Corrosion Issues Caused by Changes in Pipe Cross-Sections

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ABSTRACT

Among the most detrimental corrosion phenomena observed in the power industry are those related to a sudden expansion of a fluid beyond the saturation point. The effects of such types of corrosion may be particularly aggressive due to a combination of physical factors and a variety of chemical mechanisms that could potentially be involved. Based on data collected from over one hundred inspections carried out in the power industry and refineries, this publication is aimed at building a stronger understanding of the issues to allow plant operators to predict areas of vulnerability, mitigate the risk of potential failures, and specify a correct chemical treatment program to operate their plant at its maximum level of performance and reliability.

INTRODUCTION

This article attempts to provide an overall view of the main corrosion issues related to those process conditions that occur in the saturation zone. Hence, the content is focused on patterns observed at a sudden expansion or contraction of a pipe upon the flow of water.

This type of corrosion is most likely the least understood failure in the operation of a plant due to its complex nature; in addition to the physical factors, a variety of chemical mechanisms may also be involved. Having a strong understanding of this subject allows the prediction of areas of vulnerability, the mitigation of the risk of potential failures, and the specification of a correct chemical treatment program to operate the plant at its maximum level of performance and reliability.

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BACKGROUND

As water traverses throughout a circuit of a plant, it flows across many equipment parts and devices which are essential for process control and operation. Thus, the fluid experiences continuous variations in the cross-sectional area of the pipe. As a result, the fluid is exposed to different forces that may potentially alter its thermodynamic conditions.

By principle, the conservation of energy along the streamline does not change, so in the case of a sudden change in the cross-sectional area, the fluid will transiently vaporize in order to accommodate the excess energy. There are many destructive effects that follow this phenomenon, so that the system is threatened with an incessant degradation of performance and final operational failure.

The type of damage is of two different natures:

Chemical attack: As water expands into a pressure below the boiling point, deposition of impurities will occur. In fact, these precipitates are deposits of salt compounds, which can be very aggressive to the equipment. Depending on the nature of the accumulation, the affected zone can develop several types of corrosion patterns. Hence, sodium salts can undergo hydrolysis and produce caustic corrosion. Silica precipitates to form a very hard and impervious scale, which can lead to stress corrosion cracking. Sodium carbonate or sodium chloride can be adsorbed on the surface of the metal, affecting the protective passivation layer. Under-deposit corrosion would be expected to happen in most cases [1].

Impingement corrosion: When water expands and passes through the saturation line, the formation of bubbles will follow due to the wetness of the steam and the very high velocities reached in that location. In this case the system can be exposed to a very particular type of severe degradation called "impingement corrosion."

Impingement damage is a form of erosion-corrosion, caused by the continuous impact of bubbles in a high-velocity stream on the metal surface. This can physically destroy the affected zone due to erosion and accelerated wearing. It can also break apart the protective layer of the metal and leave the location open to chemical corrosion.

This problem is frequently encountered in low-pressure (LP) drain motorized valves feeding flash tanks, spray nozzles and diffusers at bypass attemperators, orifice plates, nozzle or pitot flowmeters, LP flash tank drains to condenser, and blowdown systems. We have also observed the same type of corrosion patterns at the deaerator nozzles.

Similar effects happen at the later stages of a steam turbine since the LP steam yields enthalpy and heat capacity as it crosses the Wilson line and expands into saturation. As a result, once again, the wetness of steam combined with its high velocity will potentially erode the blades of the turbine. By the same token, centrifugal pumps can also be damaged based on the same principle. However, these particularities have a different origin, despite displaying the same type of corrosion.

ROOT CAUSE

A sudden change in the cross-sectional area of the fluid provokes a dynamic condition in which water pressure drops sharply below its boiling point and produces instant vaporization.

Since this process is adiabatic, there is no heat exchange with its surroundings; therefore, the total enthalpy remains the same. Consequently, most of the water molecules will absorb the bulk of that energy as latent heat, turning the water into steam.

Figure 1 displays an example of the pressure drop profile as a fluid goes through a sudden change in the cross-sectional area. There are two possible situations, which both differ in the way pressure recovers afterwards. Cavitation happens when downstream pressure stabilizes above the saturation line, while in flashing, downstream pressure remains below the boiling point.

P1 represents liquid water at inlet conditions of pressure, temperature, and enthalpy. Since the fluid is incompressible, its density is fixed at that given point and the total mass is conserved. As the fluid enters into the compressed area, velocity increases. Thus, regions of turbulence will develop which will subsequently cause the pressure to drop from P1 to P2. As water is forced to cross the saturation line, density falls steeply, vapor pressure drops, and the formation of bubbles occurs.

Whenever this phenomenon occurs, the system is exposed to relevant negative consequences which are explained below.

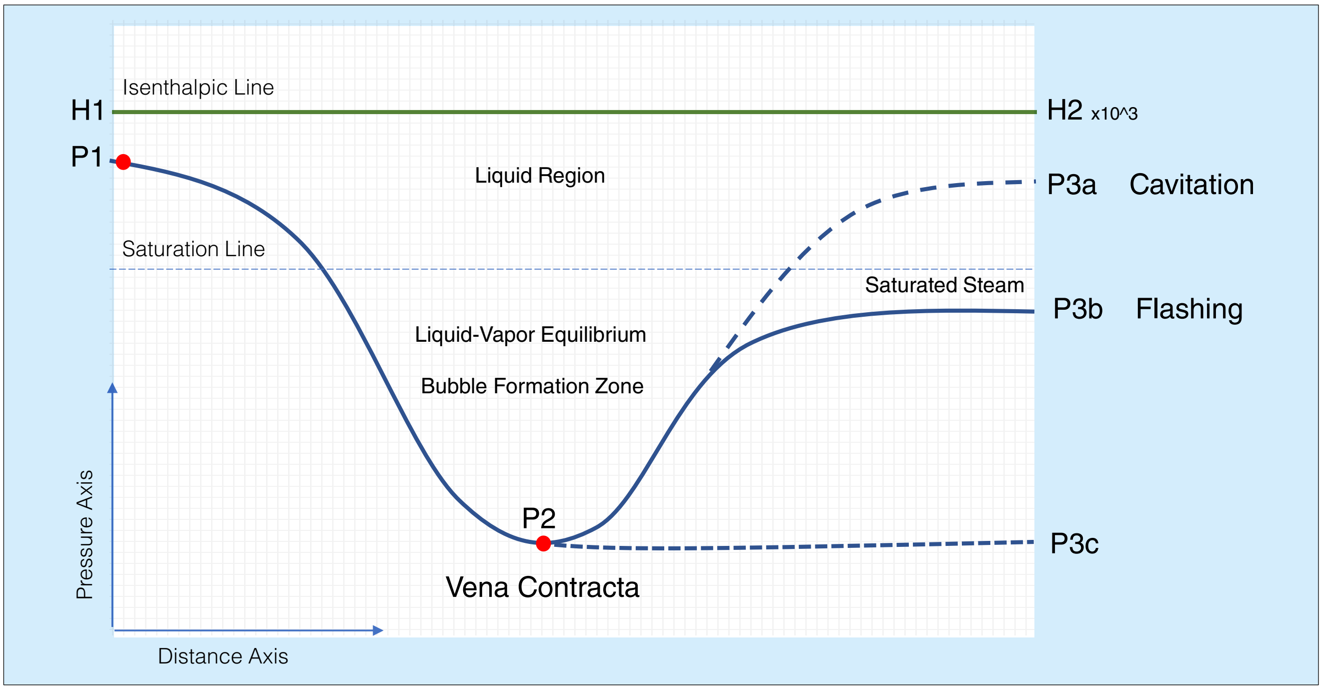

Figure 1:
General representation of the effects produced upon a fluid during a change in the cross-sectional area. Note that cavitation entails a pressure recovery above the saturation line. Flashing will happen as pressure recovers right below the saturation line. P1 = pressure before the saturation point; P2 = pressure beyond the saturation point; P3 = final pressure; H1 = initial enthalpy; H2 = final enthalpy.

CHEMICAL ISSUES AND CORROSION

It is empirically proven that the solubility of chemical species is actively dependent on pressure and temperature, among other properties. Although there is not a direct correlation to predict such a dependency, it has been observed that, for most compounds, solubility falls with a decrease in these properties.

Flashing and cavitation are very energetic phenomena, and they have the potential to break the equilibrium among the chemical species dissolved in water. It is proposed that, in the event of an abrupt loss of pressure, some ions will vaporize and escape as carryover into the steam flow, while other impurities will exceed their solubility under the given conditions and precipitate as insoluble salts.

Important note: It is relevant to clarify that the real and primary root cause of these types of problems is the high level of contaminants in the make-up water, followed by a lack of monitoring and control in the water treatment plant and neglecting to react to this situation.

Failure at the LP Bypass Attemperation System

Most prevalent harmful deposits observed in power plants and refineries are corrosion products of iron oxides, copper oxides, and related salts formed in combination with water impurities such as sodium, sulfur, phosphates, calcium, or chlorides, to mention a few.

This was the case with a new power generation facility which shut down a year after commencing operation. The reason was multiple instabilities in the LP bypass attemperation system, and a lack of full regulation in some of the control valves in the same system. The plant had been showing anomalies for several months before it went out of service temporarily.

A thorough inspection was carried out into the entire steam-water cycle, and a great deal of historical process data was carefully analyzed over the course of a few weeks. We were able to come up with the following conclusions:

- Heavy deposits were clogging the LP bypass spray nozzles.
- There was partial obstruction of the LP bypass attemperation control valve and drain motorized valves, with apparently the same type of white solid precipitate.
- Most of the condenser valves were not specified for vacuum service. Air in-leakage led to a high level of CO_2 dissolved in the system.
- A high concentration of sodium, in the form of chloride NaCl and hydroxide NaOH, was found in the make-up water, due to failures in the monitoring system.

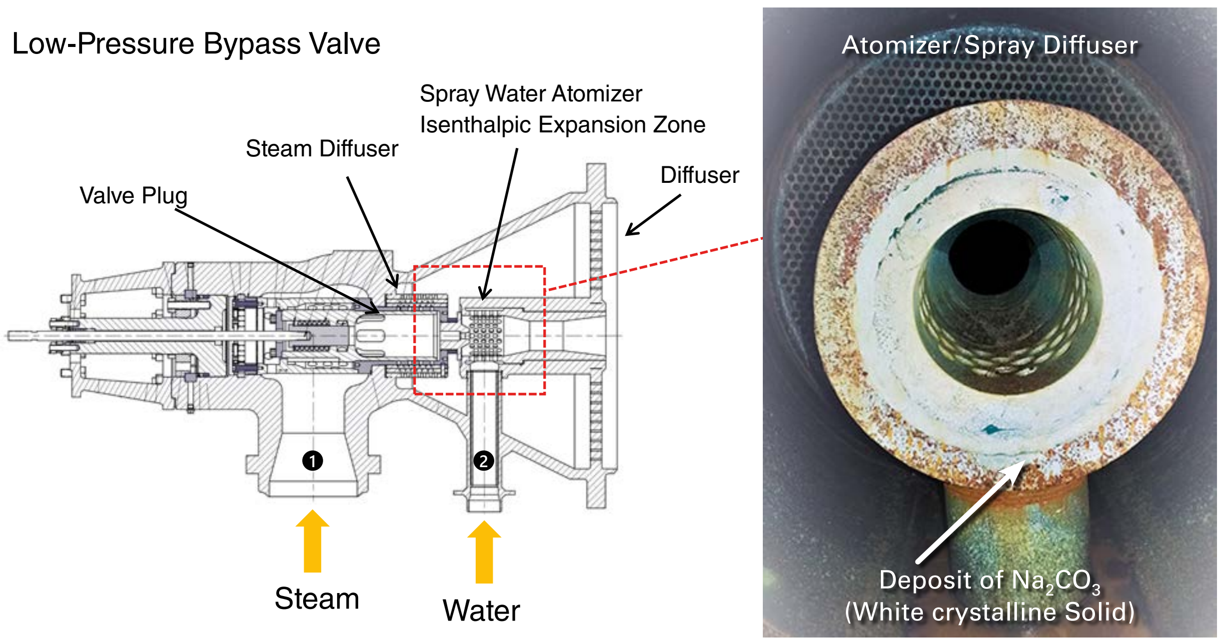

Figure 2:
Mechanical arrangement drawing for the LP bypass valve. Sodium carbonate was found at the spray water atomizer because of the low quality of the condensate. The isenthalpic expansion causes water and carbon dioxide to vaporize and brings about the precipitation of sodium carbonate, as shown in the image on the right.

Further investigation of samples collected revealed that the chemical composition of the white crystalline deposit was 62 % sodium carbonate.

After several months of continuous operation, the attemperation spray nozzles started to fail and create instabilities in the logic control as a result of the incrustations of sodium carbonate.

Figure 2 depicts the mechanical arrangement drawing for the LP bypass valve. As the main plug opens, steam initially enters the valve (point 1) via a dispersal multi-orifice spacer to prevent flow disturbance and cavitation. The steam travels through the main seat area into the outlet section of the valve. Then, the steam expands through a diffuser cage, which is connected to the mixer attemperation chamber.

Feedwater is fed through a small-bore inlet pipe (point 2) and travels directly towards a spray nozzle device. At this point, water atomization is achieved by forcing the water to flow through a small orifice cone. Since water is incompressible, kinetic energy will increase due to the sudden change in area. Consequently, the pressure will drop severely (see Figure 1) right before final expansion occurs, bringing the fluid to a rapid vaporization.

Hence, water quality is critical since nozzles are prone to clogging by the precipitation of impurities. This was the root cause of the failure at the power plant. When the contaminant level is so high that it causes precipitation at this location, extending rigorous inspection to other areas of the plant which could potentially be more damaged should be considered.

For further information, all chemical requirements are mentioned in the relevant IAPWS Technical Guidance Documents [2,3], as well as in the VGB Guideline [4].

The problem was solved by installing a double seal packing at the condenser valves to eliminate air in-leakage and connecting a redundant analyzer in the water treatment plant to help monitor and prevent future instabilities.

Derivate Problems

The reaction mechanisms described in the previous section are most likely to happen under the operational conditions of that power plant, however they are not the only possibilities. Since chemical equations are not 100 % efficient, secondary reactions may happen, such as reversible reaction processes, spontaneous mixing, or irreversible adsorption phenomena on the metal surface.

Depending on the nature of the contaminant, the solubility curve, and molecular stability, some species will precipitate as solid salts, others will go into the steam in the form of carryover and form sediment in the turbine blades, superheaters, and reheaters, and other species will attach to the metal surface and create under-deposit corrosion [5].

IMPINGEMENT CORROSION

In addition to the phenomena discussed above, pressure expansions can also lead to other varieties of subsequent mechanical problems, such as vibrations, high noise, material erosion, or wearing. These problems potentially contribute to irreversible failure, which could only be solved by replacing damaged components of the affected zones.

After an isentropic expansion, the resulting flow is a predominant mixture of vapor phase with a certain water content. This combination can be very abrasive due to the impingement of the continuous liquid droplets on the surrounding area.

Figure 3 depicts a side section of a failing control valve. Five different zones throughout the flow path of the valve can be recognized. Hot condensate enters the body of the valve at a given initial temperature and pressure P1 (Zone 1). As the plug is lifted, the valve seat opens to let hot condensate go through (Zone 2). This area is the so-called "vena contracta" (see Figure 1), in which the cross-sectional area is at its minimum, the velocity accelerates to its maximum value, pressure falls below the saturation line, and water partially vaporizes while bubbles formation occurs.

This is the area that is most vulnerable to impingement corrosion. Figure 4 shows the effects of impingement on the valve plug in a high-pressure drain system. Notice the similarity in appearance to those effects that are caused by the presence of abrasive solids. The system did not contain any solids at all, however.

The high-velocity stream generates areas of low pressure P2 (Zone 3 and Zone 4), due to the development of turbulence. These are the regions susceptible to precipitation, where most of the salt deposits which created obstruction in the plug passage were found during the inspection.

Finally, the fluid pressure partially recovers to P3 (see Figures 1 and 3) and the fluid exits the valve at new thermodynamic conditions.

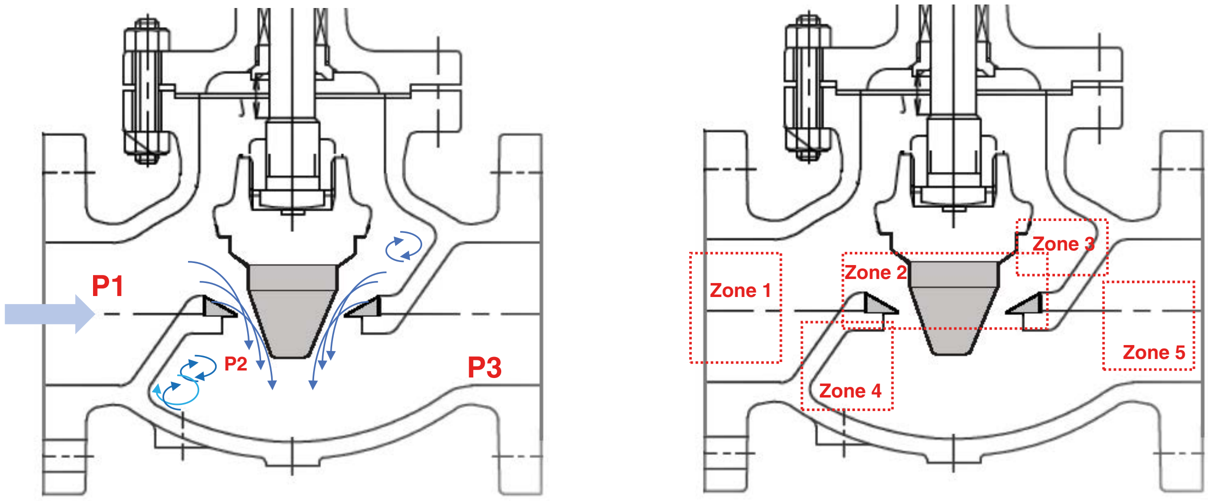

Figure 3:
Drawing of the drain control valve. The lack of sealing was due to erosion in the plug and the seat of the valve (Zone 2). The damage caused a loss of regulation and instabilities in the logic control loop.

We took the photo during the start-up of a power plant. The LP attemperation control valve and most of the high-pressure drain valves were severely eroded. All of them presented the same corrosion pattern. Figure 4 shows the effects of cavitation, but it also displays certain signs of solid particle erosion, which indicates an ineffective pre-operational cleaning. We managed to repair some valves and lapped the affected zone, but others inevitably had to be replaced.

Figure 4:
The contour of the valve plug surface next to the seat ring is the most critical part for preventing physical damage. If the outlet pressure of the valve is less than the vapor pressure, flashing occurs, and erosion will follow.

CONCLUSIONS AND RECOMMENDATIONS

When hot condensate or feedwater pressure expands sharply below the boiling point of water, the system could potentially be exposed to a variety of corrosion damage phenomena at this precise location. As water crosses the saturation line:

1. The concentration of certain impurities can exceed their maximum solubility in water and lead to the precipitation of solid salts. These compounds can accumulate and bring about further corrosion or mechanical problems.
2. Steam water bubbles will continuously hit on the metal surface and create erosion, wearing, and a high degree of intensive degradation.

It is necessary to carry out a detailed analysis to identify any critical zone subject to experiencing flashing or cavitation. In this case, first the nature of the problem must be understood, then a comprehensive plan should be prepared involving the following points:

- Improvement of the chemistry cycle
- Specification of suitable materials for aggressive conditions
- Sacrificial devices (i.e. cage seat in control valves, orifice plates)
- Valve design selection

Chemistry Conditioning

It is clearly advantageous to have a rigorous balance in the chemistry cycle of the plant and reduce impurities in the boiler water. Selecting an optimum water treatment protocol is a critical task in achieving the correct conditioning values. Reaching this goal is based upon having a strong understanding of the nature of the deposit, analyzing the chemical compatibility with plant materials, studying the influence of the effects of impurities, determining the curve of solubility for each species, and reviewing the process conditions of the location at which they were found.

Enhancing the chemistry cycle will minimize the presence of deposits, precipitations, and related chemical corrosion damage. However, the mechanical effects derived from impingement will still occur. Therefore, depending on the type of damage, other approaches must be added to this strategy.

Material Selection

Selecting the right material is critical to avoiding both physical and chemical effects deriving from corrosion. Stellite is a cobalt-based alloy (with around 30 % chromium content) specially designed for wear and corrosion resistance, and it is also able to perform perfectly at high temperature ranges. This material is commonly the preferred material for extreme service applications. In this case, the plug was made of austenitic stainless-steel type 316SS. It was not reinforced with an external protection of stellite or a hardener trim shield to protect the seat surface. Despite the excellent resistance properties of 316SS, they were not enough to withstand the conditions the material was exposed to [6].

Material selection is directly related to the long-term consistency of the power plant, however sometimes this strategy can exponentially increase the overall cost of the project. Also, while it mitigates the risk of corrosion in the expansion zone, it does not prevent precipitation from happening. Thus, the area is exposed to accumulation and potential obstructions as long as other solid impurities can travel through the system and extend the damage to other locations in the plant.

Relocation of Expansion – Sacrificial Plates

Another possibility to minimize the corrosion effects from a sudden expansion can be approached by relaxing the aggressive effects of the pressure drop at this particular location. Installing a sacrificial orifice plate downstream of the point of expansion would increase the backpressure. Consequently, the pressure drop would then remain above the saturation line. Flashing or cavitation would probably still occur, but now the damage would be on the orifice plate, which is cheaper and easier to replace than a valve.

Valve Design Selection

In the case of valves, it is possible to reduce the degradation effects by using a multistate trim or selecting an angle body configuration which would allow the energy released during the expansion to gradually dissipate.

Another possibility for approaching an alternative solution is to install a reverse flow alignment plug which would displace the restriction area past the valve seat. This way the flashing and high-velocity flow would occur right after the plug [7].

Sometimes the best possible solution does not come from just one of the above strategies but requires a combination of several of them.

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