Effect of Salt Content on The Corrosion Rate of Steel Pipe in Turbulently Flowing Solutions

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Abstract

The effect of salt content on the corrosion rate of carbon steel pipe in aerated water under isothermal turbulent flow conditions (Reynolds number= 15000-110000 and temperature of 30-60ºC) is investigated by weight loss method. The test solutions were distilled water (one time distilled) and sea water (0.5N NaCl). Also the results of 0.1N NaCl solution obtained by Hasan [2003] were considered. The effect of Reynolds number temperature on the corrosion rate is also studied and discussed. For each run, nine specimens of carbon steel were placed in the test section and the corrosion rate for each one was determined at every Re and temperature and the average was taken. The variation of friction factor with Re and temperature was determined by measuring pressure drop across the test section.

The results revealed that the salt content has considerable effect on the corrosion rate for the whole investigated range of Re and temperature. The highest corrosion rate was encountered in sea water (3.5% NaCl). Also distilled water causes considerable corrosion rate but it is lower than for the whole range of Re and temperature. Also it is found that Reynolds number increases the corrosion rate depending on temperature. Temperature affects the corrosion rate by changing two main parameters, oxygen solubility and diffusivity.

Key words: corrosion, salt, turbulent, carbon steel, friction factor.

Introduction

Most aqueous solutions (ranging from bulk natural water and chemical solutions to thin condensed films of moisture) will be in contact with the atmosphere and will contain dissolved oxygen which can act as a cathode reactant. The solubility of oxygen in water decreases significantly with the increase in temperature and slightly with concentration of dissolved salts [Shrier 2004]. The rate of corrosion processes with oxygen depolarization is determined mostly by the rate of oxygen diffusion to the metal surface. This kind of corrosion is extremely important, since it includes practically important process such as corrosion of iron and steel in neutral salts solutions, corrosion of zinc in several neutral solutions, various cases of copper corrosion [Akimov 1958, Moreira et. al. 2004].

In many corrosion problems, there is strong evidence that the rate of uniform corrosion is controlled by the rate of mass transfer. This is true whether the corrosion fluid remains static or in fast motion with respect to the metal surface. However, molecular diffusion is not the only factor which influences the rate of corrosion. In addition, in turbulent fluids, the rate of transport of eddy diffusion appears to participate in the control of the over-all transfer rate. It is well known that the rate-controlling step in most natural water corrosion processes is the cathodic half reaction of oxygen reduction[Mahato et al. 1980, Moreira et. al. 2004, Cheng and Steward 2004].

For reaction rate that is diffusion controlled, the limiting current density is:

$$i_L = z F k \Delta C \qquad 1$$

Thus the basis of the LCD technique in determining k is to measure LCD at fixed ΔC. Also if k is known then measuring i_L allows the determination of ΔC, which will be the bulk concentration. If this approach can be applied to a corrosion process in which both an anodic and cathodic reaction occur, if either reaction is diffusion controlled then the rate of corrosion will be given by

$$i_c = zFk \Delta C \qquad 2$$

The value of ΔC will be the bulk concentration of cathodic reactant for systems which are cathodically controlled and will equal the solubility limit of the relevant product when the anodic reaction is diffusion controlled. It is found from dimensional analysis that:

$$Sh = cons. \, Re^x \, Sc^y \qquad 3$$

x is usually between 0.3 and 1, y is typically 0.33 [Poulson 1983]. The geometry of a

system, i.e., flat plates, stirrers, pipes, etc. have a large effect in determining the influence of Reynolds number on corrosion rate, i.e., x .

Chlorides have probability received most consideration in relation to their effect on corrosion. The effect of sodium chloride concentration on the corrosion of iron in air saturated water at room temperature was found to increase the corrosion rate. Chlorides increase the electrical conductivity of the water so that the flow of corrosion currents will be facilitated [Uhlig 1985, Shrier 2000]. Later, Kolman et. al. [2002] found the corrosion potential becomes more negative with increasing NaCl concentration. Bahar [2002] showed that, in stationary aerated water, the limiting current density increases with increasing NaCl concentration up to 3.5%, and the corrosion potential becomes more negative.

Electrical conductivity is often a convenient and accurate measurement of salinity or chlorinity. Dissolved oxygen is a very important factor in the corrosion of metals immersed in sea water. Table 1and 2 show the oxygen contents of different solutions.

The aim of this work is to study the influence of salt content of water for wide range of Reynolds number and temperature on the corrosion rate carbon steel pipe under fully developed turbulent flow conditions using three types of solutions, distilled water and sea water (0.5N NaCl), and the data of Hasan [2003] for 0.1N NaCl solution.

Table 1: Oxygen Solubility at Atmospheric Pressure[Perry and Chilton 1998, Sense 2001].		
T, °C	Solubility, mg/l Distilled Water	Solubility, mg/l 0.1N NaCl
30	7.559	7.500
35	6.625	6.95
40	6.401	6.389
45	6.001	5.990
50	5.477	5.399
60	4.501	4.490

Table 2: Oxygen Content of Sea Water [Shrier 2000]	
T, °C	Solubility, mg/l (Sea water)
-2	8.5
0	8.08
5	7.16
10	6.44
15	5.86
20	5.38
30	5.42

Experimental Work

The dynamic system for performing the experimental work is illustrated in Fig. 1. It is composed of: electrolyte reservoir, heater and controller, pump, rotameter, specimens, PH-meter, inverted U-tube manometer, control valves, PVC flanges, and PVC tubes. The test section was composed of nine cylindrical specimens each has an inner diameter of 2.11cm and outer diameter of 2.45cm and 3cm long. The specimens were mounted in a manner to avoid discontinuities in between the specimens. The test section is mounted horizontally and preceded by 170 cm entrance region (i.e., L/d=80) of PVC tube to ensure fully developed velocity profile before the solution reaches the specimens [Bennett and Myers 1982, Brodkey and Harshy 1989]. The test section is followed by 55 cm exit length to avoid disturbance at the outlet. Two static pressure taps were installed at the edges of the test section flash to the inside surface of the extension PVC pipe. The holes of pressure taps were of 1.5 mm in diameter and the taps installed flash to the inside surface to measure the static pressure drop and avoid the disturbance of velocity profile [Coulson and Richardson 1998]. Prior to use the specimens were abraded in a sequence of emery papers grades: 120, 200, 320, 400, and 600, washed by tap water followed by distilled water, dried with clean tissue, immersed in analar methanol for 5 min, rinsed with clean acetone, and dried with clean tissue. The specimens then were stored in vacuum desicator over high activity silica gel for 1.5 h before use, then they were weighed using sensitive balance and directly exposed to the corrosion environment .The solution with a particular Re and temperature was pumped to the test section for 6 hours and the pressure drop across the later was taken after 5 minutes from the test run start.

After exposure to the corrosion environment the specimen was washed by tap water then brushed by smooth brush under running tap

water to remove part of corrosion product that is not strongly adherent. Then the outer surface of specimen is insulated by teflon tape and the specimen was immersed in 20% warm hydrochloric acid containing organic inhibitor (hexamine) for 1.5 minutes [Fontana and Green 1994]. After that the specimen was washed by tap water, distilled water, dried with clean tissue, kept in dissector for 1.5 h, and then weighed. Blank tests showed no appreciable weight loss caused by the cleaning solution.

Results And Discussion
Friction Factor

The Friction factor across the test section was determined by measuring the pressure drop via inverted U-tube manometer. where

$$f = \frac{d\Delta P}{2\rho u^2 L} \qquad 4$$

Over the years, friction factor has received a wide attention from authors. Numerous studies have been performed to study factors influencing friction factor under different conditions, e.g., isothermal and heat transfer conditions [Colburn 1933, Mody 1944, Smith and Epstein 1957, Knudson and Katz 1958, Petukhov 1970] and roughness conditions [Mody 1944, Knudson and Katz 1958]. Most of these studies have showed that the main two variables influencing friction factor (f) were Re and surface roughness. The variation of friction factor with Re for clean surface (no corrosion products formed) at different temperatures is presented in Fig.2. It is obvious that f decreases with Re for all temperatures. Also the figure reveals no appreciable effect of temperature on the friction factor. No noticeable difference between friction factor of distilled water and sea water is noticed.

Corrosion Rate

Effect of salt on the corrosion rate

Figures 3 to 5 show the variation of corrosion rate expressed in gmd (gm/m^2.day) with Re at different temperature for the three solutions. It is evident that increasing Re, increases the corrosion rate for the whole range of temperature. The sea water causes highest corrosion rate and distilled water causes the lowest corrosion rate, i.e, the higher the salt content is the higher the corrosion rate. This is ascribed to the increased solution electrical conductivity of the solution facilitating the

cathodic reaction (oxygen reduction) and anodic reaction (iron dissolution). I is to be noticed that the distilled water causes considerable corrosion rate for the whole investigated range of Re and temperature. In present work the occurrence on corrosion in distilled water may be attributed to the presence of little amount of salts in the distilled water because it is one time distilled. It is to be noted from Figs. 3 to 5 that the increase in corrosion rate with NaCl concentration in Fig. 3 (for T=30 ^{o}C) is lower than in case of 45 ^{o}C and 60 ^{0}C. This is ascribed to the fact that increasing temperature increases the electrical conductivity of the solution as evidenced by previous work [Shrier 2000].

Effect of Reynolds Number

Fig. 3 to 5 shows that at a particular temperature the corrosion rate increases with Re for the three solutions. Since the corrosion of iron in aerated water is a mass transfer controlled process [Foroulis, 1979; Mahato et al, 1980; Smith et al, 1989; Shreir, 2000], therefore increasing Re (or velocity) will increase the amount of oxygen arriving to the surface and hence the corrosion rate is increased. Increasing Re leads to decrease the thickness of diffusion layer in the wall vicinity that represents the main resistance to oxygen transport [Brodkey and Hershey 1989, and Thomas 2000, Welty et al 2001

Fig.1: Experimental Apparatus
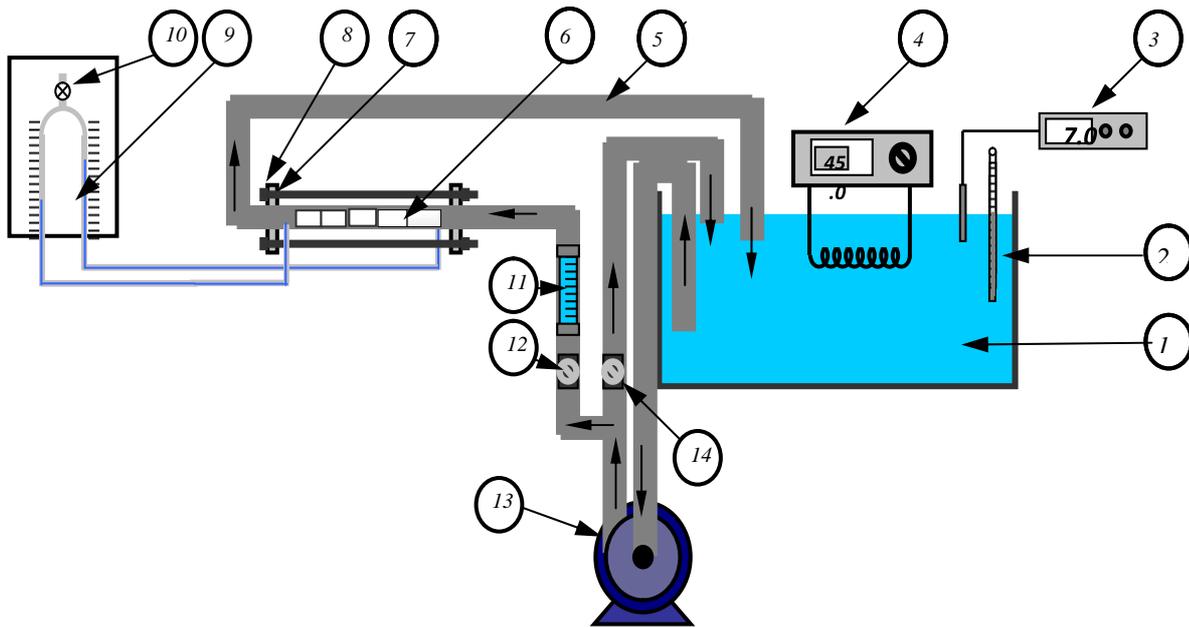
No.	Name	No.	Name
1	**0.1 N NaCl Solution**	8	**PVC Flanges**
2	**Thermometer**	9	**Inverted Manometer**
3	**PH Meter**	10	**Venting Valve**
4	**Heater & Controller**	11	**Rotameter**
5	**Connection Pipes**	12	**Test section Valve**
6	**Specimens**	13	**Centerfugal Pump**
7	**Fixation Screw**	14	**By Pass Valve**

Effect of Temperature

Observing Fig. 6, for distilled water, shows that at high Re the higher the temperature is the higher the corrosion rate. While at low Re, the corrosion rates in three temperatures are close. The same trend holds for sea water. This behavior can be explained as follows: increasing temperature leads to change two variables that act in a conflicting way. Firstly, increasing temperature accelerates the reaction rate and diffusion rate of oxygen species by increasing the molecular diffusion coefficient. Secondly, as the temperature increases the oxygen solubility decreases [Sheir 1994]. Third factor will play an important role in determining the corrosion rate is Re (or velocity). The increase in Re enhances the eddy diffusion of O_2 from the bulk of solution to the metal surface which increases O_2 transport to the metal surface leading to higher corrosion rate. Strictly speaking, the combined effect of three variables, namely, oxygen solubility, oxygen molecular diffusivity, and solution velocity (or eddy diffusion), will determine the trend of corrosion rate with increasing temperature.

The results revealed that the position of the specimen in the test section has no influence on its corrosion rate, i.e, no entrance effect of mass transfer was noticed, that is in harmony with previous observations [Mahato et al 1980]. This may be ascribed to the formed corrosion product layer which may disturb the uniformity of active sites and the oxygen amount near the surface by increasing the turbulence. Also the difference in corrosion rate among the nine specimens reaches 5%.

Fig. 3: Variation of Corrosion Rate with Re for Various Solutions at 30 °C.
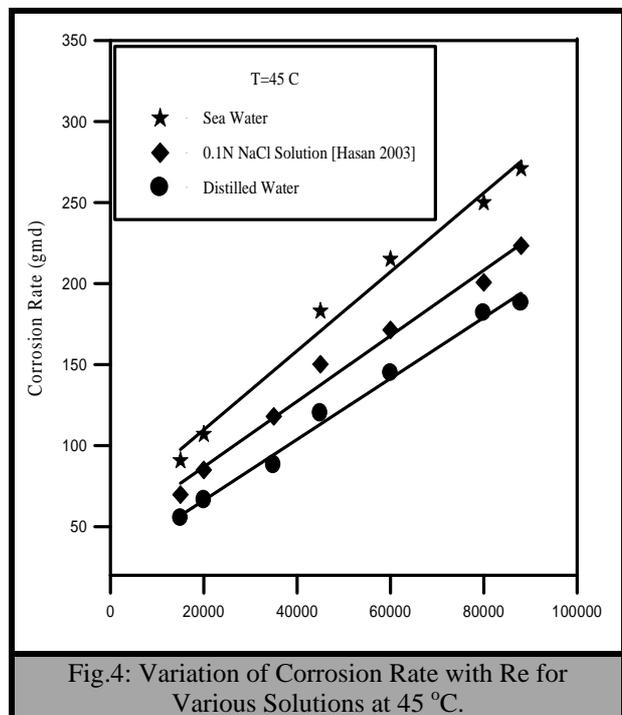
Fig.4: Variation of Corrosion Rate with Re for Various Solutions at 45 °C.

Fig. 2: Variation of friction factor with Re at different temperatures.
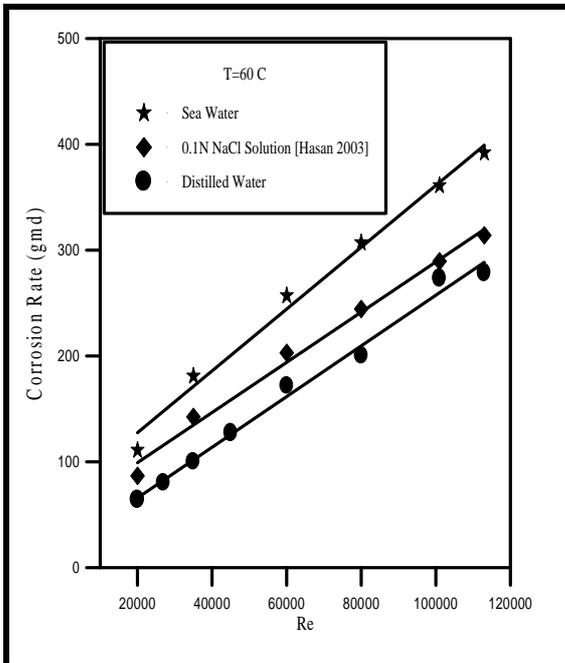
Fig. 5: Variation of Corrosion Rate with Re for Various Solutions at 60 °C.
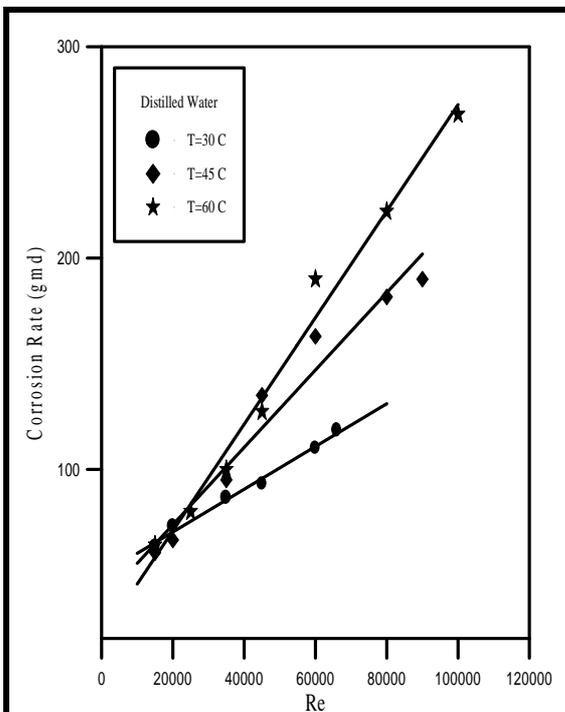
Fig. 6: Effect of Temperature on the Corrosion Rate.

Conclusions

From present investigated system the following points can be concluded:

1. Increasing salt content increases leads to increase the corrosion rate for the entire investigated range of Re and temperature by increasing the solution electrical conductivity.

2- Increasing Re, increases the corrosion rate for the three solutions at all temperatures.

3. Increasing the temperature affect the corrosion rate by changing two parameters acting in a conflicting way, i.e, oxygen solubility and oxygen diffusivity. Also increasing temperature increases the solution electrical conductivity enhancing the corrosion rate.

Nomenclature

C	Concentration, mole/m^3.
d	Pipe diameter, m.
F	Faradays constant (96487 Columb/equivelent)
f	Friction factor.
i	Current density, A/m^2.
k	Mass Transfer Coefficient, m/s.
L	Length, m
Re	Reynolds number=$\rho du/\mu$
Sc	Scmhidt number= $\mu/\rho D$
Sh	Sherwood number= kd/D.
u	Velocity, m/s
Δp	Pressure drop, N/m^2 .
μ	Viscosity, kg/m.s^2.
ν	Kinematic viscosity , m^2/s.

Abbreviations

gmd   Gram/m^2. day

L   Limiting

c   Corrosion

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تأثير المحتوى الملحي على معدل التآكل للأنبوب من الفولاذ في ظروف جريان اضطرابي

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الخلاصة:

تمت دراسة تأثير المحتوى الملحي للسائل على معدل التآكل للأنبوب من الفولاذ الكاربوني في الماء تحت ظروف جريان اضطرابي (عدد رينولدز ١٥.٠٠٠ إلى ١١٠٠٠٠) في درجات حرارة من ٣٠ م ْ – ٦٠م ْ . باستخدام طريقة فقدان الوزن . ثم قياس معدل التآكل في الماء المقطر (مقطر مره واحده) وماء البحر (N 0.5 NaCl) . كذلك تم اعتماد نتائج دراسة الباحث حسن (٢٠٠٣) الخاصة بالتآكل لمعدن الفولاذ الكاربوني في ماء حاوي على 0.1 N من ملح NaCl .

كذلك تمت دراسة تأثير السرعة ودرجة الحرارة على معدل التآكل ومناقشة ذلك. في كل تجربة تم استخدام تسعة نماذج من المعدن وقياس معدل التآكل فيها واخذ معدل القيم . اخطر النتائج أن المحتوى الملحي للمحلول يؤثر بشكل كبير على معدل التآكل في كل درجات الحرارة وعند جميع السرع (أو عدد رينولدز) . وجد أن أعلى معدل تأكل هو في محلول ماء البحر 0.5N . كذلك لوحظ إن زيادة عدد رينولدز تؤدي إلى زيادة معدل التآكل وان درجة الحرارة تؤثر على معدل التآكل بتغيير عاملين هما ذوبانية الأوكسجين ومعامل انتشاره.