Corrosion of carbon steel in synthetic freshwater for water distribution systems

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Abstract. Corrosion is one of the most common problems in water distribution systems. The purpose of this research is to investigate the corrosion rate of carbon steel in synthetic freshwater. The influence of a variety of time exposure that represents the actual conditions in practice was performed. Research conducted by weight loss methods using immersion test. The parameters of water quality were measured by using a multimeter portable (Hach HQ40d). From the experiments obtained that the corrosion rate of carbon steel in freshwater ranged between 0.41 - 0.76 mpy. The results of this study are expected as a first step, as input for prevention, to prevent leakage flow and pipe due to corrosion by the life that has been designed.

Keywords: Carbon steel, corrosion, freshwater, immersion

1. Introduction

Iron and steel pipes have been used in water distribution systems for over five centuries. Corrosion is one of the most common problems affecting domestic water supplies [1]. The chemical process slowly dissolves the metal, causing plumbing, equipment, and equipment that uses water to deteriorate and fail. Internal corrosion from the piping distribution system and plumbing can cause several water quality problems, including potential health problems, discoloration, and taste and odor problems [2]. These problems are mainly caused by corrosion on metal pipe surfaces, pipe soldering, and pipe fittings or dissolution of existing pipe scales. The impact of corrosion on water distribution systems can cause billions of dollars of damage every year. Damage caused by corrosion affects the reliability of industrial processes and water distribution systems [3].

The by-products of corrosion, which are commonly described as an off-taste, odor, or appearance, adversely affect the quality of water as it flows through the piping system [3,4]. This can have some adverse effects on the taste and quality of processed foods and beverages. Also, it causes undesirable effects on many industrial processes. The by-products of corrosion may be harmful to one's health. These contaminate can also affect the taste of processed food and beverages. Iron levels above 0.3 ppm cause rust-red staining of bathroom fixtures [5]. The by-products of corrosion often lay down deposits that reduce water flow [6]. The metals such as Copper and Iron can be toxic and can leach into the pipe of water distribution systems [7]. This leaching is caused by corrosion. The contamination of those metals can cause environmental and health problems in the short term or long...
term over time [8]. The Environmental Protection Agency has established primary drinking water standards for some metals. The maximum allowable for copper is 1.3 milligrams/liter; the maximum allowable for lead is 0.015 milligrams/liter [5]. Iron and zinc also are usually present and can cause water to have a metallic taste [8]. Therefore, the study of the rate of corrosion of carbon steel in freshwater is very important.

Many research workers recently studied the corrosion rate of carbon steel and those alloys [9-13]. Research to investigate the effect of a water level on corrosion of carbon steel in the natural water of the river has been conducted [9]. The main objective is to study if the depth of water level can effect the corrosion rate. Corrosion behavior of mild steel in seawater from different sites was investigated by using the weight loss method [10]. The corrosion rate of various carbon steels in raw water for the water at the Ammonia plant has been addressed using the weight loss method and electrochemical techniques [11]. The authors were able to study the effect of temperature and chemical composition of materials on the corrosion rate. The results obtained showed that an increase in temperatures in raw water can increase the corrosion rate of various steels, therefore, it is essential to control the stability of raw water, which tends to be corrosive in various temperatures of solutions.

Morphology and composition of corrosion products formed on the internal walls of carbon steel pipelines have also been studied revealing a strong influence of water quality on the characterization of deposit material and a direct correlation between the composition of deposits and the bacterial species found [12]. Rajesh et al (2014) [13] carried out analysis research on the effect water quality of underground water on Corrosion rates of commercially important metals. Weight loss technique was used in which test coupons with known weights were immersed in the test media which were underground water for a total exposure time of 7 days. The general observation from the results is that the rate of corrosion is directly proportional to the concentration of free chlorides, electrolytic conductivity, and total dissolved solids.

The water environment is complex in diversity, quality or composition, and operating conditions [14]. This makes the corrosion of steel by water a complicated and many-sided phenomenon. The difficulty arises from the fact of the main considerations involved the composition and surface condition of the steel, the quality of the water, and the operating conditions; the last is generally the most important.

In this work, the primary objectives of the present study were to determine corrosion rates of carbon steel in the synthesis water with different exposure time and to study correlate the water quality parameters with a corrosion rate of those steel samples. The corrosion rate of these samples was investigated by mass-loss methods. The differences between corrosion products formed of these samples after exposure are described.

2. Materials and Methods

2.1. Materials and Preparation

The corrosion specimens were cut from a plate of carbon steel from the commercial market with chemical composition in table 1. The solution used in this study is synthetic freshwater for the distribution water system.

| Table 1. The chemical composition of the specimen (wt. %). |
|-----------------------------|--------------|--------|--------|--------|--------|--------|--------|--------|--------|
| Element         | Fe            | C            | Cr           | Ni       | Mn       | Mo       | Al       | Si            | Cu       | S            | P        |
| Balancing       | 0.1768        | 0.1307       | 0.1432       | 0.7178   | 0.0105   | 0.0022   | 0.1342   | 0.4994        | 0.0409   | 0.012        |

Carbon steel plates were cut to size 70 x 20 x 2 mm and given a code. Before the immersion test, the surface of the specimen is cleaned according to the ASTM G-95 standard [15]. After cleaning, the specimens were weighed using analytical scales and then stored in a desiccator.
2.2. Weight-loss Measurement
After the immersion test for certain exposure time, the specimen is cleaned according to the procedure in the ASTM G-1 standard [16]. The analysis of the corrosion rates is carried out by weighing specimens before and after exposure. The corrosion rate determined follows [9]:

\[
Corrosion\ rate = \frac{87.6 W}{D A T}
\]

Where:
W: Weight loss (mg); D: Density of specimen (g/cm³); A: Area of sample (cm²); and T: Period of exposure (hrs).

2.3. Water Quality Analysis and Corrosion Product Analysis
The parameters of water quality as pH, conductivity, total dissolved solids, dissolved oxygen were measured by using a Hach multimeter portable (HQ40d). The morphology of the corrosion product was characterized by using a scanning electron microscope (SEM JEOL JSM-6390A) equipped with an energy dispersive spectrometer (EDS).

3. Result and Discussion

3.1. Weight loss
The corrosion rates of the specimens at different exposure time in synthetic freshwater solutions were calculated using the weight loss method as stated above. The result of the corrosion rate versus time of exposure for carbon steel shown in figure 1. The corrosion behaviors of carbon steel in the freshwater were evaluated at the 7th, 21st and 28th days. As can be seen in Figure 1, the corrosion rate of carbon steel reaches 0.76 mpy in the first week. Royani et al [9] and Peng et al [12] reported a similar trend of corrosion rate. In week 3, the corrosion rate dropped from 0.76 mpy to 0.41 mpy and then stabilized afterward such as the first week.

![Figure 1. Corrosion rate Vs exposure time.](image)

After the 7 days, the coupon immersed in synthetic freshwater was enveloped with a thin black film oxide and heavy presence of brownish rust-red which colored the water (figure 2). This indicates the fact that a corrosion reaction is taking place. Over time, the deposits turn brown which is identified as ferric hydroxide. When it was washed, the coupon gradually turned black with a considerable weight loss after 7 days. This was however followed with a decrease in weight after 21 days of exposure time. Meanwhile, Coupons immersed for the complete duration of 28 days in fresh water, it was noticed that there was weight gain rather than weight loss after 21 hours of exposure time.
Corrosion is a natural process that occurs when metals react with the environment. One of the environments in contact with metals is water that contains dissolved oxygen and is therefore corrosive. The corrosion rates depend on many factors including water pH, electrical conductivity, oxygen concentration, and temperature [10].

3.2. Water Quality Effects

3.2.1. pH. The results of measuring pH on media solution for different periods shown in figure 3. The pH value in this study is relatively stable in the range of 7 to 8. This shows that the water media used in this study is categorized as freshwater and the effect of the pH is relatively small because the value is almost the same.

Weight loss is generally found to increase with increasing pH in the range of 7 to 9, as is the level of tuberculation. Conversely, corrosion products are decreasing at higher pH. Again, this is consistent
with the increase in corrosion products incorporated into the scale layer. However, one study found that weight loss and iron concentration decreased when the pH was raised from 8.5 to 9.2.

Water can be acidic or basic in a degree of acidity, depending on several factors. Medium alkaline water (40 to 70 mg / L) with a pH between 7.0 and 8.2 is usually not corrosive. Water with a pH below 6.5 will tend to be corrosive, especially if the alkalinity is also low. However, water with a pH value above 7.5 can also be corrosive when the alkalinity is very low [14].

3.2.2. TDS and Conductivity. The values of TDS (total dissolved solids) and Conductivity measured throughout exposure for different time immersion tests are shown in figure 4 and 5. Carbon steel specimens exposed to water media showed a little increase and then a decrease slowly of TDS and Conductivity with time during the immersion tests. The iron from specimens dissolved in water separates into charged particles (ions) that conduct electricity. Conductivity is a problem only when the water has a high mineral content, pure water does not conduct electricity [17]. This conductivity escalation could be attributable to the increased of TDS in the water. Afterward, conductivity values remained fairly steady until the completion of the exposure.

![Figure 4. The changes in TDS value in the water media tests.](image1)

![Figure 5. The changes in conductivity value in the water media tests.](image2)

3.2.3. Dissolved Oxygen and Other Gases. Dissolved oxygen in water is one of the primary corrosive agents. Water exposed to the air absorbs oxygen. Hydrogen sulfide and carbon dioxide in water also can corrode metals significantly. Iron and steel corrosion rates increase with increasing the concentration of dissolved oxygen.
Carbon dioxide gas will form carbonic acid when dissolved in water [17]. It can decrease pH and therefore increase general corrosion of the piping system.

The concentration of dissolved oxygen measured throughout the exposure for different immersion times was shown in figure 6. The water solutions exposed to specimens showed a sharp decrease in DO concentration with time during immersion periods. This oxygen depletion can be attributable to the consumption of oxygen by steel specimens.

\[2Fe + O_2 + 2H_2O \rightarrow 2Fe^{2+} + 4OH^-\] (2)

DO also has a role in iron oxidation of iron (Fe^{2+}) or iron, for example [18]:

\[4Fe^{2+} + O_2 + 2H_2O + 4OH^- \rightarrow 4Fe(OH)_3(s)\] (3)

\[6FeCO_3(s) + O_2 \rightarrow 2Fe_3O_4(s) + 6CO_2\] (4)

\[4Fe_3O_4(s) + O_2 \rightarrow 6Fe_2O_3(s)\] (5)

Therefore, the oxygen concentration can have various effects on iron corrosion. As expected, the corrosion rate increases with increasing dissolved oxygen (DO) [18].

3.2.4. Water Temperature. Water temperature can also affect the rate of corrosion. In general, the corrosion rate will increase exponentially with every 10 °C rise in temperature [17]. Thus it can be announced that the hot water is more corrosive than the cold water.

Corrosion processes at higher water will be easier and faster. The rate of corrosion triples or quadruples as the water temperature rises. In this work, the temperature is kept constant (37 °C). Therefore, the effect of temperature on the corrosion rate was not explained in this study.

3.3. Surface Analysis

3.3.1. SEM Analysis. The Morphologies of the corrosion products taken from the immersion test at the 28th days were observed at a magnification of 500× (figure 7). When immersed in the freshwater, the specimens showed a dense corrosion product layer with and uniform layers on the surfaces throughout the experiment. The corrosion products formed a thin and uniform layer, covering the surface of carbon steel loosely and evenly. Extremely little changes in surface morphologies occurred with time. The morphology of the corrosion product in Figure 7 shown relatively uniform corrosion without a
trace of the local attack. Thus, it was concluded that corrosion damage on the carbon steel in freshwater is uniform corrosion.

Figure 7. The morphology of corrosion product after 28 days of exposure time

3.3.2. EDS Analysis. Elemental composition ratios of the corrosion products sampled at 28th days are shown in table 2. The results of EDS analysis demonstrated that the main elements of the corrosion products were iron and oxygen with carbon and silicon present at a much lower content as shown in the EDS results in figure 8. Similar results were also reported by Sundjono [10] and Royani [9] who studied the corrosion behavior of carbon steel in seawater and natural water. In addition, Gedge [18] studied the corrosion behavior of metal for potable water and demonstrated that the corrosion products were mainly composed of iron, oxygen, and carbon, indicating that regardless of in potable water, tap water or reclaimed water, carbon steel corrosion products are mainly composed of iron, oxygen, and carbon.

Table 2. Elemental composition ratios of the corrosion products

| Element | C  | O  | Si  | P  | S  | Ca | Fe |
|---------|----|----|-----|----|----|----|----|
| Mass (wt. %) | 2.25 | 14.78 | 2.08 | 0.06 | 0.05 | 0.06 | 80.70 |

Figure 8. EDS analysis of corrosion products

4. Conclusion
The corrosion of carbon steel was investigated in synthetic freshwater for water distribution systems. Analysis of weight loss was carried out and the results of the corrosion rate were relatively stable with the immersion period. Based on the results, the corrosion rate of carbon steel in freshwater ranged between 0.41 - 0.76 mpy. Based on the corrosion rate, we can find out the remaining life of the steel. Meanwhile, the water parameters are relatively stable except for dissolved oxygen. Decrease of
dissolved oxygen indicates a corrosion reaction between iron and oxygen. These results indicate that the corrosion rate of carbon steel is relatively constant on static fluid. For further research, it should be done with dynamic fluids to be closer to the actual conditions.

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