Determination of Water Evaporation Rate in an Assembled Bench Scale MED and Impact of Anti-Scaling Agents on the Morphology of Scale

Fosso-Kankeu E, Redelinghuys J, Waanders F, Rogers D, Bruinsma D, and Gericke G

***Abstract*—** A bench scale horizontal tube falling film evaporator was assembled in order to investigate the feasibility of implementing multi effect distillation (MED) technology in the treatment of retentate from the reverse osmosis water purification process in order to decrease water intake/usage. The main challenge regarding this application of technology is the scaling that will occur as the water becomes more concentrated, and an investigation of the effects of different anti-scaling agents and temperature on the morphology of the formed scale is paired with the primary investigation. The bench scale evaporator exhibited satisfactory performance and evaporation (1.25 L/h); while in the batch study, the acrylic copolymer anti-scaling agent yielded the most scale inhibiting performance at a temperature beneath 70°C.

***Index Terms*—**MED, anti-scaling agents, horizontal tube falling evaporator, scale inhibition.

I. INTRODUCTION

South Africa is one of many water-scarce countries. It is therefore imperative to utilize water sparingly to prevent a water restriction/scarce threat. Water scarcity is an indefinite problem which is also exacerbated by climate change (global warming). Despite the water shortage the country is facing, there is a high demand of water usage in the industries as well as for human consumption. It is therefore essential to treat and re-use industrial wastewater effluent to alleviate the problem. Another advantage regarding water re-use is to avoid on-going discharge of effluent of poor quality back to the water-course, a condition which is detrimental to the ecosystem.

Scale and corrosion is one of the main common problems that the industries encounter due to concentrated cooling water [1]. Eskom, the national Power Utility, is aware of this problem and has thus initiated investigation towards aggressive management and proper use of fresh and waste waters. The poor quality of cooling water is attributed to evaporation which occurs in the cooling towers, when natural water vapor escapes at the top of the towers causing high concentration of salts/minerals. Concentrated cooling water with such a quality is prone to scaling and corrosion of the heat exchangers and the inner surface of the pipe-system [2]. On the other hand, the salt content of the cooling water crystalizes and accumulates in the ponds of the cooling tower, which also requires cleaning, thus adding to the operating costs [2].

The present study focuses on the investigation of utilizing reverse osmosis (RO) retentate generated at the power plant's water treatment plant as feed water (back-up) to replenish water which evaporates in the cooling towers. However, the quality of the RO reject water is not suitable for cooling purposes, and therefore requires pre-treatment prior to be supplied to the cooling towers. Reject from the primary RO module is high in salinity (above 11000 ppm) and the recirculation through the RO system is not economically viable. Elsewhere, sea water of higher salt concentration has been effectively treated using multi effect distillation (MED) systems [3]. However, the main limitation of such system has been the scale formation on the tubing system responsible for heat exchange, therefore affecting the efficiency of the MED. This implies that the MED paired with the anti-scaling agents could be hybridized to the existing water treatment system at ESKOM for the treatment of relatively high salinity solutions. Traditional methods employed in wastewater treatment for industrial purposes include filtration, coagulation, decarbonization, degassing, and ion exchange, which are expensive and labor intensive as well as ineffective at times [4]. This investigation is therefore relevant as it can offer a cost-effective alternative in which wastewater can be stabilized in terms of scaling and corrosion, which is also applicable to brine solution.

If the prevention of scale formation and corrosion can be achieved by using stabilizing agents, more water can then be recycled. This stabilization will ensure the elimination of scale formation as well as corrosion [3], especially in heat exchangers. Furthermore, this will lead to reduction of water abstraction from the water-course [4].

This study is the primary investigation of the performance of a bench-top single effect evaporator for the concentration of brine in RO water reject from a coal power plant.

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II. METHODOLOGY/EXPERIMENTAL

2.1) Design and construction of single effect evaporator

2.1.1) Materials

When designing this evaporator, the three major components that the evaporator consists of were considered. The heat exchange surface, the vessel in which evaporation will take place and the drip-tray inside the vessel that dispenses the water onto the heat exchange surface.

The corroding and scale forming properties of all materials that forms part of the evaporator were evaluated. It has been established that polymers and certain polyvinyl chlorides are the appropriate materials to use when constructing the vessel of the evaporator as these polymers will not influence the concentrated water (RO retentate) that will be used in the evaporator, as these materials are corrosion as well as scaling resistant [5].

The drip tray consists polymers and poly vinyl chlorides paired with stainless steel components, as stainless steel is stable enough to resist scaling and corrosion within the water it is exposed to [6].

The heat exchange surface inside the evaporator is a metallic material, as the heat conductivity of the surface is key. Copper as well as Cu-Ni alloys have been established as successful heat exchanging surfaces especially in seawater cooled heat exchangers [7], with a mild corrosion resistance [8]. This seawater is comparable to the RO brine that the evaporator will concentrate, thus making a copper heat exchange surface applicable. The above materials are easily available and from an economic view point favorable.

Scaling can however form on this copper heat exchanger surface, and steps must be taken to prevent this from happening in order to maintain the efficiency of the heat exchange surface. This can be achieved by the addition of anti-scaling agents and controlled by the manipulation of the conditions inside the evaporator, as scaling is more prone to form at higher temperatures.

The pump that is integral to the recycle of brine from the vessel to the drip-tray is exposed to the reverse osmosis (RO) brine, and must also be composed of the appropriate materials. This pump, in order to comply with this requirement, is a magnetic drive, single stage, centrifugal pump that is constructed with thermoplastics in order to maintain chemical resistance and eliminate influence on the RO brine's concentration. Figure 1 visualizes these three major components:

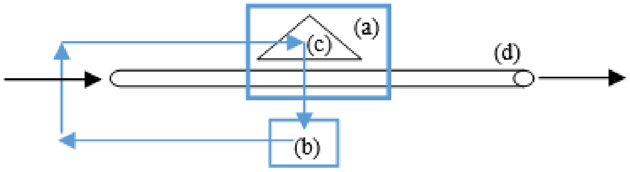

Fig. 1.Major components in design; (a), evaporating vessel; (b), recycle pump; (c), drip-tray; (d), heat source/exchange surface.

2.1.2) Design

The most intricate part of the design of the evaporator is the drip tray that evenly and with laminar flow distributes the RO brine onto the heat exchange surface. The size of the aperture, the distance between the apertures and the distance above the heat exchange surface being the factors carrying the most weight when designing the evaporator. Other weight bearing factors include the flow rate of the water moving through the drip tray, the type of flow inside the drip tray, the conductivity of the heat exchange surface as well as the length of the heat exchange surface.

The evaporator's heat source is a steam kettle/boiler that will supply steam through the heat exchange surface. This does however have a negative consequence as the temperature of the steam will be above the critical temperature where scaling is prone, as it has been reported that at a temperature above 80°C, significantly increases the rate of scale formation [3]. In order to lower the temperature whilst keeping the steam in a vapor phase to ensure efficient heat exchange, the pressure needs to be lowered. This is accomplished by the introduction of a vacuum pump.

The lowering of temperature of the heat exchange surface in order to minimize scaling in essence also lowers the evaporation tempo of the clean water from the RO brine. The pressure of the entire chamber thus also needs to undergo a pressure reduction for the water to evaporate at an adequate rate.

2.1.3) Configuration

The configuration of the evaporator consists of:

- A chamber containing the heat exchange surface and a drip tray
    - The chamber is placed under vacuum via the vapor outlet of the chamber.
    - The heat exchange surface is placed under vacuum via it's outlet from the chamber.
- A water catching tank beneath the drip tray that gets recycled to the drip tray.

2.2) Simulation of scale formation and effect of anti-scaling agent

In order to compare the morphology of the scale and effect of three different anti-scaling agents, small copper pipes were submerged inside beakers containing the RO retentate/brine obtained from ESKOM's Komati Power Station with the anti-scaling agents. These beakers were placed inside an agitated incubator and evaporated in order to let scale form.

The three selected anti-scaling agents used in this experiment was:

- Poly (sodium 4-styrene) sulfonate - (Anti-scaling agent no 1)
- Acrylic copolymer - (Anti-scaling agent no 2),
- Maleic polymer - (Anti-scaling agent no 3)

These anti-scaling agents were selected as they have different qualities and applications. Anti-scaling agent no 1 has the highest molecular weight and its main application is to function as a scale inhibitor and dispersant for metal salts and oxides as well as being an anionic polyelectrolyte. Anti-scaling agent no 3 has a molecular weight considerably less than that of no 1 and shares certain qualities. This anti-scaling agent's main application is to function as a scale inhibitor and dispersant for metal salts and oxides paired with being dopant for conducting polymers, thus also making it an anionic polyelectrolyte. Anti-scaling agent no 2's molecular weight is the smallest and has slightly different qualities than that of the first two. This anti-scaling agent has the benefit of being water soluble, can sequester metal ions and is hydrolytically and thermally stable. Its main application includes being a scale inhibitor, builder in detergents, aid in soap and detergent processing and control of water hardening. These anti-scaling agents all are manufactured by Sigma-Aldrich, a company owned by the Merck Group.

These anti-scaling agents were dosed at two different concentrations, namely 10 and 15 ppm and the simulation was completed at 95°C and 70°C where after the scale was examined by means of SEM-EDS analysis, in order to characterize the scale.

III. RESULTS

3.1) Evaporation rate of constructed bench scale MED

The bench scale evaporator was operated for 36 hours, and 45 litres of water was evaporated at a rate of 1.25 litre/hr.

3.2) Conditions of operation

The evaporator can be viewed as two processes operating simultaneously. The first is that of the heat source (system A) and secondly that of the vessel (system B).

System A comprises of a single horizontal copper pipe that functions as a heat exchanger and is connected to a boiler that continuously supplies steam, as well as a vacuum pump at the outlet of the copper pipe.

The heat exchange conditions are manipulated by the vacuum pump connected to the outlet of the exchanger. Under steady operation, the temperature of the steam is lowered from 100°C to 67°C as desired, paired with a vacuum pressure reduction of 36 kPa, before entering the vessel. The outlet temperature of the steam is lowered to 40°C, with the vacuum pressure reduction of 61 kPa, by the heat exchange that takes place in the vessel.

System B comprises of a vessel that houses the drip-tray as well as copper pipe heat exchanger through it. Ideally the vacuum on the vessel must be similar to that system A's, but due to the structural integrity of the vessel paired with the design of the brine outlet/catchment tank that is insufficient to operate under that amount of stress, the vacuum on the vessel has been decreased.

The temperature inside the vessel under steady operation is 36 degrees, with a vacuum pressure reduction of 9kPa.

The overall process schematic can be viewed in the figure below:

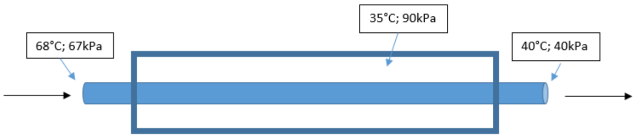

Fig. 2. Combined illustration of system A and B to showcase operating conditions

3.3) Effects of anti-scaling agents on morphology of scale

The SEM analysis images below depict the differences in the performance of the anti-scaling on the deposits formed by the RO retentate exposed to copper piping in a batch system at a temperature of 95°C:

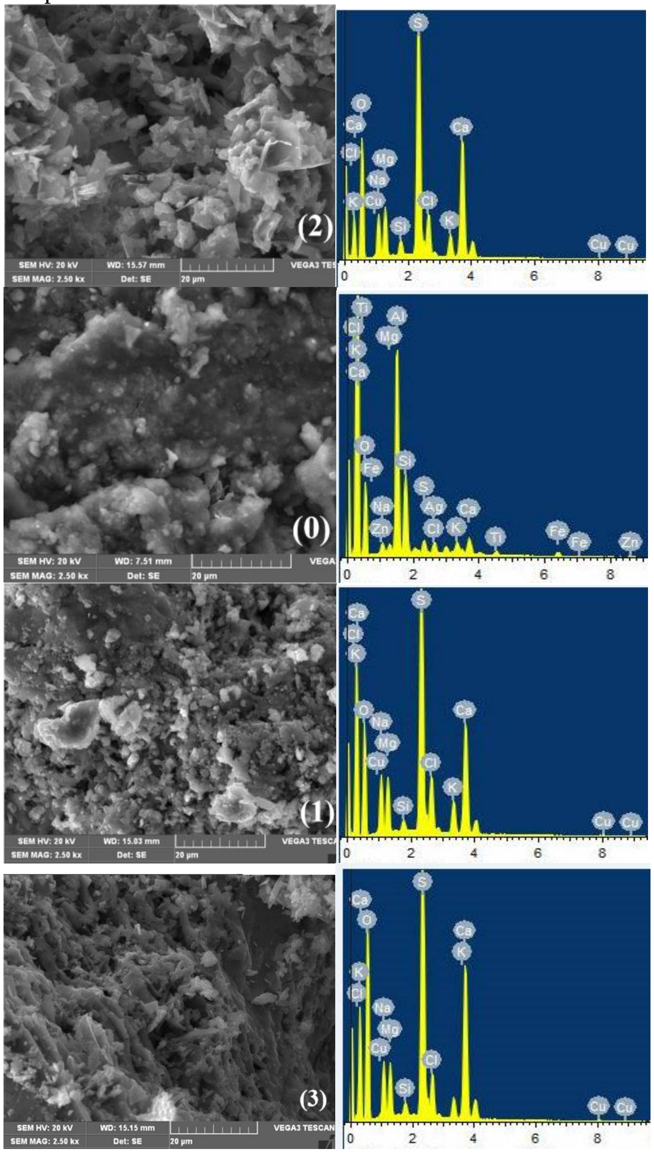

Fig. 3 SEM images and EDS-graphs showing deposit structures and compositions following usage or not of different anti-scaling agents after an evaporation period of 12 h, at temperature of 95°C; (0), No anti-scaling agent; (1), 15ppm anti-scaling agent no 1; (2), 15ppm anti-scaling agent no 2; (3), 15ppm anti-scaling agent no 3.

The SEM images paired with the EDS analysis graphs display an abundance of calcium carbonate as well as calcium sulphate present in the deposited minerals [9]. It has been reported that at temperatures above 40°C, pure amorphous calcium carbonate transforms to aragonite via vaterite formation [10]. The morphology with no anti-scaling agent shows mixed crystals containing Mg/Ca formed over a mainly magnesium hydroxide layer (brucite) of crystals covering the metallic substrate [3]. The reduction in scale formation, nucleation sites and adhesion of deposited minerals onto the formed scale is evident with the introduction of the anti-scaling agents as there is a clear variation of the scale morphology. Although it is apparent that scaling has formed, the anti-scaling agent has prevented the formation of pure complete aragonite crystals. The results indicate that the effectiveness of the agents aren't precisely identical. Anti-scaling agent no 2 shows the biggest reduction in nucleation sites as well as reduction of scale formation, followed by anti-scaling agent no 3, and anti-scaling agent no 1.

3.4) Effects of temperature on morphology of scale

The images below display the variation in the scale morphology as influenced by the temperature at which the water gets evaporated and how this influences the amount of nucleation sites. It further shows the degree of adhesion of scale and size distribution of the scale as a function of time and temperature of the water inside the agitated incubator.

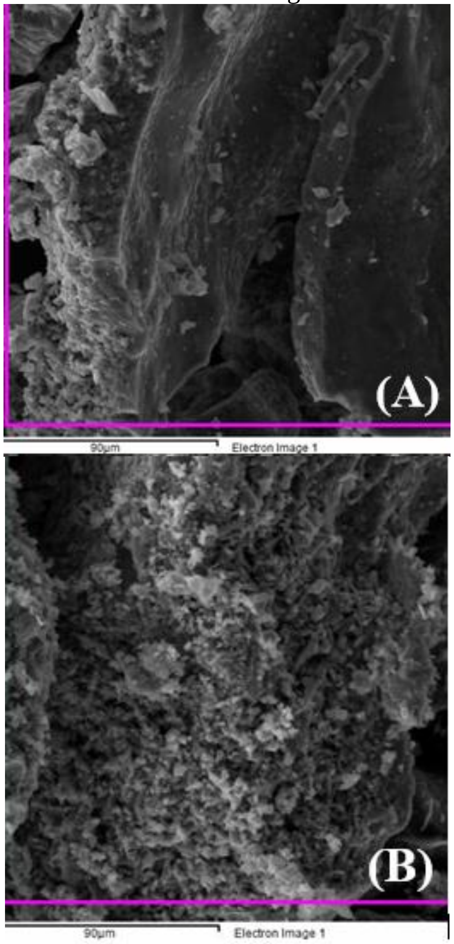

Fig. 4 SEM images showing deposit structures of a different nature with respect to morphology, nucleation present, and scale adhesion to crystal after a test period of 12 h, 15ppm of Anti-scaling agent 1; (A), t = 70°C; (B), t = 95°C

The SEM images show aragonite crystals that was initially amorphous calcium carbonate that transformed via vaterite to aragonite, as well as calcium sulphate as seen in Figure 2 [9]. The results indicate that much more nucleation sites were activated at 95°C with the morphology of the scale displaying the adhesion and scale formation on crystals than at 70°C. Mixed crystals containing calcium and magnesium grew on top of the aragonite crystals.

IV. CONCLUSION

The morphology of the scale formed by the RO brine that was obtained and tested showed clearly that conditions below 80°C are favorable to maximize scale inhibition [3]. The anti-scaling agents all displayed a reduction in scale formation potential, with acrylic copolymer (Anti-scaling agent 2) as an active ingredient displaying the largest degree of inhibition.

With regards to the bench scale evaporator, system A is more than satisfactory and needs no modification to increase evaporation rate. It fulfils all requirements and is suitable for a further investigation. System B's structural integrity and brine outlet/catchment tank design is the evaporation's limiting effect and a further investigation into improving the vessel's structural integrity needs to be initiated. Furthermore, the brine outlets of the vessel paired with the brine catchment tank designs needs to be re-evaluated and adapted to optimize the evaporator. System B has been operated at a lower pressure for short periods of time, and displayed immense evaporation in these short periods of time, displaying the feasibility of this investigation as well as the advantages of this type of water treatment.

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