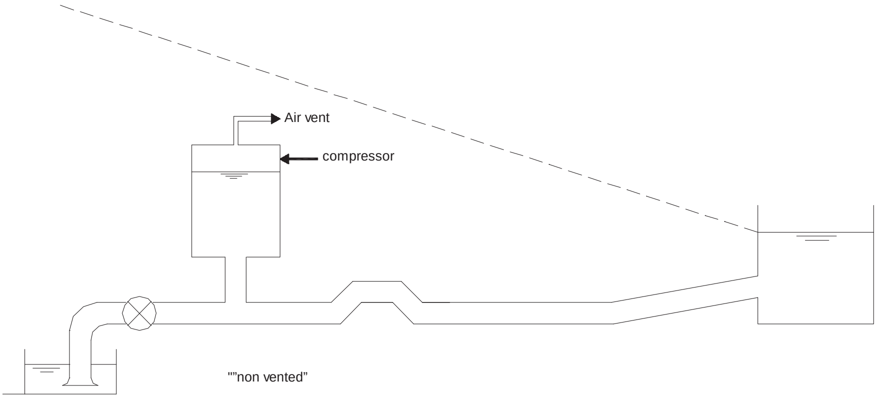


Figure 7. Non-aerated surge vessel

One of the disadvantages of a surge tower is its height (and thus cost and the siting challenges). If the capacity increases, so that the discharge head exceeds the surge tower level, then the surge tower cannot be used anymore. A surge tower is typically installed in the vicinity of a pumping station in order to protect the WSS downstream. A surge tower could also be installed upstream of a valve station to slow down the over pressure due to an emergency valve closure.

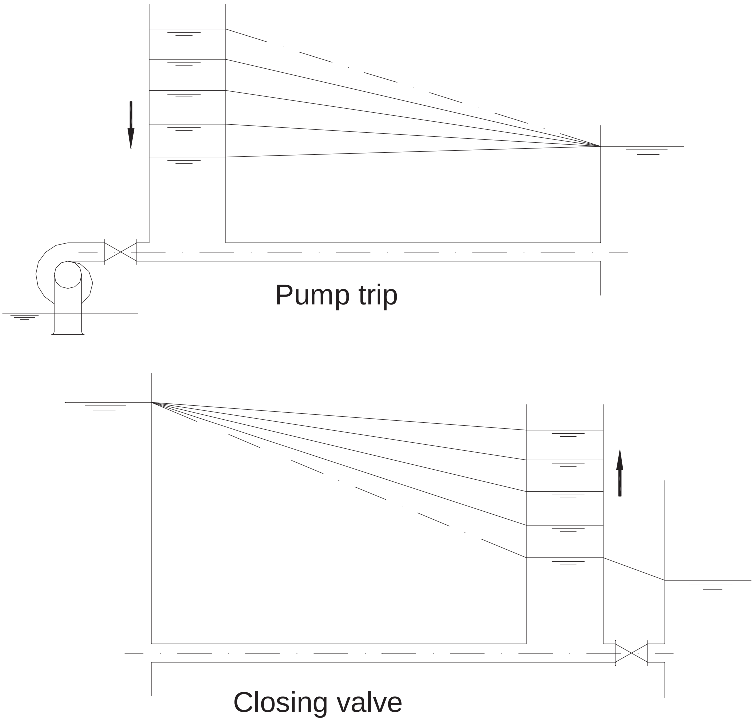


Figure 8. Surge tower near pumping station or valve station.

Another device that reduces the velocity change in time is the flywheel. A flywheel may be an effective measure for relatively short transmission lines connected to a tank farm or distribution network. A flywheel can be an attractive measure if the following conditions are met:

1. Pump speed variations are limited.
2. The pump motor can cope with the flywheel during pump start-up, which means that the motor is strong enough to accelerate the pump impeller - flywheel combination to the pump's rated speed. If the polar moment of pump and flywheel inertia is too large for the motor, then a motor-powered trip may occur and the rated speed cannot be reached.

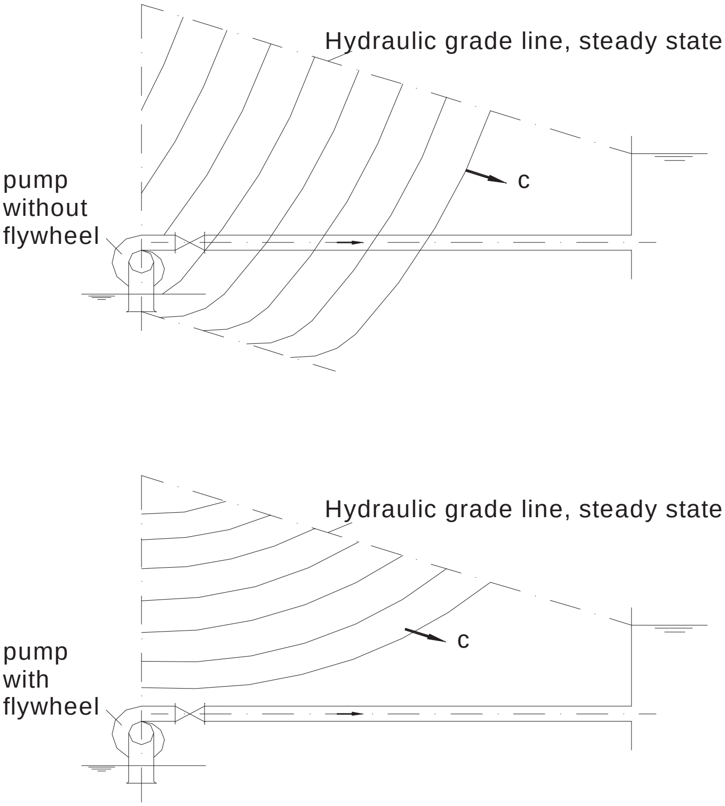


Figure 9. Effect of flywheel on transient pressure after power failure in the pumping station

A by-pass check valve is effective at sufficient suction pressure, which becomes available automatically in a booster station. Wavefront steepness is not affected until the by-pass check valve opens. A similar reasoning applies to the other pressure-limiting devices. Furthermore, the release of air pockets via air valves is an important source of inadmissible pressure shocks. Air release causes a velocity difference between the water columns on both sides of the air pocket. Upon release of the air pocket's last part, the velocity difference Δv must be balanced suddenly by creating a pressure shock of half the velocity difference (Figure 10). The magnitude of the pressure shock is computed by applying the Joukowsky law:

$$\Delta p = \pm \rho \cdot c \cdot \Delta v / 2 \tag{5}$$

A large inflow capacity is generally positive to avoid vacuum conditions, but the outflow capacity of air valves must be designed with care.

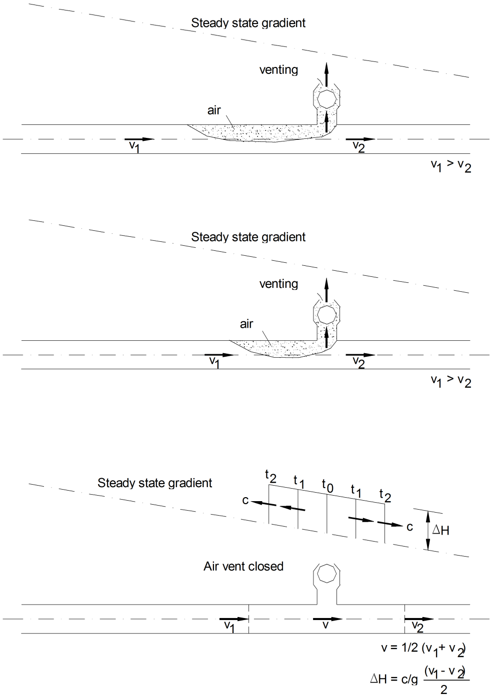


Figure 10. Pressure shock due to air valve slam.

3.4. Design of normal procedures and operational controls

The following scenarios may be considered as part of the normal operating procedures (see also appendix C.2.2. in standard NEN 3650-1:2012):

1. Start of pumping station in a primed system.
2. Normal stop of single pump or pumping station.
3. Commissioning tests.
4. Priming operation or pump start in partially primed system.
5. Procedure to drain (part of) the system for maintenance purposes.
6. Normal, scheduled, valve closure.
7. Stop of one pumping station or valve station and scheduled start of another source.
8. Other manipulations that result in acceleration or deceleration of the flow.
9. Switch-over procedures.
10. Risk assessment of resonance phenomena due to control loops.

Normal operating procedures should not trigger emergency controls. If this is the case, the control system or even the anti-surge devices may have to be modified. As a general rule for normal operations, discharge set-points in control systems tend to exaggerate transient events while pressure set-points automatically counteract the effect of transients. Two examples are given.

The first deals with a single pipeline used to fill a tank or supply reservoir. Suppose a downstream control valve is aiming for a certain discharge set-point to refill the tank or reservoir. If an upstream pump trip occurs, the control logic would lead to valve-opening in order to maintain the discharge set-point. This will lower the minimum pressures in the pipe system between the pumping station and the control valve. On the other hand, if the control valve aims for an upstream pressure set-point, the valve will immediately start closing as soon as the downsurge has arrived at the valve station, thereby counteracting the negative effect of the pump trip.

The second example is a distribution network in which four pumping stations need to maintain a certain network pressure. The pumping stations have independent power supply. Suppose that three pumping stations follow a demand prediction curve and the fourth pumping station is operating on a set-point for the network pressure. If a power failure occurs in one of the discharge-driven pumping stations, then the network pressure will drop initially. As a consequence the pump speed of the remaining two discharge-driven pumping stations will drop and the only pressure-driven pumping station will compensate temporarily not only the failing pumping station, but also the two other discharge-driven pumping stations. If all pumping stations would be pressure-driven pumping stations, then the failure of a single pumping station will cause all other pumping stations to increase their pump speed, so that the loss of one pumping stations is compensated by the three others.

The simulation of the normal operating procedures provides detailed knowledge on the dynamic behaviour of the WSS. This knowledge is useful during commissioning of the (modified) system. For example, a comparison of the simulated and measured pressure signals during commissioning may indicate whether the system is properly de-aerated.

It is emphasized that a simulation model is always a simplification of reality and simulation models should be used as a decision support tool, not as an exact predictor of reality. The design engineer of complex WSS must act like a devil’s advocate in order to define scenarios that have a reasonable probability of occurrence and that may lead to extreme pressures or pressure gradients.

4. Modelling of water supply systems for transient analyses

This section provides some guidelines on the modelling of a pipeline system with respect to pressure surge calculations.

It is recommended to model the top of the pipes in computer models, because the dynamic behaviour may change significantly at low pressures due to gas release or cavitation.

The modelling and input uncertainties raise the question of which model parameter values should be applied in a particular simulation. The simulation results may be too optimistic if the model parameters are selected more or less arbitrarily. The model parameters should be selected such that the relevant output variables get their extreme values; this is called a conservative modelling approach. The conservative choice of input parameters is only possible in simple supply systems without active triggers for control procedures. Table 4 lists the parameter choice in the conservative modelling approach.

Critical Scenario	Output Criterion	Model Parameters (conservative approach)
any operation (cavitation not allowed)	max. pressure and min. pressure	high wave speed or low wave speed, high vapour pressure
upstream valve closure or pump trip (cavitation allowed from process requirements)	max. pressure due to cavity implosions	high vapour pressure
upstream valve closure or pump trip	min. pressure	high friction and low suction level
downstream valve closure	max. pressure	high friction and high suction level
upstream valve closure or pump trip (surge tower present)	min. pressure and min. surge tower level	low friction and low suction level
downstream valve closure (surge tower or present)	max. pressure, max. surge tower level	low friction and high suction level
critical operation	criterion	model parameters (conservative approach)
upstream valve closure or pump trip (air vessel present)	min. air vessel level	low friction and low suction level and isothermal air behaviour
upstream valve closure or pump trip (air vessel present)	min. pressure (close to air vessel)	low friction and low suction level and adiabatic air behaviour
upstream valve closure or pump trip (air vessel present)	min. pressure (downstream part)	high friction and low suction level and adiabatic air behaviour
downstream valve closure (air vessel present)	max. air vessel level	low friction and high suction level and isothermal air behaviour
downstream valve closure (air vessel present)	max. pressure (close to air vessel)	low friction and high suction level and adiabatic air behaviour
downstream valve closure (air vessel present)	max. pressure (upstream part)	high friction and high suction level and adiabatic air behaviour
Single pump trip, while others run	max. rate of fluid deceleration	high friction and low suction level

Table 4. Overview of conservative modelling parameters for certain critical scenarios and output criteria.

If control systems are triggered to counteract the negative effect of critical scenarios (pump trip, emergency shut down), then the extreme pressures may occur at other combinations of input parameters than listed in Table 4. Therefore, a sensitivity analysis or optimisation routine is strongly recommended to determine extreme pressures in these kind of complex water supply systems.

5. Concluding remarks

Since flow conditions inevitably change, pressure transient analysis is a fundamental part of WSS design and a careful analysis may contribute significantly to the reduction of water losses from these systems. It is shown that pressure transient analyses are indispensable in most stages of the life cycle of a water system. Section 2 shows that existing standards focus on a certain maximum allowable incidental pressure, but also emphasises that other evaluation criteria should be part of the surge analysis, including minimum pressures, component specific criteria and maximum allowable shock pressures. It is recommended that pressure shocks due to cavity collapse, air-release or undamped check valve closure should never exceed 50% of the design pressure. The main contributions of this paper, as compared to existing pressure transient design guidelines, include an overview of emergency scenarios and normal operating procedures to be considered, as well as the integrated design of control systems and anti-surge devices. These will lead to a safe, cost-effective, robust, energy-efficient and low-leaking water system.

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