

Effect of Some Factors on the Thermal Performance of Shell and Tube Heat Exchanger

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Abstract: This research aimed to study the effect of 0.1 M of HCl, H₂SO₄ and NaCl solutions at 61°C on the thermal performance and corrosion behavior of commercially pure copper tubes in the used Shell and Tube Heat Exchanger (STHE). The tests are performed with a counter-flow arrangement for 120 h. The flow rates for the tube side solution (aqueous solution) and shell side solution (tap water) adjusted and kept constant at 150 and 50 L h⁻¹, respectively. According to the obtained results, the greater decrease in thermal performance is observed in HCl solution than in H₂SO₄ solution and finally in NaCl solution with a decrease in percentage ε were (11.6, 10.1 and 6.9), respectively. Besides, the results of visual inspection of the interior tubes walls degradation and variation of the used aqueous solution characteristics are showed that the HCl acid solution is more corrosive than H₂SO₄ acid and NaCl salt solutions. The XRD analysis results revealed that the corrosion products are formed by more than one reaction mechanism and formed different hydrated and complex corrosion products.

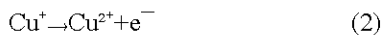
Key words: Shell and tube heat exchanger, thermal performance, aqueous solution characteristics variation, visual inspection appearances, XRD analysis

INTRODUCTION

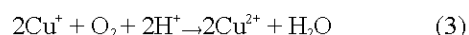
Shell and Tube Heat Exchanger (STHE) use to exchange and transfer heat from a hot to a cold fluid (Thulukkanam, 2013). Generally, it consists of a round tubes bundle placed in a round form in a cylindrical shell. The corrosion in the heat exchangers can be defined as the destruction or deterioration of heat transfer surface due to the operation conditions and the characteristics of working fluids. The corrosion of heat exchanger tubes causes thinning of heat transfer surface, crevices, holes and also complete failure of the exchanger. Due to corrosion of exchanger tubes, fouling occurs. Fouling is the formation and accumulation of undesired deposits on heat transfer surfaces which impede the heat transfer (Thulukkanam, 2013; Shah and Sekulic, 2003). In acidic solutions (pH<6) such as HCl or H₂SO₄ with oxygen presence (e.g., in aerobic moving water conditions), copper dissolve to form Cu²⁺ ions which is more stable form in these conditions (Oliphant, 2003; David and Hendrix, 2006). The dissolution of copper to form Cu⁺ and Cu²⁺ ions can be described as follow (Frankel and Landolt, 2007):



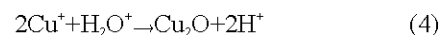
Cu⁺ is further oxidized:



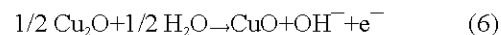
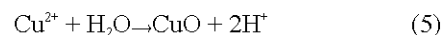
In presence of oxygen, non-electrochemical oxidation reaction of Cu⁺ to Cu²⁺ is possible:



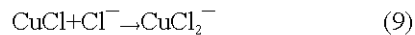
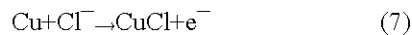
In solutions with (pH 6-8) with relatively high oxygen content (e.g. in aerobic moving water conditions), copper can initially form an insoluble layer of cuprite (Cu₂O). This red to brown magenta corrosion product is the most stable species in these conditions and will produce a semi-protective film which reduces further corrosion (Oliphant, 2003). Cu⁺ ions can react with water to form cuprite (Cu₂O) as follow (Frankel and Landolt, 2007):



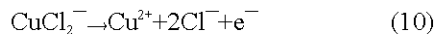
In alkaline solutions (pH>8) with a high oxygen content, copper dissolve to form tenorite (CuO). This corrosion product (black to brown in color) is the most stable form in these conditions and forms a protective oxide film against further corrosion (Oliphant, 2003). Tenorite (CuO) can be also formed from further oxidation of cuprite to tenorite as follow (Frankel and Landolt, 2007):



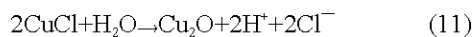
Pitting corrosion of copper and its alloys always occurs under relatively low flow velocity, usually $0.6-0.9 \text{ m sec}^{-1}$ associated with chloride ions (Carvalho, 2014). Aggressive pitting solutions have pH range of (7.2-7.8), high total dissolved salts content including chlorides and the presence of dissolved oxygen gas (Oliphant, 2003). In chloride solutions with chloride concentration <math><1 \text{ M}</math>, the dissolution of copper takes place to form solid copper (I) chloride salt (CuCl) which does not protect the metal enough and reacts with excess chloride ions to form the soluble CuCl_2^- . Besides, can diffuse through the solution and reacts with excess chloride ions. CuCl film can transform into a soluble CuCl_2^- complex and the later hydrolyzes to produce a passive Cu_2O layer and so a decrease in the corrosion rate can be observed. The reactions take place as follow (Sherif, 2012; Sherif and Park, 2006):



The produced CuCl_2^- may be further oxidized to Cu^{2+} ions according to the following reaction:



The hydrolysis of CuCl can partially protect the copper and result in reducing the attack of chloride ion as follow:



Several studies have been evoked in this field. Ranjbar (2010), Frankel and Landolt (2007) is examined the failure of the used copper-alloys tubes in a STHE. Initially, yellow brass tubes tested and then replaced by Cu-5Ni alloy tubes. The flow-velocity of cooling water was very low and led to deposits accumulation and tubes diameter reduction. According to the obtained results, the cooling water which contained a high percentage of calcium/magnesium compounds, TDS and a lot of large-size solid particles led to crystallization and particulate fouling of the interior tubes walls of the exchanger. The very low velocity of the cooling water led to the deposition of extraneous solids inside tubes surfaces. The yellow brass tubes exhibited erosion and dealloying (dezincification) corrosion. The Cu-5% Ni alloy suffered from erosion-corrosion but it has higher resistance against dealloying and erosion corrosion if it compared with the former alloy. Sameh *et al.* (2009)

investigated the corrosion behavior for cylindrical rod of high purity copper in deaerated and oxygenated 0.1 M H_2SO_4 solutions by employing the rotated cylindrical electrode under the conditions of turbulence flow. The results of potentiostatic-polarization measurements are obtained at various temperatures (283, 288, 293 and 298°K) and different rotation speeds (100, 200, 300 and 400 rpm). Corrosion rate of copper is increased by increasing the temperature and/or velocity for both deaerated and oxygenated solutions. Hagioglu *et al.* (2010) is simulated the exposure conditions in different environments of some samples made from yellow tombac (zinc-copper alloy), pure copper and aluminium. The tombac, copper and aluminium samples are exposed to 3% NaCl solution for 144 h at 35°C by using a salt fog chamber. The samples surface morphology before and after the corrosion tests are analyzed by scanning electron microscope. Also, the crystalline structure of the metallic samples is assayed with the X-ray diffractometer. The obtained results showed that the corrosion process depends on the nature of the material. Copper resistance to accelerated corrosion in 3% NaCl was higher than aluminium and yellow tombac.

MATERIALS AND METHODS

Description of the used STHE: In the present research, the used STHE consisted of transparent plastic shell (its inner diameter and length are 150 and 255 mm, respectively) in which tubes bundle are fitted at the center of the shell, stainless steel hot water tank (solution tank), two 3 KW electric heating elements, cold water tank, two centrifugal type water pumps, two flow meters, four thermocouples (type K) for the exchanger inlet and outlet and one for heating tank (hot water tank). The exchanger is operated and connected for all tests in counter-flow configuration. Figure 1 shows the schematic diagram of the STHE.

The used devices and equipments: The used apparatuses are digital electronic weighing scale (type POINEER with 0.1 mg accuracy), 0-14 pH meter (type ECO Testr PH1), X-ray diffractometer (type XRD-7000) and atomic absorption spectroscopy (type GTA-120).

Preparation of STHEs tubes and solutions: The 18 commercially pure copper tubes with the length, inner and outer diameters are 310, 10.5 12.7 mm, respectively are prepared to use in exchanger. The chemical composition of the used copper is shown in Table 1. The used aqueous solutions in the tests are 0.1 M of sodium chloride salt (NaCl), sulfuric acid (H_2SO_4) and Hydrochloric acid (HCl).

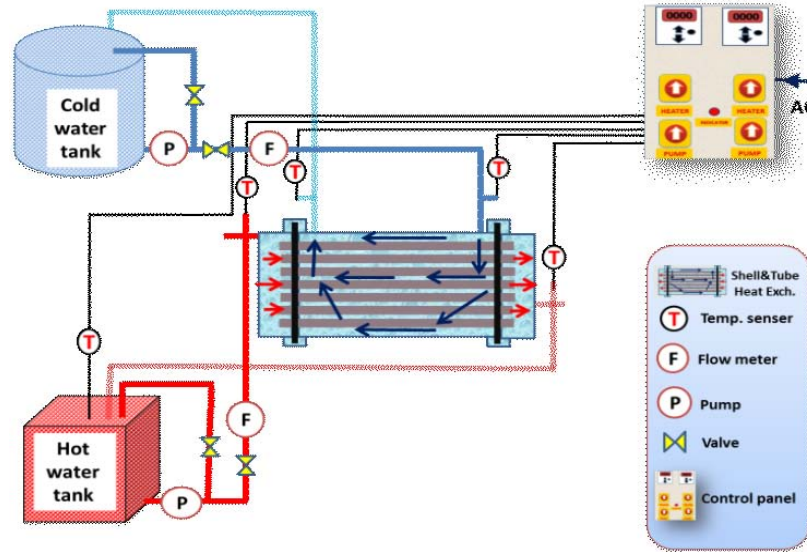


Fig. 1: Schematic diagram of the used STHE

Table 1: The chemical composition for the used copper tubes

UNS No.	Compositions (wt. %)	
	Pb	Cu
Cu-12200	0.015-0.14	99.9 min

Experimental procedures: The hot water tank is filled with the prepared solution and the cold water tank is filled continuously with the tap water. The apparatus supplied with electrical energy from the main switch.

The flow meter reading for the circulated hot solution is adjusted at 150 L h^{-1} and for the cold water at 50 L h^{-1} and the thermostat temperature for the inlet hot solution is adjusted at about $61(\pm 0.4)^\circ\text{C}$ while the inlet cold water temperature is ranged between $(19-27)^\circ\text{C}$.

The pH value and temperature of the hot solution are recorded every ten degree of temperature raising until the steady state temperature (61°C) reached at the tube side inlet is. At the steady state STHE operation condition, the temperature at tube-side and shell-side solution and also the pH value and temperature of the hot solution in the tank are recorded every 2 h. After 16 h of operation, the STHE is switched OFF. The operation of STHE is started after about 8 h and continued for 14 h with recording the pH value and temperature for the same explained positions above.

The cyclic operation of the STHE is repeated until completing 120 of the actual operating time (where the total time for the operation and shutdown was about 178). After completing the wanted 120 actual operating hours, the system is turned off and then the shell side water is drained and the tube side water (hot solution) is discharged to a clean plastic container for using it in solution characteristics variation analysis (ion release

test). The corrosion products of interior tubes wall are collected and dried at 120°C then used for XRD analysis.

The tube inlet and outlet channels are opened and the tested tubes are removed. The system is completely washed and cleaned by using distilled water and prepared to use it with a new group of copper tubes (bundle). The internal surface of the tubes at different corrosion conditions are photographed by using a digital camera (type Nikon-P900) at 1X and processed by the aid of computer program.

Calculations of STHEs overall thermal resistance and effectiveness:

The overall thermal resistance and effectiveness of the heat exchanger slightly changed with corrosion progress. The effect of the corrosion and fouling progression investigated and studied by continuously evaluating the inverse thermal conductance ($1/UA$) and effectiveness (ϵ) of a heat exchanger. The heat transfer equation of heat exchanger is as follow (Thulukkanam, 2013; Shah and Sekulic, 2003):

$$Q = UAF\Delta T_{lm} \tag{12}$$

The mass flow rate of fluid is related to the volumetric flow rate as follow:

$$\dot{m}_h = \dot{V}_h \rho_h \text{ and } \dot{m}_c = \dot{V}_c \rho_c \tag{13}$$

The log-mean temperature difference (LMTD or ΔT_{lm}) is defined as:

$$LMTD = \Delta T_{lm} \frac{\Delta T_1 - \Delta T_2}{\ln \frac{\Delta T_1}{\Delta T_2}} \tag{14}$$

where, ΔT_1 and ΔT_2 are temperature differences between two fluids at each end of a counter flow or parallel flow exchanger. For a counter flow exchanger:

$$\Delta T_1 = T_{h,i} - T_{c,o} \text{ and } \Delta T_2 = T_{h,o} - T_{c,i} \quad (15)$$

For any parallel or counter flow exchanger (as in 1-1 STHE) (Shah and Sekulic, 2003):

$$F = 1 \quad (16)$$

$$1/UA = \frac{\Delta T_{lm}}{\dot{m}_h C_{p_h} (T_{h,i} - T_{h,o})} = \frac{\Delta T_{lm}}{\dot{m}_c C_{p_c} (T_{c,o} - T_{c,i})} \quad (17)$$

The effectiveness of a heat exchanger is defined as the ratio between the actual heat load to the maximum possible heat load and expressed as (Thulukkanam, 2013; Shah and Sekulic, 2003):

$$e = \frac{Q}{Q_{max}} = \frac{\dot{m}_h C_{p_h} (T_{h,i} - T_{h,o})}{C_{min} (T_{h,i} - T_{c,i})} = \frac{\dot{m}_c C_{p_c} (T_{c,o} - T_{c,i})}{C_{min} (T_{h,i} - T_{c,i})} \quad (18)$$

In the present study, shell side water (cold water) is the minimum fluid, therefore, Eq. 20 can be simplified and write as:

$$e = \frac{T_{c,o} - T_{c,i}}{T_{h,i} - T_{c,i}} \quad (19)$$

Where:

- Q = Duty or actual heat load (W)
- U = Overall heat transfer coefficient (W/m².k)
- A = The surface area for heat transfer (m²)
- F = Temperature correction factor
- ΔT_m = Logarithmic mean temperature difference (°C)
- \dot{m}_c, \dot{m}_h = Mass-flow rates for cold water and hot solution (kg sec⁻¹)
- \dot{V}_c, \dot{V}_h = Volumetric-flow rate for the cold water and hot solution (L h⁻¹)
- ρ_c, ρ_h = Density for the cold water and hot solution at fluid mean bulk temperature (kg/m³)
- C_{p_c}, C_{p_h} = Specific heat for the cold water and hot solution at fluid mean bulk temperature (°C)
- $T_{h,i}, T_{h,o}$ = Hot solution inlet/outlet temperatures (°C)
- $T_{c,i}, T_{c,o}$ = Cold water inlet/outlet temperatures (°C)
- ϵ = Heat exchanger effectiveness
- Q_{max} = Maximum possible heat load
- Q_{min} = Heat capacity rate for minimum fluid (W/K)
- ΔT_{max} = Cold water and hot solution inlet temperature difference (°C)

RESULTS AND DISCUSSION

Performance of copper tubes STHEs: Generally, the corrosion products (deposits) layers provide an additional resistance to heat transfer because the thermal conductivity of deposit layers is very low if compared with that of the copper. In HCl solution, it is observed that the heat exchanger effectiveness decreased from 0.31318-0.27671 with a percentage of decreasing about 11.6%. The effectiveness in H₂SO₄ solution is decreased from (0.31388-0.28197) with a percentage of decreasing about 10.1%. While in NaCl solution, it is decreased from (0.31578 to 0.29397) with a percentage of decreasing about 6.9%. The decrease in the effectiveness of copper tubes exchanger with the time is showed in Fig. 2, in the exchanger effectiveness drop was greater in HCl solution than H₂SO₄ solution while it was smallest in NaCl solution. One of the reasons of the effectiveness drop can be explained by the increase in heat exchanger overall thermal resistance with the time as shown in Fig. 3 due to the tubes wall corrosion and products layers deposition on it and the change in the solutions characteristics as a result of contamination with the dissolved corrosion products and compounds. Figure 3 shows that the inverse of thermal conductance is increased with the time duration of operation, the greater

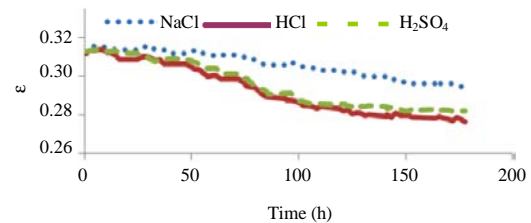


Fig. 2: The ϵ vs. time for copper tubes exchangers operated in 0.1 M (HCl, H₂SO₄ and NaCl) solutions at 61 °C temperature and 150 L h⁻¹ volumetric flow rate, respectively

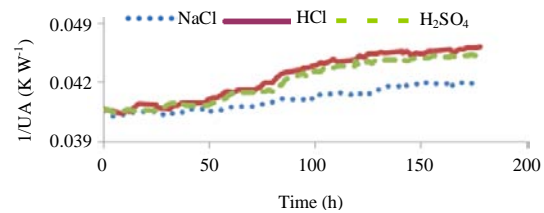


Fig. 3: The 1/UA vs. time for copper tubes exchangers operated in 0.1 M (HCl, H₂SO₄ and NaCl) solutions at 61 °C temperature and 150 L h⁻¹ volumetric flow rate, respectively

values of the inverse of thermal conductance obtained at HCl solution and the lower values were obtained at NaCl solution.

Visual appearances of corroded interior tubes surfaces:

The visual appearance inspection results of the interior tubes surface are examined and photographed at the end of operating time and testing the exchangers at previously mentioned solutions and conditions (after the bare tubes brought out of the exchanger and longitudinally cut and split into two half and left to dry). The visual observations of corroded surfaces and corrosion products deposits on the interior surface of the tested tubes are shown in Fig. 4. The corroded interior tubes surface photos indicates the most corrosion damage and deterioration for the copper interior tubes wall are took place in HCl solution than H₂SO₄ solution. But NaCl solution tends to the lowest damaged surfaces. In HCl solution, red to brown layers of corrosion products and deposits are clearly observed on the internal surface of tubes. The tubes surface in HCl solution are stained, tarnished and exhibited general harsh and uniform corrosion over the entire area where these deposits removed due to the flowing solution or adhered at some other locations on the corroded surface. In H₂SO₄

solution, also general and uniform surface corrosion took place but with less formed corrosion products and tubes surface damage if compared with HCl solution. Interior tubes surfaces are tarnished and exhibited some green to brown corrosion products at some areas while other areas exhibit brown deposits with some surface roughing as a result of general corrosion. In NaCl solution, the interior tubes surfaces tarnished and exhibited a black to brown color as well as non-uniform or locally attacked at some locations on the surface. Under these dark layers severe wide, shallow and large cavities and pits are revealed.

Finally, the effect of solution flow at 61°C in all STHes tests is obviously clear on the internal surface of tubes through observing harshness, scraping and removing the corrosion products or deposited layers at some areas. This action accelerated due to the erosion corrosion process and existence of corrosive chemicals (such as O₂ and Cl⁻) in the solutions.

The aggressiveness of HCl molecule is because it decomposes into two active ions (H⁺ and Cl⁻). Chloride ions aid to breakdown and destruction of the formed protective oxide film and exposure of the metal surface to the acidic solution (H⁺ ions). By hydrogen ions, the attack becomes more aggressive and dangerous since H⁺ ions are contributed in cathodic reaction. However, the sulfate

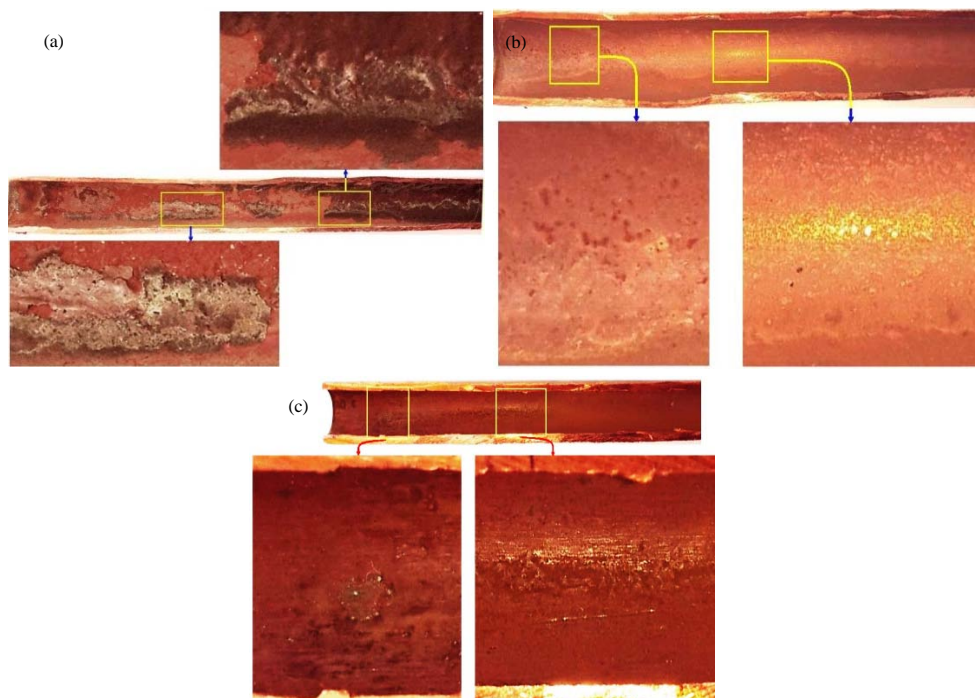


Fig. 4: Visual appearances of the corroded interior surfaces of copper tubes in 0.1M: a) HCl; b) H₂SO₄ and c) NaCl solutions at 61°C temperature and 150 L h⁻¹ volumetric flow rate, respectively

Table 2: Original and final results for the used solutions in the characteristics in the STHes operated at 61°C temperature and 150 L h⁻¹ volumetric flow rate

Sample	Cu (ppm)	Al (ppm)	Cond. (µsec cm ⁻¹)	TDS (µsec cm ⁻¹)	pH	Cond. decreasing (%)	Decreasing(‰)
Solution before test							
HCl	0.003	0.002	38900	19061	1.1	-	-
H ₂ SO ₄	0.004	0.003	51300	25137	0.9	-	-
NaCl	0.002	0.002	13265	6500	7.6	-	-
Solution after Cu test							
HCl	340.000	-	6300	3087	4.0	83.80	11.6
H ₂ SO ₄	287.000	-	10910	5346	2.9	78.73	10.9
NaCl	0.600	-	12659	6164	8.2	4.56	6.9

ions (SO₄⁻²) do not have the ability (as chloride ions) to destroy the protective film, therefore, it is less aggressive. Also, the twice amount of released H⁺ from the dissolution of H₂SO₄ molecules lead to polarization action of H⁺ at cathodic areas, hence the slower cathodic reaction of H⁺ and lower corrosion damage. While the sodium chloride molecules have only Cl⁻ as attacker ions to the metal surface without H⁺ assistance. Therefore, the corrosion damage was the lowest at NaCl solutions.

Variation of solutions characteristics: The recorded data and obtained results indicated that the increasing of pH values for acidic solutions were gradual with small trend at the beginning of STH operation then suddenly increased after (~55 h) of operation then became stable with time. The variation of pH value with time indicates the higher conversion rate of H⁺ to H and evolution of H₂ (i.e., higher cathodic reaction) in HCl solution than H₂SO₄ solution then higher corrosion rate. While the variation of pH for sodium chloride salt solution was smaller and semi-stable if compared with the acidic solutions. Figure 5 shows the variations of pH values for the used aqueous solutions in the STHes with the time operated at the mentioned conditions. Ion release test is done in the North Gas Company by using atomic absorption spectroscopy. The dissolved metal ions (in ppm) in the test solution are measured before and after the end of the STH operation. Besides, the conductivity and TDS of solution before test and at the end of test are measured by using conductivity-meter. Due to corrosion, the solutions are polluted and contaminated by dissolved metal ions and other non-dissolved corrosion products and this led to decrease and drop the solutions conductivity and hence corrosion rates. The percentage of conductivity decreasing was greater in HCl if compared with H₂SO₄ while it was very small in NaCl solution. The experimental results of solution characteristics variation and thermal effectiveness drop values for exchanger operated are shown in Table 2.

XRD analysis results: The identification of the corrosion products are obtained by XRD analysis in the

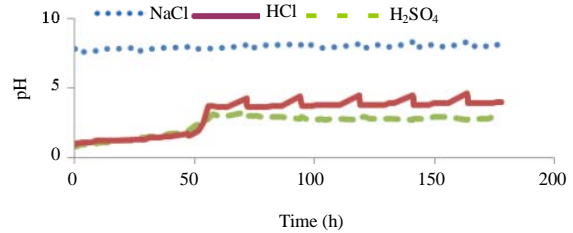


Fig. 5: The pH values vs. time for the used aqueous solutions in the copper tubes STHes operated at 61°C temperature and 150 L h⁻¹ volumetric flow rate, respectively

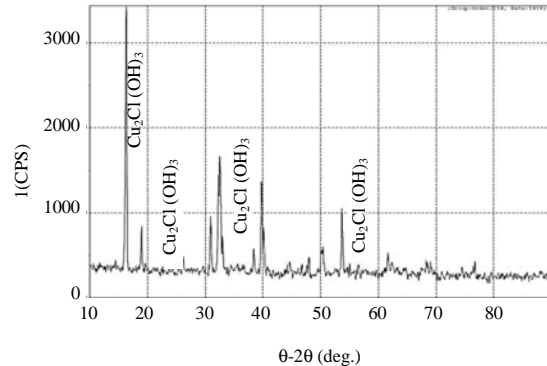


Fig. 6: XRD result for copper tube corrosion products in 0.1 µ HCl solution

Commonalty Company for Geologic Scanning/Baghdad (by using XRD-7000 device with Radiation: CuKα1 and λ: 1.54056Å). The results of XRD test for the formed deposits in HCl solution showed that deposits buildup consisted mainly of copper chloride hydroxide (Cu₂Cl(OH)₃). The deposits and corrosion products buildup in H₂SO₄ solution contained copper sulfate hydrate (CuSO₄·H₂O), cuprite (Cu₂O) and copper sulfite hydrate (Cu₂SO₃·CuSO₃·2H₂O). The deposits accumulated due to the exposure to NaCl solution consisted of cuprite (Cu₂O) and paramelaconite (Cu₄O₃). The XRD results for copper tested in the mentioned solutions are shown in Fig. 6-8.

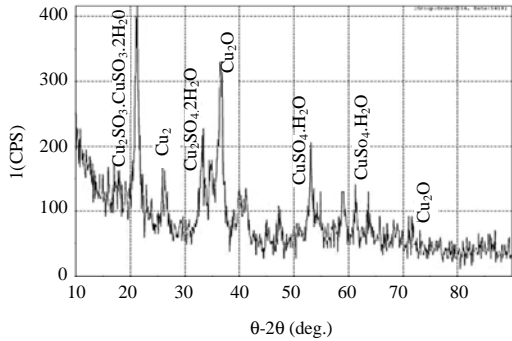


Fig. 7: XRD results for copper tube corrosion products in 0.1 μ H_2SO_4 solution

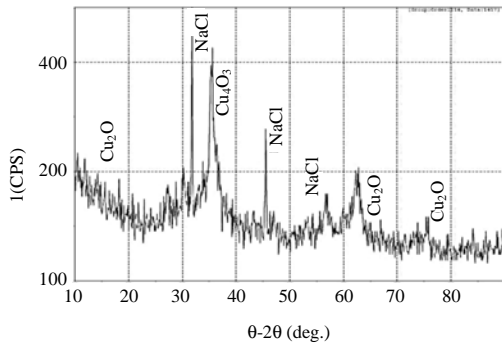


Fig. 8: XRD results for copper tube corrosion products in 0.1 μ NaCl solution

CONCLUSION

The following main conclusions are obtained on the basis of the results:

- The highest drop in thermal performance is observed in HCl acid solution followed by H_2SO_4 solution but the lowest performance drop is observed in NaCl solution
- The highest corrosion damage for the interior surface of exchanger tubes is observed in HCl acid while the lowest corrosion damage is observed in the NaCl salt solutions
- The highest variations of solution characteristics and pH values at the end of operation are observed in HCl acidic solutions while the lowest variations are observed in the NaCl salt solutions
- HCl acid solution was more corrosive than H_2SO_4 acid and NaCl salt solutions
- Generally, the corrosion types were in the form of erosion corrosion and some evidences of pitting corrosion occurrence

- According to XRD analysis results, the reactions between interior surfaces of tubes and solutions took place with more than one mechanism. Besides, more complex and hydrated corrosion products are formed because of flowing manner of solution, long time and relatively high temperature

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