A method for inhibiting scale formation and corrosion in a cooling water system

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ABSTRACT

The polymeric inhibitors made show promise inhibiting corrosion and scale formation in the recirculating cooling water system. In this paper, polymer blends were prepared by mixing an anionic polymer, poly(acrylic acid) and polyaniline dispersion. The blends have been evaluated for their effectiveness to retain the dissolved minerals in the cooling water and to protect carbon steel against corrosion in alkaline recirculating cooling water conditions. Monthly water analyses have been conducted on makeup and recirculating cooling waters in the presence of the new treatment, and the active chemical components were monitored. Stressed system conditions have been established by increasing the temperature (15–50°C) and cycles of concentration (1.5–4.5 cycles) to perform a series of scales and corrosion tests. The results obtained from these studies show that the present polymer blends used at 100 ppm concentration have an inhibiting effect on the calcium and magnesium scales up to 91 and 82%, respectively. The weight loss and corrosion polarization resistance method (Corrater system) measurements were carried out to investigate the ability of polymer blends to inhibit within the aqueous system the corrosion of carbon steel. An inhibition efficiency of nearly 81% is achieved for 100 mg/L concentration of polymer blends.

Keywords: Cooling water; Acid-free conditioning; Mineral deposition; Corrosion inhibitor; Scale inhibitor; Poly(acrylic acid); Polyaniline dispersion

1. Introduction

Water is the most commonly used cooling fluid in industrial systems, such as in heat exchangers, cooling towers, and related equipment. Depending on the quality and availability of fresh water supply, the recirculating cooling water systems contain varying amounts of solids suspended or dissolved, most likely both [1]. Dissolved solids usually consist of mineral complexes in the form of crystals, which in a process described as nucleation continue to grow; they are characterized by the extent of their solubility and especially of their potential insolubility at particular temperatures.

A full description of the open recirculating cooling water systems used in these studies, with further details, is given in the section "Corrosion and scale evaluation equipments". In cooling water plants, the water losses can occur by evaporation, windage, and

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blowdown. As a result, the concentration of minerals dissolved and suspended solids, which remain in the cooling water, increases [1]. However, when the water is further concentrated in the recirculating cooling water system, it will become saturated. Concentrating the water any more will result in a supersaturated solution, which eventually leads to the formation, growth, and deposition of a dense, adherent scale. The scale deposits on the metal surface by adhesion in heat exchangers, and then lowers the thermal efficiency of the heat exchangers. In addition, the scale formation may also frequently cause local corrosion under the deposits [2,3].

Early water treatment programs to address such problems, particularly in evaporative cooling systems cause considerable environmental pollution by heavy metals and phosphate [4–9]. However, some methods comprise utilizing acid to control the pH and thereby reduce the potential for scaling. The most common solutions include the addition of scale inhibitors and the addition of pH change agents to dissolve the scale. One type of pH agents which has been used for many years in the treatment of cooling water systems is mineral acids such as hydrochloric acid (HCl) and sulfuric acid (H_2SO_4) [10,11]. Calcium carbonate is soluble in an acidic medium, when the pH of the recirculating cooling water is lowered; scale generally becomes less of a problem. However, low pH can cause corrosion, which in turn can be an additional source of fouling. In addition, mineral acids pose a high level of hazard and are corrosive, thereby increasing the human and capital risk involved in handling it [11,12].

In response to the risks and the disadvantages of mineral acids, many studies have been carried out to develop an acid-free organic compound as an inhibitor for controlling scale in cooling water [13–15]. The cooling water pH is kept on the alkaline side to reduce corrosion and consequently, calcium carbonate scaling remains as a potential problem. More recently, some researchers have focused on a wide range of modern polymeric deposit control agents, including poly(acrylic acid) and often with novel multifunctional chemistries [16–18], which under stressful operating conditions can act as a scale inhibitor [19,20], but without a marked effect on corrosion.

In this study, a new treatment approach to treating cooling water systems using synthetic organic polymers has been developed, in which the composition comprises a water-soluble polymer blend. The blends were prepared essentially by mixing low molecular weight poly(acrylic acid) and polyaniline in a stable dispersion form [21]. The objective of this paper is to reduce or prevent the scale formation and to achieve inhibition of

corrosion in aqueous systems, which have a pH of at least 8.7 and contain hardness. Using the polymer blends under the effect of various experimental conditions, including inhibitor concentration, temperature, and cycles of concentration, the corrosion and scale tests were carried out and discussed. Furthermore, we investigate the polymer blends' effect on the corrosion and scaling tendencies in a specified range, when more stressed conditions exist in the pilot cooling tower.

2. Materials and experiments

2.1. Materials

We need for the polymerization of acrylic acid the following materials: Acrylic acid (C_2H_3COOH), distilled water, potassium persulfate ($K_2S_2O_8$), thioglycolic acid ($C_2H_4O_2S$), sodium thiosulfate ($Na_2S_2O_3$), and ethyl acetate.

The pieces of equipment required for the polymerization of acrylic acid include the following: 2 L jacketed reaction vessel with an anchor stirrer paddle, a nitrogen atmosphere, vacuum filter apparatus with filter funnels and flask, water bath, Whatman #42 filter paper, and test tubes.

2.2. Measurements

The characterization of poly(acrylic acid) was carried out with the following equipments: pH meter HI8417, Gel Permeation Chromatography (GPC) using a Waters Analytical GPC and FTIR measurements (Perkin-Elmer model 1000 FTIR Spectrophotometer with samples in KBr pellet form). The 500 MHz ^{1}H-NMR spectroscopy was used also for the characterization of poly(acrylic acid).

To perform water analyses, we will combine three methods: titration method, Hach method (Model DR/2010), and colorimetric method. The following reagents were used: 0.02 N sulfuric acid solution (H_2SO_4), phenolphthalein and methyl orange indicators; 0.0282 N silver nitrate solution, 0.01 M EDTA solution; ammonium thiocyanate solution, sulfa ver 4 powder pillow, molybdate 3 and citric acid powder pillow, and amino acid F powder pillow. The equipments used for the water analyses are: spectrometer Pye Unicam PU 8600, hydrometer (range 1.000–1.220 Sg), and thermometer (range −10–100°C).

2.3. Poly(acrylic acid) synthesis

The polymerization of acrylic acid has been known for over a century; several methods were developed to produce poly(acrylic acid) [22–30].

In the present paper, the polymerization reactions to produce low molecular weight of polymers were carried out in a 2 L jacketed reaction vessel equipped with a stirrer, a reflux condenser, a thermometer, and a nitrogen gas inlet. A solution of 0.1 mol of pure acrylic acid in 100 ml of distilled water was placed into a reaction vessel, which was stirred continuously while nitrogen is bubbled through this solution for about 10 min. A nitrogen atmosphere was provided and maintained throughout the reaction for 1 h to flush out the dissolved oxygen in the mixture. Thioglycolic acid ($C_2H_4O_2S$) as a chain transfer agent is added at 8 mmol to a previous solution. After a period of 2 min, an amount of 2 mmol of sodium thiosulfate ($Na_2S_2O_3$) and 1.1 mmol of potassium persulfate ($K_2S_2O_8$) in 4 ml of water, used as a redox initiator system for the polymerization of monomers, are slowly introduced dropwise into the vessel while stirring for 1 h. The polymerization was carried out at 70°C. The polymer was isolated by precipitation by mixing the aqueous solution with ethyl acetate, and then filtering, and drying in vacuum at 50°C for 2 days. The resulting average molecular weight (Mw) is about 3,500 g/mol in about 70% yield as determined by the GPC. The chemical polymerization of acrylic acid can be represented by the following equation (Fig. 1).

2.4. Formulation of inhibitor

The inhibitor was prepared by mixing the poly (acrylic acid) (Mw: 3,500 g/mol) and polyaniline (Mw: 7×10^4 g/mol) dispersed by the ethoxylated fatty alcohol as a nonionic surfactant having an average hydrophilic–lipophilic balance value of 15.26. The formula ratio of each component in the polymer blends was 1:1 by wt. of poly(acrylic acid) and polyaniline dispersion. The selection of this composition was based on the screening tests of various concentrations of the components.

The aqueous dispersion of polyaniline was made according to the previous research [21]. The conductive polymer dispersion was obtained by dissolving 50 mg of polyaniline in 25 ml of camphor sulphonic acid with a constant stirring, and left to obtain polyaniline dispersion. About 10 ml from the previous
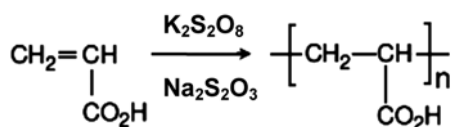
solution, was measured and placed into a flask and diluted to 100 ml with deionized water. At room temperature (20–25°C), and under magnetic stirring, we start to add nonionic surfactants dropwise, while temperature, conductivity, and the fractional volume of surfactants were recorded. A series of a dispersion process were performed showing the effect of increasing the surfactant concentration to 10 and 20 g/ml on the critical micelle concentration value and steric stabilizer of polyaniline.

2.5. Corrosion and scale evaluation equipments

Several tools have been developed to measure corrosion and scale using direct and indirect means. Among the successful experimental tools employed today are the pilot plant [24]; it is used to determine treatment effectiveness, and to establish the optimum level of polymer treatment. The tests were conducted in the pilot cooling tower, as per ASTM Standard methods specially (G-4, G-46 and G-96), as shown in the schematic diagram in Fig. 2 [31,32].

The water leaving the basin passes through a heat exchange rod, which includes two heat exchange rods running at approximately 1,000 watts. The water then passes through a corrosion coupon rack; in accordance with this technique, dried, precleaned, and pre-weighted coupons (three specimens) of carbon steel with dimensions of ($13 \times 102 \times 2$ mm^3) are suspended

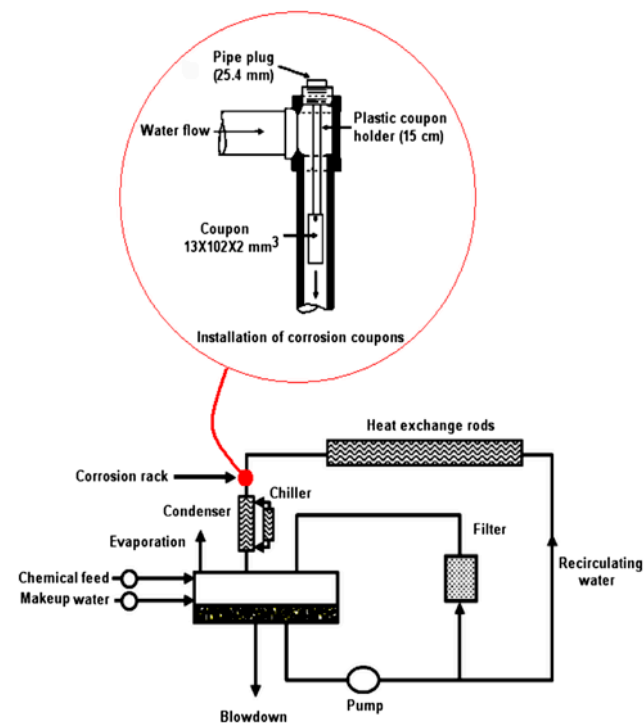Fig. 2. Flow diagram of dynamic test.

Fig. 1. Synthesis of poly(acrylic acid) by chemical polymerization of acrylic acid.

and placed into a corrosion test rack for 28 days to perform weight loss (WL) tests for corrosion coupons and scale tests. Following removal, they are cleaned, reweighed, and observed. The metal loss (expressed in mpy) and the type of attack (general, pitting) is then determined and reported.

Carbon steel comprising various metals was used for the tests, the chemical composition average is given (by% weight) as follows: C = 0.08%, Mn = 0.52%, Si = 0.21%, P = 0.005%, S = 0.007%, and iron.

The flow and, therefore, velocity through the rack are selected and controlled. There are positions for both meter probes and scales with corrosion coupons, so that short-term and long-term corrosion rates and scale deposition can be effectively measured. The corrosion meter Corrater RCS 9000 HS (Corrosion Polarization Resistance Method) will be used for the range 0.05–1,096 mg/dm^2/day (0.01–200 mpy) in electrochemical evaluation. This technique is linear polarisation resistance, which monitor the corrosion and allows the corrosion rates to be measured in real time [33,34]. The unit duplicates heat transfer surfaces, since temperature or heat flux can have a significant effect on the scaling, fouling, or corrosion rates being experienced in the system, monitoring this variable is important [12].

3. Results and discussion

3.1. Characterization of poly(acrylic acid)

3.1.1. Infrared spectroscopy

The IR spectrum of the polymer was recorded in the spectral range of 400–4,000 cm^{-1}. Fig. 3 shows the FT-IR spectrum of poly(acrylic acid). The most important vibration bands which allow the identification of poly(acrylic acid) are: 802 cm^{-1}, out-of-plane C–H bond [35,36], 1248.8 cm^{-1} due to the stretching band of C=O groups [35,36]; 1453.7 cm^{-1} the stretching of C=C double bond [35,36], the peak at 1715.4 cm^{-1} is characteristic of the carbonyl component of the carboxylic acid groups, and the bands attributable to C–H stretching of 2826.3 cm^{-1} [37,38]. However, the broad adsorption from 3,000 to 3,500 cm^{-1} corresponds to the stretching of O–H groups [37,38].

3.1.2. NMR spectroscopy

Poly(acrylic acid) was characterized by NMR spectroscopy, using deuterated dimethylsulfoxide (DMSO-d$_6$) as a solvent at 25°C. Fig. 4 shows the ^{1}H-NMR spectrum; the assignments and chemical shifts of the ^{1}H signals are given as below δ (ppm): 1.4–2.1
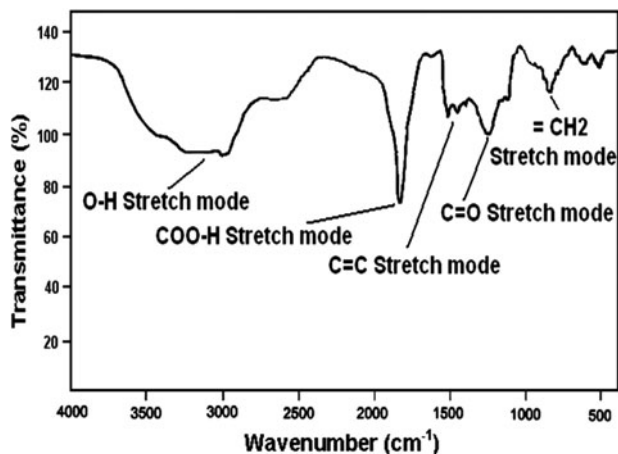

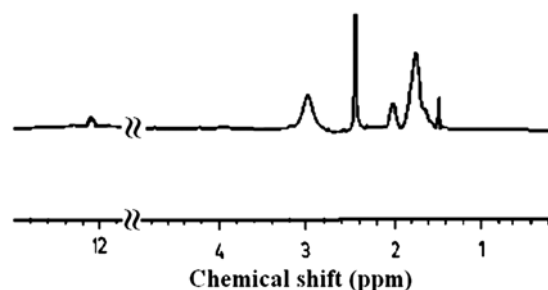Fig. 3. FT-IR spectrum of poly(acrylic acid).

Fig. 4. ^{1}H-NMR spectrum of poly(acrylic acid).

(–CH$_2$–), 2.75–3.07 (–CHCO–) [39], we have also observed a small peak at 12.0–12.1 can be attributed to the carboxylic acid (–COOH) [40].

3.2. Scale deposits essays

The poly(acrylic acid) and polyaniline dispersion prepared in the present study were evaluated in aqueous systems in which corrosion and scales are problems, and in particular, in cooling water systems.

Extensive research reported that calcium carbonate growth inhibition in the presence of low-molecular weight poly(acrylic acid), the inhibiton ffect either the nucleation or the crystal growth. This was attributed to the chemical structure of polymer operate by adsorption onto the mineral surface at growth sites, even more the poly(acrylic acid) can disperse the microcrystals of calcium carbonate [41,42]. Additional benefits are achieved from the synergistic inhibition of polymer blends, which also helps to inhibit the corrosion, over a wide range of operating conditions.

The structural characteristics of polyaniline/poly(acrylic acid) blends nanocomposites have been studied extensively and show the polymer blends are

amorphous [43], comprise homogeneous aggregates of intimately mixed interpolymer complexes [44]. Other studies have shown that the poly(acrylic acid) monomer structure chains should be relatively extended as microhelices at low concentrations. It was also found that a long helix was formed after the arrangement of the short helices, while the dispersion of polyaniline was produced [45,46].

The polymer blends as shown in Fig. 2 used in the present study have the chemical structural formula below:

where the surfactants used to stabilize the particles of polyaniline dispersions is alcohol (C18) poly (18)
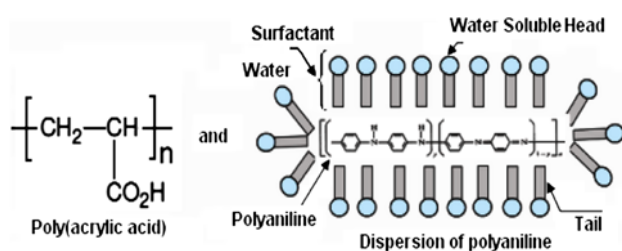

Fig. 5. Schematic representation the chemical structural of polymer blends.

ethoxylate ($C_{54}H_{110}O_{19}$). The adsorption of polymer blends on a metallic surface and mineral crystals is influenced by the presence of the following functional groups in the polyaniline molecule such as –NH–, =N–, –CHO, R–OH, and –R=R– with the carboxylic acid group –COOH of poly(acrylic acid) [34,47–49].

The stressed system design allows for increases and decreases in concentration cycles in the range of 1.5–4.5 cycles by continuous addition of makeup water and blowdown. The increased stress can challenge the chemical treatment proposed in the areas of corrosion and deposition control.

Monthly water analyses were performed prior and over the experimental period, on both the cooling water recirculation and the makeup water samples. Results of these analyses are shown in Table 1 below. In the beginning, the Cycle of Concentrations (COCs) is 2.86, based on the concentration ratio of chloride, which is the usual analytical parameter used for determining cycles of concentration [11]. Then, the COC in the cooling tower systems were gradually increased over a one-month period.

The polymer blends under evaluations were introduced at 100 ppm concentration in a 24-h period intermittently into the recirculating water system, for the physicochemical conditions as shown in Table 1. The physicochemical experiments were run every single day, for a period of one month for the test on makeup and recirculating waters. The cycles of concentration increased up to 3.22 cycles, and then held at that point for one week to observe water chemistry and the formation of scale. The system was maintained at a temperature of 40°C and pH of 8.9; low scale was formed on the test heat exchanger, which corresponds well with that obtained later from the analyses of the coupon and allows higher cycles of concentration to be maintained without severe scaling problems.

Table 1
Average values for recirculation cooling water and makeup water chemistries with residual ratios (COC), before and after adding the polymer blends, for a period test of one month

Tests	Prior treatment			Polymer treatment		
	Makeup	Recirculating	COC	Makeup	Recirculating	COC
Temperature, °C	26	41.00	NA	26	40	NA
pH	7.75	8.70	NA	7.8	8.9	NA
Conductivity, μs/cm	475	1171.3	2.47	480	1,250	2.60
Total alkalinity, mg/L as $CaCO_3$	124.79	287.5	2.3	141	367	2.60
Calcium, mg/L as $CaCO_3$	139.46	363.50	2.61	140	360	2.57
Magnesium, mg/L as $CaCO_3$	83.54	208.80	2.50	72	240	3.33
Sodium, mg/L	18.00	183.89	NA	18.00	183.89	NA
Chloride, mg/L	48.79	140.0	2.86	49.7	160	3.22
Sulfate, mg/L	65.77	210.00	3.19	70.18	206	2.94
Total iron, mg/L as Fe	ND	0.25	NA	ND	0.15	NA
TDS, mg/L	304.00	749.6	2.47	307.2	800	2.60
Silica, mg/L as SiO_2	1.88	5.5	2.93	1.91	6.01	3.15

Notes: ND: Not Detectable.
NA: Not Applicable.
COC: Cycle of Concentration.

At the end of each day (24 h), three pre-weighed coupons were removed from the corrosion coupon rack and weighed to determine the scale mass that had developed on the coupons. An average value of 0.2 g of scale deposit was obtained at the end of one month of testing time. However, according to the favorable results obtained above, the maximum stable water saturation chemistry is set at 3.5 cycles of concentration while the present polymer blends provide a good performance.

3.2.1. Effect of the inhibitor on calcium and magnesium scale deposition

Fig. 6 shows the results obtained for calcium and magnesium inhibition in the presence of the blended polymer in the evaporating pilot cooling tower. The polymer inhibitor efficiency was calculated using the modified following equation for magnesium [50]:

$$\text{Inhibition Efficiency } (\%)$$
$$= 100 \times \left(\frac{[\text{Ca or Mg}]_{\text{Sample}} - [\text{Ca or Mg}]_{\text{Blank}}}{[\text{Ca or Mg}]_{\text{Initial}} - [\text{Ca or Mg}]_{\text{Blank}}} \right) \tag{1}$$

where:

[Ca or Mg]$_{\text{Sample}}$ = Ca or Mg concentration in the presence of inhibitor at 24 h.

[Ca or Mg]$_{\text{Blank}}$ = Ca or Mg concentration in the absence of inhibitor at 24 h.

[Ca or Mg]$_{\text{Initial}}$ = Ca or Mg concentration at the beginning of the test.

The polymer blends was added into cooling water, which have the physicochemical specification as in Table 1; while the inhibition efficiency was calculated
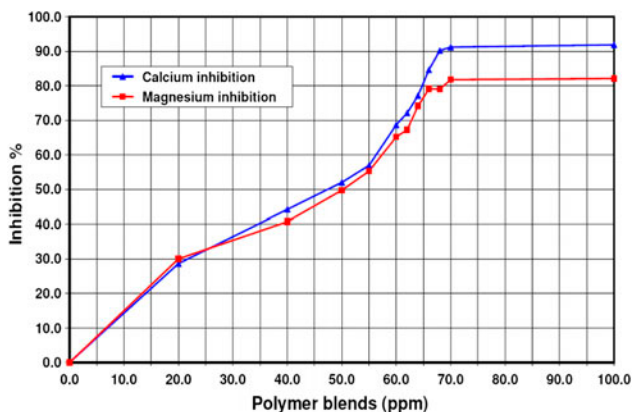
using Eq. (1) after 24 h test time. It has been shown that the presence of the polymer has an effect on controlling the crystal growth; at 20 ppm concentration of polymer, we have significant inhibition efficiency of about 30%. This preliminary result led to increase the polymer concentration to 100 ppm. As noted in Fig. 6, the inhibition effectiveness obtained for calcium and magnesium scales reaching a constant value around of 91 and 82%, respectively.

3.2.2. Scaling tendency indicators

The Langelier Saturation Index (LSI), the Ryznar Stability Index (RSI), and the Puckorius Scaling Index (PSI) are designed to be predictive tools for calcium carbonate scales [51–54]. These methods allow the maintaining balance of the scale formation and corrosive tendencies of the recirculating water while addressing such problems by polymer blends inhibitor.

The LSI calculations are based on the bulk system concentration of calcium hardness with other parameters, but they do not take into account other species that may affect the activity of the calcium or carbonate ions [51,54,55]. For this reason, we will run some experimental tests to obtain some results on the Calcite Saturation Index (CSI).

As shown in Fig. 7, the cycles of concentration were increased from 1.5 to 4.5, while the pH of cooling water was kept constant at 8.9. The LSI indicated that the cooling water has a tendency for calcium carbonate to precipitate. In this study, the LSI reaches 2.5 after one month of continual testing; this is considered a stress condition, where the polymer provides effective cooling water treating even in high electrolyte concentrations, which is running at 4.5 concentration cycles and temperature up to 50°C.

Fig. 6. The inhibition % vs. polymer blends concentration at a temperature of 41 °C and pH of 8.70 in the pilot-scale cooling tower tests.
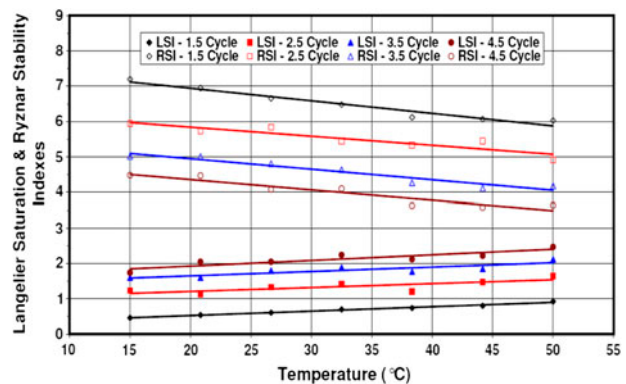

Fig. 7. LSI and RSI vs. temperature for selected cycles of concentration values.
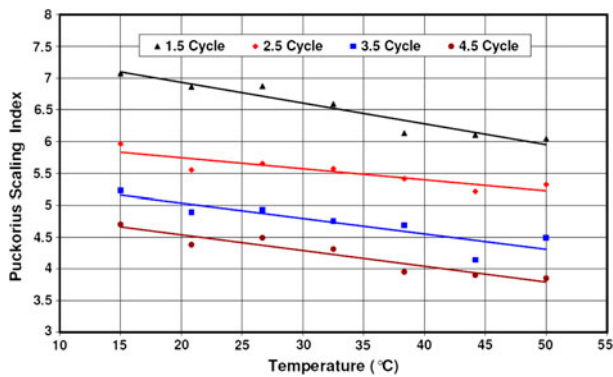
Fig. 8. PSI vs. temperature for selected cycles of concentration values.

The RSI is also a corrosion index that predicts the influence of calcium carbonate dissolution on carbon steel [52]. The RSI values ranged from 7.2 to 3.64 as shown in Fig. 7, indicate the scale tendency increases as the index decreases. Consequently, the cooling water is expected to be corrosive where the water becomes saturated with oxygen. In this study, the oxygen content is about 6.46 ppm; which produces cathodic depolarization and will increase the corrosion rate.

Moving away from LSI and over RSI to PSI, Puckorius, or Practical Scaling Index (PSI) which was introduced in 1983 [53]. The PSI is another index that takes into the account two other critical parameters: the buffering capacity of the water, and the maximum quantity of the precipitate that can form in bringing water to equilibrium. The result in Fig. 8 shows that PSI can achieve 3.65 with the addition of polymer blends and without scale formation.

Experimental scaling tendencies data have been obtained from the above studies show that the recirculating water requires effective scale inhibitor to prevent the formation and deposition of materials. The polymer blends deal with these challenging problems at higher concentrations and temperature, while maintaining balance of the scale formation and corrosive tendencies of the recirculating water.

3.2.3. Calcite and magnesite saturation breakpoint

The CSI calculation of the relative degree of calcium carbonate saturation is given by the ratio of the ion activity product and the solubility product [20]. The (CSI) calculation takes into account the effects of many complex pairings possible; it can be a good index to use for evaluating water treatment performance.

Another objective of this study is to determine the maximum CSI that could be achieved by increasing

concentration cycles in the cooling system. The polymer blends formulation is able to achieve a CSI_{max} of 128 with cycles of concentration up to 4.5, as shown in Fig. 9.

Based on the CSI result, it was determined that 3.5 cycles of concentration was a safe target for the pilot cooling water function, so the CSI is approximately 59 with the temperature and pH was maintained to 40°C and 8.9, respectively.

Fig. 10 shows a typical calcite and magnesite saturation breakpoint study grab sample measurement of conductivity with calcium and magnesium hardness. As the COC was increased, the conductivity and hardness increased until scaling occurred. The point at which the scaling occurred was indicated by a maximum in the calcium and magnesium hardness values as happened on the day 06/10 for magnesium scales, and 20/10 for calcium scales; and further shows both calcium and magnesium scales on the day to be 30/10. As the scale developed, the calcium and magnesium hardness decreased while the conductivity remained constant. The designed polymer treatment at 100 ppm is allowed increasing concentration of cal-
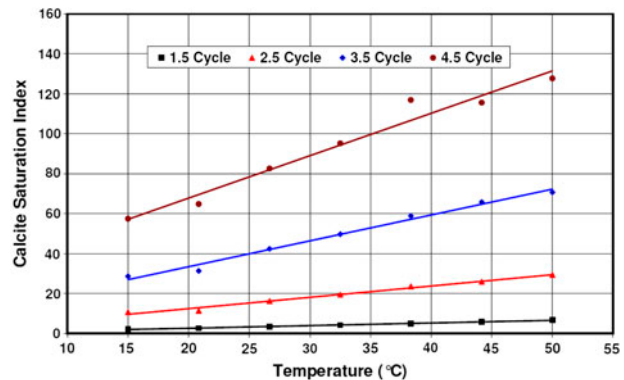

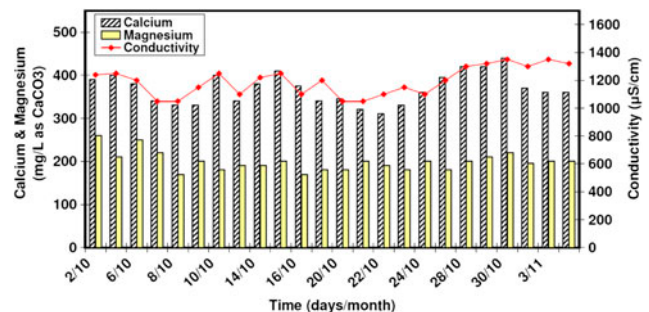Fig. 9. CSI vs. temperature for selected cycles of concentration values.

Fig. 10. Calcite and magnesium saturation breakpoint test shows conductivity, magnesium and calcium vs. time for cooling water recirculating.

cium in the cooling water up to 440 mg/L as $CaCO_3$ and magnesium up to 250 mg/L as $CaCO_3$, then the calcium and magnesium drop to 370 mg/L as $CaCO_3$ and 220 mg/L as $CaCO_3$, respectively, due to scale formation.

Over the course of the experiment, the system was operated up to 4.5 Cycles of concentration. Despite this substantial increase in the cycles of concentration, the calcium and magnesium hardness remained in balance, while the polymer blends still providing good scale inhibition performance. The polymer blends structural rigidity; the units of its chain molecules and stereochemical orientation appear to satisfy a steric requirement for calcite and magnesite growth inhibition. However, in the aqueous mediums, the carboxyl groups of poly(acrylic acid) are negatively charged; they act as an antiscalant or dispersant to the formation of the insoluble precipitate and will prevent or minimize the scale formation [56].

3.3. Corrosion inhibitor essays

3.3.1. Electrochemical tests

The polymer blends prepared in the present study were evaluated for controlling corrosion in pilot cooling water systems as described previously in Fig. 2. The corrosion polarization resistance method [57,58] was used under the same conditions as in Table 1.

The data in Table 2, illustrate the effectiveness of the polymer blends of the present study in inhibiting corrosion of carbon steel metal. The combination of the poly(acrylic acid) and polyaniline dispersion produces a synergistic effect on corrosion, in addition to the adsorption of polyaniline films over the metal surface; the poly(acrylic acid) anions electrostatically adsorbed on the carbon steel [59]. In addition to the presence of functional groups in the polyaniline mole-

cule describe in section (3.2. Scale deposits essays), the adsorption of polymer blends is influenced by the presence of π bonds in their structures and the group specially R–COOH and –CO– of poly(acrylic acid). It has also been noted that the molecular area plays an important role to inhibit carbon steel.

The percent efficiency of the inhibitor is expressed below by Eq. (2) [21].

Inhibition Efficiency (%)
$$= 100 \times \left(\frac{CR_{uninhibited} - CR_{inhibited}}{CR_{uninhibited}} \right) \quad (2)$$

where
$CR_{uninhibited}$ = corrosion rate of the uninhibited system.
$CR_{inhibited}$ = corrosion rate of the inhibited system.

The blank solution when no polymer blends were employed defines the corrosion rate of the carbon steel in uninhibited cooling water. The test data in Table 2 show the poly(acrylic acid) and polyaniline dispersion are effective to reduce the corrosion rate to less than 2 mpy (10.96 mg/dm^2/day) at an amount of 20 mg/L of polymer blends. Since corrosion rate of 2–4 mpy (10.96–21.92 mg/dm^2/day) is generally considered to be an acceptable rate in open cooling systems [20,60], the excellent corrosion protection afforded by the compositions of this research can be readily appreciated.

Measuring corrosion rate by the corrosion polarization resistance method was used at 100 ppm of polymer blends to identify the action of the inhibitor. Fig. 11 shows the corrosion of carbon steel in the inhibited cooling water was much higher than that for the inhibitor-free cooling water. The inhibition efficiency of the corrosion is about 81.57%; this is calculated by Eq. (2) using the average corrosion rate.

3.3.2. WL tests

Fig. 12 shows the WL test results of carbon steel with, and without the polymer blends treatment. Coupons are removed, cleaned, dried, and weighted, and also inspected, no pitting was observed on coupon surfaces, after 28-day immersion in cooling water.

The results indicate that the new polymer blends can reduce the corrosion rate by 78%; the average corrosion rate obtained is 1.47 mpy (8.09 mg/dm^2/day). Equipment inspections and heat exchanger testing have confirmed excellent corrosion protection. The efficiency with which the polymer blends inhibitor

Table 2
Corrosion-inhibiting efficacy in cooling water

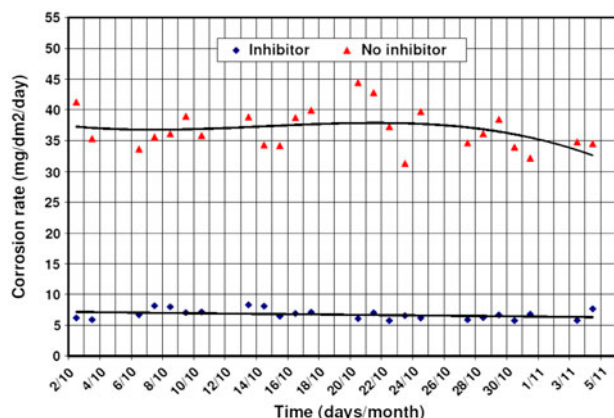| Concentration of polymer blends (mg/L)	Corrosion rate (mg/dm^2/day)	Inhibitor efficiency (%)
Blank	36.77	None
20	8.86	75.90
40	8.20	77.70
60	8.01	78.22
100	6.93	81.15
200	6.20	83.14
300	6.10	83.41

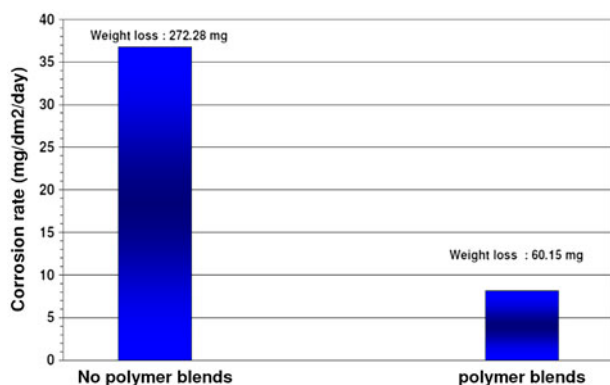Fig. 11. Corrosion rate of carbon steel with and without inhibitors.

Fig. 12. Corrosion rates of carbon steel tests with and without polymer blends.

decreases the corrosion of carbon steel was calculated as follows:

$$\text{Inhibitor Efficiency } (\%) = 100 \times \left(\frac{W - W_{\text{inhib}}}{W} \right) \qquad (3)$$

where

W = Weight loss of the uninhibited system.
W_{inhib} = Weight loss of the inhibited system.

The corrosion inhibiting composition of the present study is particularly advantageous in that the composition is capable of inhibiting corrosion in a wide variety of conditions encountered in a processing subject to corrosion, including high pH of 8.9, high temperature of 50°C, and high cycles of concentration up to 4.5 cycles.

4. Conclusions

In this work, we have found over a wide range of conditions employed in a cooling system; the polymer blends provide a sufficient effect to inhibit calcium and magnesium scales; and also to protect metals from dissolution, while maintaining the scale and corrosive tendencies of the recirculating water in balance. The scale and corrosion tendencies have been observed, and show, as a first result, a positive LSI value, which has reached 2.5 after one month of testing time. This indicates that the recirculating cooling water being supersaturated with calcium carbonate. The RSI index confirms the LSI results; at RSI values ranging from 7.2 to 3.64, the polymer blends are able to control corrosion and scale. The PSI index has a wide variation from 7.1 to 3.65, and continues to confirm the results obtained from LSI and RSI prediction tools. In addition, the efficiency of the polymer blends to inhibit scale formation and corrosion was evaluated in stressed cooling water conditions, while the temperature reaches 50°C with high electrolyte concentrations and a pH of at least 8.7. The results showed that the polymer blends used at 100 ppm can effectively inhibit the formation of scale in the recirculating cooling water, up to 91% for calcium scale and 82% of magnesium scale, and allows for significantly higher CSI up to 128, when the cycles of concentration reach 4.5. However, the corrosion-inhibiting efficiency was significantly around 81% for 100 ppm of polymer blends concentration.

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