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The effect of temperature and hydrodynamics on carbon steel corrosion and its inhibition in oxygenated acid–salt solution

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ABSTRACT

Corrosion of carbon steel in hydrochloric acid (HCl)–sodium sulphate (Na_2SO_4) solution mixture was investigated using rotating cylinder electrode (RCE) for a range of rotation velocity, 0–2000 rpm, solution temperature of 32–52 °C, and different oxygen concentrations. The corrosion rat was determined by using both weight loss method and electrochemical polarization technique. Different acid and salt concentrations were used ranged from 0.01 to 0.2 M for salt and 0.5 to 5% for acid. The conjoint effect of increased oxygen concentration and high rotational velocity was studied based on experimental measurements of O_2 concentration. The effects of operating conditions on indole and cetyl trimethyl ammonium bromides (CTAB) inhibition efficiency were also studied and discussed. The results showed that increasing the rotational velocity leads to an increase in the corrosion rate depending on the concentration of salt and acid. Increasing the temperature and acid concentrations leads to an increase in the corrosion rate while the corrosion rate exhibited unstable trend with salt concentration leads to change of corrosion. It is found that increasing O_2 concentration leads to a considerable increase in the corrosion rates especially at high rotational velocity. Indole and CTAB inhibitors exhibited very good inhibition efficiency in most conditions investigated with the former exhibited better inhibition efficiency arriving up to 87% at low rotational velocities. The inhibition efficiency of both inhibitors was found to decrease with increasing velocity. In addition, indole inhibitor reveals excellent inhibition efficiency even at high temperatures while CTAB efficiency decreased appreciably with temperature increase.

1. Introduction

Carbon steel, the most widely used engineering material, accounts for approximately 85% of the annual steel production worldwide. Despite its relatively limited corrosion resistance, carbon steel is used in large tonnages in marine applications, chemical processing, petroleum production and refining, construction and metal processing equipment [1,2]. Hydrochloric acid is the most difficult of the common acids to handle from the standpoints of corrosion and materials of constructions. The wide use of HCl has led to the concentration on the corrosive effects of this acid on carbon steel. However, most equipment in industries is usually corroded owing to the general aggression of acid solutions [3]. On the other hand the sulphate ion has a greater effect on the corrosivity of the water than the chloride ion. Generally corrosion of turbine caused by a thin film deposit of fused salt (sodium sulphate) on alloy surface (carbon steel) is an example of corrosion in sodium sulphate [4–6]. Also, sodium sulphate causes serious attack to the tubes of the boiler [7]. In addition sodium sulphate is presented in considerable concentration in crude oil causing corrosion for the handing pipelines. It is widely recognized that the corrosion of carbon steel may be accounted for by the anodic reaction as in Eq. (1)

$$Fe_{(s)} \leftrightarrow Fe^{2+} + 2e^- \quad (1)$$

It is well known that the rate controlling step in most corrosion process is the cathodic half reaction. The most important cathodic process in aerated waters is oxygen reduction. This rate is limited by the speed at which oxygen can reach the surface of the metal. If the corrosion process is under cathodic diffusion control then the flow increases the corrosion rate [8,9]. On the other hand if the cathodic process requires high activation energy, temperature will have the most significant effect. The effects of concentration, velocity, and temperature are complex and it will become evident that these factors can frequently outweigh the thermodynamic and kinetic considerations [9]. Temperature gives such a great effect on the rate of corrosion on metal, in case of corrosion in a neutral

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Nomenclature

F	Faradays constant (96,487 columb/equiv.)
C	Concentration (mol/m^3)
C_b	oxygen solubility (mol/m^3)
i	current (A)
rpm	revolution per minute
CR	corrosion rate (gmd)
t	time of exposure (day)
u	rotational velocity (rpm)
V	volt
N_{Fe}	molar flux of iron (mole/m^2 s)
ΔW	weight loss = $w_1 - w_2$ (g)
IE	inhibition efficiency
z	number of electron freed by corrosion
T	temperature (°C)
A	surface area (m^2)

Subscripts

b	bulk
c	corrosion
s	salt

solution, the increase of temperature has a favorable effect on the overpotential of oxygen depolarization and the rate of oxygen diffusion, but it leads to a decrease of oxygen solubility. In case of corrosion in an acid medium, the corrosion rate increases with temperature increase because the hydrogen evolution overpotential decreases [10]. In aerated acidic solution two cathodic reactions appear typical reactions are the reduction of hydrogen ions and the reduction of dissolved oxygen gas [9,11]:

$$2H^+ + 2e^- \leftrightarrow H_2(\text{inanacidicsolution}) \qquad (2)$$

However, if oxygen is present, two other reactions may occur:

$$O_2 + 4H^+ + 4e^- \leftrightarrow 2H_2O(\text{acidsolutions}) \qquad (3)$$

The acid–salt corrosive solution is practically encountered in many situations such as: in petroleum wells where HCl is used to remove the scales and stones containing different salts, in hydrotreatment plants in petroleum refineries due to salt precipitation and HCl formation, acid cleaning of scaled surfaces, and in the boilers when the acids (such as HCl and H_2SO_4) form due to hydrolysis in presence of water containing salts.

In order to prevent or minimize corrosion rates of metallic materials corrosion, inhibitors are usually used in the industry. Organic, inorganic, or a mixture of both inhibitors can inhibit corrosion by either chemisorptions on the metal surface or reacting with metal ions and forming a barrier-type precipitate on its surface [12]. Heterocyclic compounds with polar functional group and a conjugated double bond have been reported to inhibit mild steel corrosion [13–16]. Inhibition of these organic compounds is attributed to the interaction between mild steel surface and inhibitor molecules via their adsorption. The adsorption process is influenced by factors such as the nature and surface charge on the metal, the type of the aggressive media, the structure of the inhibitor, and the nature of its interaction with metal surface. The inhibition efficiency depends strongly on the structures and chemical properties of the species formed under the experimental conditions studied. The extent of adsorption is dependent upon the electronic structure of the metal and the inhibitor. Surfactants are molecules composed of a polar hydrophilic group, the "head", attached to a non-polar hydrophobic group, the "tail". In aqueous solution the inhibitory action of surfactant molecules may be due to the physical (electrostatic) adsorption or chemisorptions onto the metallic surface, depending on the charge of the solid surface and the free energy change of transferring a hydrocarbon chain from water to the solid surface [17]. The corrosion inhibition of surfactants is related to the surfactant's ability to aggregate at interfaces and in solution. The effectiveness of surfactant inhibitor is dependent on its properties in a particular medium. Most surfactants inhibitors are compounds containing nitrogen, phosphor, sulfur, and OH group by which the molecule can become strongly adsorbed [18]. As the concentration of individual surfactant molecules increases, the tendency for physical adsorption and aggregation increases, and the associated aggregation or adsorption is evidenced by decreasing surface tension. Thus, surface tension is an important indicator of surfactant aggregation and adsorption. As the concentration of surfactant molecules approaches the critical micelle concentration (cmc), surfactant molecules form dimmers, and multiple molecule aggregates. Spherical aggregates of surfactant molecules in which hydrophobic hydrocarbon chains are inside the sphere, and the polar head groups form the outer perimeter of the sphere are known as micelles [19]. Earlier studies have shown good inhibitory effect of indole on corrosion of mild steel in acids [16,20,21] under stationary conditions. It is of scientific significance to investigate the effect of flow velocity of liquid and the temperature on the inhibitory effect of this inhibitor. Many previous studies [1,18,19,22] have used the cetyl trimethyl ammonium bromides (CTAB) as a corrosion inhibitor for carbon steel and other metals and attained good inhibition efficiency but most of these studies investigated the stationary conditions. So, the effect of temperature and hydrodynamics on this inhibitor needs to be investigated and discussed.

The aim of this work is to study the influence of velocity, temperature, and oxygen concentration on the corrosion rate of carbon steel in a solution containing different concentrations of HCl and Na_2SO_4. Also, it is aimed to study the efficiency of indole and cetyl trimethyl ammonium bromides (CTAB) corrosion inhibitors in such systems under different operating conditions.

2. Experimental work

Fig. 1 shows the experimental apparatus which was composed of stirrer to obtain different rotational velocities, water bath having temperatures range of 10–95 °C to obtain different solution temperatures, power supply to provide a constant applied voltage between the electrodes, digital ammeter to measure the current, digital voltmeter to measure the potential, variable resistance (rheostat) (0–10^6 Ohm) to control the current flow, electrical connections between cathode (specimen) and the cell. Air pump was used to pump the air through the solution and oxygen meter to measure the solubility of oxygen in solution in mg/l at each condition. pH meter was used to monitor the pH of the solution, and conductivity meter to measure the electrical conductivity of the solution. Cylindrical carbon steel specimen was prepared to fit the specimen holder (for both weight loss and polarization experiments) having dimensions of 30 mm long (L), 22 mm inside diameter (d_i), and 25 mm outside diameter (d_o) measured using electronic digital caliper. It served as a cathode. Before each experiment, the carbon steel specimen (working electrode) was polished with 120, 180, 220, 400 and 2000 grid silicon carbide paper, washed with brushing by plastic brush with running tap water, immersed in ethanol for 30 s dried with clean tissue, and then dried by using electrical oven to temperature of about 110 °C for 10 min [23]. The specimen then was stored in vacuum desiccator over high activity silica gel until use. In weight loss