Desalination and Water Treatment
www.deswater.com
doi: 10.1080/19443994.2014.940642

55 (2015) 2515–2525
August

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Corrosion of heat exchanger in thermal desalination plants and current trends in material selection

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Received 19 February 2014; Accepted 16 June 2014

ABSTRACT

Heat Exchanger constitutes an integral component of thermal desalination plants. Heat exchanger plays an immensely important role since the success of the whole process of low pressure evaporation and condensation depends upon the efficiency of heat transfer. The chemically aggressive environment surrounding the different sections of the thermal desalination plant including heat exchangers can cause failure due to corrosion and/or erosion. The cases of heat exchanger failure in seawater processing plants including desalination plants have been reported frequently. Besides investigating the cause(s) of failure in heat exchanger, the selection of appropriate heat exchanger material is the important issue in the realm of desalination technology. The work of a number of investigations related to erosion and corrosion of heat exchanger materials in thermal desalination plants reported in recent literature has been cited. The analysis of the published information provides in-depth knowledge of heat exchanger materials under plant operational conditions and assisted in formulating the selection of best and cost effective material for the plant. This paper presents some recent cases of failure of heat exchangers in thermal desalination plants. The studies include investigations on the mechanistic and causes of failure, and finally the recommendations concerning with the prevention or combating the failure. From the results of the case studies, an overall picture of the behavior of materials in respective operating environment emerges and consequently, initiates selection of better material. The paper also encompasses the recent trends in material selection of heat exchanger for thermal desalination plants. Besides the applications of conventional materials which include cupronickel and titanium, the potential of some recently developed plastic based composite is discussed.

Keywords: Condenser tubes; Multi-effect and MSF desalination plant; Localized corrosion; Crevice corrosions; Galvanic corrosions; Non condensing gas; Venting system; Plastic hear exchangers

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Presented at the Conference on Desalination for the Environment: Clean Water and Energy 11–15 May 2014, Limassol, Cyprus

1. Introduction

1.1. Heat exchangers

Heat Exchangers constitute an integral component of thermal desalination plants. Heat exchanger tubings constitute the single largest procurement item in an multistage flash (MSF) plant. According to Oldfield and Todd for each m^3/d water production, about 25 kg of heat exchanger tubing is required [1]. Heat Exchangers play an immensely important role since the success of the whole process of low pressure evaporation and condensation depends upon the efficiency of heat transfer. The chemically aggressive environment surrounding the different sections of the thermal desalination plant including heat exchangers can cause failure due to corrosion and/or erosion. This is a major problem as the cases of failure in heat exchangers of seawater processing plants including desalination plants have been reported frequently. It has been reported that more than 70% of corrosion failures in desalination plants are attributed to heat exchanger tubes [2]. Heat exchanger tubes handle seawater and condensing vapors which are fluids of completely different properties. These fluids subject the tubing to severe environments from the point of view of corrosion/erosion damage. In this scenario, the selection of appropriate heat exchanger materials is a formidable task for erection of high performance, thermally efficient, and cost-effective desalination plant.

1.2. Role of heat exchanger in thermal desalination process

There are three major sections in a heat exchanger in an MSF plant, namely, (i) Heat Rejection (ii) Heat recovery and (iii) Brine Heater (Fig. 1).

In heat rejection section, raw seawater is passed through the heat exchanger tubes at the top and is heated by the steam flashed from the bottom section. A major portion of the raw seawater is discharged to the sea from the heat rejection system and the remaining portion is chemically treated, deaerated, and passed through the tubes of the heat recovery, where it is heated again by the flash steam which is condensed and collected on trays as desalinated water. After passing through the highest state of the recovery section, the water enters the brine heater where it reaches its highest temperature, called “top brine temperature” (TBT). TBT is usually achieved through extraction from a steam turbine power plant located adjacent to the MSF unit.

In the first stage (recovery section), the pressure and temperature of steam and water are at their highest. Both the temperature and pressure drop from the first stage to the last stage of heat rejection. This causes flash boiling of the incoming brine at each stage. A portion of the brine in the last stage is discharged and the remaining portion is mixed with incoming raw seawater and used as re-circulating brine to continue the cycle.

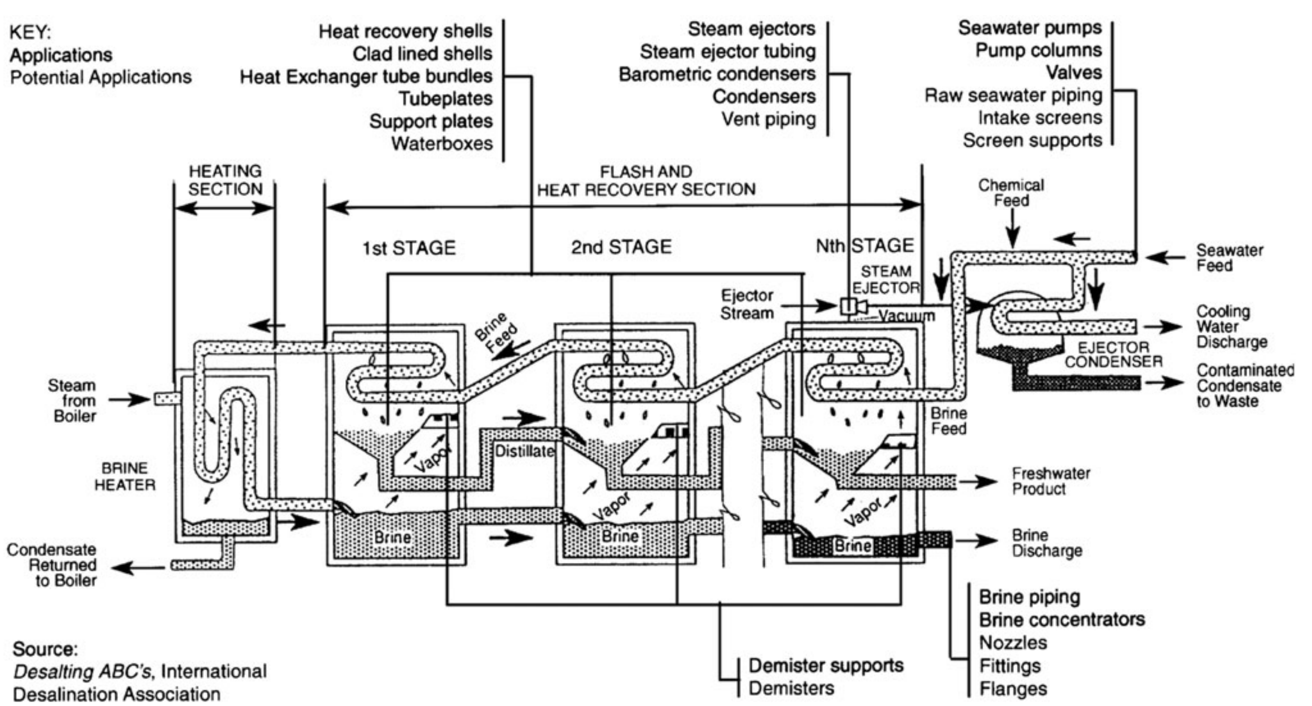

Fig. 1. Diagram of a MSF distillation plant.

Considering the material selection in different sections of MSF plants, the brine heater is the hottest part of the heat exchanger with a strongly scale forming solution. The 70/30 CuNi or modified 66/30/2/2 Cu–Ni–Fe–Mn alloy are usually used as brine heater tube material in most of the plants. However, titanium tubing (ASTM B338) has also been used in some plants. For tube plate material, 90/10 Cu–Ni alloy, naval brass or NiAl bronze the most adopted tube plates materials.

The heat recovery section normally has its first three or four stages operated at high temperatures, which may cause an attack on the outer surface of the tubes due to non-condensable (NC) gases. Inside the tube, however, the water is deaerated and virtually oxygen-free. Due to its least vulnerability towards corrosion, 90/10 CuNi has been used in the recovery section in most of the desalination plants. However, in some plants, 70/30 CuNi has been used in high temperature stages and 90/10 CuNi in lower temperature stages, with Ti tubing been used in only one plant.

The seawater flowing in heat rejection tubes is natural (not deaerated), very often chlorinated (against biofouling), and may also contain suspended solids and sulfides. This is indeed a very severe environment. Ti metal tubing (ASTM B338) has been used in most of the plants, but in some plants 90/10Cu/Ni and 70/30Cu/Ni are employed.

Cupronickel alloys have shown good performance under high water velocity, ammonia contamination, the presence of suspended solids and elevated temperatures. In modified alloys, the addition of small amounts of Fe and Mn strengthens the metal matrix, thus counteracting impingement corrosion that leads to continuous removal of the protective corrosion layers formed on copper alloys during initial service. It has been found that the additions not only provide stability to surface protective film, but also increases its self-healing propensity. Therefore, Cu–Ni–Fe–Mn, the so-called modified alloys are finding increasing application as heat exchanger materials replacing the plain cupro-nickel alloys. Spaces between the tube rolled on tube plates are active sites for deposition and crevice attacks. Rust bleeding appears from joints of 90/10 tubes and tube sheets made of CS lined with 1 mm 90/10.

Titanium possesses excellent anti-corrosion and heat transfer properties but there are problems of crevice corrosion and hydrogen adsorption in high temperature salt water. The addition of noble metal like Pd improves corrosion resistance. Thus, Ti-0.15 Pd and Ti-0.05 Pd-0.3 Co alloys have excellent resistance toward crevice corrosion.

Table 1 summarizes the composition of materials used in different SWCC MSF desalination plants. Considering the material selection in new plants (Al-Khobar-III, Shoaiba-II, and Medina-Yanbu-II), it appears that materials having improved corrosion resistance and better mechanical characteristics have been employed while comparing with materials in older plants. In heat recovery section, in most of the cases cupronickel 90/10 has been replaced by modified cupronickel alloy (Cu/Ni30/Fe2/Mn2) which has better corrosion and erosion resistance properties. Cu70/Ni30 tubes were employed in brine heaters of majority of older SWCC MSF plants, but in new

Table 1
Materials for heat recovery and heat rejection systems

Plants	Year of operation	Heat recovery tube	Heat rejection tube	Brine heater
AI-Jubail-I	1982	Ti	Ti	Ti
AI-Jubail-II	1983	Cu 90/Ni 10	Ti	Cu 70/Ni 30
Al-Khafji	1986	Cu 90/Ni 10	Ti	Cu 70/Ni 30
Al-Khobar-II	1983	Cu 90/Ni 10	Ti	Cu 70/Ni 30
Al-Khobar-III	2002	1–4:Cu/Ni30/Fe2/Mn2 5–13: Cu90/Ni10	Ti	Cu/Ni30/Fe2/Mn2
Jeddah-II	1978	Cu90/Ni10	Cu90/Ni10	Cu90/Ni10
Jeddah-III	1979	Cu90/Ni10	Cu90/Ni10	Cu90/Ni10
Jeddah-IV	1981	Cu/Ni10/Fe10	Cu90/Ni10	Cu90/Ni10
Yanbu-I	1981	1–10:Cu70/Ni30 11–21:Cu90/Ni 10	Ti	Cu/Ni30/Fe2/Mn2
Yanbu-II	2000	Cu90/Ni10	Ti	Cu/Ni30/Fe2/Mn2
Shoaiba-I	1989	Cu90/Ni10	Cu70/Ni 30	Cu70/Ni 30
Shoaiba-II	2003	Cu/Ni30/Fe2/Mn2	Cu/Ni30/Fe2/Mn2	Cu/Ni30/Fe2/Mn2
Shuqaiq-I	1989	Cu90/Ni10	Ti	Cu70/Ni 30

Note: Information data collected from concerned plant authorities.

plants, the brine heater tubes are made of modified alloy.

1.3. Literature review

The results of a number of investigations related to erosion and corrosion of heat exchanger materials in thermal desalination plants, have been reported in recent literature [3–21]. The analysis of the published information provide in-depth knowledge of heat exchanger materials under plant operational conditions and assisted in formulating the selection of best and cost effective materials for the plant.

Corrosion problems in low temperature units of Abu Dhabi MSF desalination during early stages of operation were reported. Severe crevice corrosion occurred at the joints of Ti tubes and 904L tube sheets [3]. Anodes, initially Al alloys but replaced within 3 or 4 months with iron, were installed to provide CP and to neutralize acidity inside the crevices. Al–brass tubes suffered impingement corrosion and were replaced with 90/10 Cu–Ni. Failure of condenser tubes in stage 4 of Jeddah MSF plant was reported [4]. Corrosion of condenser tubes appeared to be mainly due to the dissolution of CO_2 along with some S-containing compounds. It was recommended that stages 1–4 should be directly connected to the vent line for quick and complete ventilation of NC gases present at the vapor side of the evaporator.

Vapor side corrosion (VSC) of evaporator in MSF unit #100 of the Al-Khafji desalination plant was investigated [5]. Corrosion rates of Cu–Ni coupons exposed to NC gases in vent lines were much higher than those exposed in different evaporator stages. Higher reactivity of Cu–Ni was attributed to the presence of S in NC gases. A maxima in corrosion rates was found in the middle stages in all the alloys. This has been explained by a combined effect of temperature, air leakage into the vent line, and cascading of NC gases, all providing the most favorable condition for corrosion in these stages. After 14 years of evaporator (C4 area) operation at Al-Jubail Phase-2 plant, a sudden appearance of large numbers of 90/10 Cu–Ni tube failure in the first stage was noted [6]. The application of eddy current provided the following information: (i) the defective tubes were concentrated at the center of the lower half of the bundle, (ii) the corrosion started on the external surface (vapor side), (iii) most of the defects are concentrated at the tube end close to the steel sheet, and (iv) metal losses from the external was also noted on some of the tubes at the tube support point. It was found that tube failure is due to the crevice corrosion which is accelerated by the following conditions: (i) galvanic action between 316 SS and 90/10 Cu–Ni, (ii) low pH due to accumulation of CO_2, and (iii) vibration of tubes due to the gap created between tube and the support. Corrosion behavior of cupronickel 90/10 and 70/30 alloys, in simulated vapor side environments existing in thermal desalination plant, was investigated on laboratory scale at 90–95˚C [7]. In pure water vapors, corrosion resistance of Cu-30 Ni was superior to Cu-10 Ni. Injection of CO_2 increases the severity of 30% Ni alloy and corrosion rates appeared to be of the same magnitude as that of 10% Ni alloy. During VSC, general surface thinning appeared. The VSC mechanism where CO_2 and O_2 are present in the condensate films involves a fairly complex process of oxide/hydroxide formations and dissolution [7].

Corrosion resistance and performance of cupronickel 90–10 and 70–30 alloys and Ti alloy (R50400) were tested in a specially designed and constructed MSF test unit at 3 different temperatures: 50, 70, and 90˚C and exposure time varied from 30, 90, 150, 210, 270, to 300 d and in presence of air [10]. The results of the studies show higher corrosion rates for 10% Ni alloy (0.017 mm/yr) compared to 30% Ni alloy (0.0032 mm/yr) at 90˚C. Ti alloy shows a much lower corrosion rate of 0.0003 mm/y compared with SS 3160 S and S31254 under similar conditions indicating that SS alloys outperformed the Ti alloys. The corrosion rates were found to be higher in vapor environment compared to liquid brine environment.

An experimental study on crevice corrosion and hydrogen absorption of Ti was carried out in deaerated neutral NaCl solution similar to those in MSF desalination plants [13]. The results of the study showed that Ti was subjected to crevice corrosion above 80˚C in neutral deaerated 6% NaCl solution, but PdO/TiO_2 coated Ti was not subjected to corrosion. When Ti was used as a tube material, corrosion and erosion or impingement do not occur. In general, Ti completely prevents the corrosion of desalination plants.

Cupronickel condenser tubes carrying out seawater were found to undergo failures due to overall thinning, formation of shallow channels, pits, and greyish black internal deposits in one of the units [17]. In another unit, tube failure was noticed without any significant thinning, but there was presence of deposits. The increased seawater velocity as well as deficiency of iron in the cupronickel alloy had resulted failure in first case, whereas, relatively low velocity of water associated with the deposition of sludge and biofouling was the cause of failure in the second tube. The failure of the tubes could be prevented by maintaining right velocity of seawater.

A number of cupronickel heat exchanger tubes in a thermal desalination plant were found to be localized corrosion attack at 6 O'clock position [19]. Two mechanisms were proposed. In the first, the corrosion is attributed to process control in which, due to evaporation of large amount of seawater, a scale film is formed on the external surface of Cu–Ni tubes. This may generate corrosion microcells which in turn, act as a potential site for localized corrosion in presence of CO_2 and O_2 gases dissolved in condensate water. The latter reduces pH and enhances the corrosion attack in a short period of time. Alternatively, condensation of water drops, containing dissolved CO_2 and O_2 gases on cupronickel tube can be the main cause of corrosion failure.

Vapor-side corrosion (VSC) of condenser tubes (copper/nickel alloys) in MSF desalination plant was investigated in distilled water over a range of relevant environmental conditions [20]. Interesting results were obtained. Cu-Ni alloys form a protective film at ambient temperature, but at 80˚C a non-productive behavior was observed. At short exposure times (up to 15 d), Ti and 316 SS exhibit much superior corrosion resistance than copper/metal alloys over the entire range of experimental conditions.

VSC failure in 2 MGD multi-effect thermal compressor plant at Jebel, Dhana, UAE was reported after 16 months of operation [21]. The 90/10 Cu–Ni tubes were found to have corrosion in two forms namely, corrosion fatigue and pitting corrosion. The corrosion fatigue was in the form of a circumferential crack at a flat portion of the tube in the center of a tube span. It was believed the surface flat had developed as a result of fretting against tube and had worn away to the point of failure. It appeared that damage occurred at the top rows. The other tube samples showed pitting corrosion. Some of the pitting had perforated, while other showed pitting on the outer surface only. The pitting corrosion is attributed to the formation of carbonic acid by the dissolution of CO_2 in the condensing water vapor in presence of oxygen (air). It was recommended that the oxygen levels to be reduced by ensuring that the distillate vessels are air-tight as possible, thus reducing the tendency towards pitting corrosion.

1.4. Development of plastic heat exchangers

The plastic materials can be an attractive alternative to relatively expensive corrosion resistant metals for applications in heat exchangers. The plastic/compact heat exchangers have found some applications in processing industry but their use in desalination plants is very limited. The main benefits that emerge by the application of plastics in evaporators in thermal desalination plants include: (i) ease of construction, (ii) lower installation and erection cost, (iii) ability to operate at higher TBT without fear of scale formation, and (iv) virtual elimination of air in leakage problem. The basic drawback is the poor thermal conductance of plastic materials but some work is in progress on making plastics as suitable materials for heat exchangers. El-Dessouky and Eltouney [22] reported a study concerning with compact heat exchanger for single-effect mechanical vapor compression desalination system. The study includes, determination of power consumption and the evaporator and preheaters specific heat transfer area for various tubing materials such as PTFE plastic, high steel alloys, 90/10 and 70/30 cupronickel alloys, and Ti. The specific cost was evaluated and lowest cost was obtained for PTFE system because of lower cost of PTFE. Corrosion consideration and associated reduction in the cost of corrosion inhibitor, gave an added edge for the use of PTFE plastic. Polymer compact heat exchangers (PCHE) have been introduced commercially in the beginning of the present century, exhibited promising application in thermal engineering processes. Three main categories of PCHE are currently available. Recently, polymer film compact heat exchanger (PFCHE) design, having a thin (100 μm) polymer film which address the thermal conductivity deficiency of heat exchanger has been introduced [23]. Due to excellent thermal, chemical, and mechanical stability, polyether ether ketone (PEEK) is adopted in the PFCHE design. Based on above consideration, a falling film plate evaporator with heat transfer surface made out of high performance polymer PEEK has been developed [24]. Overall heat transfer coefficients with the prototype heat exchanger at MED process conditions have been measured experimentally. The values are comparable to those of metallic falling heat exchangers.

2. Case studies

2.1. Case-1: investigation on the failure of evaporator tubes in a MED plant

Failures were reported in Al–brass tubes in reheater type desal units D-03 and D-04, respectively. Both D-03 and D-04 have 35 mm OD and 1 mm thickness. Investigations were followed to determine the cause of failures.

The desal D-03 tube was located on top rows below the distribution tray. This tube had a perforation of 18 × 10 mm size at the center along with many perforations of smaller sizes (Fig. 2). The maximum allowable velocity of liquid impingement on Al–brass material (desal tube) is around 2 m/s. These tubes are susceptible to impingement corrosion when the velocity exceeds the said limit in the plant. The impingement condition is particularly severe when they are in the

Fig. 2. Close up view of failed portion of evaporator tubes D-03 showing few surface depression marks.

top zone of two rows of the evaporator chamber. The D-03 tube was in fact below the spray distribution trays of the evaporator chamber and one, therefore, expects the impingement occurring by the flowing seawater.

The D-04 tube was ruptured at one end with rupture length of approx. 360 mm (Fig. 3). In case of D-04 tube, the failed area of the tube was facing the bottom of the evaporator. The inspection of the rupture area indicates that the material (Al–brass) wastage at the failure area had led to the failure of tube. Rupture edges are thin and ragged because of the wasted brass. The wastage brass appears to be the effect of erosion-corrosion.

Conclusions:

Desal D-03 Tube

(1) Failure of the tube is due to impingement attack of seawater on the tube surface.

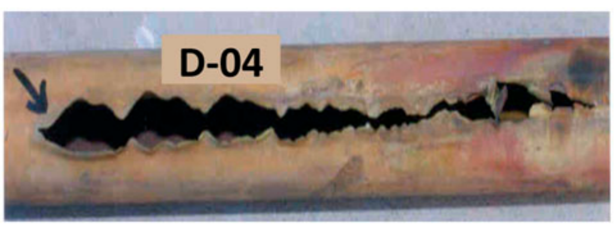

Fig. 3. Tube D-04 showing rupture edges due to erosive thinning.

(2) Perforation of tubes is due to material wastage by pitting preceded by liquid impingement.

Desal D-04 Tube

(1) The failure of the tube most likely due to erosion-corrosion.
(2) The erosive thinning of material had led to rupture of the tube.

2.2. Case-2: failure of Al-Wajh desal-effect tubes

Failures were reported in the 2nd effect chamber of desal unit in the form of perforations in the tubes during service.

The failed tubes of desal units were located at the first and second row of the tube bundle of the 2nd effect chamber. In all, 31 numbers of tubes have failed during service. The tubes were located just below the seawater distribution trays and were in service since 13 years.

The tubes were inspected physically on receipt. The tubes were of size 19 mm OD × 1.0 mm thickness. The outer surface of the tubes contained patches of visibly thick scales and pits. Both the tubes surface contained small and big size (approximately 15 mm dia) holes (Fig. 4). The big size holes are characterized by undercut groves with directional pattern moving away from the center of the holes. Substantial thinning of the metal near the edges of the holes is seen indicating erosion-corrosion of the metal occurred from the top surface during the service. Plenty of surface pits are also noticed on the tubes. The inner portion of tube surface contained uniform layer of greenish colored scale deposits and were free from pitting.

The chemical composition as determined from XRF and wet chemical analysis methods found to be Aluminium Brass (UNSC8700). Methods of metallography, SEM and EDX were employed during investigation. The surface area containing large holes and containing scales were examined by SEM. Outer scale deposits near the holes were analyzed by EDX.

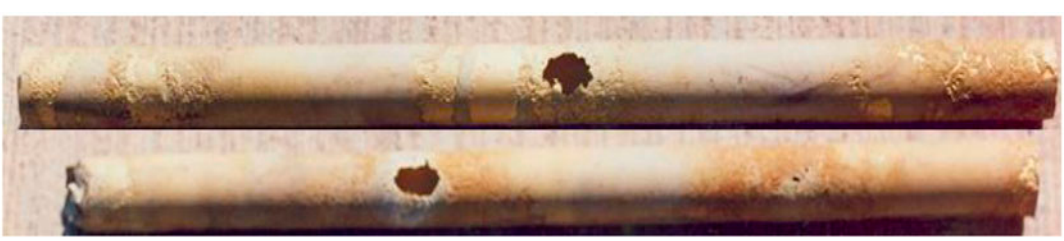

Fig. 4. Photograph of leaked tubes in as received condition.

The deposits were found to be consisted of S, Cl, Mg, Ca, and O_2 indicating the presence of sulfides, chlorides, and oxides. The inner surface scales deposits were mainly consisted of copper-oxide. The outer scale deposits were non-uniform in thickness and discontinuous in nature whereas the inner scales were uniformly thick. The gradual thinning and subsequent perforation of the tubes led to believe that this is the case of attack on metal from the outer surface agent during service.

Based on the investigation carried out the following conclusions are drawn:

(1) The failure of tubes is most likely due to erosion-corrosion.
(2) Non-uniform spray distribution pattern of seawater on the tubes was responsible for the observed localized perforation of tubes.
(3) Development of non-adherent protective oxide film during service might have also been responsible for the premature failure of the tubes.

It was recommended that (i) during plant maintenance, thorough cleaning of seawater distribution trays, holes/nozzles of the trays and ensuring uniform spray pattern on the tubes during operation would help in limiting the erosion-corrosion, and (ii) use of better condenser tube material such as 90Cu/10Ni could avoid early failure of the desal tubes.

2.3. Case-3: condenser tube corrosion of Jeddah IV MSF desalination plant

Corrosion failure occurred in condenser tubes of unit # 16 of Jeddah IV, module 1, stages 4–6. The tube samples were corroded and a few holes were found. A detailed inspection of vent lines, duct, and other related components inside the evaporators of module 1 was carried out. It was found that out of 5,400 tubes around 200 tubes were plugged due to leakage problem. All plugged tubes were in the lower third of the tube bundles on 2 sides of the vent extraction position. The failed tubes were taken out for failure investigations.

The inspection of the evaporator in module 1 provides following information about the features of vent system (Fig. 5).

(1) In stage 1 vacuum is not created, therefore brine temperature is not too high. Gases coming out from the brine are released in the atmosphere.
(2) Stages 2 and 3 are directly connected to the vent line. Here flash of brine takes place and gases evolved, are vented out quickly.
(3) Stage 4 is connected, through pipe A to a direct vent line and an opening to the atmosphere as well. However, the pipe A is closed and the opening of this pipe in the evaporator is near the roof. The venting stages 4 and 5 evaporator is done through the other pipe B which is connected to the vent extraction tray. Through the pipe-B, NC gases are cascaded to the stage 6 where it is finally joins the vent line.
(4) The major fault of the design of the evaporator of stage 4 was the absence of any direct connection with the vent line. It seems that due to poor venting of this corrosive gases evolved, enter into pipe A were trapped and get condensed. The condensate will be acidic in nature due to dissolution of CO_2 and other corrosive gases, e.g. H_2S, Cl_2, SO_2, etc. The condensate drops on the 2 sides causing general corrosion of the tubes. It also corrodes the nearest partition wall of stages 3 and 4.

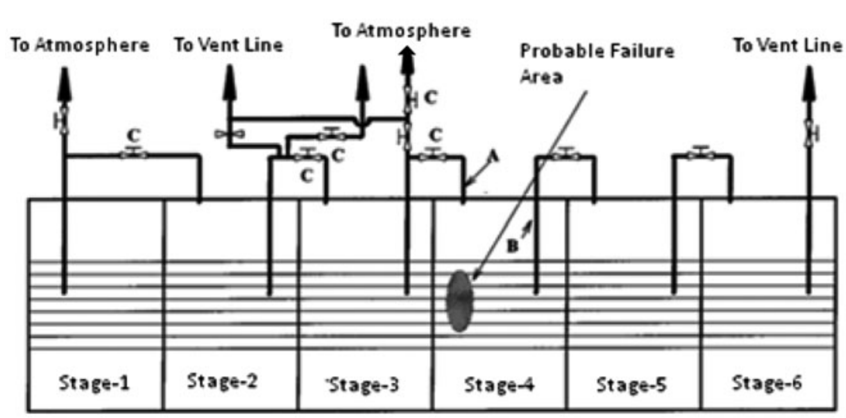

Fig. 5. Vent line in unit 16, module 1 of Jeddah IV desalination plant.

The new points emerged from investigations include:

(1) Failure of the tubes occurs on both the end of the vent extraction tray.
(2) Failure area of the tube shows thinning of the tube wall due to constant dissolution of the metal.
(3) Considerable amount of deposits were found below the failed zone, which appeared to be condensed mass of flowing corrosion products.
(4) Poor venting in stage 4 appears to be the main cause of the problem.

Conclusion:

The failure of condenser tubes in stage 4 (cascade between 3 and 4) is due to the dropping of the acid condensate from closed vent pipe A resulting in the corrosion of tubes.

Recommendation:

Stage 4 should be directly connected to the vent line either by opening the valve of the vent line A or by some appropriate design modification.

2.4. Case-4: leakages in the heat exchanger tubes of heat recovery section at Al-Jubail plant

The rise in conductivity of product water from Desal #27 in Al-Jubail plant was reported and the unit was shut down for inspection. The leakage in the heat exchanger tube of heat recovery section (stage #1) was attributed as the cause of problem. Out of 176 tubes inspected, 9 tubes showed 100% loss in thickness. Four tube samples of about 1–2 m long from desal #27 were received. A shining ring mark of about 5 mm wide was found on the external side of both ends. A noticeable loss in metal was observed all over this ring on the outlet. While on inlet a similar mark appeared but metal loss (reduction in wall thickness) was only about 1 mm from vapor side. In Desal #27, the reduction in tube wall thickness of both ends (inlet and outlet) and perforations under the tube supports was clearly visible.

Following conclusions were derived from investigations:

(1) Eddy current test results show loss in tube wall thickness of about 71% at locations or under the tube supports. While in 29% tubes, the reduction in wall tubes was reported in other locations.
(2) At the tube ends, especially the inlet and to some extent the outlet, the reduction in tube wall thickness was found adjacent to the tube sheet. While at tube supports, it was under the tube supports.
(3) The corrosion of tubes was localized at the crevices between tube and tube sheets or tube supports. The presence of O_2 and accumulation of CO_2 in the vapor space could have also contributed in the corrosion of tubes.
(4) Presence of CO_2/O_2 and/or Cu^{2+} could have also contributed in the corrosion of tubes.

It was recommended that venting system of the first stage should be thoroughly evaluated in order to assess the possibility of CO_2 accumulation.

2.5. Case 5: some corrosion problems in condenser system at Al-Jubail MSF desalination plant

2.5.1. Corrosion of tube support

The tube supports are fabricated from 316 L in first two stages and from carbon steel for the other stages. The stainless steel supports were in good condition but the carbon steel supports were found corroded. The corrosion was observed at two locations: at the bottom which is welded to product water tray and at the tube opening. The mechanism of corrosion in both locations appeared to be galvanic (Fig. 6).

The lower section of the tubes support was connected to the product water tray which was fabricated from 3,16l L, therefore, the galvanic corrosion had occurred. Almost 35% of the original thickness was lost due to corrosion. The main factors controlling the galvanic action in this location are: (i) pH, (ii) conductivity of product water, and (iii) oxygen content.

Fig. 6. Corrosion of lower section of tubes support and lugs.

The second problem facing tube support is tube opening. The carbon steel tube support was in contact with the tube material made of Cu 90/10Ni. Due to the difference in corrosion potential between these materials the galvanic action actuated. The main factor controlling the galvanic action in this location was the NC gases which affected the pH of condensing water over the tubes.

2.5.2. *Failure of first stage condenser tubes*

Failure of 90/10 Cu–Ni condenser tubes in the first stage of C-4 units was noticed after 14 years of plant operation. Eddy current technique was employed to assess the condition of the tubes (Fig. 7). An analysis of the results reveals the following information:

(1) The defective tubes are concentrated at the center of the lower half of the tube bundle.
(2) The corrosion started on the external surface (vapor side).
(3) Most of the defects are concentrated at the tube end closer to the tubes sheet.
(4) Metal losses from the external surface have also been noticed on some of the tubes at the tube support points.
(5) The severity of corrosion in the tube is higher at one end compared to other end.

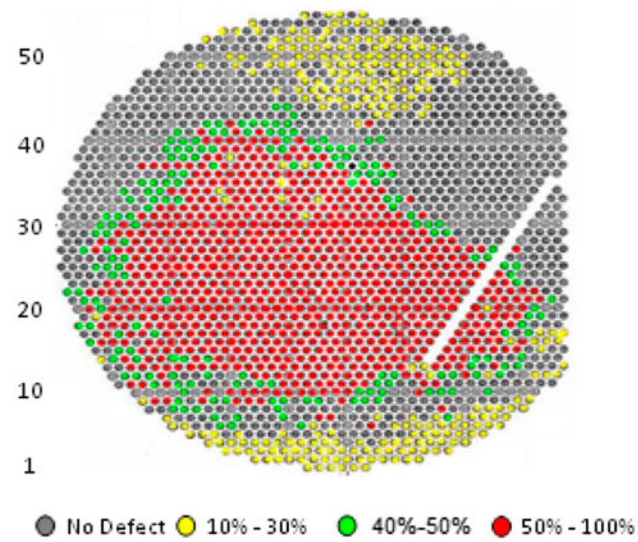

Fig. 7. Results of eddy current studies of first stage condenser.

It was concluded the tube failure is related to crevice corrosion which is accelerated under the following conditions prevailing around the tube bundle: (i) galvanic corrosion between 316 SS and 90/10 Cu–Ni, (ii) Low pH due to accumulation of CO_2, and (iii) vibration of tube due to the gap created between tube and tube support.

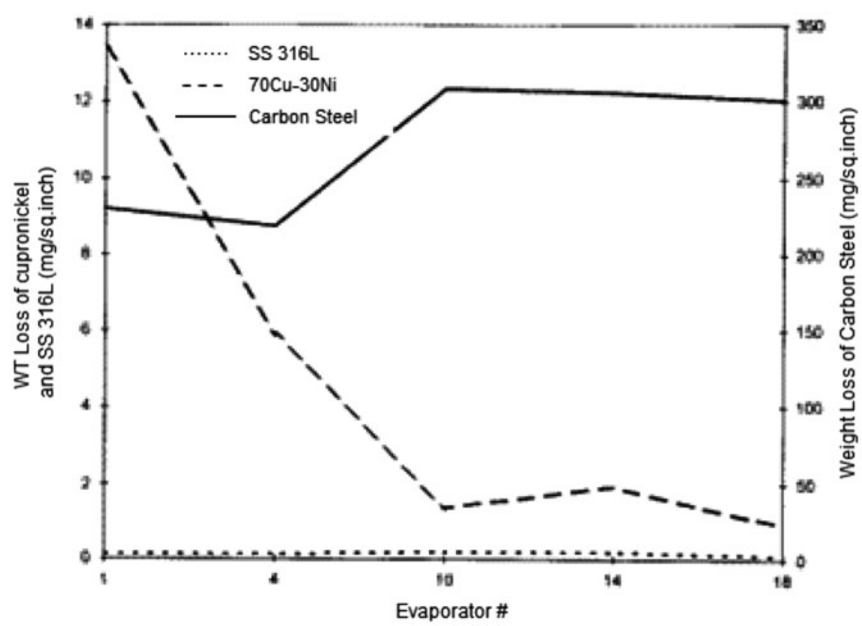

Fig. 8. VSC of different materials exposed for 9,000 h in flash chambers of MSF desalination plant. (Plots showing weight losses in different materials at different stages of evaporator.)

2.6. Case 6: corrosion of evaporators and vent line in MSF units of Al-Khafji plants

VSC of evaporators in 3 MSF units of Al-Khafji desalination and power plants was investigated. Corrosion rates of CuNi coupons exposed to NC gases in vent lines were much higher than those exposed in different evaporator stages. High reactivity of CuNi was attributed to the presence of sulfur in NC gases. A maxima in corrosion rates was found in the middle stages (10–13) in all the alloys (Fig. 8). This has been explained on the basis of a combined effect of temperature, air leakage into vent line and cascading of NC gases, all providing the most favorable condition for corrosion in these stages.

3. Conclusions

Following conclusions have been derived from the results of study concerning with corrosion of heat exchangers in thermal desalination plants and current trends in material selection.

(1) An analysis of the results of the case studies carried out for a number of thermal desalination plants, reveals the following information:

   (a) In most of the heat exchanger failure cases, the main cause of the problem is the poor venting system which resulted in accumulation of non-condensing gases (mainly CO_2) and in consequence, corrosion of materials.
   (b) Cases of localized corrosion around the tube bundle are quite common which is aggravated by the presence of crevices between tube and tube sheet or tube support.
   (c) Galvanic action between 316L SS/cupronickel alloys or any other coupling of dissimilar metals is quite a familiar feature in regions around heat transfer tubes.
   (d) An appropriate material selection and a well-thought design are the important considerations to avoid failure of heat exchangers.

(2) A survey of heat exchangers metals in different thermal desalination plants leads to the following pertinent points:

   (a) In majority of the new plants, in heat recovery sections, cupronickel Cu90/Ni10 has been replaced by modified Cu/Ni30/Fe2/Mn2 alloy which has better corrosion/erosion properties. In brine heater of the new plants Cu/Ni30/Fe2/Mn2 has invariably been used.
   (b) Titanium and modified alloys Cu/Ni30/Fe2/Mn2 prove to be most reliable and dependable for heat exchangers and appear to be the best choice for future thermal desalination plants.

(3) Use of corrosion resistant plastics in heat exchangers appears to be the best choice for future desalination plants because of their impeccable corrosion resistance and low cost. However, the main drawback is their poor heat transfer characteristics. Corrosion resistance plastic materials are commercially available but they have found limited applications specially in desalination technology. Plastic/compact heat exchangers using PTFE, PCHE and PFCHE employing PEEK showed promising applications for heat exchangers. More extensive research is required to ensure plastic as a viable material for thermal desalination plants.

References

[1] J.W. Oldfield, B. Todd, in: Proceeding of IDA World Congress on Desalination and Water Reuse, Abu Dhabi, UAE, 1995, November 18024.
[2] Anees U. Malik, Saleh A. Al-Fozan, Corrosion and material selection in MSF desalination plants, Corros. Rev. 29 (2011) 153–175.
[3] S. Narain, H. Sami Asad, Corrosion problems in low temperature desalination units, Mater. Performance 31(4) (1992) 64–68.
[4] N. Asrar, A.U. Malik, S. Ahmad, Early failure of cupro-nickel condenser tubes in Thermal Desalination Plants, Desalination 116 (1999) 135–144.
[5] N. Asrar, A.U. Malik, S. Ahmad, Materials performance vapor side corrosion in thermal desalination plants, Mater. Performance 38(4) (1999) 68–71.
[6] Saleh A. Al-Fozan, Anees U. Malik, MSF evaporator materials evaluation after 20 years in service, Desalin. Water Treat. 2 (2009) 334–341.
[7] Z. Khalid, T.Hodgkiers Al-Subaie, Corrosion of copper-nickel alloys in simulated vapor-side environments, Desalination 158 (2003) 43–50.
[8] M.A. Al-Thubaiti, T. Hodgkiess, S.Y.K. Ho, Environmental influences on the vapor side corrosion of copper–nickel alloys, Desalination 183 (2005) 195–202.
[9] T. Hodgkiess, G. Vassiliou, Complexities in the erosion corrosion of copper–nickel alloys in saline water, Desalination 183 (2005) 235–247.
[10] Ali Al-Odwani, E.F. El-Sayed, Mohammad Al-Tabtabaei, Mohammad Safar, Corrosion resistance and performance of copper- nickel and titanium alloys in MSF distillation plants, Desalination 201 (2006) 46–57.

[11] J.Ibrahim Georgy, V. Kain, G.K. Dey, MIC failure of cupronickel condenser tube in fresh water applications, Eng. Fail. Anal. 16 (2009) 934–943.
[12] H.M. Shalaby, H. Al-Mazeedi, H. Gopal, N. Tanoli, Failure of titanium condenser tube, Eng. Fail. Anal. 18 (2011) 1990–1997.
[13] Kazutoshi Shimogori, Hiroshi Sato, Fumio Kamikubo, Toshio Fukuzuka, Corrosion resistance of titanium in MSF desalination plant, Desalination 22 (1977) 403–413.
[14] H.M. Shalby, Failure investigation of metal be sheet and Ti tubes of surface condenser, Eng. Fail. Anal. 13 (2005) 780–788.
[15] R. Rautenbach, S. Schäfer, Development and testing of ultrathin super austenitic tubes for heat exchangers in desalination plants, Desalination 127 (2000) 13–17.
[16] C. Sommariva, H. Hogg, K. Callister, Forty-year design life: The next target material selection and operating conditions in thermal desalination plants, Desalination 136 (2001) 169–176.
[17] R.K. Pandey, Failure analysis of refinery tubes of overhead condenser, Eng. Fail. Anal. 13 (2006) 739–746.
[18] Al-Odwani Ali, E.F. El-Sayed, Mohammad Al-Tabtabei, Mansour Ahmed, Corrosion resistance and performance of steel alloys in MSF distillation plants, Desalination 201 (2006) 35–45.
[19] K. Abouswa, F. Elshawesh, O. Elragei, A. Elhood, Corrosion investigation of Cu–Ni tube desalination plant, Desalination 205 (2007) 140–146.
[20] D. Mantzavinos, T. Hodgkiess, S.L.C. Lai, Corrosion of condenser tube materials in distilled water, Desalination 138 (2001) 365–370.
[21] M.E. El-Dahshan, S. Al-Malek, E. Al-Katheeri, Vapour side corrosion in a ME desalination plant at Jebel Dhana, Desalination 155 (2003) 67–78.
[22] H.T. El-Dessouky, H.M. Ettouney, Plastic/compact heat exchangers for single-effect desalination systems, Desalination 122 (1999) 271–289.
[23] L. Zaheed, R.J.J. Jachuck, Review of polymer compact heat exchangers, with special emphasis on a polymer film unit, Appl. Thermal Eng. 24 (2004) 2223–2258.
[24] J.B.P. Christmann, L.J. Krätz, Hans-Jörg Bart, Falling film evaporation with polymeric heat transfer surfaces, Desalination 308 (2013) 56–62.