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Review of biological stability and corrosion potential in drinking water distribution system

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Abstract:

In this paper, the corrosive properties of the water treatment plants system and biological stability were clarified. Several studies and dissertations published in this subject were reviewed in this paper. The problem of corrosion was explained and the reasons for their occurrence, Methods are used to reduce this characteristic, water stability and the factors affecting corrosion, Stability and correlations, which included five indicators: Langelier Saturation Index (LSI), Ryznar Stability Index (RSI), Puckorius Scaling Index (PI), Larson–Skold Index (LS), Aggressive Index (AI).

Keywords: Biological stability, Corrosion, Water stability.

Introduction:

Corrosion is one of the most important problems in the drinking water industry. It can affect public health, public acceptance of a water supply, and the cost of providing safe water. Physical, chemical, and biological quality of water, type and degree of scaling and corrosive compounds and water sources in terms of ground or surface are important parameters in the determination of its suitability for general and industrial purposes [1]. Corrosion is the physical-chemical interaction between the metal and its surroundings which is usually electro-chemical in nature and can lead to a change in the metal properties [2]. The corrosion tends to release the metal pipe particles into the fluids. If the corrosion occurs quickly, it forms a hole and then perforation of pipes which is considered as a path for water contamination in a state of negative suction; but if the water has a tendency to scaling, the diameter of pipe will reduce over the time due to the formation of sediments layers in the inner part of the pipes which ultimately results to the reduction of flow rate (2-3). Unfortunately, there are no precise figures of corrosion and scaling damages in the Iran; nevertheless, the surveys indicate that 30% of treated water losses is related to decays of pipelines caused by the corrosion which also reduce the shelf life of sanitary equipment [3,4]. Corrosion and scaling are major problems in water distribution systems that may cause economic problems, and hydraulic, aesthetic and health effects [5]. Corrosive water can react with household plumbing and metal fixtures resulting in the deterioration of the pipes and increased metal content of the water. Consumption of water with elevated levels of toxic metals, such as lead and copper, has been shown to cause both acute and chronic health problems. In addition, taste and odors, as well as the appearance of delivered water, are adversely affected. The scale could clog or reduce the flow in pipes, cause build-up in hot water heaters and reduce their efficiency, and impart an alkali taste to the water [6, 7; 5]. Corrosion and scaling is one of the most important factors influencing drinking water quality that cause health disorders and economic problems. Corrosive pipes are in the exposure of microbial contamination and elevated water metal concentrations such as iron, zinc, copper, manganese, lead, selenium, and arsenic that in addition to endangering the health of people, cause consumer complaints due to the smell, taste, and color of the water [8]. Corrosion tends to increase the concentrations of many metals in tap water. In water distribution networks, pipes made of different materials, corrosion causes entrance of various substances into the water body [9] and the occurrence of the toxic metals lead and cadmium is attributable almost entirely to leaching caused by corrosion of plumbing materials. Three metals – copper, iron, and zinc – cause staining of fixtures, or metallic taste, or both [11; 10]. Nickel has sometimes been mentioned as a potential contaminant from the plating of decorative plumbing fixtures [12; 13; 14]. Corrosion products attached to pipe surfaces or accumulated as sediments in the distribution system can shield microorganisms from disinfectants. These organisms can reproduce and cause problems such as bad tastes, odors, slimes, and additional corrosion [15; 16; 17]. The term corrosion is also commonly applied to the dissolution and carbonation reactions of cement-based materials. An increase in pH often occurs as a result of this reaction, which can be detrimental to disinfection and the aesthetic quality of the water, as well as the release of asbestos fibers is of regulatory concern. In general, plastic plumbing materials are more corrosion resistant, but they have their own degradation mechanisms and other potential problems, such as brittleness, taste, odor, biofilms support, and both organic and inorganic leachates [18]. There is little information in this specific context and this issue is neglected even in the approved standards. In addition to financial losses, the release of by-products resulting from the corrosion can easily diminish the willingness of consumers to use water. Moreover, the possibility of releasing heavy metal such as lead, copper, chromium and cadmium can endanger the human health [4-19].

Scale formation plays an important role in the formation of gastrointestinal tract (GIT) diseases. The studies show that the by-products of corrosion resulting from inner surface of pipes, can accumulate or deposit in the distribution networks, thereby protecting microorganisms from the effects of disinfectants. These microorganisms can replicate and participate in creating various problems such as undesirable taste and odor, biological mass and increasing of corrosion [20-21]. There is increase in secondary pollutants in corrosive water, such as increase in the concentration of iron, zinc, copper and manganese which is higher than the given standards in drinking water which lead to taste, odor, color and stains on sanitary services (22). Recently, the parameters including alkalinity, calcium hardness, conductivity, temperature and pH were analyzed to determine the corrosion or scaling of drinking water and the corrosion or scaling potential as estimated by Langelier and Ryznar indexes; if the corrosive or scaling of water were observed, then the necessary measures should be taken to remove the problem and to achieve the favorable state [23,24]. Monitoring and corrosion measurement is an important part of monitoring of stages of the drinking water supply system and its changes. It can be used for determining the efficiency of arrangements against corrosion during a chemical water treatment [25].

Water stability:

Stability of water is the tendency of water to either dissolve or deposit minerals varying with its chemical makeup. Water that tends to dissolve minerals is considered corrosive and that tends to deposit mineral is considered scaling. Corrosive water can dissolve minerals like calcium and magnesium, also can dissolve harmful metals such as lead and copper from plumbing utilities whereas scaling waters deposit a film of minerals on pipe walls and may prevent corrosion of metallic surfaces. If the scale deposition is too rapid, it also can be harmful and can damage appliances, such as water heaters, and increase pipe friction coefficients; in extreme cases, scale may clog pipes [26]. The economic and health aspects of corrosion, which may not be obvious without network observation, is a significant concern for water supply [27]. Monitoring of water stability is an appropriate tool for preventing water leaks and decreasing the cost of replacing pipes, pumps, and equipment [28, 29]. Water scaling can cause staining, block nozzles and coat internal wall of pipework [30]. Deposits can also greatly impact the efficiency of boilers and heat exchangers substantially increasing energy and maintenance costs [31, 32]. Water heaters, and increase pipe friction coefficients; in extreme cases, scale may clog pipes [26]. The economic and health aspects of corrosion, which may not be obvious without network observation, is a significant concern for water supply [27]. Monitoring of water stability is an appropriate tool for preventing water leaks and decreasing the cost of replacing pipes, pumps, and equipment [28, 29].

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Parameter effect on corrosion and water stability:

Chemical properties related to corrosion and scale formation of water include pH, alkalinity, dissolved oxygen content and total dissolved solids (TDS). The main physical characteristics are temperature, flow and velocity of water [33]. The most influential properties of drinking water when it comes to the corrosion and leaching of distribution system materials are pH and alkalinity. Other drinking water quality parameters of interest are temperature, calcium, free chlorine residual, chloramines, chloride, sulphat and natural organic matter (NOM). Any change to the drinking water treatment process may

impact corrosion in the distribution system and in household plumbing. Corrosiveness of particular water depends on its chemical properties (e.g. pH, alkalinity, dissolved oxygen content, dissolved solids etc) and physical characteristics (temperature, flow, velocity), as well as the nature of the pipe material. In addition to general corrosion, localized pitting corrosion may also occur if there are imperfections in the metal, oxide film or scale. Pitting is accelerated by high levels of chloride and sulfate. Microorganisms can also promote corrosion by creating areas with different concentrations in oxygen, minerals and metals. Some microorganisms also catalyze reactions associated with corrosion process. Corrosion products of iron pipe provide habitats for microbial growth and react with disinfectant residuals, preventing the disinfectant from penetrating the biofilm [22]. Corrosion scales formed by the accumulation of corrosion products could serve as the breeding ground for microbes and sinks for heavy metals or other contaminants (e.g., arsenic, vanadium, lead) [23,24]. Effect of different the temperatures in distribution system corrosion. In one study, weight loss decreased for iron samples held at 13 versus 20 °C (34). Other studies found lower iron concentrations and corrosion rates [36] and fewer customer complaints of red water [35] during the colder winter months. Finally, one utility reported more red water incidents during warmer summer months (M. Pearthree, personal communication). Similarly, several studies have found differences in the corrosion of lead [37; 38] and copper at different constant temperatures. At least five key parameters that influence corrosion can vary with temperature: biological activity, dissolved oxygen (DO) solubility, solution properties (e.g. viscosity), ferrous iron oxidation rate, and thermodynamic properties of iron scale

Corrosion indices:

Corrosion indices have been developed by researchers, which easily calculate and predict corrosion or scaling tendency and can be useful in corrosion control program. LSI is one of the most common scale prediction tools for calcium carbonate scaling [39]. Unlike the RSI, LSI has no theoretical basis and is defined by a simple empirical relationship that was found by trial and error. Another empirical equation, PSI, is a variation of the RSI, but differs by using equilibrium pH instead of measured pH. From an empirical study, [40] developed an index based upon chloride and sulfate aggressiveness toward pitting corrosion and alkalinity as minimizing factor toward aggression, called LI [40]. In an attempt to govern proper type of Asbestos-Cement pipe type and its wholeness during operation, AI was developed. [41]. The studied of stability indices of drinking water in Dehloran indicates that the water is corrosive; therefore, the water quality in distribution network should be absorbed constantly and necessary measurements should be taken to control the corrosion [50]. Details of these indices are presented in Table.1). As is clear from Table 1, saturated pH, an important factor in determining corrosion or scaling of water, is affected by the chemical and physical properties of water given in Table 2.

Table1. Corrosion and saturation indices used in the study

Index	Equation	Index value	Water condition
Langelier saturation index	$LSI = pH - pH_s$	$0 > LSI$ $0 = LSI$ $0 < LSI$	Super-saturated, tend to precipitate $CaCO_3$ Saturated, $CaCO_3$ is in equilibrium Under-saturated, tend to dissolve solid $CaCO_3$
Ryznar stability index	$RSI = 2pH_s - pH$	$6 > RSI$ $6 < RSI < 7$ $RSI > 7$	Super-saturated, tend to precipitate $CaCO_3$ Saturated, $CaCO_3$ is in equilibrium Under-saturated, tend to dissolve solid $CaCO_3$
Puckorius scaling index	$PSI = 2(pH_{eq}) - pH_s$ $pH_{eq} = 1.465 \times \log_{10}[\text{alk}] + 4.54$ $pH = 1.465 + \log(T.ALK) + 4.54$	$PSI < 6$ $PSI > 7$	Scaling is unlikely to occur Likely to dissolve scale
LS index	$LSI = (Cl^- + SO_4^{2-}) / (HCO_3^- + CO_3^{2-})$	$LS < 0.8$ $0.8 < LS < 1.2$ $LS > 1.2$	Chloride and sulphate are unlikely to interfere with the formation of protecting film Corrosion rates may be higher than expected High rates of localized corrosion may be expected.
Aggressive index	$AI = pH + \log(\text{alk})(H)$	$AI > 12$ $10 < AI < 12$	Non-aggressive Moderately aggressive Very aggressive

Table 2. Values of (A, B, C and D) for pHs calculation

TDS (mg/L)	A	CaH (mg/L $CaCO_3$) ^a	C	Alk (mg/L $CaCO_3$)	D
50–300	0.1	10–11	0.6	10–11	1
400–1,000	0.2	12–13	0.7	12–13	1.1
Temperature (°C)	B	14–17	0.8	14–17	1.2
		18–22	1.3	18–22	1.3
		23–27	1.4	23–27	1.4
		28–34	1.5	28–35	1.5
0–1	2.6	35–43	1.2	36–44	1.6
2–6	2.5	44–55	1.3	45–55	1.7
7–9	2.4	56–69	1.4	56–69	1.8
10–13	2.3	70–87	1.5	70–88	1.9
14–17	2.2	88–110	1.6	89–110	2
18–21	2.1	111–138	1.7	111–139	2.1
22–27	2	139–174	1.8	140–176	2.2
28–31	1.9	175–220	1.9	175–220	2.3
32–37	1.8	230–270	2	230–270	2.4
38–43	1.7	280–340	2.1	280–350	2.5
44–50	1.6	350–430	2.2	360–440	2.6
51–55	1.5	440–550	2.3	450–550	2.7
56–64	1.4	560–690	2.4	560–690	2.8
65–71	1.3	700–870	2.5	700–880	2.9

^aCaH, calcium hardness.

Evaluation of the Indices:

A brief note on the five indices, along with their computations have been briefly illustrated below:

1 Langelier Saturation Index (LSI) The Langelier saturation index (LSI) is probably the most widely used indicator of cooling water scale potential. This index indicates the driving force for scale formation and growth in terms of pH as a master variable [24]. The LSI is an equilibrium model derived from the theoretical concept of saturation and provides an indicator of the degree of saturation of water with respect to calcium carbonate. It can be shown that the Langelier saturation index approximates the base 10 logarithm of the calcite saturation level. The Langelier saturation level approaches the concept of

saturation using pH as a main variable. Thus, the LSI can be interpreted as the pH change required to bring water to equilibrium. The algebraic difference between the actual pH of a sample of water and its computed pHs is called the Calcium Carbonate Saturation Index. Hence, Saturation Index equals

pH minus pHs.

$$LSI = pH - pH_s$$

Table (1) below shows the values of LSI:

Scale and Corrosion potential tendencies of water with different Langelier Saturation Index values (LSI) (48)

Index value(LSI)	Description	Index value (LSI)	Description
- 5	Severe Corrosion	0	Near Balanced
- 4	Severe Corrosion	0.5	Some Faint Coating
- 3	Moderate Corrosion	1	Mild Scale Coating
- 2	Moderate Corrosion	2	Mild to Moderate Coatings
-1	Mild Corrosion	3	Moderate Scale Forming
-0.5	None- Mild Corrosion	4	Severe Scale Forming

Calculation of the value for pHs can be done using the nomograph or through the use of the following equation $pH_s = (9.3 + A + B) - (C + D)$ [10] Where: $A = [\log (TDS) - 1]/10$, TDS in ppm $B = [-13.12 \log (T + 273)) + 34.55]$, Temperature, T in °C $C = [\log (\text{calcium hardness}) - 0.4]$, Ca hardness in ppm (asCaCO₃)

$D = \log (\text{alkalinity})$, alkalinity in ppm as (CaCO₃) It is apparent that the temperature at which the calculation is made has considerable impact upon the results. This index is a qualitative indication of the tendency of calcium carbonate to deposit or dissolve. If the index is positive, calcium carbonate tends to deposit. If it is negative, calcium carbonate tends to dissolve. If it is zero, the water is at equilibrium.

2. Ryznar Stability Index (RSI)

The Ryznar stability index (RSI) uses a correlation established between an empirical database of scale thickness observed in municipal water systems and associated water chemistry data. Same parameters in the Langelier saturation index are also used in the Ryznar index (49)

Like the LSI, the RSI has its basis in the concept of saturation level. The Ryznar index takes the form:

$$RSI = 2(pH_s) - pH$$

Table (2): Scale and Corrosion potential tendencies of water with different Ryznar Index (RI) values (47)

Index value(RI)	Description
Less than 5.5	Heavy scale formation
5.5 to 6.2	Some scale will form
6.2 to 6.8	Non –scaling or corrosive
6.8 to 8.5	Corrosive water
More than 8.5	Very corrosive water

This index is often used in combination with the Langelier index to improve the accuracy in predicting the scaling or corrosion tendencies of water.

3. Puckorius Scaling Index (PI) The Puckorius scaling index (PSI) is based on the buffering capacity of the water, and the maximum quantity of precipitate that can form in bringing water to equilibrium.

Water high in calcium, but low in alkalinity and buffering capacity, can have a high calcite saturation level. The high calcium level increases the ion activity product. Such water might have a high tendency to form scale due to the driving force, but scale formed might be of such a small quantity as to be unobservable. The water has the driving force, but not the capacity and ability to maintain pH as precipitate matter

forms. The PSI index is calculated in a manner similar to the

Ryznar stability index.

Puckorius uses an equilibrium pH rather than the actual system pH to account for the buffering effects:

$$PSI = 2(pH_s) - pH_{eq}$$

where pH_s is still the pH at saturation in calcite or calcium carbonate

$$pH_{eq} = 1.465 \times \log_{10} [\text{Alkalinity}] + 4.54$$

If $PSI < 6$, Scaling is unlikely to occur and > 7 , it is Likely to dissolve scale.

4. Larson–Skold Index (LS)

The Larson–Skold index is based upon evaluation of in situ corrosion of mild steel lines transporting Great Lakes waters. The index is the ratio of equivalents per million (epm) of sulfate (SO_4^{2-}) and chloride (Cl^-) to the epm of alkalinity in the form bicarbonate. Larson–Skold index = $(epm_{Cl^-} + epm_{SO_4^{2-}}) / (epm_{HCO_3^-})$

The index has proven to be a useful tool in predicting the

Aggressiveness of once through cooling waters. The LS might be interpreted by the following guidelines:

Index < 0.8 chlorides and sulfate probably will not interfere with natural film formation, while

$0.8 < \text{index} < 1.2$ chlorides and sulfates may interfere with natural film formation. Higher than desired corrosion rates might be anticipated and Index > 1.2 the tendency toward high corrosion rates of a local type should be expected as the index increases. [42].

5. Aggressive Index (AI)

The Aggressive Index (AI), originally developed for monitoring water in asbestos pipe, is sometimes substituted for the Langelier Index as an indicator of the corrosivity of water. The LSI was simplified without the involvement of temperature and ionic strength as AI. It is simple to use and convenient to apply because it does not include the complicating effects of temperature or dissolved solids [43]. The Aggressiveness index (AI) is defined as follows

$$AI = pH + \log (AH)$$

Where: AI = Aggressiveness index, A = total alkalinity, mg/L as calcium carbonate, and H = calcium hardness, mg/L as calcium carbonate. AI > 12 is deemed to be Non aggressive, a value between 10 and 12 is considered Moderately aggressive and < 10 is deemed Very aggressive. Table 1 illustrates the Interpretation of the Saturation Indices and criteria for categorizing the stability of the water

Table 3. Scale and Corrosion Tendencies of water with various Aggressive Index (47)

Index value(AI)	Description
Less than 10	Highly corrosive
10 -12	Moderate corrosion
More than 12	Scaling

Biological stability:

The WHO drinking water guideline states: “Water entering the distribution system must be microbiologically safe and ideally should also be biologically stable” [45]. Water treatment systems normally have source water protection and multiple barriers for pathogens to ensure that microbiological safety requirements are met [45]. However, the “biological stability” requirement is considerably less defined, both in terms of what it actually means and how it can be achieved. Intuitively, biological stability would imply no changes occurring in the concentrations and composition of the microbial community in the water during distribution. In many countries a disinfectant residual (e.g., monochloramine) is maintained in the distribution network to inhibit microbial growth and thus enforce stability [44; 45]. During drinking water distribution, multiple factors such as pipe materials, flow velocity, temperature shifts, mixing zones and stagnation zones, sediments, biofilms, or in the worst-case scenario, intrusion of untreated water from the subsurface, can influence the biological stability of the water [46; 45]. None of the above mentioned conventional growth potential methods are capable to detect or predict the impact of such factors accurately on their own. Biological stability of drinking water has been gaining considerable attention in the fields of water treatment and water quality maintenance. Biologically stable drinking water is defined as one which would not cause reproduction of coliforms and heterotrophic bacteria. Bacterial regrowth is bacterial growth in drinking water after treatment, especially the growth of microorganisms within the distribution system. The link between biodegradable organics in drinking water and bacterial regrowth in potable water distribution systems has been noted by several researchers since 1980 [44]

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