Scaling Conditions Inside Improved Bench-Scale Single Effect Vacuum Evaporator

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

***Abstract*—** An investigation into the potential of scale formation during the application of MED (Multi-Effect Distillation) technology for the treatment of Reverse Osmosis (RO) Retentate was carried out in this study. An improved bench scale single effect evaporation unit was designed using Solidworks Simulation Package and appropriate materials. Operating conditions were determined to be 80°C and 0.48 bar with the design constructed to maximize evaporation. Once assembled, RO Retentate was introduced to the evaporator and an evaporation rate of 4L/h (22.3L/m2/h) and the variation of the concentrations of scale forming elements determined – the evaporation translates to 34.5% water recovery. Speciation using PHREEQ-C modelling software showed that the concentrations of scale forming agents such as CaCO3 and CaSO4 increased after evaporation. Scale prediction was explored using French Creek software.

***Keywords*—** MED, scale formation, RO retentate, PHREEQ-C, French Creek.

I. Introduction

South Africa is a water-scarce country. Water consumers are forced to explore the utilization of all available water sources, and the water scarcity is being worsened by climate change. Despite the water shortage the country is facing, the demand for water usage in industry and for human consumption stays high, creating an ever-increasing dependence on seasonal rainfall. Wastewater effluent is becoming more valuable as advances in technology makes the recovery, treat and re-use of waste water more attractive [1 – 11]. When water is being treated and re-used, a common occurrence whenever any form of heat exchange or membrane is used, scale is prone to form when not properly avoided [11]. Eskom, South Africa's National Power Utility, is allocated 2-3% of the national available fresh water to generate electricity. Eskom is however under pressure to minimize its water usage and has set a target of lowering its usage to 1.34L of water per kilowatt electricity produced by 2020, from the 1.39l/kW presently [12, 13]. Of the total water intake, 98% is lost via evaporation in the cooling towers of the power plants. The re-usage of certain streams can potentially lower the amount of freshwater in-take needed to replenish the amount of water lost due to evaporation. Eskom, has thus initiated an investigation towards water management and proper usage of all available waters sources. Reject from the primary RO module is high in salinity and the recirculation through the RO system is not economically viable. Sea-water of high salt concentration has been treated using multi-effect distillation (MED) systems encouraging the usage of this technology for this application [4]. Most MED-Evaporators makes use of the horizontal tube evaporation principle. This principle makes use of a distribution system that evenly distributes water on top of a bundle of horizontal tubing. The water then flows from tube to tube partially evaporating on the tubes. A typical tubing network usually evaporates around 33.3% of the feed water [14]. A limitation of such a system is the scale formed on the heat exchange surfaces due to the quality of the water, therefore negatively affecting the efficiency of the MED [15]. This implies that MED technology could be hybridized to the existing water treatment system as it will help Eskom adhere to their zero liquid effluent discharge (ZLED) policy as stipulated in their water use licences [11]. The application of this technology to treat inland and waste waters will see the MED-evaporator possibly serving a dual-purpose. The primary purpose of MED is to serve as water producing/recycling technology that can treat brine solutions. The secondary purpose of the technology when applied to a power plant will be to dissipate some of the abundant heat present – alleviating the amount of heat energy the cooling towers must dissipate to some extent thus lowering the amount of cooling water needed [16]. Scaling potential can be determined by using PHREEQ-C, an open-source modeling package developed by the US Geological Survey [17]. French Creek software can also be used as it combines multiple saturation and stability indices to accurately predict the scaling potentials of the minerals present in the water. This is similar to PHREEQ-Cs capabilities but with the additional capability of predicting which anti-scalant will yield the best results and the simulation of the addition thereof [18].

Scaling is caused by concentrated minerals in water when they become insoluble. When mineral constituents remain soluble, they have no negative effect on heat transfer efficiency [19].

Scale formation occurs in alkaline water, and is attributed to the presence of scale forming ions such as Ca2+ and/or Mg2. Calcium carbonate is one of the most common scale forming

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minerals [20]. Process parameters however, do play a role in the scale formation within a pipe-system, especially temperature and flow rate [15], as these parameters can influence deposit (scale) structures, shape, size and composition.

It is apparent that there are multiple steps involved in scaling, and these steps will be briefly explained with a schematic representation thereof in Figure 1.

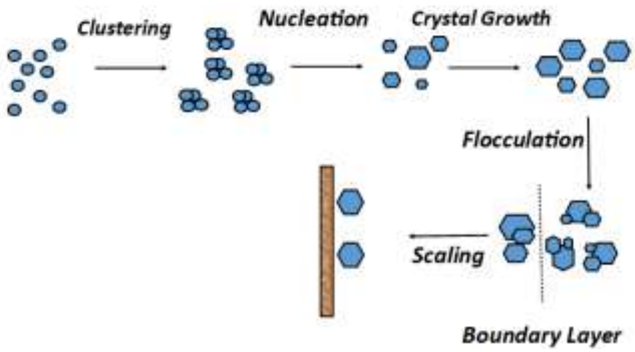

Fig 1: Schematic of processes involved with the formation of mineral (Reproduced from [21])

When mineral ions are present in water, and if these ions become more concentrated over time, the ions present will eventually become abundant enough for the water to be supersaturated with these ions. Mineral ions under increasingly supersaturated conditions will, due to their polarity and random thermal motion, form clusters. Once these clusters pass a critical size, nucleation will take place. As soon as nuclei are formed, spontaneous crystallization will take place forming larger particles. Subject to the surface properties and composition of these particles, the particles can either aggregate to create larger particles, or stay suspended in the water for a period. After enough time these particles and present mineral ions will diffuse through the hydraulic boundary layer [21] and form scale after depositing onto a solid surface.

In this study, reverse osmosis (RO) retentate from Lethabo Power Plant was evaporated in an improved bench-top single effect evaporator and the variation of the concentration of scale forming elements evaluated.

A. Operating Conditions

1)Temperature

The evaporator's heat source is a steam generator that will supply steam through the heat exchange surface. There is one drawback regarding the steam generator as heat source – the temperature of the steam. The steam will have a temperature higher than the critical temperature where scaling is prone, as it has been reported that at a temperature above 80°C, the rate of scale formation is substantially increased [15].

2)Pressure

When evaluating pure water's saturation pressure as described by Milo Koretsky, and by making use of the software that accompanies the handbook "Engineering and Chemical Thermodynamics" namely "Thermosolver" certain operating parameter targets can be determined [22]. The Saturation Pressure Calculator of the Thermosolver software package uses the Antoine Equation of state, and the results are displayed in Table 3. The ambient pressure of Potchefstroom is 0.875 bar, and this was considered when determining the vacuum needed at different temperatures.

TABLE 1: OPERATING PARAMETER TARGETS OF EVAPORATION CHAMBER

Temperature	Solver Saturation Pressure (bar)	Size of vacuum needed (bar)
75	0,38559	0.4013
80	0,4737	0.48941

Thermodynamically, when a temperature target of 80°C is achieved, the pressure inside the evaporation chamber of the MED needs to be as close to 0.47 bar as possible for optimal evaporation to take place as this is the saturation pressure of water at 80°C.

3)Materials

The scale forming properties of the materials combined with the strength and effect of temperature of the materials to be used had to be evaluated, as the material will be exposed to a pressure reduction, high temperature and water with an increasing scaling potential.

The design of the evaporator can be divided into three main components. The evaporation chamber, the dual heat exchange surface running through the evaporation chamber, and drip tray that dispenses the water onto the heat exchange surface inside the evaporation chamber.

Polymers and certain polyvinyl chlorides are deemed appropriate materials to be used when constructing the evaporation chamber of the evaporator as well as the drip tray as these polymers will not influence the concentrated water (RO retentate) that will be used in the evaporator, as these materials are scaling resistant [23]. Stainless steel has an unreactive nature with regards to scaling potential, largely due to the unavailability of nucleation sites available for the scale to attach to [24] and will be used inside the evaporation chamber to control the height of the drip tray above the heat exchange surface.

The dual heat exchange surface inside the evaporator is metallic to provide the necessary heat conductivity needed at the exchange surface. Cu-Ni as well as copper alloys have been used as successful heat exchanging surfaces especially in seawater cooled heat exchangers [25], with a mild corrosion resistance [20]. When comparing the high salinity of seawater to RO retentate, copper will perform as a sufficient heat exchange surface due to its mild corrosion resistance. Without proper pre-treatment, the copper heat exchange surfaces are mildly susceptible to scaling.

The material of the pump that recycles the brine from the evaporation chamber to the drip-tray is exposed to the high scaling potential water, and must thus be constructed with appropriate materials. A magnetically driven, single stage, centrifugal pump constructed using thermoplastics will suffice due to its chemical resistance.

These three key components are depicted in figure 2:

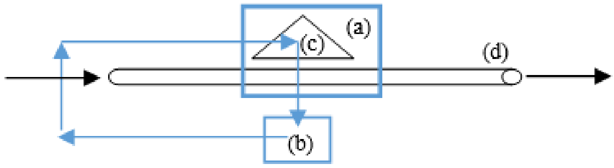

Fig 1:: Main components in MED design; (a), evaporation vessel; (b), recycle pump; (c), drip-tray; (d), heat source/exchange surface.

II. Design & Configuration

A. Evaporation Chamber

The initially commissioned bench scale MED [26] had a few areas where it had to be improved to conduct more realistic and extensive experiments. Firstly, the structural integrity of the evaporation chamber had to be significantly improved to increase the vacuum applied to it without the structure failing [26]. The initial bench scale MED could function with a pressure reduction of 0.09 bar before the risk of structural decomposition occurs.

Simulation on Solidworks (3D design and simulation software whilst evaluating a range of polycarbonate thermoplastics resulted in a material selection and design consisting of multiple and extensive internal rib structures. The Solidworks Simulation Packet recommended a material thickness of 12 mm.

To characterize the effects of time, temperature and environment on polycarbonate thermoplastic, Loughborough University (UK) performed widespread testing on a polycarbonate (PC) thermoplastic over a year long period of time, the evaluation was conducted at temperatures ranging from -40 °C to 140 °C. The tensile strength of the material determined in this investigation is at 80°C stays well above 300 bar [27].

It is thus apparent when examining the material properties that the Solidworks design simulation yielded satisfactory

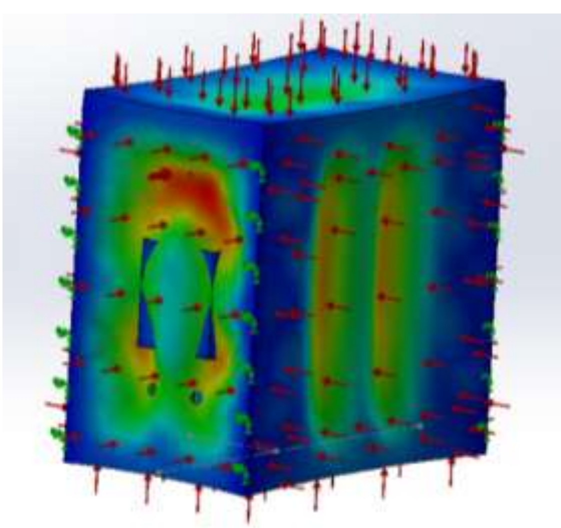

Fig 2: Solidworks simulation displaying a maximum displacement of 4 mm

results and that the design's structural integrity will not be compromised when exposed to the target pressure reduction of 0.41bar.

B. Vacuum Pumps

The vacuum pumps' characteristics were of such a nature that changes had to be made to accommodate them. The problematic area being the operability of the current vacuum pumps as they are operating very near to and above the recommended temperature ranges with the initial recycling closed circuit cooling water configuration.

The vacuum pump's cooling system needed to be altered to a 'once through' system from a recirculating system to run the pumps for a longer period whilst preventing the risk of overheating.

C. Drip-Tray

The drip-tray had to fulfill a duel-purpose. Firstly, the drip-tray plays a key part in the structural integrity of the evaporation chamber. Secondly, laminar flow of water onto the heat exchange surface. Multiple factors influence the latter named; namely the size and distance between the apertures, the distance the drip-tray is above the heat exchange surfaces being the factors carrying the most weight when designing the evaporator. Other factors include: flow rate of the water moving through the drip tray, turbulence of flow inside the drip tray, the conductivity of the heat exchange surface and the length of the heat exchange surface. Consequences when not designed correctly include decreased heat exchange efficiency and increased scale formation.

D. Operation

To achieve the ideal operating conditions, the temperature of the steam providing the heat needs to be lowered to below 80°C, and a vacuum of 0.41 bar needs to be created inside the evaporation chamber. This will be achieved with the incorporation of two Busch LX 0030-0430 B Vacuum Pumps. One creating a vacuum inside the evaporation chamber to increase evaporation at the lowered heat exchange surface temperature, and the other lowering the temperature of the steam flowing through the heat exchange surface.

E. Method of Evaluating MED Performance

Due to the once-through cooling of the vacuum pump that removes the vapour from the evaporation chamber, an accurate measurement of amount of water evaporated measurable will be challenging due to the addition of the cooling water inside the pump before entering a catchment tank. The method in which the amount of water evaporated will be calculated, will be by making use of Phreeq-C software to verify the volumetric calculations and level differences inside the MED. This software includes the PITZER database and calculation capabilities which include determining the amount of water evaporated based on the increase in the concentration of the minerals present.

III. Methodology

A. Assembly

Once the design was finalized and materials obtained, the assembly entailed milling the polycarbonate to the right sizes where after it was glued together. Stainless steel fittings and un-reactive reinforced plastic piping was used to assemble the closed water circuit running from the evaporation chamber to the recycling pump to the drip tray. The piping was further reinforced with stainless steel springs to ensure the vacuum will not influence the flow of the brine/water. The available steam supply piping had to be adapted and positioned to the inlet of the MED with valves to control the supply and pressure with pressure and temperature gauges before, inside and after MED. A frame to house the different components was also designed and constructed. A silicon sheet lining was used as sealant beneath the lid of the MED to ensure an airtight seal. A continuous cooling liquid supply with buffer tank was incorporated to the design to ensure adequate vacuum pump operating temperatures.

B. Water Sampling and Analysis

Water/RO Retentate was sampled directly from Lethabo Power Plants RO-Retentate Stream using clean and dry 25l containers. Samples were sent for analysis to Midvaal Water Company, as their Scientific Services division and laboratory is SANAS (South African National Accreditation System) accredited. The results from this analysis were used for scale formation modelling.

C. Operation and Control of MED

The control of the MED comprises of the manipulation of various valves. The pressure valve on the steam supply line provides the means of altering the temperature of the steam entering the MED as the steam supply is placed under vacuum. A pressure regulating valve on the MED provides the means to manipulate the pressure in the MED. A valve regulating the flow from the recirculation pump provides the means of influencing the flow to the drip tray – ultimately the flow of water onto the heat exchange surface

IV. Results

A. Performance of MED

1) Parameters

The targeted parameters were obtained. A steam supply temperature varying between 78°C and 80°C, paired with a vacuum varying between 0.40 and 0.44 bar inside the evaporation chamber of the MED ensured rapid evaporation. The temperature inside the MED stabilized at 60°C with the steam exit temperature stabilizing around 50°C.

2) Evaporation Rate

When evaluating the water level pre-and post-evaporation, an 8cm level difference translated into 24L of water being evaporated from the initial 70L over a 6-hour run time. Displayed in Figure 5 is the water flow onto the heat exchange surfaces.

B. Analysis of Water

The water prior to the evaporation and after evaporation were both analysed using Inductively Coupled Plasma Atomic Emission Spectroscopy (ICP-AES) to determine the elements present and to view the increase in concentration. These analyses were then used for scale prediction and modelling. Displayed in Table 2 is the increase in concentration of certain scale influencing and forming elements:

Fig 3:Drip tray's laminar water flow distribution on-to heat exchange surfaces

Table 2:Concentration in mg/L of a) RO-Retentate before MED-Evaporation and b) after MED-Evaporation

Element:	a)	b)
K	10100	13400
Ca	2830	3310
Na	2000	1340
Mg	174,92	231,83

C. Prediction of Scale Formation and Modelling

Using the initial water analysis from Midvaal Water Company as input parameters paired with the operating conditions inside the MED the Figures 5,6 and 7 reveal temperature and pH at which Aragonite and Calcite are superaturated and the Langelier Saturation Index.

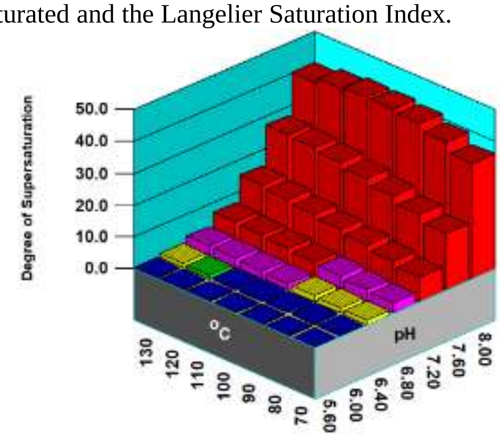

Fig 4: Aragonite Saturation Level vs Temperature vs pH

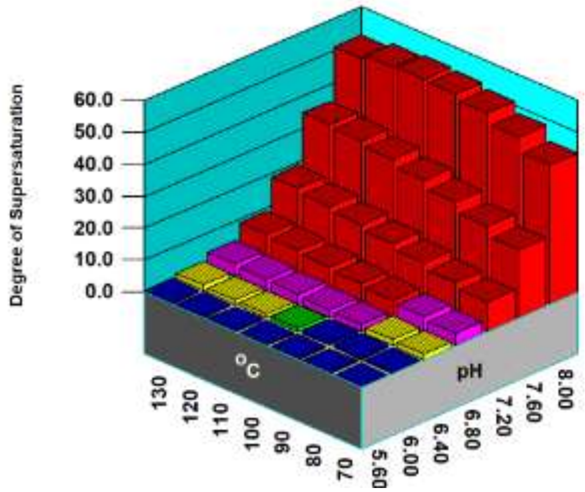

Fig 5: Calcite Saturation Level vs Temperature vs pH

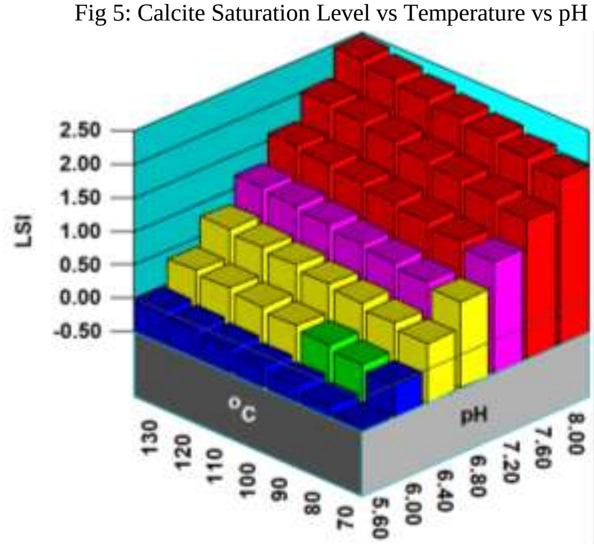

Fig 6: Langelier Saturation Index

These graphs were generated using French Creek Modelling Software.

French Creek software has thus confirmed that scale will form and that various elements will become over saturated at 80 °C, 0.48 bar pressure and a residence time of 6 hours.

When using Phreeq-C modeling software, the amount of water that evaporated is slightly less than the volumetrically determined amount, depending on which element's balance used. When evaporating 24L of water with this modelling software differences from ICP-AES analyses occur as displayed in Table 6. The reason for this difference is because Phreeq-C did not take the scale formed on the heat exchange surface into account. According to the Phreeq-C modelling roughly 13L of water should be evaporated to obtain identical Calcium concentration to the ICP-AES analyses, but when taking the scale formation on the heat exchange surface into account and evaluating the increase of other non-scaling elements into account, 24L of water evaporated is deemed a realistic and accurate measurement. Furthermore, the speciation of elements before and after evaporation shows that more scale forming agents such as $CaCO_3$ and $CaSO_4$ are likely to occur after evaporation than in the feed water; implying that scale formation will probably takes place .

V.CONCLUSION

The designed bench-scale single effect vacuum evaporator exhibited a performance that complied with all the design requirements. The vacuum inside the vessel was maintained between 0.4 and 0.44 bar with the steam temperature varying between 78° and 80 °C. The evaporation rate of the RO-Retentate was volumetrically measured to be 4l/h (22.3L/m^2/h) and this was verified by making use of PHREEQ-C modelling software. The improved structural integrity of the evaporator and vacuum pump cooling adaptations paired with the doubling of heat exchange surface area increased the evaporation tempo from 1.25l/h to 4l/h. This implies that roughly 34.5% of the feed water/RO-Retentate was evaporated that can then theoretically be recycled whilst absorbing some of the abundant heat present at the Power Station to in turn lower the amount of cooling water needed. The speciation using PHREEQ-C modelling software further shows that evaporation increases the concentration of scale forming agents, requiring the use of anti-scaling agents if the evaporator is to be operated for longer period of time.

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