Practical information on electrochemical corrosion of water pipelines

Praktyczne aspekty elektrochemicznej korozji przewodów transportujących wodę do picia

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Some aspects of drinking water ductile iron pipeline's electrochemical corrosion are discussed in this paper. We include: the impact of water parameters on its corrosivity, the relationships between the cement mortar lining and head loss to flow, pipeline diameter, and the total alkalinity of water, lifetime of the cement mortar lining. The discussion is limited strictly to some practical remarks with little theoretical background.
Keywords: electrochemical corrosion, corrosivity of water, mortar lining of pipes

Opisano wybrane aspekty elektrochemicznej korozji przewodów wodociągowych. Dyskusja ta dotyczyła: oceny korozyjności wody na podstawie jej parametrów fizyczno – chemicznych, wpływu wyprawy cementowej rurociągów na opory przepływu, związków pomiędzy jakością wody i oporami przepływu oraz trwałością wyprawy.
Słowa kluczowe: korozja elektrochemiczna, korozyjność wody, wyprawa cementowa przewodów rurowych

Introduction

Corrosion of ductile iron and steel pipes creates significant expenses of repair, renovation, and replacement of pipelines. Corroded pipes cause unnecessary losses of water. If a significant part of pipes underground is constructed of ductile iron or steel elements, then the measurement of ferric concentrations in outflows from the treatment plants and more distant points in the pipe network can be used to evaluate the speed of corrosion. Also, since ductile iron is typically used in large pipes, the flow of electric current and the electric potential can be measured to predict the intensity of corrosion processes. Some known facts about water and soil can be also useful in predicting the danger of rapid electrochemical corrosion. These aspects are the subject of the discussion presented below.

Water parameters which determine its corrosivity

The corrosivity of water in relation to both iron and concrete is particularly high for acidic waters containing: chlorides, dissolved sulphates, and high oxygen concentration. Thus, for water pH values below 6, pipes of steel or cast iron should not be recommended. Natural corrosion inhibitors include phosphates and silica, the second forming difficult-to-remove boiler scales. Preliminary assessment of the corrosivity of water in relation to steel and concrete can be carried out according to DIN 50930:1993 "Corrosion of metals. Susceptibility of metallic materials to water corrosion". Over time, this standard has been extended to six parts.

Role of pH in corrosion

It is undeniable that acidic waters are highly aggressive and that higher pH causes thickening of the H_2 polarization layer, slowing corrosion. However, in older pipelines, high pH values adversely affect the composition of a natural protective layer. From all products of electrochemical corrosion in ductile iron, the best protective properties are exhibited by $FeCO_3$ (siderite). At high pH values, dissolved iron ions quickly oxidize in accordance with the equation of the oxidation kinetics:

$$d[Fe^{2+}]/dt = -K(T) \cdot [Fe^{2+}] \, [O_2] \cdot [OH^-]^2 \cdot (\beta)^{1/2} \quad (1)$$

in which K(T) is the oxidation constant, T is the absolute temperature, and is the buffer capacity. The concentration of hydroxyl ions $[OH^-]$ is raised to the second power, so the oxidation of iron strongly depends on the pH of water. The activity of H_3O^+, and consequently the pH, are related to the activity of hydroxyl ions through the ionic product of water. In contrast to bivalent iron, which when the solubility is exceeded in waters of transient hardness precipitates as $FeCO_3$, trivalent iron precipitates as hydroxide or inorganic complexes with hydroxyl ions, and therefore does not build a stable protective layer and may cause problems with the brown-red water after hydraulic hammer. Thus, the role of pH is twofold, and, therefore, rather neutral or only slightly alkaline drinking water is recommended (pH≈7.2-7.8).

Effect of cathode and anode reactions on water pH

Continuous microbiological risk is caused by the growth of biofilm on the walls of water pipes and steel corrosion products. According to Sontheimer, H., Kolle W., Kuch A. [17,18], pipeline corrosion products and deposits formed as a result of water instabilities have very different mechanical properties. These reactions have no effect on the pH of the water flowing through the pipe but the changes in pH are important for water trapped in the pores of corrosion products and scales attached to the pipe walls. For the bigger differences in pH of these waters, the faster are the corrosive processes. In the new

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pipes, the cement mortar lining maintains a pH of about 12 in contact with the internal wall of ductile iron conduits.

Impact of buffer capacity

Differences in pH of water trapped in the sediment or the protective layer of corrosion products covering anode and cathode areas, are larger for smaller buffer capacity of water. This capacity depends on the total alkalinity and pH. The buffer capacity is defined as the number of moles per litre of strong monobasic acid or strong base with one OH^- group required to produce an increase or decrease of one pH unit in the solution. Depending on the pH value, the buffer capacity increases or decreases as the pH increases. However, for the same pH value, but for the lower total alkalinity, always the buffer capacity is smaller. A smaller buffer capacity means a greater potential difference between the anodic and cathodic areas, which accelerates corrosion. Thus, pure water with low total alkalinity, and therefore usually also with low hardness, is corrosive.

Concentrations of chlorides and sulphates

Both sulphates and chlorides speed up the electrochemical corrosion of steel, grey iron, and ductile iron pipes transporting drinking water. High electrical resistivity is typical for waters of weak corrosion properties, if the total alkalinity is also high. Microorganisms can cause microbiologically induced corrosion of metals. Very often leakages of pipelines are caused by pit corrosion occupying small surface area, but of high speed of penetrating depth. Water can also contain natural corrosion inhibitors, such as phosphates or silica. Also, phosphates are often added to water in treatment plants to inhibit corrosion in the distribution system. However, phosphorous play a role of a nutrient for microorganisms from the biofilm growing on inner pipe walls, so this method is not always advised for protecting pipelines transporting drinking water. Phosphorous from phosphates is easily accessible to microorganisms.

Composition of the protective layer

Microbiological risk is caused by the growth of biofilm on the inner pipes wall, including ferric corrosion products. According to Sontheimer, H., Kolle W., Kuch A. [17] pipeline corrosion products and deposits formed as a result of water instability have very different mechanical properties. Natural protective layers forming on the walls of steel

and cast-iron pipelines are on the surface composed of $FeOOH$, MnO_2, $CaCO_3$, $CaSO_4 \cdot 2H_2O$, α-$FeOOH$, Fe_3O_4, deeper composed of α-$FeOOH$, γ-$FeOOH$, $FeCO_3$, FeS, $Fe_3(PO_4)_2 \cdot 8H_2O$, $FeCO_3$, and at the ductile iron matrix surface level of $FeCO_3$, FeO_x, C (in the form of graphite), SiO_2, Fe_3P. The composition of these layers depends on the composition of water, its redox potential, and the pH. Relationships between water quality parameters and the composition of these layers is summarized in detail in the sterhaus' dissertation [13]. The biofilm is made of polysaccharides, a polymer excreted outside some microorganisms, such as bacteria, algae and fungi. Polysaccharides bond microorganisms to the pipe wall and protect them against disinfectants.

Sediment transport in water pipes

Average shear stress in flowing water at the pipeline wall can be calculated from the formula (2) [9,15]:

$$\tau = 4 \cdot D \cdot \rho \cdot g \cdot S \qquad (2)$$

in which D is the internal diameter, ρ - density of water, g - acceleration due to gravity, and S - hydraulic slope. So, if the hydraulic slopes are the same average shear stress values at the pipeline-water interface would increase in proportion to the inner diameter of the pipe. Mains with a larger diameter should be operated at higher economic flow speeds but the hydraulic slopes that correspond to the higher economical velocities of flow are still smaller. Therefore, the average shear stress values in pipes of larger diameters are higher, but less than proportionally to the diameter. Because of that sediment transport can be observed from large diameter pipes to smaller diameter pipes.

Periodic problems with "red water"

The following causes of periodical brown-red water occurrence are listed by Li et al.[11]: corrosion of steel or ductile iron, development in the distribution systems of ferrous and manganese bacteria, extended water retention time in the pipelines, low flow velocity and poor technical condition of connections.

Impact of indoor installations on network corrosion

According to the electrochemical series, the metals connected to each other in water environment will form sequentially from the left to right of the anode in the following order: Mg: Zn: Fe: Cu. Because of that electrodes containing magnesium are used in the

cathodic protection of kitchen water heaters, zinc coatings ensure uniform corrosion of steel and ductile iron surfaces covered with it, preventing formation of pitting corrosion. Contrary to galvanizing, copper coating of ferric containing water pipes is not allowed, because then the copper surface would become the cathode, and accidentally exposed fragments of steel or cast iron become the anode. This would lead to corrosion pitting and leaks. Copper is a relatively expensive material, but because of low equivalent sand roughness and relatively high corrosion resistance quite often used in indoor water plumbing. As long as a connection with high electrical resistance will not be used between steel or cast-iron pipe underground and the copper indoor plumbing, it is the copper that generally constitutes the cathode, and a steel or cast iron pipe in the street - an anode. So, the use of copper installations increases the corrosion rate of the ductile iron or steel water supply pipes from streets. However, anode areas occur also locally in copper installations releasing copper ions into the water. So people living in buildings of copper plumbing are advised to use the water for hygienic purposes in the morning, and then collect it for drinking and food making. Since the released copper partially settles on the walls of steel and zinc, it is necessary to avoid the use of galvanized steel pipes behind copper elements. Heat exchangers usually create similar problems.

Welded and socket connections

Ductile iron pipes are socket-joined while steel pipes can be also socket-joined, but more often they are welded. Steel pipes are usually somewhat more expensive than ductile iron pipes, so they are applied when welded connections are required because of unstable soil. During electrochemical corrosion the intensity of electric current indicates the corrosion rate. The welds are highly conductive; therefore currents can flow through the entire pipeline, which is a phenomenon undesirable and poses a risk of intensive electrochemical corrosion. This disadvantage is at the same time an advantage, as welded steel pipelines are ideal for cathodic protection, while socket joints make it very difficult to use. However, making welded joints is arduous and requires removing a thin ring of inner cement mortar lining. For pipes of diameters up to 600mm these uncovered connections are to some extend protected by a self-repairing mechanism – solving and precipitating of calcium carbonate. For pipelines of 600mm and larger diameters additions of cement mortar lining from the inside can be made by hand.

New and cemented pipelines

Immediately after constructing of a steel or a ductile iron pipeline, the cement mortar lining is in contact with water for the first time. As a result, the lime base dissolves, raising the pH value and finally increasing the solubility of some heavy metals, including aluminum and chromium as well as arsenic, barium and cadmium. The situation is similar after cementing steel or gray iron old pipes. Some requirements for pipes cementation are described in the following standards: ISO 4179: 1985, PN-92 / H-74109, American Water Works Association Guidelines C104. According to ISO 4179 the following minimal thicknesses of the cement lining are requested: for the diameter DN 100-350 mm lining thickness d = 3 mm, for DN 350-600 mm d = 5 mm, for DN 700-1200 mm d = 6 mm, for DN 1400-1600 mm d = 9 mm. The aluminum content in the cement depends on its type and varies within 5% up to 36% by weight, based on Al_2O_3. The tendency of releasing aluminum from the cement mortar lining depends not only on the composition of the cement, but also on the quality of flowing water. Especially a lot of aluminum is initially released from cement coatings in low-alkaline soft waters [3,10,12,14, 20]. The procedure of computing the calcium carbonate equilibrium in water and the Langelier Saturation Index with and without taking into account inorganic complexes of calcium and magnesium is described elsewhere [2,5,6,7,8], as well as the calculation of the water buffer capacity, which value is necessary for predicting the final pH after reaching the equilibrium in respect to $CaCO_3$. This pH is required for calculating the solubility of Alum.

Berend and Trouwborst [3] described the case of conveyence of water with low total alkalinity and hardness and a negative LSI Saturation Index (relative to calcium carbonate) by ductile iron pipeline internally protected with a new cement coating. The length of the conduit in this study was 2600m. During extremely slow flow, at contact time of more than two days, the concentration of aluminum was observed to increase from 5 µg / L to almost 700 µg / L after slightly more than two months after starting the operation of the pipeline. Recommended concentration of aluminum in drinking water according to US EPA should not exceed 5-200 µg /L. The statistical studies [16] indicate a possibility of more frequent incidence of Alzheimer's disease with aluminum concentrations exceeding 100 µg /L. According to the Regulation of the Polish Minister of Health of March 29, 2007 Journal of Laws of April 6, 2007, the concentration of aluminum in drinking water in Poland should not exceed 200 µg /L, which corresponds to the European Directive and

WHO recommendations. From these data two important conclusions emerge. First, cementation should be carried out in stages, in which the total length of the treated sections will depend on properties of the transported water, especially on its buffer capacity, and probably from other parameters, such as the saturation index for calcium carbonate [6,8]. For smaller diameters these distances should be shorter because of smaller ratio of water volume to the wall surface area.

Due to the need, in many cases, to shorten the period for which the pipeline is to be taken out of service, centrifugal spraying has recently become increasingly popular with thin epoxy or/and polyurethane linings, which, however, are more expensive. They offer some advantages such as slightly greater hydraulic capacity and elimination of applying compressed air to remove clogging of small diameters connections to houses. According to a large bank of data collected by DIPRA [4] and elaborated by Dąbrowski and Li [10], application of plastic covering of inner pipes surface is not really profitable for reducing head loss to flow in the cement mortar lining unless it is done properly and carefully. In this interpretation [10] of Bond's data [4], the equation [1] relating the Hazeny –Willians C coefficient with the Darcy-Weisbach f friction parameter was used. However, it remains an open question whether the data collected by DIPRA should be recognized as being independent. The mechanisms of ductile iron protection by epoxy or cement mortar linings are totally different. In the first case a mechanical barrier is created against oxygen and ions while in the second case the primary mechanism of protection is chemical, by high value of water pH in the lining pores along the pipe wall. Moreover, the epoxy layer does not allow maintenance of high pH values at the point of contact of water with the wall of a steel conduit, just like cement mortar. In the field, applying both linings requires removing in 100% of rust that is not strongly bounded, but some roughness of the pipe inner surface is welcome for cement mortar lining.

Ground water level

One of short-term water quality risks concern the time of maintaining of a damaged pipeline. Proper drainage of the trench is essential during maintenance. Otherwise, shallow groundwater and soil may flow into the pipeline. Also, leaving the trench dry allows for much more precise action. After each maintenance activity, a pipeline is washed carefully and disinfected, but nevertheless, many of us have unfortunately had a few experiences observing a brief outflow of high turbidity water out of our sinks.

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