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A NOVEL ENHANCED-MULTI EFFECT THERMAL SEPARATION TECHNOLOGY (E-METS) FOR DESALINATION

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ABSTRACT

This manuscript presents the thermal-hydraulic performance of a patented novel hybrid thermal separation technology, i.e. Enhanced-Multi Effect Separation (E-METS), developed primarily for desalination and brine concentration applications. The E-METS technology implements novel evaporation techniques, namely, i) enhanced forced flow boiling, ii) membrane distillation (MD) and, iii) flashing, to yield higher distillate output and superior energy efficiency. The primary objective of this experimental research is to demonstrate the E-METS technology as a viable alternative for desalination, brine management for desalination plants or industrial effluents with high Total Dissolved Solid (TDS) levels.

The current experimental investigation reported in this manuscript demonstrates the distillation performance characteristics of our 14-effect E-METS technology demonstrator, which is comprised of Poly(methyl methacrylate) – PMMA modules integrated with high performance finned titanium tubes, enhanced surface 100 µm titanium substrates, and porous PTFE hydrophobic membranes with reference pore diameter of \( d_p \approx 0.45 \) µm. Integrated heat recovery concepts were implemented for heat recovery to accommodate efficient feed preheating. In our experiments, saline feeds with TDS of up to 38,400 ppm (~38.4 g/L) were used as feed, with the top brine temperature (boiling point) maintained below 80°C. All experimental data have been acquired under steady-state conditions. From our experimental observations, we were able to achieve an average membrane flux of \( \approx 18 - 23.1 \) L/m²-hr with an overall specific thermal energy consumption of \( \approx 58 - 68.5 \) kWh/m³, corresponding to a GOR \( \approx 9.1 - 10.8 \). The produced distillate are of superior quality, containing a TDS level of less than 10 ppm. Our current hybrid multi-effect E-METS technology was able to demonstrate up to \( \approx 4.2 \)x higher membrane distillate flux when compared against multi-effect membrane distillation systems, while maintaining sustainably improved energy efficiency vs. state-of-the-art thermal separation technologies. Summarizing in brief, this is a first step forward in our effort towards implementation of E-METS for desalination and brine management applications.

Keywords: enhanced flow boiling, membrane distillation, hybrid thermal separation, multi-effect, energy efficiency.
I. INTRODUCTION

‘Water’ is the ‘Essence of Life’. It is an irreplaceable precious resource that is core of life on earth, a vital commodity that is critical for human survival, socio-economic developments and for the preservation of a healthy ecosystem. Current trends indicate that two-thirds of the world’s population will be living in water-stressed countries by 2025 [1]. With a rising global population and increasing water withdrawals, intelligent water management and unconventional water resources via sustainable desalination are the ultimate challenges towards securing a long term sustainable development for all.

Seawater desalination has been around for millennia. While we have witnessed improvements through the years, the general concept of distillation and filtration are still being employed for desalination to produce potable water safe for human consumption. Conventionally, the most widely employed separation technologies are generally categorized into thermal, such as Multi-Stage Flash (MSF), Multi-Effect Distillation (MED), Thermal Vapor Compression (TVC) etc., while membrane desalination comprise mostly of Reverse Osmosis (RO). For both technologies, the main challenge still revolves around the vicious cycle of energy demand.

Thermal distillation processes requires two type of energy forms, namely, thermal energy for distillation and electrical energy to operate the system’s components. For Reverse Osmosis (RO) desalination, electrical energy is consumed to drive the high pressure pumps to facilitate the separation process. As reported in [2], energy cost can comprise up to 66% of the overall operational and maintenance cost for thermal desalination projects and 41% for RO desalination plants. Reduced energy consumption levels is therefore the main challenge to lower operational cost for desalination plants.

1.1 Energy Consumption of Conventional Thermal and Membrane Desalination

The energy consumption for desalination plants are mainly dependent on the following factors, namely, i) the type of separation processes involved, ii) the feed salinity which affects water recovery ratio, iii) plant capacity design, and iv) materials used [3]. In total energy requirement terms, Sommariva [4] concluded that it was impossible to accurately compare the heat and power on the same basis for thermal desalination (consuming both thermal and electrical energy) vs. Reverse Osmosis (RO). Hence, it was proposed that a widely accepted method, i.e. reference cycle method, can be used to align electrical power and thermal energy inputs, whereby the method addresses the equivalent loss of electrical power generation associated with steam extracted from the power plant steam cycle into a thermal desalination plant.

1.1.1 MULTI STAGE FLASH (MSF)

Semiat [5] reported that according to manufacturer’s performance data, specific thermal energy consumption of conventional MSF plants are in the range of 190 – 282 MJ/m³ (52.8 – 78.3 kWh/m³), corresponding to a Performance Ratio (PR) of 8 – 12. The higher PR is only achieved by increasing the Top Brine Temperature (TBT) to ~110 °C. Electrical energy consumption for MSF plants were reported to be in the range of ~2.5 – 5 kWh/m³. In co-generation implementations, the extraction steam pressures for MSF desalination plants are in the range of ~2.2 – 2.5 bar absolute [4]. Hence, the total energy requirements after considering the work subtracted from the steam cycle is expected to be in the range of 14 – 25 kWh/m³. In general, the wide scale application of MSF desalination plants, more specifically in the Gulf region is due to the abundance of fossil fuel and the large-scale production capacity requirements. Moreover, MSF is also more robust towards scale formation when compared against MED, while the overall plant performance is less affected by feed quality.

1.1.2 MULTI-EFFECT DISTILLATION (MED)

MED plants, as per manufacturer specifications cited in [3,5] reported thermal energy consumption levels in the range of 145 – 230 MJ/m³ (40.3 – 63.9 kWh/m³), corresponding to Performance Ratio (PR) of 10

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1.1.3 REVERSE OSMOSIS (RO)

Large scale state-of-the-art RO plants consume on average 3.4 – 4.3 kWh\textsubscript{e} of electrical energy to produce 1 m\textsuperscript{3} of permeate from raw seawater feed. The low energy consumption levels reported earlier is achieved via the integration of energy recovery devices for seawater desalination. Recent large-scale RO desalination plants such as the Al Tawelaah plant in the UAE has reported electrical energy consumption below 3 kWh/m\textsuperscript{3}. Modular design, availability of novel membranes and the flexibility of integrating multiple passes renders the RO process highly scalable and attractive for large-scale desalination. RO systems are even more attractive for brackish water desalination, registering an energy consumption range of only ~1.5 – 2.5 kWh/m\textsuperscript{3} [5,6]. However, the drawbacks of RO are the significantly higher energy consumption levels and low water recovery ratio for higher salinity feeds due to higher osmotic pressure requirements. Moreover, the produced permeate contains higher TDS when a single pass RO configuration is implemented. However, significant improvements in permeate quality can be obtained with the integration of an additional 2\textsuperscript{nd} RO pass and polishing to further reduce permeate TDS levels to below < 20 ppm [4].

1.1.4 MEMBRANE DISTILLATION (MD)

Membrane distillation (MD) has gained wide widespread attention since the 1980s due to the availability of novel membranes, a result of advanced membrane engineering and research [7]. The attractiveness of the MD process is related to the capability of using low grade waste heat for the separation process and for brine concentration applications. Within this context, one of the most promising MD implementation for desalination and brine concentration to date can be directed towards the Vacuum Multi-Effect Membrane Distillation (VMEMD) system [8-10]. Synthetic seawater desalination with a six-effect VMEMD system recorded the best membrane flux of ~4.9 l/m\textsuperscript{2}-hr with a GOR ~3.73 (equivalent to ~172 kWh\textsubscript{th}/m\textsuperscript{3}). In later desalination trials with salt solutions, a membrane flux of ~5.4 -5.9 l/m\textsuperscript{2}-hr (3.5wt% NaCl) and ~4.7 – 5.6wt% (7.0wt%) were achieved for a four-effect VMEMD system [10]. It has been reported in [9] that increasing the number of effects from 2 to 4 effects for their VMEMD system showed a reduction in the membrane distillate flux from 3.8 to 3.0 L/m\textsuperscript{2}-hr.

1.2 RESEARCH OBJECTIVES

The primary scope of this experimental investigation is dedicated towards the development of a novel thermal separation technology to achieve lower specific thermal and electrical energy consumption. To achieve significantly higher distillate flux, we have developed a hybrid thermal separation water technology that incorporates multiple interdependent thermodynamic processes within a compact and modular configuration to reduce the thermal resistance of the phase change processes. With lowered...
energy requirements, it is therefore a step forward towards achieving a lowered cost of desalinated seawater.

II. ENHANCED-MULTI EFFECT THERMAL SEPARATION (E-METS)

The Enhanced-Multi Effect Thermal Separation (E-METS) concept revolves around a patented invention, initiated to develop a reliable and economical solution for seawater desalination, brine concentration or industrial wastewater treatments (IWWT). The ‘hybrid’ Enhanced-Multi Effect Thermal Separation (E-METS) concept implements advanced flow boiling/cooling principles conventionally employed in state-of-the-art nuclear power plants for water desalination. The concept is the first of its kind for thermal water separation. The second innovation integrates multiple vaporization and condensation processes, embedded within a compact membrane distillation module for enhanced energy efficiency with higher production capacity. The vaporization processes comprise enhanced tube flow boiling, flash evaporation, enhanced pool boiling and membrane distillation. Condensation processes include vapor condensation on enhanced tube surfaces and titanium substrates with boiling brine reheat. In general, the E-METS system integrates advanced distillation, condensation, feed preheating and heat recovery processes within a compact distillation system. This is opposed to a single-evaporation/condensation process traditionally implemented in conventional thermal separation technologies. Summarizing in brief, the E-METS technology delivers key technological benefits of conventional water purification technologies, both thermal and membrane systems, into a scalable, highly modular configuration.

2.1 DESCRIPTION OF THE E-METS PROCESS

A typical E-METS separation system can comprise up to 25 effects or more for thermal water separation. The inclusion of multiple effects enables thermal energy recovery and reuse for re-vaporization of saline feed for lower energy (thermal and electrical) consumption. Each individual effect will comprise at least one feed module comprising the evaporator and a vapor module with an integrated condensation-evaporation section. The feed and vapor module is separated by a porous hydrophobic membrane (feed module – vapor module) and a surface enhanced surface titanium substrate (vapor module – feed module), as shown in Figure 1 and Figure 2. For illustration purposes, a simplified descriptive process flow is as follows:

![Figure 1: Schematic of the E-METS process with enhanced distillation and heat recovery concept.](image-url)
Figure 2: The multiple E-METS vaporization and condensation heat recovery processes.

Step 1: Thermal energy which can be in the form of steam, hot water or exhaust gasses will be supplied to the flow boiling tubes located in the first effect of the feed chamber. Onset of flow boiling of the salt water is then initiated in the feed chamber, producing vapor (steam).

Step 2: The vapor rises to the top of the feed chamber and is transported across the porous hydrophobic membrane into the condensation sections of the vapor chamber.

Step 3: The vapor (steam) condenses on the external tube-side of the pre-heating tubes. Latent energy is recovered to pre-heat the raw salt water feed (the feed flows upstream from the last effect to the first effect).

Step 4: Simultaneously, the salt water is channeled from the feed module into the evaporator section containing the flow boiling tubes located in the bottom section of the vapor chamber (as illustrated in Figure 2). The latent heat of condensation (due to vapor condensation) is recovered for feed re-vaporization via in-tube flow boiling. Thereafter, the two-phase boiling salt water is then channeled into the feed module adjacent downstream. A small constriction is used to induce a minor pressure drop and initiate feed flashing, followed by expansion when the feed reaches the downstream feed module. (Refer Section VI – FUTURE WORK)

Step 5: Simultaneously, vapor condensation occurs on the side of the titanium substrate in contact with the vapor. During the condensation process, the recovered thermal energy is then used to partially re-vaporize the salt water feed in contact with the enhanced surface of the titanium substrate.

Step 6: The vapor phase rises to the top section of the feed module before being vented into the adjacent vapor module and this process is repeated for the remaining numbers of effects.

2.1 THE 14-EFFECT E-METS TECHNOLOGY DEMONSTRATOR
The current manuscript reports the desalination experimental campaign performed with our current 14-effect technology demonstrator. Today, the E-METS technology demonstrator is capable of desalinating
marine salt feed with ~38.4 g/L of salt content, producing ultrapure distillate with less than 10 mg/L. The lab-scale technology demonstrator produces up to ~140 liters of distillate per day. Energy consumption levels improved significantly with ~90% lower energy consumption, at ~58 – 68.5 kWh/m³, when compared against the 1-effect system. The current 14-effect technology demonstrator has already accumulated up to ~280 hours of desalination operation without any observable performance degradation on the salt rejection capability. The evolution and research milestones for the E-METS proof-of-concept is shown in Figure 3.

Figure 3: The evolution of the multi module E-METS technology demonstrator.

Research Milestones
- Milestone 1: A 1-effect proof of concept was first constructed to validate the E-METS technology. Validation was successful with thermal energy consumption at ~640 kWh/m³. Total cumulative desalination time was ~320 hours*.
- Milestone 2: The 1-effect proof of concept was extended to a 6-effect technology demonstrator. Thermal energy consumption improved to ~121–126 kWh/m³ (6-effect). Total cumulative desalination time was ~800 hours*.
- Milestone 3: The 6-effect technology demonstrator was scaled-up to become a 14-effect system. Thermal energy consumption is further reduced to ~58 – 68.5 kWh/m³ (refer Table 1). Total cumulative desalination time was ~280 hours*.

*The desalination campaign involves experiments that were carried for a period of between 6 – 8 hours/day. The cumulative desalination time reported in the milestones above comprise the sum of the individual desalination experiments performed separately on the 1, 6 and 14-effect modules.

2.2 DESALINATION TEST FACILITY
The current desalination experimental facility is comprised of the E-METS modules, a 100 liters saline feed reservoir (marine salt solution), LAUDA thermostats (to initiate feed flow boiling and to maintain a constant feed inlet temperature at 20/30°C), pumps (vaccum, distillate and brine), plate heat exchangers, distillate/brine tanks, and a National Instruments data acquisition system. The schematic diagram of the test facility is depicted in Figure 4.

Process Flow:
(1) - Saline feed is first drawn from the feed reservoir, channeled into heat exchanger 2 that is connected to a LAUDA thermostat 2 to regulate the feed inlet temperature at 20 or 30°C.
(2) – The feed enters the E-METS module from the last effect, initiates feed preheating via heat recovery from the brine, followed by latent heat recovery from the condensing vapor in the vapor modules upstream. The feed flows in series from the last effect to the first effect upstream.
(3) – The pre-heated feed flows into heat exchanger 1 for a final pre-heating close to the boiling point, before entering the flow boiling module (1st effect).

(4) – The feed undergoes distillation via enhanced flow boiling, flashing, membrane distillation and pool boiling. The saline feed flows in series from the first effect to the last effect downstream.

(5) – The rejected brine is collected into a brine tank before being discharged via a pump back into the feed reservoir for brine recirculation.

(6) – The produced distillate is collected into a distillate tank.

(7) – Hot water flows from the LAUDA Thermostat 1 into the flow boiling tubes located in the 1st effect flow boiling module to initiate enhanced flow boiling of the pre-heated saline water feed.

A vacuum pump (not shown in Figure 4) is connected to the distillate and brine tanks to allow flow boiling at sub-atmospheric pressures (less than 460 mbar) and boiling point of < 80°C.

**Figure 4: Schematic diagram and process flow of the E-METS desalination test facility.**

2.3 THE E-METS MODULES

The modules are comprised of machined PMMA blocks with an active distillation area of 100 mm x 100 mm (equivalent to ~0.01 m²). Porous hydrophobic membranes with nominal pore sizes of ~0.45µm were used for our desalination experiments. Twenty five (25) pieces of the hydrophobic membranes, amounting to a total membrane area of 0.25 m² were integrated into the E-METS modules between the feed and vapor modules to facilitate vapor diffusion and the membrane distillation process. Surface enhanced Titanium substrates of ~100µm nominal thickness were integrated between the vapor and feed modules to allow enhanced vapor condensation (the side of the Titanium substrate in contact with the vapor) and enhanced flow boiling on the side of the Titanium substrate in contact with the flow boiling feed. The surface modification involves the introduction of micro-cavities acting as bubble nucleation sites to reduce the thermal resistance of the condensing vapor – boiling feed. The modules also contain three high performance externally finned/internally ribbed Titanium tubes, to accommodate feed flow boiling in the 1st effect and three tubes in each vapor module to accommodate vapor condensation – heat recovery for feed preheating. Images related to the E-METS modules assembly, feed/vapor modules – Titanium tube assembly, pristine/enhanced Titanium substrates and saline feed flow boiling are shown respectively in Figure 5(a) – 4(d).
Pressure sensors with a range of 0 – 2 bar were mounted on all feed and vapor modules (except the 4th effect) to measure the feed and vapor saturation pressures. Multiple calibrated Type K 250 µm thermocouples were installed to measure the heating water (inlet/outlet), feed preheating, boiling saline feed and vapor temperatures. All temperature, pressure and flow rate data were acquired with our data acquisition system for post processing upon the completion of each series of the desalination experiment.
III. EXPERIMENTAL RESULTS

The desalination experimental campaign involves the performance characterization of E-METS for a wide range of feed salinity from PSU ~10.6 – 38.4. Two inlet feed temperatures, i.e. 20/30°C, were tested to observe the effects of feed inlet cooling temperatures on the distillate production and the GOR. Similarly, tests for two different feed flow rates were carried out to for the higher feed salinity experiments, i.e. PSU ~37.6 – 38.4, to study the effects of feed flow rate on the distillate performance and specific thermal energy consumption. Table 1 presents the desalination global experimental results for saline feed of PSU ~10.6 – 38.4. The measured distillate specific conductance was less than 1.5 µS/cm for all the experiments. All experimental data have been acquired under steady-state conditions and the boiling point (including Boiling Point Elevation – BPE) maintained below 80°C. Distillate heat recovery features have not been implemented on the current E-METS demonstrator. In all our experiments, the produced distillate is channeled out from the last vapor module at temperatures between 60.6 – 64°C.

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Table 1: E-METS desalination results for feed PSU ~10.6 – 38.4 and Tfeed,inlet = 20 & 30 °C.

The current E-METS system can achieve up to ~137 liters of distillate production per day for feed PSU ~37.6, inlet feed temperatures at 20.1°C and Pvapor (last effect) at 189 mbar. Specific thermal energy consumption (SECth) was evaluated to be ~58 kWh/m³. For higher feed inlet temperatures, i.e. Tfeed,inlet ~30°C, the specific thermal energy consumption increased dramatically as expected. However, the GOR obtained for all desalination experiments are in the range of 9.1 – 10.8. In general, the feed salinity, feed and vapor pressures, feed inlet temperature, the feed flow rate and the number of effects are important parameters that affects the distillate production, GOR and specific thermal energy consumption of the E-METS system. The effects of these individual parameters are discussed in detail in the following section.
IV. DISCUSSION

The distillate production (L/hr), GOR and thermal energy consumption is highly sensitive to certain parameters including feed inlet temperatures, feed salinity, system pressures, flow rates and the number of distilling effects. All these parameters are interdependent on each other and potentially affect the thermodynamics of the desalination process. In this manuscript, they are carefully analyzed and discussed so as to enable the system to yield optimum performance with respect to future deployment for desalination applications.

4.1 MEMBRANE DISTILLATE FLUX (LMH)

The current E-METS system integrates a total 0.25 m² of hydrophobic membranes for vapor diffusion and membrane distillation. The membrane distillate flux plot is shown in Figure 7. From the experimental results, it is evident that integrating multiple processes such as boiling/flashing/membrane distillation is high advantageous when compared against any single vaporization process conventionally employed in state-of-the-art desalination plants or systems.

![Figure 7: Acquired membrane distillate flux with the E-METS desalination system.](image)

4.2 FEED INLET TEMPERATURE

As reported in Table 1, distillate production and GOR generally decreased when the inlet temperature increased from 20°C to 30°C. The drop in distillate production is attributed to multiple reasons. In general, condensation heat transfer (rate of vapor condensation) is highly dependent on the temperature difference between the condensing vapor and the preheated feed inlet temperatures. A higher temperature difference, i.e. $T_{\text{vapor}} - T_{\text{feed}}$, will result in a higher rate of condensation and vice versa. Hence, a higher feed inlet temperature of ~30°C explains the lower amount of distillate produced when compared against $T_{\text{feed,inlet}}$ ~20°C. An observable secondary effect is a higher system overall pressure (higher feed and vapor pressures) at higher feed inlet temperatures. A higher system pressure increases the boiling point of the saline feed in the first effect, as shown in Table 1. Given that the heating water inlet temperatures were always regulated at ~88°C, a lower wall superheat ($T_{\text{HOT WATER}} - T_{\text{boiling}}$), similarly resulted in a lower amount of produced vapor via flow boiling due to lower flow boiling heat transfer. The third effect from the higher overall system pressures induced inefficient flashing, hence contributing to lower vapor production. This effect is clearly distinguishable in the rejected brine temperatures as shown in Table 2.
whereby higher brine outlet temperatures were observed globally for the series of experiments with higher feed inlet temperature of ~30°C. Summarizing in brief, higher feed inlet temperatures lowers the condensation heat transfer, reduces flow boiling vapor production and flash evaporation.

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Table 2: Experimental results (feed PSU ~10.6 – 38.4 and Tfeed,inlet = 20 & 30 °C).

4.3 FEED SALINITY- BOILING POINT ELEVATION (BPE)

Boiling Point Elevation (BPE) is generally associated with increasing feed salinity. In our experiments, BPE was estimated to have increased from ~0.13°C (PSU ~10.6) to ~0.51°C for PSU ~38.4 according to correlations proposed by Sharqawy et al. [10]. The distillate production plotted as a function of salinity is depicted in Figure 6.

In general, lower distillate production was observed at higher feed salinities for both feed inlet temperatures of ~20°C and ~30°C. The higher distillate production for PSU~37.6 at inlet feed temperature ~20°C was due to lower vapor pressures in the vapor modules, which was a result of a larger valve opening in connection with the vacuum pump. The motive of this valve setting was to investigate the effect of lower feed and vapor pressures on distillate production. Here, it is conclusive to note that lower system pressure induces flash evaporation and membrane distillation, which can potentially be used to offset the adverse effects of BPE due to increasing salinity. However, a larger vacuum valve opening is undesirable as it induces re-vaporization (flashing) of the condensed distillate collected in the distillate tank. Similarly, the effects of higher vapor module pressures were investigated for the PSU~10.7 and ~10.6 experiments by setting a smaller vacuum valve opening. By observation, it can be concluded that lowering the last effect vapor pressures to ~200 mbar could potentially yield much higher distillate production to achieve a higher GOR.
4.4 SYSTEM PRESSURE
The system pressure, i.e. feed and vapor module pressures, play an important role in the amount of distillate production. Lowering the feed pressure will induce additional vapor generated via flow boiling and flash evaporation. A higher transmembrane pressure drop due to lower vapor chamber pressures will further supplement the increased distillate production via membrane distillation. Although a lower system pressure is advantageous, the current 14-effect E-METS technology demonstrator does pose some limitations. The reasons are due to the relatively small amount of heat transfer area integrated for feed preheating, flow boiling and the number of integrated effects. The primary limitations identified as follows:

- **Feed preheating** – The driving force for condensation heat transfer is dependent on the temperature difference of the condensing vapor and the feed to be preheated. Lowering the saturated vapor pressures/temperatures will impede an efficient condensation process. Second, lower vapor pressures will reduce the maximum attainable preheated feed temperature. This will incur additional thermal energy in the form of final preheating to raise the feed temperature up to the boiling point, resulting in a lower GOR.

- **Distillate flashing** – The lowest attainable vapor pressure (last effect) for optimum efficiency was identified to be in the range of ~200 mbar, while the temperature of the rejected brine after brine-feed heat recovery (refer Figure 6B) is in the range of ~54 - 60°C. Lowering the last effect beyond ~200 mbar induces distillate flashing in the conduit and distillate collection tank, hence increased losses of vapor through the vacuum connection line. As the vapor lost does not contribute to latent heat recovery for feed preheating, a lower GOR is expected.

The limitation of the current technology demonstrator can be resolved by increasing the number of effects to maintain a low vapor pressure in the last effect. Given that the pressure drop per effect for the current E-METS demonstrator is less than ~7.5 mbar/effect, it is positively feasible to increase the number of effects of up to 25 or more to achieve a higher GOR.

4.5 FEED FLOW RATE
In reference to Table 1 and 2, increasing the feed flow rate yields higher distillate. Comparing the experimental results for PSU~37.6 and ~38.4 for feed inlet temperatures of ~30°C, a +15% increase in flow rate from 1.32 to 1.52 L/min yielded a +11% increase in distillate production albeit a slight drop in GOR. A lower system pressure was also observed in the process. The higher distillate production and lower system pressure is explained by the higher single-phase heat transfer efficiency for the preheating feed. Improved single-phase feed heat transfer in the preheating tubes will promote enhanced condensation heat transfer on the external tube side of the preheating tubes, which then results in a lower thermal resistance. However, we strongly believe that an optimum feed flow rate corresponding to an optimum GOR exists and we foresee an extensive experimental campaign to be carried out in the near future to study the effects of feed flow rate.

4.6 NUMBER OF EFFECTS
It is known from state-of-the-art multi effect distillation systems that an increase in the number of effects not only increases distillate production but also lowers energy consumption to achieve a high GOR. The specific thermal energy consumption of the current E-METS system is at ~58–68.5 kWh/m³ for PSU~37.6 – 38.4, depending on the feed inlet temperature. This represents lower thermal energy consumption of up to 54% when compared against the 6-effect technology demonstrator. Given the current limitation of the current 14-effect configuration, we are looking forward to achieve lower thermal energy consumption, i.e. 30 – 40 kWh/m³, by extending the number of effects to 25 or more while always maintaining the feed boiling point < 80°C.
V. CONCLUSIONS

We have designed and fabricated a 14-effect multi-effect desalination technology demonstrator, i.e. E-METS, that is capable of seawater desalination at ~58 – 68.5 kWh/m³, corresponding to a GOR of ~9.1 – 10.8. The current 14-effect technology demonstrator is capable of producing up to ~140 L/day of distillate. Multiple parameters including feed inlet temperatures, feed salinity, system pressures, flow rates and the number of distilling effects have been identified to affect the distillate yield and the GOR (or specific thermal energy consumption). With the known performance characteristics of the current E-METS system, we anticipate a scale-up of the current system to 25 effects to demonstrate higher GOR with specific thermal energy consumption levels at ~30 – 40 kWh/m³.

VI. FUTURE WORK

The first step involves the plan to scale-up the current technology demonstrator to a 25-effect configuration to demonstrate better energy efficiency for desalination. The second phase of research will include the development of the new E-METS system that incorporates internal flow boiling tubes for latent heat recovery - internal flow boiling and low cost heat exchanger devices, i.e. comprising Electrochemically Machined (ECM) Titanium substrates with nanotube arrays, to increase distillate yield. The 3D-CAD drawing of the next generation E-METS desalination system is illustrated in Figure 9.

Figure 9: E-METS desalination system with integrated internal flow boiling tubes and electrochemically machined (ECM) Ti substrates (refer Figure 2 for process flow).
The final objective of the E-METS research program is to fabricate a scaled-up containerized E-METS desalination pilot system that is capable of producing up to 500 m$^3$/day which will be deployed for desalination or industrial wastewater (TDS treatment) applications. For industrial wastewater treatment, the E-METS technology is extendable to applications for mining wastewater management, power sector process water and wastewater treatment, food and beverage, shale oil and gas wastewater recycling, semiconductor, pharmaceutical and petrochemical industries. The anticipated containerized E-METS system with 500 m$^3$/day capacity is depicted in Figure 10.

![Figure 10: Containerized E-METS unit with 500 m$^3$/day desalinated water production capacity.](image)

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VIII. REFERENCES