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CORROSION INHIBITORS IN THERMALDESALINATION PROCESS: A REVIEW

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Abstract : With the increase in global population, water scarcity has become an increasing problem. So, we are trying to find various resources from which we can get water in portable form. One such technology that is gaining attention is Desalination technologies. This method is more prominent in middle eastern countries due to the high-water scarcity there. In desalination the various salts and minerals are removed from sea water to make it useable for human consumption and irrigation. One specific method of desalination is thermal desalination in which the sea water is converted into vapour which is free of any salts or minerals. But desalination comes with a downside of corrosion. The salinity from sea water can leads to the corroding of the equipment of the desalination plant. This will decrease the efficiency of the plant. This review is based on the different corrosion inhibitors used in thermal desalination process.

***Index Terms* – Desalination Technologies, thermal desalination, corrosion, corrosion inhibitors**

I. INTRODUCTION

Living standards are fortunately improved over time but this has increased the rate of consumption of water and has imposed water stress along with other issues such as population growth, drought and climate change for most countries especially the countries with low water resources. So far, several solutions are provided to deal with the issue of water stress. In the coming years the global demand of clean municipal and industrial water; the water required for food processing and production, and the water needed in the energy sector, will increase considerably, according to a World of Bank report. This report informs that 1.6 billion people are subject to water scarcity.

Modern desalination technology, to reduce potable water storage in the future, is the true response to this critical situation. Since a lot of countries have access to the sea, a good solution to deal with this problem is the desalination of sea water. Desalination process is also used in submarines and ships, which are on long travels and have high drinking water demand.

Desalination is a water-treatment process that separates salts from saline water to produce potable water or water that is low in total dissolved solids (TDS). It is not a new process; it has been practiced since ancient times at places with water scarcity. The people of Israel, wandering in the Sinai desert was desperately searching for water, and then their leader Moses found bitter water. In an act of magic, threw a piece of wood into the water that become fresh water. The process has just become more advanced in the recent years.

Types of Desalination technology:

Two distillation technologies are used primarily around the world for desalination are Thermal distillation (Thermal distillation technologies are widely used in the Middle East, primarily because the region’s petroleum reserves keep energy costs low) and Membrane distillation: Membrane distillation technologies are primarily used in the United States. These systems treat the feed water by using a pressure gradient to force feed the water through membranes.

Al-sahali and Attorney (2007) studied types of desalination processes and their importance. Types of desalination process are membrane desalination and thermal desalination. Membrane desalination included processes like Multi effect evaporators, multistage flash distillation, vapour compression evaporators and thermal desalination included Reverse osmosis and electrodialysis. Reverse osmosis (RO) and multistage flash desalination (MSF) are used most frequently in desalination plants. Desalination plant also used multiple effect evaporators (MED) and mechanical vapour compression process (MVC).

Thermal desalination is a process that involves changing saline water into vapor. This vapor, or steam, is generally free of the salt, minerals, and other contaminants that were in the saline water. When condensed, this vapor forms a high-purity distilled water. There are several different methods of achieving this distillation. The quality of water produced and the heat consumed in its production can both be defined when the system is designed. The efficiency of these systems covers an order of magnitude. The selected efficiency is project-specific and reflects the increased capital cost for higher efficiency designs that is offset by a lower operating (energy) cost. Conversely, where low cost or low-grade thermal energy is utilized, there is economic justification in utilizing lower efficiency designs.

Hisham T et al. (1999) studied parallel Multiple effect evaporators in comparison with Multistage flash distillation. Different configuration like parallel flow (MEE-P), the parallel/cross flow (MEE-PC), and systems combined with thermal (TVC) or mechanical (MVC) vapor compression were studied. Dependence of physical properties on temperature, salinity and Thermodynamic losses were studied. Experiments revealed that performance of MEE-P was similar to MEE-PC.

Various processes under Desalination technology:

1. Multi-stage flash distillation

Multi-stage flash distillation is the process of passing saline solution through multiple chambers. In these chambers, the water is heated and compressed to high temperature and pressure. As the water slowly flows through the chamber, the pressure drops and the water boils rapidly. Steam, which is fresh water, is generated by boiling in each chamber, and is condensed and recovered.

2. Multi-effect distillation

Multi-effect distillation employs the same principals as the multi-stage flash distillation process except that instead of using multiple chambers of a single vessel, MED uses successive vessels. The water vapor that is formed when the water boils are condensed and collected. The multiple vessels make the MED process more efficient.

3. Vapor compression distillation

Vapor compression distillation can function independently or be used in combination with another thermal distillation process. VCD uses heat from the compression of vapor to evaporate the feed water. VCD units are commonly used to produce fresh water for small- to medium-scale purposes such as resorts, industries, and petroleum drilling sites.

Aly et al. (2003) studied use of mechanical vapour compression in the desalination process. The MVC system was studied mathematically and experimentally. The overall mass and energy balance for MVC was studied. The performance of desalination plant was increased when operating temperature was increased from 70℃ to 98℃ which also affected on heat transfer coefficient.

Tonner (2008) examined the various limitations in thermal desalination process that was being studied. The heat loses occurring in the plant were studied with the power to water ratio and the values were compared. The possible guidelines and recommendations that could be implied into building a new desalination plant to make it more energy efficient and overcome all the barriers that were recommended.

Mohammad Al-Sahali & Hisham Ettouney (2007) studied the various design parameters that were considered for the desalination plants. The costing with each parameter was studied thoroughly. There were many developments made in the Multiple effect evaporation (MEE) and Mechanical vapor compression (MVC) which could have been subject to further increase in the unit capacity, adoption of efficient heat pumps, use of inexpensive construction materials, and use of compact type evaporators. Such developments would have resulted in considerable cost reduction, which would make the process highly competitive against the MSF or the RO process.

Equipments Used in Thermal Desalination Plant

The various Mechanical equipments are Pipes tubes and ducts; Saline water pumps, vertical and centrifugal; Valves, diverse types; Gasketed plate and frame HE; Fittings and flanges; Steam and gas turbines; Compressors; Control and flow Instrumentation

The various Thermal equipment are Evaporators; Vapor condensers, diesel engines; Flash cambers; Demisters; Condensers; Deaerators; Chlorinators and Storage tanks.

Material of Construction of Equipments:

Carbon steel is used as a the main material of construction due to its easy availability and cheap cost . But in these plants also corrosion is seen. So few corrosion inhibitors are mixed with steel while construction. The tubes of heat exchangers are made of copper .

Acid Cleaning:

Due to the excessive use of saline water in the desalination plants one of the major challenges is avoiding scaling. So, few scaling inhibitors are installed in the evaporators, which will retard the scaling when the plant is in operation. Although such measures are used, the amount of scaling doesn't reduce drastically. Hence a chemical treatment to remove scale deposits, time to time is done.

In acid cleaning, a dilute acid is circulated in all the equipments of the plant where scaling has occurred. This is done till all the scale deposits are dissolved. the choice of acid depends on the scale formed, whether it is calcium carbonate scale or magnesium hydroxide scales. Now this process is a concern for the large metallic units in the desalination plant, as they have a risk of corrosion. So normally a corrosion inhibitor is added to the acid cleaning process. The choice of inhibitor depends on the material used in the desalination plant and how each one reacts to the inhibitor.

Corrosion In Thermal Desalination Plant:

Desalination plants (DPs) have a high level of corrosion risk since they handle and process aggressive saline water under severe operating conditions which include filtration, heat exchange, distillation, evaporation, agitation and circulation and high flow velocities, often turbulent. This saline water which is from sea, brackish and brines cause localized corrosion such as pitting, crevice, galvanic and stress corrosion. In addition, biological fouling and mineral scaling are frequent nuisances that alter the equipment surface performance and induce corrosion. The damage from corrosion increases maintenance expenses and generate problems in Desalination Plant. Pollution and corrosion are interrelated processes since many atmospheric pollutants (e.g., sulfur oxide [SOx], nitrogen oxide [NOx], COx, and hydrogen sulfide [H2 S]) accelerate corrosion, and corrosion products such as rust pollute water bodies. Both pollution and corrosion are pernicious processes, which impact environmental quality and structural durability. Unless prevented, corrosion and the build-up of scale and biological fouling impact the desalination plant operation and, in extreme cases, even lead to equipment shutdown. So various corrosion inhibiting methods are used. The main factors influencing metal corrosion in saline water are Salinity, Conductivity, Dissolved oxygen, pH and Physical factors.

Khalid et al. (2003) studied that the corrosion behaviour of all the materials tested was relatively insensitive to mildly flowing seawater. But it was seen that severe jet impingement reduced the corrosion resistance-drastically for the 3 16L and 430 alloys. The study also indicated that the corrosion behaviour of titanium, the super austenitic stainless steel and the nickel-base alloy was not sensitive to increases in salinity. In contrast, higher TDS (55,000 mg/l) water was more aggressive than seawater of 35,000 mg/l TDS towards the lower-alloyed materials.

Corrosion Control Methods:

Corrosion Control methods that minimize or eliminate corrosion include the selection of suitable Corrosion Resistance Alloys, application of coatings and linings to Carbon Steel, and Cathodic Protection. The technical process of selection is usually divided in to three main stages. First of all, Analysis of the requirements and collection of the relevant information about the conditions imposed by the desalination process and the corrosion resistance required by the equipment. Then, Selection and evaluation of candidate materials by screening of the information collected in the first stage. Laboratory and pilot plant corrosion tests are performed by exposing suitable materials in the desalination process fluids and environments (ISO 845 and ASTM G4, G31) and finally Selection of the most appropriate material based on its costs, availability, easy fabrication and repair, maintenance, and safety. Corrosion resistance is the main property to be considered in the choice of materials for DPs equipment, but the final selection must be a compromise between technological and economic factors. It is sometimes more economical to use a high priced CRA that will provide long and trouble-free service than to use a lower priced material that may require frequent maintenance or replacement. The selected CRA should be able to perform its function safely for a reasonable period and at a reasonable cost.

Hamid Reza Golsefatan et al. (2017) evaluated that DLC coating on stainless steel was an effective way to deal with its corrosion in corrosive environments containing chlorine ions as thermal desalination plant. The DLC films were deposited on stainless steel substrate by a cathodic vacuum arc method with a graphite and Chromium (interlayer) targets. Thin film characteristics were specified by Raman spectrometer. Corrosion behaviour of the surface was investigated by electrochemical cyclic polarization. The results illustrated that uniform corrosion was decreased by this coating and DLC can open a new perspective on increasing the operational lifetime of desalination plants. However, to reach the optimum conditions more experimental work is needed. Information obtained from cyclic polarization curves of uncoated and coated samples showed that corrosion rate of the coated samples was less influenced by sodium chloride concentration and were almost constant in a wide range of the concentration.

The important methods of corrosion control :

1. Corrosion resistant alloys: The prime consideration during the selection of materials of construction is their corrosion characteristics. CRA used in the desalination industry can be broadly divided into two groups. B. Ni base alloy, Cubase alloy, SS. Ni alloys are one of the most important because they withstand corrosion in a variety of environments, including chloride-rich SW. They are divided in two groups: those constituted mainly by Ni and those which employ Cr as a major alloying element. Their corrosion resistance depends upon the presence of Nickel and Chromium oxides imparting a passive state. They are used in DPs for the fabrication of high-pressure pumps and brine concentrators in thermal DPs.

Copper-base alloys: the main alloys used in DPs are: Cu-Ni for tube and shell-heat exchangers and condensers; bronze (Cu-Sn) for ship propellers and parts of pumps for seawater transportation and brass (Cu-Zn) for hot and cold-water circulation. But with these alloys a blue, green layer of corrosion products is formed on the Cu-alloys surface which does not provide effective protection.

Titanium and aluminum alloys. e.g., UNS A95052 Ti has good corrosion resistance in strongly oxidizing environments, e.g., nitric acid and wet chlorine but not with reducing acids, e.g., hydrochloric acid. Ti shows excellent resistance to seawater and saline water, but it does not tolerate even trace amounts of fluorides which cause severe corrosion. Its corrosion resistance is due to a stable, protective, strongly adherent film of titanium oxide (TiO2). Alloying of Ti with palladium (Pd) and other noble metals yields corrosion resistant alloys. Aluminum (Al) corrodes under both acidic and alkaline conditions yielding Al+3 and AlO2 - aluminates ions, respectively. In thermal desalination equipment Al tubes are utilized in huge heat-exchangers for condensation of water vapor with seawater. These CRAs have an outstanding corrosion resistance, mechanical strength and weldability. This corrosion resistance is due to the tough and durable self-healing protective film of metal oxides formed in the presence of air and moisture.

2. Increasing surface resistance or coating using resistant materials:

CS is the main material used for erecting plant structures, water storage vessels, tanks, and pipelines. Due to its limited corrosion resistance, CS should be protected by coatings and, where in contact with water or soil, by cathodic protection (CP). In this regard many studies are conducted by researchers and different techniques are proposed to modify the surface and improve steel behaviour against corrosion. Surface chemical modification, use of lasers to change the surface properties or changing the surface phase such that the new phase has higher corrosion resistance to the mass are methods presented in many studies and can increase the lift time of the parts.

3. Corrosion monitoring (CM):

It is the practice of measuring the corrosion events and rate by continuously exposing materials probes in a body of water or a operating DP. Modern electrochemical, electronic, mechanical, non-destructive, and computational devices are applied in the field of CM such as potentiometry, multielectrode probes, electrical resistance, communication networks, remote CM, expert programs and artificial neural networks. CM techniques provide daily warning of costly corrosion damage and critical information, where the damaging event is occurring and about the rate of deterioration. This information is helpful for taking decisions about the type, urgency and cost of preventive and curative measures to be applied on site without delay.

4. Use of anti-corrosion chemicals:

Corrosion inhibitors can prevent metal corrosion. These materials are widely used in various industries such as petroleum, gas, chemicals and water. But most of these materials have their own toxicity and may cause new pollution to the environment. Two new technologies that have come up regarding corrosion control are Magnetic Corrosion Inhibitor and Quantum Technology. The magnetic organic corrosion inhibitor expects to overcome organic corrosion inhibitor’s defect of weak binding force and improve its inhibition efficiency, by the introduction of magnetic force. It could form film by organic lipophilic group on the surface on the carbon steel, and enhance the binding force by its magnetic force. While the Quantum Technology method is based on the quantum information theory and biological information technology. Water itself solves the rust and scale problems. The activity of water is greatly enhanced, the nature of water is changed and the ability of dissolving and containing ions is enhanced, under the action of vibration wave. At the same time, the physical characteristics of calcium, iron, magnesium, and other related substances in the seawater are changed, leading to the preventing corrosion and fouling.

II.CORROSION INHIBITORS:

Scaling that is formed in desalination plants results in decrease in the plant’s efficiency. So thermal desalination plants are frequently shut down for acid cleaning. Generally inexpensive acids like HCl and H_2SO_4 which results in formation of sulphate scales which can induce severe corrosion in desalination plant. Due to high water demand long shut downs are undesired. So, corrosion inhibitors are used in acid cleaning process.

Compounds containing oxygen, Nitrogen and sulphur heteroatoms are used as inhibitors in acid cleaning.

Deyab and Mohsen (2021) used an ionic liquid, tributyl(ethyl)phosphonium diethyl phosphate (Ph-IL) as a corrosion inhibitor for acid cleaning process with 4% sulfamic acid in Aluminium alloy AA5052 in multiple effect distillation unit in desalination plant. Ph-IL with sulfamic acid as a corrosion inhibitor in acid cleaning process resulted in enhanced corrosion resistance of efficiency up to 93% at 1.5×10^{-4}. Cathodic and anionic part of this ionic liquid was adsorbed which showed that Ph-IL molecules covered the anodic and cathodic sites. Ph-IL formed a significant barrier for corrosion process. Surface morphology of was studied by SEM-EDX analysis, which showed that Ph-IL formed a protective layer on the surface of AA5052. Use of polarization and EIS measurement confirmed the protective ability of Ph-IL.

Mandour et al. (2021) formulated an azo ligand Bis-(1,5- dimethyl-4-[(E)-(3- Methyl phenyl) diazenyl]-2-phenyl-1,2-dihydro-3H-pyrazol-3-one) which was used in acid cleaning process for copper metal. Study revealed that azo ligand was efficient inhibitor for copper metal in 1.0 M HCl solution. Azo ligand and its metal complexes were studied using elemental analysis, spectroscopic techniques, magnetic moment, and thermal analysis. Potentiodynamic polarization revealed that inhibitor has mixed inhibition effect and also confirmed that both anodic and cathodic reactions controlled by the azo ligand and was very efficient with efficiency of about 87.1% in very small concentration of azo ligand of about 5×10^{-4} ppm. Inhibition efficiency increased with increase in concentration of azo ligand. Electrochemical impedance spectroscopy revealed that the corrosion mechanism of copper metal in presence of inhibitor azo ligand was controlled by charge transfer reaction and diffusion process.

EIS results revealed that azo ligand has good inhibition efficiency of about 90.2% at concentration 5×10^{-4} ppm. Some metal complexes were synthesized such as Fe(III), Cr(III), Ru(III), Hf(IV) and Zr(IV). Electrical conductivity measurement revealed that metal complexes show higher conductivity than free ligand and lies in the range of semiconductor. The metal compounds are used in production od wires, electronic device and as corrosion inhibitor for copper metal. Surface morphology was studied by EDX and SEM which proved that azo ligand has very good inhibition effect to retard corrosion rate.

El-Katori et al. (2021) formulated three novel ionic liquids (3-(2-ethoxymethyl)-1-octyl-1H-imidazol-3-ium chloride, 1-decyl-3-(2-ethoxy methyl)-1H-imidazol-3-ium chloride and 1-dodecyl-3-(2-ethoxymethyl)-1H-imidazol-3-ium chloride) and their chemical structures were studied by spectra tools. The inhibition impact of this ionic liquids was studied on stainless steel in 2.0M HCl solution using various methods like electrochemical measurements. These measurements revealed that this ionic liquid provide corrosion resistance and inhibit in both cathodic and anodic process. Potentiodynamic polarization confirmed that this inhibitor showed mixed type of inhibitor effect and does not modify corrosion mechanism. EIS revealed that double layer capacitance diminished by adding ionic liquid as compared to blank solution and this ionic liquid formed a compacted adsorbed layer. The anti-corrosion properties of these ionic liquids depend on its adsorption potential. Surface morphology was studied using immersion experiment and then was analyzed by XPS.

Zhang et al. (2020) developed an environment friendly inhibitor from 10-methylacridinium iodide (MAI) and sodium citrate (SC). The inhibition performance was studied by weight loss, electrochemical techniques, static test, and surface analysis techniques. For corrosion inhibition optimum mass ratio for MAI and SC was found to be 1:2 and for scale inhibition optimum mass ratio was 1:3. It was found that corrosion efficiency of MAI and SC mixture was up to 92.7% and scale efficiency was up to 98.3%. Electrochemical study revealed MAI-SC acted as mixed inhibitor and also suppressed the anodic dissociation of mild steel to control acid corrosion. Surface morphology was studied using SEM, SECM, XPS. Surface morphology revealed that inhibitor promoted surface protection by decreasing the interaction between metal surface and corrosion solution. The protective layer was formed on the metal surface which was made oh Fe (III), C(IV), O^{2-}, N(III), and Fe (II). Surface morphology also revealed that MCI-SC inhibitor can distort and disperse the crystal lattice of calcium carbonate without scale and also played an important role in inhibition of calcite (110) surface growth. Quantum chemical calculations revealed that MAI-SC inhibitor showed scale inhibition effect.

Obot et al. (2020) formulated a green and cost-effective inhibitor based on date palm leaves extract for use during acid cleaning of thermal desalination plants. The inhibitor formulated was tested against carbon steel, Ni resist, and 316 L stainless steel in 2% HCl solution at 40℃ temperatures under static and hydrodynamic conditions using weight loss and electrochemical techniques. Experiment was performed under static condition in a thermostatic water bath for 6, 24, and 72 h immersion in the test solutions. Hydrodynamic experiment was conducted for 24 and 72 h immersion under rotation speed of 415 rpm. The performance of formulated corrosion inhibitor is compared to the commercial acid corrosion inhibitor, TBZ (thiabendazole). It was observed under static and dynamic conditions ,0.4% of formulated inhibitor provided excellent corrosion inhibition up to 72 h. The formulated inhibitor gives lesser corrosion rate (mm/yr) than commercial inhibitor. It was also observed that the inhibition efficiency of formulated inhibitor was higher than commercial inhibitor. Surface morphology was studied using SEM and elemental composition was determined using SEM with EDAX. The formulated inhibitor inhibited anodic and cathodic reactions. Cyclic potentiodynamic polarization experiment suggested that there was no pitting corrosion in the studied medium. SEM pictures revealed smoother surfaces due to corrosion inhibition by the formulated inhibitor.

Deyab et al. (2020) evaluated the use of TOE for preventing the corrosion of cooling systems in desalination plants by physisorption. Electrochemical methods and surface observations were used to find effects of corrosion on inhibition. It was observed that in a seawater environment, adsorption of TOE compounds on metal pipes decreased the corrosion and forms the protective layer. The optimum TOE efficiency was 94% as it increased the energy barrier for corrosion process. TOE works as an anodic inhibitor. Analysis like HPLC identified the presence of active promoters of corrosion inhibition. SEM, FT-IR and UV spectra confirmed that TOE prevented corrosion attacks on metal surfaces. Nyquist and Bode plot confirmed the improvement of inhibition effect with increase in TOE concentration. It showed that charge transfer resistance increases and constant phase element decreases drastically.

Hemapriya et al. (2020) formulated corrosion inhibitor from biodegradable waste like human hair (HHR). The performance of inhibitor was tested on mild steel in 1mol/L of HCl. The behaviour of HHR inhibitor in metal corrosion was tested using electrochemical and weight loss techniques. The study revealed that HHR exhibited an efficient corrosion inhibition on metal surface by adsorption. It was studied that the efficiency of HHR inhibitor increased when its concentration was increased and when temperature was increased the efficiency decreased. The electrochemical results revealed that HHR acts as mixed type inhibitor for acid corrosion cleaning in1mol/L HCl. Surface morphology was studied using SEM-EDX, AFM, FT-IR. SEM-EDX, AFM and FT-IR revealed that HHR formed a dense and ordered protective film on the metal i.e., mild steel surface.

Zhang et al. (2020) evaluated an effective and biodegradable inhibitor that was Stevioside from Stevia leaf which was a potential pickling inhibitor when combined with Zn^{2+} cation for CCS. Stevioside was used to inhibit CCS corrosion in HCl solutions. Weight loss test, electrochemical techniques and surface analysis methods were used to study the corrosion inhibition performance in Stevioside and Stevioside- $Zn^{2+.}$ The combination of Zn^{2+} with Stervioside was used to improve uniformity and anti-corrosion properties. By electrochemical test, the improved inhibition efficiency was found to be 95.68% with the molar ratio of 1:2. Polarization diagrams showed that Stevioside and Stevioside- Zn^{2+} acts as mixed type inhibitors and it had dominant anodic inhibitor properties. SEM and SECM studies showed the presence of a protective film on the electrode surface. XPS results revealed the protective film is mainly composed of oxides/hydroxides of iron. These surface morphologies confirmed the effectiveness of this green inhibitor.

Singh et al. (2020) formulated use of tobacco extract from the discarded cigarettes (NDC) as corrosion inhibitor in copper and zinc corrosion in artificial sea water. Ability of tobacco extract from discarded cigarettes as inhibitor was investigated by electrochemical, weight loss, and surface characterization methods. Potentiodynamic polarization results revealed that NDC acts as mixed type inhibitor with cathodic predominance. It was suggested that by increasing NDC concentration inhibition efficiency is increased up to 96.8% for copper and 98.2% for zinc. Electrochemical frequency modulation trend suggested low corrosion density in presence of NDC. Surface morphology was studied by SEM test and AFM analysis. Study revealed formation of protective layer of NDC inhibitor on the surface of metal. The protection layer of NDC reduced corrosion of metal.

Alamria et al. (2019) formulated a cost effective and environment friendly molecule TBZ (Thiabendazole) which was evaluated as potential acid corrosion inhibitor for a typical carbon steel (C1020 grade) used for MSF plant. The experimental used electrochemical and immersion techniques. Electrochemical measurements were taken after 1, 4 and 8 h immersion in 1.0 M HCl at 25 °C which showed that TBZ was an excellent corrosion inhibitor and has 90% inhibition efficiency. When TBZ was mixed with iodide ions it improved inhibition efficiency up to 94.3%. In the presence of iodide ions, TBZ attained improved efficiency with 4 mm concentration after 4h of testing but did not increase after 8 h. However, weight loss measurements indicated that the corrosion inhibition performance of TBZ in combination with KI decreased with immersion time up to 24 h and temperature up to 60 °C. This process was further confirmed by SEM-EDX and ATR-IR spectroscopy. It showed that inhibition process was due to the SEM-EDX and ATR-IR spectroscopy confirm that the inhibition process was due to the formation of an adsorbed film that protects the steel surface against corrosive medium. Further studies by DFT and Monte Carlo gave molecular and atomic insight on mechanism of interaction between the steel surface and inhibitor. TBZ shifted the steel corrosion potential towards cathodic potential and thus its inhibition mechanism was more cathodic than anodic. The adsorption of TBZ on C1020 carbon steel alleviated localized corrosion of the steel.

Deyab (2019) evaluated the influence of Benzethonium chloride (BCCS), a cationic surfactant as a corrosion inhibitor for 316L SS in MSF Desalination plants. The experiment involved electrochemical polarization, weight loss, surface tension, conductivity, surface characterizations and quantum chemical studies. The electrochemical study of specific conductivity as a function of concentration of BCCS was done at 298K. The weight loss experiment was conducted for an immersion time of 5h at 298K and was repeated thrice to get a reliable result. On conducting adsorption isotherm studies, it was found that the best isotherm to describe BCCS behaviour was Temkin Isotherm. By collaborating the experimental and quantum calculation data, it was evaluated that for a maximum efficiency of 92.3% the BCCS concentration needed was 3.5×10^{-4} M. From the comparative studies on the SEM images done in the presence and absence of BCCS, it was clear that on addition of the said concentration of BCCS resulted in a more smooth and clean metal surface than on the control specimen. It was indicated from the experimental results that BCCS acts as a good corrosion inhibitor for 316L SS in acid cleaning operation by sulfuric acid solution.

Onyeachu et al. (2019) studied the effect of a benzimidazole derivative, 2-(2-bromophenyl)-1-methyl-1H-benzimidazole (2BPB) as a corrosion inhibitor. The specimen used was Cu-Ni 70/30 and 90/10 alloys in 1 mol/dm3 HCl solution at low and high temperatures. The various techniques used for the study was e weight loss, electrochemical (potentiodynamic polarization (PDP), electrochemical impedance spectroscopy (EIS), & cyclic voltammetry (CV)), and surface characterization (scanning electron microscopy (SEM) & Fourier transform infrared spectroscopy (FTIR)) techniques. It was seen that performance of 2BPB improves with the increase in immersion time and the addition of Iodide ions but decreases with the rise in temperature. The potential at different concentrations of 2BPB is compared with current density. It was seen that on addition of iodide ions on 2BPB the corrosion inhibition performance is enhanced. From the SEM studies it was observed that the corrosion inhibitor is adsorbed on the alloy surface. 2BPB was found to behave like a mixed type corrosion inhibitor inhibiting both anodic and cathodic corrosion reactions. The study also suggested that 2BPB was a low toxic formulation as an acid corrosion inhibitor on the alloy specimens.

Obot et al. (2019) reported that corrosion inhibitors for acid cleaning were mostly investigated for iron and its alloys. Copper and titanium alloys were widely used in industrial desalination heat exchangers. The chemistry of nitrogen compounds such as amines and azole have been extensively studied. The chemistries of oxygen and sulphur were scarce in literature. Developing of an effective inhibitor formulation for acid cleaning involved mixing of actives, surfactants and synergists. The interactions between the inhibitor and metal surface were studied through surface characterization techniques such as XPS & TEM. Hence it was concluded that naturally occurring chemicals provided a brighter future and promising substitute for synthetic chemical substances. These chemicals are readily available, less toxic and cost effective.

Tripathy et al. (2019) formulated palmitic acid imidazole (PI) in a microwave reactor to explore its inhibiting property in mild steel corrosion in 1 mol L−1 H2SO4.In ambient conditions it was seen that the obtained product showed an efficiency of 90% and on addition of little amount of KI to the formulated PI further increase the efficiency to 98%. The evaluation was done using experimental measurements, quantum chemical calculations and MD simulation. The potentiodynamic studies with different concentrations of H2SO4 with PI was compared and it shows the positive effect of PI as corrosion inhibitor. The results obtained from the theoretical calculation corroborated well with experimental findings evaluated from electrochemical measurements. The surface topography analysis and water angle measurements revealed the surface protective and water repellent property of PI. It was also seen on performing the DFT, FIs analysis, MD simulations and RDF analysis, the molecular property and corrosion inhibiting mechanism was well understood. The MD simulation showed the inhibitor action of PI in the presence and absence of various corrosive species.

Deyab (2019) formulated a sulfonium based ionic liquid namely Triethyl sulfonium bis (trifluoromethyl sulfonyl) imide (TESFI). Efficiency of TESFI was tested by Chemical, Electrochemical, and quantum chemical calculation methods. TESFI showed good corrosion inhibition upto 97.8% at concentration 120ppm. It was observed that efficiency of inhibition decreased with temperature from 97.8% to 88.2% when the temperature was changed from 303K to 343K. Corrosion inhibition of TESFI on SS carried by adsorption. It was confirmed by Quantum chemistry method that TESFI showed a good corrosion inhibition.

Obot et al. (2019) formulated two alkyl carboxylates named Sodium Octanoate (Na-Octa) and Sodium Dodecanoate (Na-Dodeca) as corrosion inhibitors for X60 steel in 0.5 M HCl solution. The effect of inhibition was studied by theoretical calculation, weight loss method and electrochemical method. Efficiency of inhibitor was studied by density functional theory (DFT) and also was used to study its electronic properties. The HOMO and LUMO levels of neutral and protonated form of the alkyl inhibitor were studied and they indicated that the molecules have ability to donate electrons to Fe surface and also electron donation ability was independent of the length of alkyl chain. Changes in Electronic structure confirmed chemisorption nature of adsorption process. Na-Octa and Na-Dodeca showed optimum inhibition efficiency at 10mM concentration but it decreased with increase in concentration up to 30mM. Inhibition Efficiency increased with increase in temperature for Na-Dodeca but decreased for Na-Octa. Inhibition efficiency decreased with increase in number of carbon atoms so it was found that inhibition efficiency of Na-Octa was greater than Na-Dodeca.

Deyab (2018) evaluated the inhibition effect of aromatic nitro compounds as corrosion inhibitors in the heat exchangers of MSF desalination plants. Chemical and electrochemical studies were conducted on titanium strip for an immersion time of 6 hours. The aromatic compounds formed a good protective layer on the titanium surface. From the chemical studies it was found that on increasing the concentration of the aromatic nitro compound, the corrosion rate decreases. It was also found that the increase in temperature had a negative effect on performance of inhibitor. Three different structures of aromatic nitro compounds were studied in this experiment and their results were compared. The results from the weight loss experiment and EIS methods were combined for the different nitro compounds. From the SEM studies it was noticed that the corrosion effect was greatly reduced on the surface of titanium strip, on the addition of 600 ppm nitro compound. It can be concluded that the inhibition effect of aromatic nitro compounds is due to the presence of electron rich N, O and aromatic rings.

Tansug et al. (2014) evaluated the use of Methyl 3-((2-mercaptophenyl)imino)butanoate as a corrosion inhibitor for copper. For the experiment MMPB was synthesised in the lab and electrochemical studies were done in 0.1M HCl solution. It was seen from the electrochemical studies, that inhibition effect of MMPB was very high against copper in acidic medium. The presence of the thiol group aided to the adsorption of the molecule to the copper surface by forming a protective layer. On studying the effect of temperature on the compound it was found that the inhibition efficiency decreased with the increase in temperature. The EDX results proved that film of the inhibitor molecule with Cu–inh complex and CuCl deposit. From the SEM studies, it was concluded that MMPB inhibitor provided protection of up to 96.60% to the copper surfaces for a 7 days exposure period.

Fouda et al. (2009) studied the effect of some crown ethers as corrosion inhibitors on stainless steel 430 in 2M HCl solution. The experimental results were studied using weight loss, galvanostatic polarization technique, SEM and EDX examination on four structures crown ethers: Dibenzo-18-crown-6; 4, 13-Diacethyl, 1, 7, 10, 16-tetraoxa-4, 13-diazacyclo-octadecane; 4, 7, 13, 16, 21, 24-hexa-oxa-1, 10-diazo-bicyclo-(8, 8, 8)-hexacosane; Dibenzo-24-crown-8 as compounds I, II, III and IV respectively. The inhibition efficiencies and the degree of coverage for different concentrations of different inhibitors was calculated and compared, which showed that greater the coverage of the inhibitor higher was the inhibition efficiency and compound IV showed the highest inhibition efficiency. From the SEM and EDX studies it was seen that there was adsorption of the crown ether onto the steel surface. It was concluded that the inhibition action of the crown ethers obeyed the Temkin adsorption isotherms.

Zhang et al. (2009) evaluated the use of glutathione as a non toxic corrosion inhibitor for cleaning copper in HCl solution . The experimental results were obtained using the weight-loss technique, cyclic voltammetry, electrochemical impedance spectroscopy (EIS) and potentiodynamic polarization techniques. Based on the studies it was found that the maximum efficiency for glutathione was seen at 92.7% at 10 mM concentration and the efficiencies increases with increase in inhibitor concentration and decreases in temperature. It was seen that the adsorption of the compound followed the Langmuir isotherm and the adsorption was strong physical adsorption. But the information about the toxicity of glutathione was not clearly specified.

Hodgkiess et al. (2005) performed a laboratory experiment to check the need for corrosion inhibitors in acid cleaning of thermal desalination plant, since it was difficult to find an inhibitor which could be used in a multi-metal equipment. The experiment was performed in the absence of an inhibitor at laboratory scale and the acid cleaning environment was stimulated. The corrosion behaviour of carbon steel, stainless steel and Cu-10Ni alloy in HCl solution was studied. The electrochemical and weight loss experiments were performed for 6-7 hrs with the acids at a pH of 2 at 20-55℃. The relative polarisation performance of each of the specimens was compared in the electrochemical studies. In the weight loss studies, it was seen that the directly measured weight losses were extremely low in the absence of the inhibitor. The findings of other studies in literature were compared with these data to understand the need of corrosion inhibitor better. In conclusion it was seen that it was difficult to find a corrosion inhibitor that was functional in a multi- metal system and hence acid cleaning operations without the use of corrosion inhibitors could be done keeping in mind how infrequently the cleaning process is done in industries.

Polo et al. (2003) evaluated the use of derivatives of Trifenylmethane, FA and FB as copper corrosion inhibitors at 0.001,0.005 and 0.01M in Hydrochloric acid solution. These derivatives were tested with BTA for comparative purposes, which was also an effective corrosion inhibitor for copper in HCL solution. The experimental procedure was done for 3 hours and then gravimetric studies were done using 10% sulphuric acid solution. A comparative study of corrosion rate between 298K – 328K was done. By using the Langmuir and Frumkin equations the slope and coverage for copper was studied. In conclusion, it was understood that FB and BTA compounds have better inhibition efficiency as compared to FA. The molecular surface area method as projected according to the Frumkin model was the best model for the correlation of the effectiveness of the inhibitors.

Lisac et al. (1998) investigated the efficiency of various imidazole derivatives as corrosion inhibitors for copper in medium hydrochloric and sulfuric acid. On the basis of the electrochemical studies, it was seen that BTA and its derivatives are good corrosion inhibitors except for 4-methyl-5-imidazole-carbaldehyde. It was also seen that 4–methyl imidazole provided the best protection for copper for an efficiency of 89.6%. It was seen that imidazole actives performed better in HCl as compared to

H2SO4 solution. From the experiments it was concluded that Imidazole and BTA which are organic compounds are cheap and non-toxic.

D.D.N. Singh et al. (1995) explored the possibilities for the use of DBSO in pickling of mild steel in sulfuric acid solutions. To improve the efficiency of base metal TU, copper cations (Cu^{2+}), and chloride ions (Cl^{-}) were incorporated with DBSO. It made an optimized composition of 0.01% DBSO + 0.02% copper sulfate ($CuSO_4 \cdot 5H_2O$) + 0.2% sodium chloride (NaCl). This composition had synergistic effect and optimum performance. Various pickling parameters such as pickling time, acid strength, temperature, and amount of $FeSO_4 \cdot 7H_2O$ accumulated in the pickling bath were studied for metal dissolution rates. The OC showed the lowest corrosion rate at all the acid strengths. The performance of OC and DBSO increased with increase in acid strength because of the protonation of DBSO in acid solution to form cationic species. An increase in the acid strength was expected to increase the concentration of the proton form of the inhibitor which improved in inhibition of corrosion reaction. In the presence of inhibitors, the cathodic and anodic curves shifted from high to low density regions.

III.CONCLUSION:

Desalination is the need of the hour due to the increasing water scarcity. But corrosion is an unavoidable consequence of thermal desalination technology. By the use of corrosion inhibitors , we can overcome this problem . This review paper includes the different kinds of corrosion inhibitors that are developed by various researchers for desalination processes.

IV.ABBREVATIONS:

EIS: Electrochemical Impedance Spectroscopy

SEM: Scanning Electron Microscope

EDX: Energy Dispersive X-ray

DBSO- Dibenzyl Sulfoxide

TU- Thiourea

OC- Optimized Composition

BTA: Benzotriazole

FA: Fuchsin Acid

FB: Fuchsin Basic

BTA: Benzotriazole

MMPB: Methyl 3-((2-mercaptophenyl)imino)butanoate

SEM: Scanning Electron Microscope

EDX: Energy Dispersive X-ray

MSF desalination: Multi stage flash desalination

EIS: Electrochemical Impedance Spectroscopy

SEM: scanning electron microscopy

HOMO-Highest Occupied Molecular Orbital

LUMO-Lowest Unoccupied Molecular Orbital

PI: palmitic acid imidazole

KI: Potassium iodide

MD: Molecular dynamics

DFT: Density functional theory

FI: Fukui indices

RDF: Radial distribution function

XPS- X-ray Photoelectron Spectroscopy

TEM- Transmission Electron Microscopy

2BPB: 2-(2-bromophenyl)-1-methyl-1H-benzimidazole

PDP: potentiodynamic polarization

BCCS: Benzethonium chloride

MSF Desalination: Multi- stage flash desalination
SEM: Scan electron microscope

MSF – Multistage Flash

TBZ – thiabendazole

KI – Potassium Iodide

SEM-EDX - Scanning electron microscopy with energy dispersive X-ray spectroscopy

ATR-IR - Attenuated total reflection infrared spectroscopy

SEM-scanning electron microscopy

AFM-Atomic Force Microscopy

NDC- tobacco extract from the discarded cigarettes

CCS- Carbon capture and storage steel

SEM - Scanning Electron Microscopy

SECM- Scanning electrochemical microscopy

XPS - X-ray photoelectron spectroscopy

HHR- Inhibitor from Biodegradable Waste Like Human Hair.

SEM-EDX- Scanning Electron Microscopy and Energy-Dispersive X-Ray Spectroscopy

AFM- Atomic Force Microscopy

FT-IR- Fourier Transform Infrared

TOE - Taraxacum ofcinale extract

TDS: Total dissolved Solids

BW: Brine wells

DP: Desalination Plants

CRA: Corrosion Resistant Alloys

CRM: Corrosion Resistant Materials

HPLC - High Performance Liquid Chromatography

SEM - Scanning Electron Microscopy

FT-IR - Fourier Transform Infrared Spectroscopy

UV spectra – Ultraviolet Spectra

SEM: Scanning Electron Microscope

EDAX: Energy Dispersive X-Ray Spectrophotometer

MAI-SC- 10-Methylacridinium Iodide and Sodium Citrate Inhibitor

XPS-X-ray photoelectron spectroscopy

EIS- Electrochemical Impedance Spectroscopy

AD: Adsorption Desalination

RO: Reverse osmosis

MSF: multistage flash desalination

DLC: Diamond Like Carbon

MEE: Multiple effect evaporation

MVC: Mechanical vapor compression

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