

VDI 2035, Part 2

Guideline for Prevention of Damage in Water Heating Installations

Original document published by the Society of German Engineers
Summary by Elysator Engineering AG

1. Preliminary Remarks and Background

VDI 2035, Part 2, published in August 2009, is *the* authoritative guideline in Europe for prevention of damage in water-based heating systems. As of November, 2012 it is applicable as a European Standard for all of the European continent, as cited by the European Committee for Standardization. The inclusion of more detailed water requirements, with reference to VDI 2035, is the most significant change to the 2012 update of European Standard EN 12828. This change is an indication of the growing awareness, among hydronic heating professionals in Europe, of the causes of corrosion and the means of corrosion prevention.

This guideline applies to all water heating installations where flow temperature under normal conditions is not intended to exceed 100°C (212°F).

2. Corrosion Prevention Basics

The likelihood of corrosion damage is limited when the following parameters are met

- Proper planning and commissioning
- Proper sealing of the system from oxygen entry
- Proper design of the pressure control system
- Adherence to guide values for O₂ content, electrical conductivity, and pH of heating water
- Routine maintenance

The composition of the heating water is of central importance for corrosion and its prevention. The chief characteristics which determine corrosion are as follows

- 1) Dissolved Oxygen content
- 2) Electrical conductivity¹
- 3) pH

For prevention of damage, these are the three principal factors which need to be controlled. The guide values given in section 5 must be complied with.

3. Causes of Corrosion

Corrosion is an electrochemical process whereby two partial reactions occur concurrently.

In the anodic partial reaction, dissolution of the metal produces metal ions and electrons. These liberated electrons are consumed during the cathodic partial reaction.

¹ In this document, whenever the word 'conductivity' is used alone, it is intended to mean '*electrical* conductivity', (in contrast to thermal conductivity).

If anode and cathode stabilize in different locations, as is typical in hydronic heating systems, the result is local corrosion, or pitting.

A. Oxygen

Corrosion reactions in hydronic heating systems are primarily determined by the presence of oxygen in the heating water. Thus, oxygen concentration in the heating water should be kept as low as possible.

Oxygen virtually always enters the system during filling procedures. This is because normal drinking water contains approx. 8-11 mg of dissolved oxygen per liter of water. However this quantity is generally used up (through corrosion processes) within a short period of time without significant damage occurring. However, oxygen can be harmful if it is able to consistently enter the system from the ambient air. This may occur due to a number of factors, such as partial formation of underpressure in the system, air entrapment during filling and top up procedures, direct contact between system water and outside air, and oxygen diffusion through permeable components such as seals, plastic pipes, diaphragms and hoses.

If negative pressure arises consistently in the system, corrosion damage due to large quantities of oxygen will be virtually unavoidable.

If automatic top-up systems are used, they should be adequately monitored so as not to allow overly high top-up quantities.

B. Electrical Conductivity

Electrical conductivity is the second chief factor that influences corrosion in hydronic heating systems. As a rule, lower conductivity decreases the potential for corrosion to occur. Dissolved oxygen and conductivity are inversely related such that at a lower conductivity level, the system can tolerate comparably higher oxygen levels without increased corrosion occurring. Similarly, at a high conductivity level, the system will experience corrosion, even at a relatively low oxygen level.

C. pH

The third factor that drives corrosion is pH value. An alkaline pH is advantageous to most metals in hydronic systems (with the exception of aluminum and aluminum alloys, which have special requirements, as outlined in Section 4.C.). In normal operation, it is typical to see a rise in pH due to a process called self-alkalinization. Because of this natural process, it is not necessary to alkalinize the water in most cases.

4. Corrosion Damage

A heating system will typically be composed of metallic and non-metallic components. Failure or damage of one given component may cause further damage elsewhere in the system. Therefore, understanding of interactions between water parameters and system materials helps heating professionals prevent, properly diagnose, and fix problems.

All metals—with the exception of gold, platinum, and palladium—naturally experience corrosion. However, a number of metals used in hydronic heating systems have the ability to form protective layers or films that help protect them from further corrosion. These films are formed through

corrosion processes—that is, oxidation of the metal. But once a film completely covers the surface of a metal, as long as it is undisturbed, the film will normally protect the underlying metal from further corrosion. However, protective films of various materials have optimum resistance under differing chemical conditions. Copper, for example, integrates easily into hydronic heating systems, while aluminum components require special consideration.

Corrosion itself is an electrochemical process, and as such occurs in electrochemical cells, involving an anode and a cathode. One location is able to function as an anode and another as a cathode primarily due to local differences in the composition of the material as well as water chemistry conditions (dissolved O₂ content, pH, or other factors). Anodic and cathodic locations can also occur within the same piece of metal when thermal or mechanical stress is applied. The greater these local differences, the greater the electrode potential, and therefore the greater the potential for local corrosion. Uniform corrosion, however, may be much less damaging, and may not necessarily affect lifetime of a system. The rate of corrosion is also influenced by electrical conductivity. Low electrical conductivity impedes the flow of charged particles necessary for corrosion; high conductivity facilitates the process.

Protective layers of metals can be damaged by both chemical and physical processes—e.g. low pH, vibration, high flow, and thermal stress. Too much oxygen can also prevent normal formation of the protective film. Defects in the protective film permit local corrosion to the damaged area. Due to the natural process of a galvanic cell (i.e. an electrochemical cell involving an anodic site and a cathodic site), the corrosion current will always be focused on the weaker, damaged area. This is the site where pitting will occur.

Non-metallic materials typically fail either due to incorrect handling during installation (e.g. insufficient sealing pressure), overstretching of polymers due to thermal expansion, improper material selection, or chemical factors such as excessively high pH or addition of chemical inhibitors.

A. Unalloyed and low-alloyed ferrous materials

Unalloyed and low-alloyed ferrous materials (black steel, carbon steel, cast iron) corrode when they are in the presence of both water and oxygen. The resulting corrosion product is an iron oxide—most typically either iron (III) oxide (Fe₂O₃) or magnetite (Fe₃O₄). Corrosion to iron is determined primarily by oxygen content in the heating water.

The most common type of corrosion for low alloyed ferrous materials is local pitting, where trough-shaped areas form and are covered or surrounded by corrosion by-products. These corrosion by-products may cause further harm to the heating system by clogging underfloor radiant tubing and fittings, harming circulators, or depositing in the boiler, which causes boiler damage—in particular to heat exchangers and pumps.

Galvanized steel is unfavorable in hydronic heating systems because the zinc coating easily flakes off at temperatures over 140°F, and, when dissolved in water, behaves similar to a water hardener.

When using unalloyed and low-alloyed ferrous materials, oxygen should be kept as low as possible, and pH should be maintained between 8.2 and 10, with an optimum pH range of 8.5-9.5. Low salt content will also help to inhibit corrosion.

B. Copper and copper alloys

Copper and various brass (copper-zinc) alloys are largely resistant to corrosion damage as long as pH stays within the range of 8.3-9.5 and oxygen content is low. Within this pH range, and in the presence of low oxygen levels, copper typically forms copper oxide (Cu_2O), which functions as a protective layer against further corrosion.

At flow rates (or local turbulent zones) exceeding 2 m/s, erosion to copper may occur. This form of corrosion, however, is most common in conjunction with a constant supply of oxygen.

Copper alloys can also be vulnerable to stress corrosion cracking if tensile stresses exist in combination with the presence of nitrogen compounds, such as ammonia (NH_3) or ammonium (NH_4^+). These compounds may be formed by the reduction of nitrate.

Brass (as a copper-zinc alloy) may be subject to dezincification under certain water conditions. This occurs primarily in water containing oxygen. However, in areas of low pH, selective corrosion to zinc can occur even in the absence of oxygen. Dezincification causes a substantial loss in strength of the metal.

In systems with a constant supply of oxygen, damage is observed when sulphides are present. Hydrogen sulphide (H_2S) can convert normal copper oxide films (Cu_2O), which offer protection against corrosion, to copper sulphide films (Cu_2S), which offer no such protection. Copper sulphide films take the form of a black crystalline covering. Sulphides may occur in the system either as a result of sulphate ions in the fill water, through microbial processes of sulphate-reducing bacteria, or chemically (for example, through introducing the oxygen-scavenging agent sodium sulphite— Na_2SO_3). Sodium sulphite causes formation of hydrogen sulphide, which increases likelihood of corrosion.

If water samples containing sulphides are mixed with dilute acid, they will produce a characteristic odor of rotten eggs.

C. Aluminum and aluminum alloys

Corrosion to aluminum is primarily determined by the pH value of the heating water. In the presence of water within the pH range of 6.5-8.5 aluminum is able to form a protective layer of aluminum oxide, which protects the underlying metal against further corrosion. This layer is broken up, however, in acidic water with a pH below 6.5 or in alkaline water with a pH above 8.5. At these pH levels (<6.5 or >8.5), corrosion damage is likely to occur even in oxygen-free water.

Systems containing aluminum are best operated at a low saline level (electrical conductivity <100 $\mu\text{S}/\text{cm}$) and without the use of chemical inhibitors or electrochemical devices. If aluminum is used in conjunction with other metals, such as steel and copper, the recommended pH of system water is 8.2-8.5. Since maintaining this pH range will likely be unfeasible, low electrical conductivity is recommended to limit corrosion damage.

Flow velocities >2m/s may also cause erosion to aluminum.

D. Stainless steel

Due to their chromium content, stainless steels typically form a chromium oxide film in the presence of water and oxygen, which protects against further corrosion of the metal.

Common stainless steel alloys experience corrosion in water with a high concentration of chloride ions. This can lead to pitting corrosion, or, in conjunction with tensile stress, to stress-corrosion cracking.

Only certain stainless steels which contain molybdenum, such as type 316L, are resistant to damage in the presence of water with a relatively high chloride content.

E. Plastics and Seals

Oxygen molecules (O_2) are small enough to diffuse directly through polymer chains in standard plastic and rubber. Due to the difference in partial pressure on either side of plastic tubing, oxygen from the outside air will seek entry into the heating water. Thus, oxygen entry through plastic components should be restricted as much as possible. Changes in temperature can affect solubility of oxygen in the heating water—gases being more soluble in water at lower temperatures—however, it is the difference in partial pressure that drives oxygen diffusion. This is in accordance with Henry's law. An oxygen-barrier is therefore recommended.

If seals are incorrectly selected or improperly fitted, water in the sealing area will escape from the system. Since the leak will be slow, water will evaporate upon escaping, which leads to accumulation of water constituents at the outside edge of the seal. This can lead to corrosion from the outside.

Seals and packings are vulnerable to excessive alkalinity of system water, therefore a pH level above 10 should be avoided. Elastomers and plastics can also be damaged by chemical inhibitors, coating amines, and oil-like substances.

The use of coatings, such as zinc or epoxy resin, or enameling, is not recommended.

F. Galvanic Corrosion (contact corrosion)

In mixed installations, involving different types of metals in contact with one another, galvanic corrosion may take place. This occurs when two different metals are in direct contact in the presence of both oxygen and a fluid to carry ions (called an electrolyte). This form of corrosion is driven by the difference in electrode potential between two different metals. When the metals come into contact, the less noble metal acts as an anode, giving up electrons and corroding at an accelerated rate. The more noble metal functions as a cathode, consuming electrons sent from the anode, and being thus protected from the process of corrosion.

The probability of damage due to galvanic corrosion decreases as water becomes less conductive. Low electrical conductivity is therefore advised.

In general, the oxide of any given metal will be more noble than the base material. For this reason, any defects or breaks in a protective metal oxide film will create a galvanic cell—the metal oxide functioning as a cathodic site and the exposed metal functioning as an anodic site. This causes local corrosion to the metal.

G. Gas bubbles and gas cushions

Gas bubbles arise at locations of lowest pressure (e.g. the highest point of the installation) or highest temperature (e.g. heat generators). They are then transported to locations with low current velocity, where they can interrupt water circulation and, due to their low thermal conductivity, hinder heat transfer. This causes reduced output, flow noise, and areas of local overheating.

5. Corrosion Protection

To prevent damage from corrosion, the three fundamental parameters of water composition—dissolved oxygen content, electrical conductivity, and pH—should be controlled.

Oxygen content and electrical conductivity are related such that lower conductivity permits relatively higher O₂ without additional corrosion. Similarly higher conductivity may allow for corrosion damage even at relatively low O₂ levels. As such the following guidelines are recommended:

- In low-saline operation—that is, operation where electrical conductivity of system water is less than 100µS/cm—dissolved O₂ shall be less than 0.1 mg/l.
 - In low-saline operation, pH value of water shall remain in the range of 8.2-10.
- In saline operation—that is, operation where electrical conductivity of system water is in the range of 100 µS/cm-1500 µS/cm—dissolved O₂ shall be less than 0.02 mg/l.
 - In saline operation, pH value of water shall remain in the range 8.2-10.

A. Prevention of Oxygen entry

Care should always be taken to limit oxygen entry as much as possible. Normal air contains approximately 78% Nitrogen and 21% Oxygen. However, O₂ molecules are smaller, and permeate faster than N₂. Concentration of O₂ in normal water is 8-11 mg/l. This concentration is approximately 100 times higher than maximum O₂ levels in low-saline operation, and approximately 500 times higher than maximum concentration in saline operation.

In systems with overhead open expansion vessels, air is able to enter the system easily. Systems with closed diaphragm expansion vessels limit air entry and are therefore recommended. Problems may occur, however, under the following conditions:

- If the expansion vessel is improperly sized and cannot absorb the expansion volume of water.
- If the pressure in the expansion vessel does not match the static pressure of the heating system.
- If the system contains too little water, and system pressure is therefore too low
- If there is a significant amount of tubing that is non-oxygen-tight

It is recommended, therefore, that systems first be sealed from large-scale oxygen entry. If oxygen entry is inevitable, other solutions must be sought. Physical air-removal devices are not highly effective, often permitting aeration as well as air removal. Chemical and electrochemical solutions are discussed in sections D and E.

B. Recommendations for Electrical Conductivity

Electrical conductivity—often equated with ‘salinity’—is a measurement of water’s ability to transport charged particles. Since the electrochemical process of corrosion consists of a movement of ions through water, electrical conductivity is essentially a measurement of the potential rate of corrosion. Conductivity should therefore be kept as low as possible. An appropriate level is <100µS/cm.

Conductivity is primarily determined by the mineral content of the fill water. However any additives, such as oxygen scavenging agents, will increase conductivity of system water.

A measurement of electrical conductivity is distinguished from a measurement for ‘hardness’ in that conductivity takes into account all ions in a given sample, while ‘hardness’ only considers cations that cause scaling, such as calcium. Demineralization of water will *also* inhibit the formation of scale, as it removes all mineral ions, including those that cause scaling. Water softeners, which exchange so-called “hard ions” such as Ca^{2+} and Mg^{2+} with softer ions such as Na^+ or K^+ , reduce scaling but do not necessarily reduce electrical conductivity, and are therefore not suitable as a means of treatment for prevention of corrosion.

Note: Oxygen-free water has a tendency to absorb atmospheric oxygen from its surroundings. This is due to the atmosphere “pressing” the gas molecules into the system, in accordance with Henry’s Law. However, this phenomenon only applies to gasses. No similar phenomenon occurs with regard to minerals (dissolved solids). Water has NO tendency to absorb minerals from its surroundings. Systems using demineralized water are consistently observed to exhibit improved resistance to corrosion, and demineralization is therefore recommended for fill water whose conductivity exceeds $100\mu\text{S}/\text{cm}$.

C. Recommendations for pH

The pH value of heating water should be slightly alkaline—that is, within the range 8.2-10 (at 77°F). However in most cases there is no need to alkalinize fill water. This is because of the natural process of self-alkalinization, which is consistently observed in hydronic systems. Due to this process, system water should stabilize within the recommended range of 8.2-10 within a few weeks of operation.

When evaluating pH, heating professionals should take into account the metals used in a system. If aluminum is present, pH should ideally not exceed 8.5, however in most cases a pH value under 9 is sufficient to avoid corrosion damage to aluminum.

The pH value of system water may drop as a result of insufficient rinsing of antifreeze agents or from addition of chemicals (e.g. ascorbic acid). If system water fails to self-alkalinize after 2-3 weeks, it should be tested after 8-12 weeks. If pH value is still below the recommended range, contractors should alkalinize water by some other means. This may be achieved by the insertion of a sacrificial anode to the system, or by use of chemical alkalizing agents. In the latter case, contractors should note that overdosing with trisodium phosphate will further mineralize water and create sludge. Alkalinization with ammonia or ammonifying compounds should also be avoided, due to the added risk to copper and copper alloys.

D. Chemical Treatment and Corrosion inhibitors

Water treatment involving chemical additives should be restricted to rare and exceptional cases. Corrosion inhibitors raise conductivity of system water and, in the event of overdosing or underdosing, lead to additional corrosion. Underdosing can cause pitting corrosion. Overdosing can damage elastomeric materials, such as the diaphragms of expansion tanks, as well as face seals at pumps. It can also cause deposits, resulting in clogging, and can accelerate formation of biofilms, which cause further corrosion.

The use of sodium sulphite as an oxygen scavenging agent puts copper at special risk due to the formation of sulphide ions and the increase in conductivity. Hydrazine is highly toxic and should not be used. Organic oxygen-scavenging agents should be avoided, since they contribute to the formation of biofilms.

The use of antifreeze agents does not fall within the scope of this guideline.

E. Electrochemical Treatment

Electrochemical devices may prevent corrosion to system metals through use of sacrificial anodes or other electrochemical means. Such devices should be located downstream from the point of oxygen entry and should receive constant through-flow.

When ‘active’ metals (such as magnesium or zinc) are used, the device should allow for by-products of the anodic reaction—e.g. magnesium oxide—to be trapped and removed.

F. System Design, Planning, & Maintenance

Components that are vulnerable to oxygen permeation should be avoided. If these components are inevitable, some means of limiting oxygen should be employed.

The most important element of maintenance is to check system pressure, to ensure that states of underpressure do not arise, which permit entry of oxygen.

Conductivity and pH value should be measured and documented at least once per year. If values are significantly outside of the recommended range, system water should be flushed and refilled with demineralized water and pH should be monitored.