The 6th International Supercritical CO_2 Power Cycles Symposium
March 27 - 29, 2018, Pittsburgh, Pennsylvania

Thermal Desalination as Cooling for a Supercritical Carbon Dioxide Brayton Cycle

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ABSTRACT

Multi-effect distillation (MED) is commonly used for seawater desalination. MED offers numerous advantages over other existing thermal desalination systems. MED systems are commonly integrated with a steam-Rankine power cycle, for simultaneous production of power and freshwater. Low-pressure steam is extracted from the power cycle to act as a heat source for the MED. The operating temperature of the low-pressure steam must be hot enough (~70 °C) to drive the MED system. This necessitates an increase in the operating pressure on the power-cycle condenser, resulting in a decrease in power production. Hence, integration of MED with the steam-Rankine cycle is a parasitic load for the power plant.

The supercritical carbon dioxide (sCO_2) Brayton cycle is being pursued as a new power cycle because of its potential for higher energy efficiency and compact turbomachinery. The sCO_2 exiting the low-temperature recuperator is quite hot and is cooled as a sensible-heat fluid before flowing back to the compressor. The CO_2 exiting the low-temperature recuperator is sufficiently hot to drive an MED system, rather than being rejected to the environment. Such a thermal integration could lead to simultaneous production of power and potable water without affecting the sCO_2 Brayton cycle efficiency.

The objective of the present study is to maximize the distillate production from MED without acting as a parasitic load. Optimal feed configuration for the MED is identified for maximizing the distillate concentration. Techno-economic analysis showed the cost of distillate for MED is about 30% lower than distillate produced by reverse osmosis (RO).

1. Introduction

By 2025, 67% of the world population is expected to suffer from water shortage [1], sea water desalination can be a possible solution. The two most commonly used desalination technologies are reverse osmosis (RO) and thermal desalination. RO is a pressure-driven membrane desalination technology that uses electrical energy to pump the distillate across the membrane. In contrast, thermal desalination uses thermal energy for distillate production. The most commonly used thermal desalination technologies are multi-stage flash and multi-effect distillation (MED) systems. MED has begun to overtake multi-stage flash because of higher energy efficiency, reduced maintenance cost, simpler geometry, and a higher heat-transfer coefficient [2]. In MED, several evaporators, known as “effects,” are placed in series. The external heat source, conventionally steam, acts as a heat source for the first effect of the MED system and produces vapor. This vapor acts as a heat source for the second effect, where additional vapor is produced, which acts as a heat source for the third effect, and so on.

Thermal desalination systems are often integrated with a steam-Rankine power plant to simultaneously produce water and power. To have a feasible energy integration between the MED and Rankine cycle, the steam existing the turbine should be hot enough to drive the MED. This increases the heat rejection temperature for the Rankine cycle and decreases the power-plant efficiency; hence, it is a parasitic load for the power plant. The supercritical carbon dioxide (sCO_2) Brayton cycle is an upcoming power cycle with potential advantages of higher efficiency, high power density, turbomachinery compactness compared to a steam turbine, and lower cost. In addition, its ability to integrate thermal energy storage and dry cooling makes it more favorable for use with a concentrating solar power plant [3]. The waste heat rejection for a sCO_2 Brayton cycle is at a fairly high temperature (about >80°C) and can drive a thermal desalination system. The sCO_2 rejects its waste heat in the form of sensible heat, compared to latent-heat rejection for a Rankine cycle. This paper focuses on integrating MED with a sCO_2 Brayton cycle without reducing the power-plant efficiency.

2. System description

Figure 1 shows a schematic for MED integrated with a sCO_2 Brayton cycle. The sCO_2 coming from the power cycle is first cooled by demineralized water, which acts as a heat source for the MED. The pressurized sCO_2 from the recuperator loses its heat to demineralized water in two different printed-circuit heat exchangers (PCHEs). This heat exchange maximizes the net energy available for the first effect of the MED. After partially losing its heat in $PCHE_1$, the sCO_2 enters $PCHE_2$ and is cooled to a compressor inlet temperature (>31°C) by losing its heat to the demineralized water W_2. The heated demineralized water is cooled in a conventional plate-and-frame heat exchanger (PFHE) by seawater.

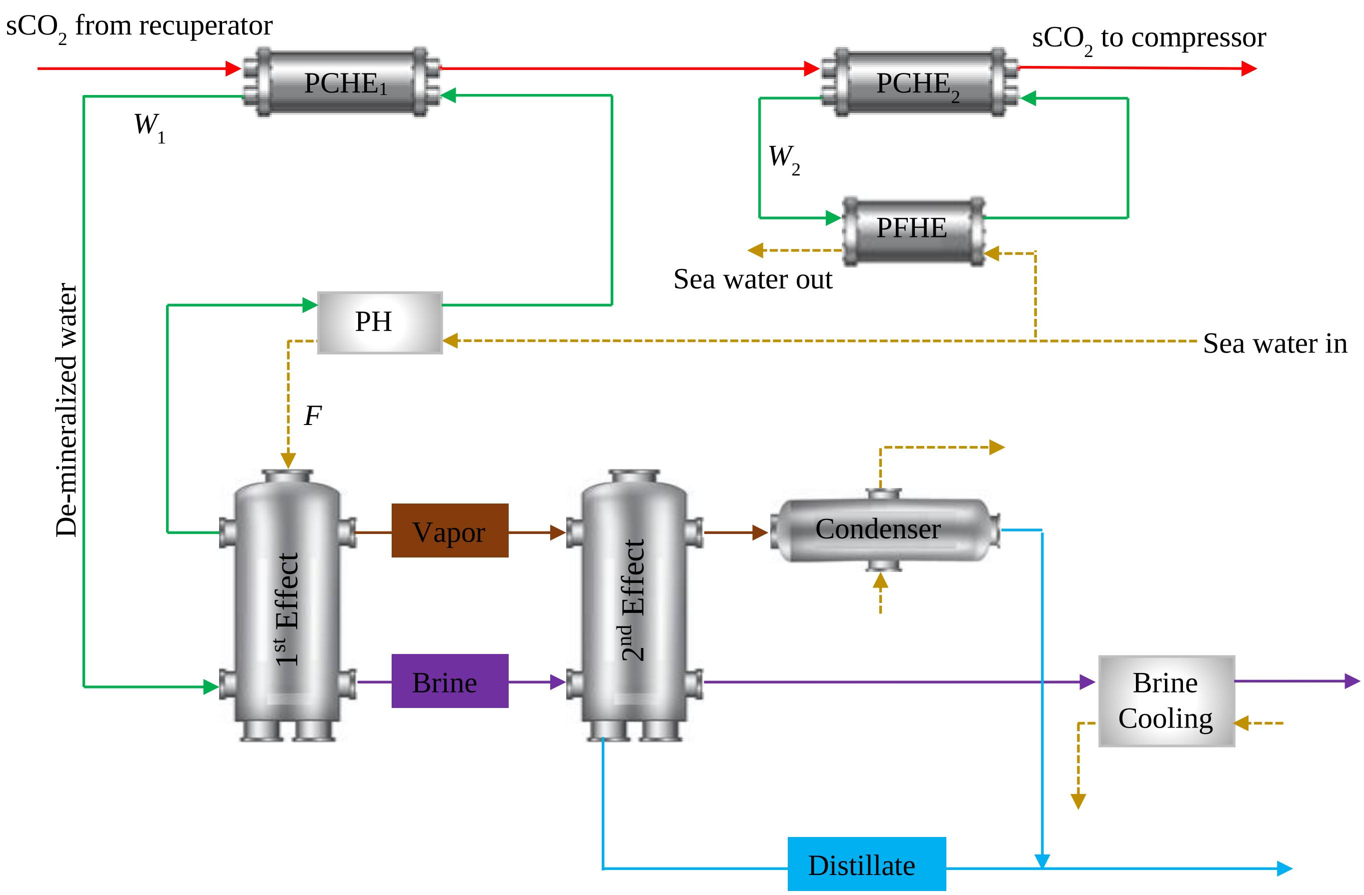

Figure 1: Schematic for forward feed MED integrated with sCO_2 recompression cycle.

The heated demineralized water from $PCHE_1$ acts as a heat source for the first effect of the MED system. The pattern in which feed seawater enters the MED often dictates its energy requirement and distillate production. The two most commonly used feed seawater flow patterns for MED is forward feed and parallel/cross feed. Figure 1 shows the schematic for forward-feed MED. In forward feed, the entire feed seawater with flowrate F enters the first effect of the MED. The demineralized water W_1 acts as a heat source for the first effect of the MED, and the feed partially vaporizes to produce vapor and partially concentrated brine, which acts as a feed for the second effect. The vapor produced from the first effect loses its latent heat in the second effect, and emerges as distillate. The partially concentrated brine from the first effect is further concentrated in the second effect because of the latent heat added, and additional vapor is generated. This vapor is cooled in the condenser to produce distillate. The concentrated brine from the second effect passes through a brine cooling exchanger, where it is cooled by seawater and discharged back into the sea. The demineralized water W_2 exiting the first effect of the MED enters the feed preheater (PH) and increases the feed temperature to the first-effect operating temperature. Only one feed preheater is required for forward feed, irrespective of the number of operating MED effects.

Figure 2 shows the schematic with parallel/cross-feed MED integrated with a sCO_2 Bryton cycle. In parallel/cross feed, the feed seawater (F) enters each MED effect with almost an equal feed flowrate, i.e., $F_1 \approx F_2 \approx F/2$. The brine attains its maximum concentration after each effect, compared to the last effect for forward-feed MED. The demineralized water, after losing its heat to the first effect of the MED, preheats the feed. 2-effect MED requires two preheaters. In PH_1, feed F_1 is preheated, whereas in PH_2, the entire feed (F_1+F_2) is preheated. For parallel/cross feed, the number of feed preheaters equals the number of operating MED effects. For the same effect temperature, forward feed provides more opportunity for feed preheating, compared to parallel/cross feed, where the entire feed is preheated to the first-effect operating temperature.

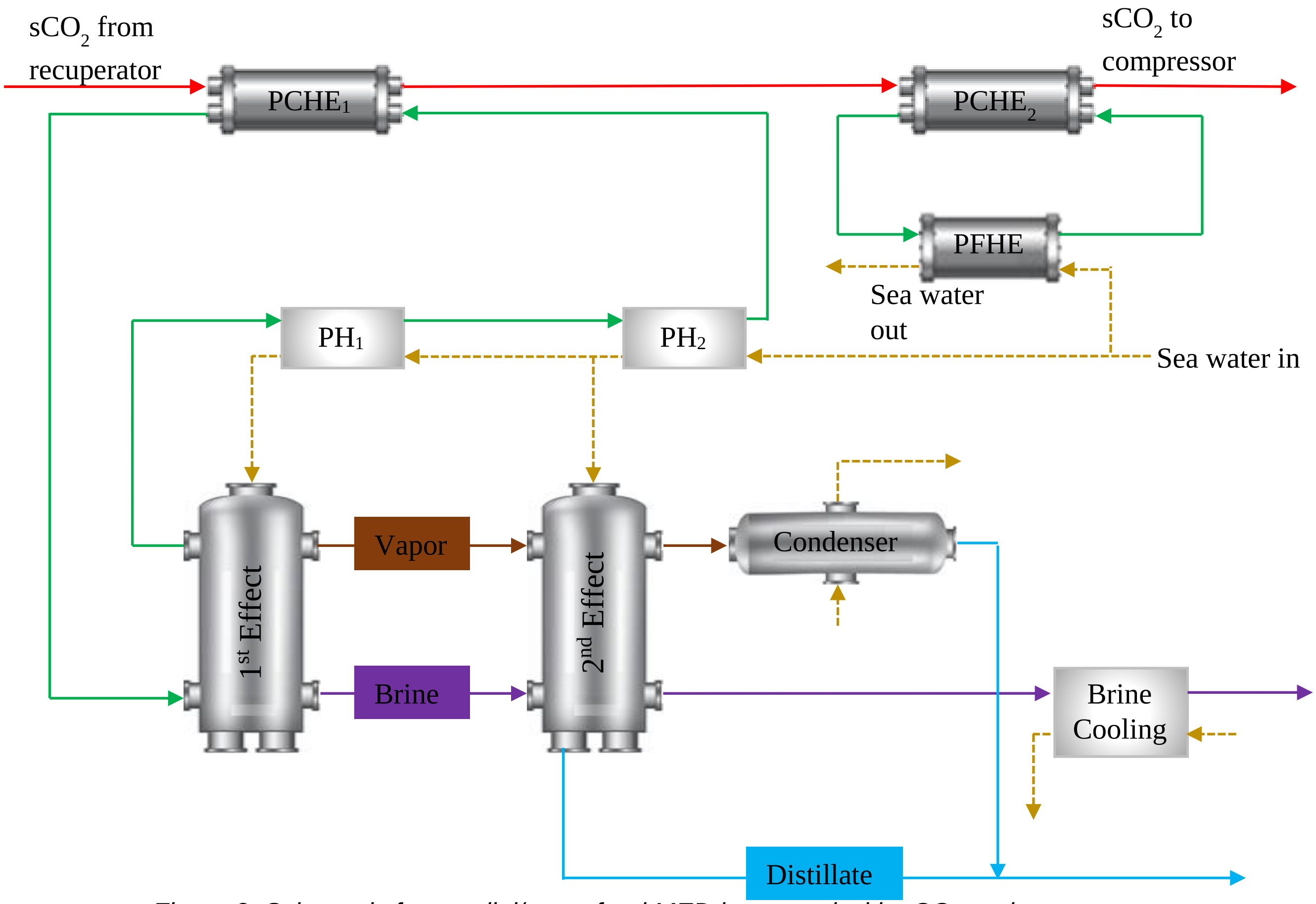

Figure 2: Schematic for parallel/cross feed MED integrated with sCO_2 cycle.

If steam is used as heat source for the MED, parallel/cross feed is the most energy efficient feed configuration for MED[2], but the same might not hold true for a sensible heat source. The objective of this study is to find the optimal feed flow configuration for MED integrated with sCO_2 Brayton cycle.

3. System modelling

For forward feed MED the energy balance for the first MED effect is:

$$W_1 Cp_w \left(T_{W_1,out} - T_1 - \Delta T_{MED}\right) = V_1 H_1 + b_1 h_1 - F h_{f1} \quad (1)$$

The left-hand side of Eq. (1) shows the energy available for integration from the sensible heat source to the first MED effect, where Cp_w is the sensible heat of the demineralized water, $T_{W1,out}$ is the temperature of demineralized water coming from $PCHE_1$, T_1 is the first-effect operating temperature, and ΔT_{MED} is the minimum temperature driving force for MED (pinch temperature for MED). The right-hand side of Eq. (1) represents the energy required for vaporization in the first MED effect, where V_1 is the vapor flowrate from the first effect, H_1 is the vapor enthalpy, b_1 is the brine flowrate, h_1 is the brine enthalpy, and h_{f1} is the feed enthalpy entering the first effect. For the second effect to the last effect, the energy balance for forward feed is given as:

$$V_{n-1}\lambda_{n-1} + b_{n-1}h_{n-1} = V_n H_n + b_n h_n \tag{2}$$

where λ is the latent heat of vaporization. The mass balance for forward feed is given as:

$$b_n = b_{n-1} - V_n \tag{3}$$

and for the first effect, the brine flowrate $b_1 = F\text{-}V_1$. For detailed modeling of forward-feed MED, see [4].

For parallel/cross-feed MED, the energy balance for the first MED effect is given as:

$$W_1 Cp_w \left(T_{W_1,out} - T_1 - \Delta T_{MED}\right) = V_1 H_1 + b_1 h_1 - F_1 h_{f1} \tag{4}$$

The energy balance of the second effect and onward for parallel/cross feed is:

$$V_{n-1}\lambda_{n-1} + b_{n-1}h_{n-1} = V_n H_n + b_n h_n - F_n h_{f_n} \tag{5}$$

and the mass balance for the system is:

$$b_n = F_n + b_{n-1} - V_n \tag{6}$$

For detailed modeling of parallel/cross-feed MED, see [2].

4. Illustration

Table 1 shows the sCO_2 design parameters coming from the recuperator. For a 100MW$_e$, sCO_2 Brayton cycle with net cycle efficiency of 49.2%, the sCO_2 with mass flowrate of 558 kg/s and temperature of 79.5°C comes from the low-temperature recuperator. sCO_2 is cooled to 32°C before flowing back to the compressor. sCO_2 heats the demineralized water W_1 from 46.1°C to 71.3°C in PCHE$_1$, with a mass flowrate of 282 kg/s for 2-effect MED. For forward-feed MED, the stream W_1 is cooled from 71.3°C to 46.7°C and produces 12 kg of distillate from the first effect. The stream W_1 exchanges 4.8 MW of thermal energy in feed preheater PH$_1$ to preheat the feed seawater from 17.5°C to 43.7°C, and then returns back to PCHE$_1$. The net distillate produced by 2-effect forward-feed MED is 24.13 kg/s (2,085 m^3/d). Figure 3 shows the results for MED integrated with a sCO_2 Brayton cycle with various numbers of effects for forward feed and parallel/cross feed.

Table 1. System design parameters

Power cycle efficiency	49.2%
Power Output	100 MW$_e$
sCO_2 inlet pressure	7.66 MPa
sCO_2 mass flow rate	558 kg/s
sCO_2 inlet temperature	79.5°C
sCO_2 exit temperature	32°C
Seawater Feed temperature	17.5°C
Seawater Feed concentration	33,200 ppm
Last effect temperature	40°C

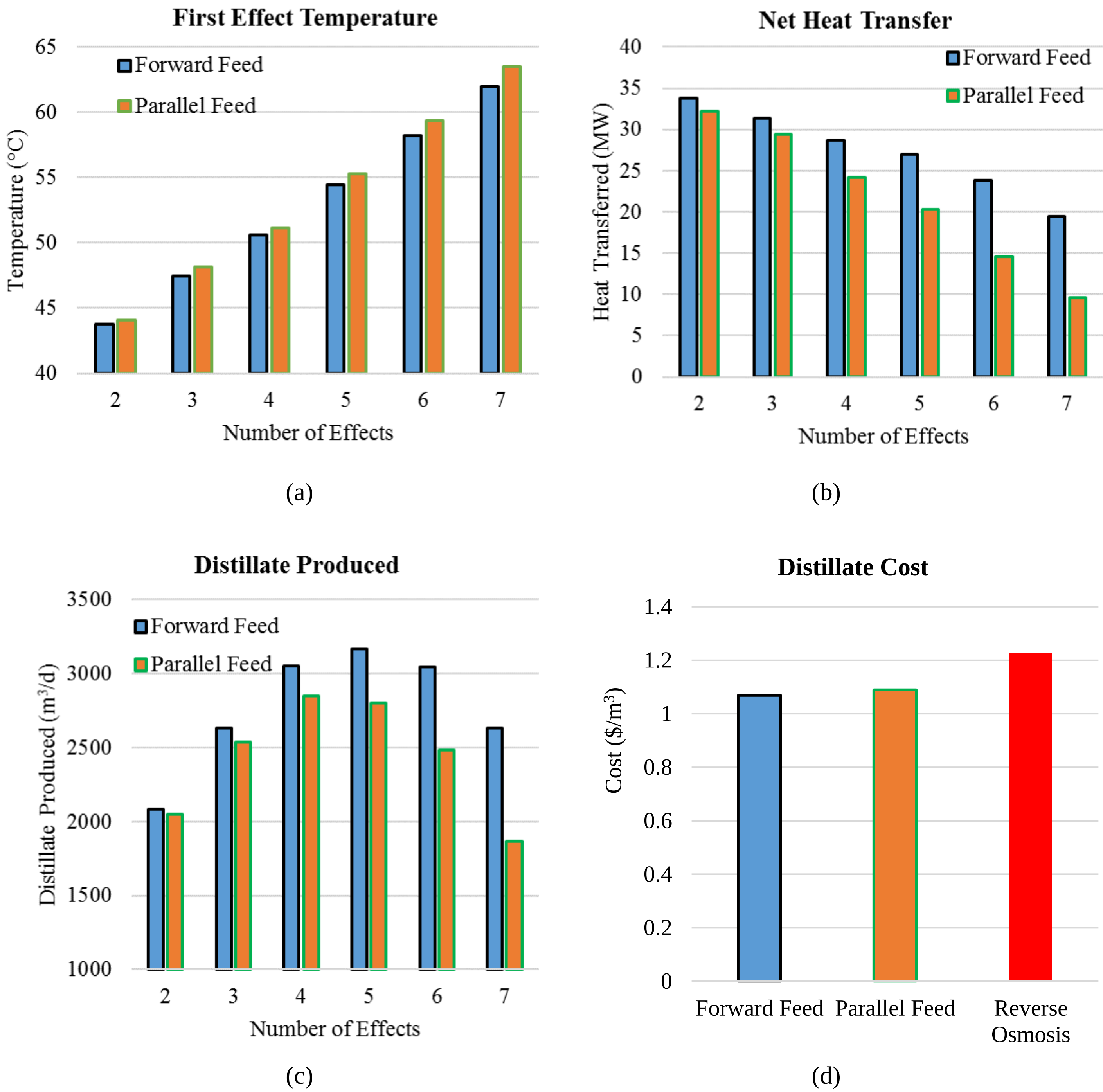

Figure 3: Results for variation in number of effects on (a) the first effect operating temperature for forward feed and parallel/cross feed (b) net heat transfer for forward feed and parallel/cross feed (c) net distillate produced for forward feed and parallel/cross feed, and (d) distillate cost based on maximum production for forward feed (5-effect), parallel/cross feed (4-effect) and reverse osmosis.

Figure 3a shows the variation in the first-effect operating temperature for forward feed and parallel/cross feed with various numbers of effects. The effect operating temperature is calculated as:

$$T_{n-1} = T_n + \Delta T_{MEE} + BPR_{n-1} \tag{7}$$

where ΔT_{MEE} is the minimum-temperature driving force between two consecutive effects, and *BPR* is the boiling-point rise. Boiling-point rise is a function of brine concentration [5], where the higher the brine concentration, the higher the BPR. With a known last-effect temperature (40^{o}C), Eq (7) can be used to calculate the first-effect operating temperature. The last effect temperature is same as the condenser operating temperature for the Rankine cycle. For parallel/cross-feed MED, each effect is operating at maximum brine concentration and has a higher BPR compared to forward-feed MED, where only the last effect is operating at the maximum brine concentration. This results in a higher first-effect operating temperature for parallel/cross feed. For 2-effect MED, the first-effect temperature for parallel/cross feed is 44^{o}C and forward feed is 43.7^{o}C; this difference increases with an increase in the number of effects. For 7-effect MED, the first-effect temperatures are 63.5^{o}C and 61.9^{o}C for parallel/cross feed and forward feed, respectively. An increase in effect operating temperature decreases the net heat available for the first-effect MED from demineralized stream W_2.

Figure 3b shows the net heat available for energy integration from water stream W_2. The net heat transfer between MED and demineralized water stream W_2 is the sum of net energy available for the first effect of the MED and the feed preheating. The net heat transfer decreases with an increase in the number of effects because of the increase in the effect operating temperature. The net heat available for energy integration between MED and stream W_2 is higher for forward feed compared to parallel/cross feed because of higher feed preheating and lower first-effect operating temperature. For 2-effect MED, the net heat transfer is 33.8 MW and 32.2 MW, and for 7-effect it is 19.5 MW and 9.6 MW for forward-feed and parallel/cross-feed MED, respectively.

With an increase in number of effects, the distillate production increases proportionally (for constant heat supply); but with a sensible heat source, the net heat available for energy integration decreases. These two factors oppose each other. Hence, for forward feed, the maximum distillate production is 3,166 m^3/day with 5-effect MED. For parallel/cross feed, the maximum distillate production is 2,800 m^3/day for 4-effect MED. For the same number of operating effects, forward feed yields higher distillate production compared to parallel/cross feed (shown in Figure 3C).

Figure 3D shows the cost of distillate or forward feed and parallel/cross feed for maximum distillate produced. For 5-effect forward feed, the distillate cost is 1.07 \$/m^3, whereas for 4-effect parallel/cross feed, it is 1.09 \$/m^3. Hence, with a sensible heat source, forward feed is the better feed configuration. If an RO system was used for distillate production, the cost of distillate is 1.23 \$/m^3, which is 15% higher than MED. The electricity consumption for RO is assumed to be 3.5 kWhr/m^3 [6]. For MED integrated with a sCO_2 Brayton cycle, forward feed is the optimal feed configuration. The capital cost of RO is 0.60 \$/m^3 and MED is 0.85 \$/m^3 (from Desaldata [6]). In addition of capital cost and electricity cost, other cost incudes labor cost, overhead cost and variable cost, which amounts to 0.19 \$/m^3 for MED and 0.25 \$/m^3 for RO (from Desaldata [6]).

5. Sensible heating evaporators

The previous section dealt with integrating MED with a sCO_2 Brayton cycle via a demineralized water loop. The demineralized water loop exchanged heat with the MED in the first effect and the preheaters. To further enhance the energy integration, intermediate sensible-heat evaporators (e.g., 2B Effect) can be used, as shown in Figure 4. The demineralized water first loses heat in the first effect and then flows to PH1. From PH1, it passes to sensible-heat evaporator 2B, and produces additional distillate. The demineralized water coming from effect 2B, flows into the second preheater and then flows back to $PCHE_1$. The intermediate sensible-heat evaporator 2B is placed in parallel to effect 2A, which is a conventional evaporator using vapor as a heat source from the first effect. The distillate produced from the 2B effect combines with the distillate produced from the 2A effect. For *K*-effect MED, *K-1* intermediate sensible-heat evaporators and *K* preheaters are required, irrespective of feed flow.

Results for MED with intermediate sensible-heat evaporators is shown in Figure 5. The temperature profile in Figure 5(a) is similar to Figure 3(a). It is interesting to note that the net heat transfer increases with an increase in the number of effects, shown in Figure 5(b). With intermediate sensible-heat evaporators, the net heat available between the water-stream temperature coming from $PCHE_1$ ($T_{W1,out}$) and the last-effect operating temperature is the same. Additional heat transfer will occur in the last feed preheater, which increases with an increase in feed flowrate. The distillate produced increases with an increase in the number of operating effects, as the net heat-transfer increases. The net distillate produced by forward feed is almost the same as parallel/cross feed for a given number of operating effects (see Figure 5(c). The distillate cost for MED with forward feed and parallel/cross feed is 0.98 $/m^3 and 0.95 $/m^3, respectively, whereas with RO, it is 1.23 $/m^3 (see Figure 5(d). The capital cost for MED with intermediate sensible heating evaporators is calculated using the methodology proposed by Christ et al. [7]. With intermediate sensible-heat evaporators, both feed configurations produce almost the same amount of distillate, but the distillate cost is lower for parallel/cross feed.

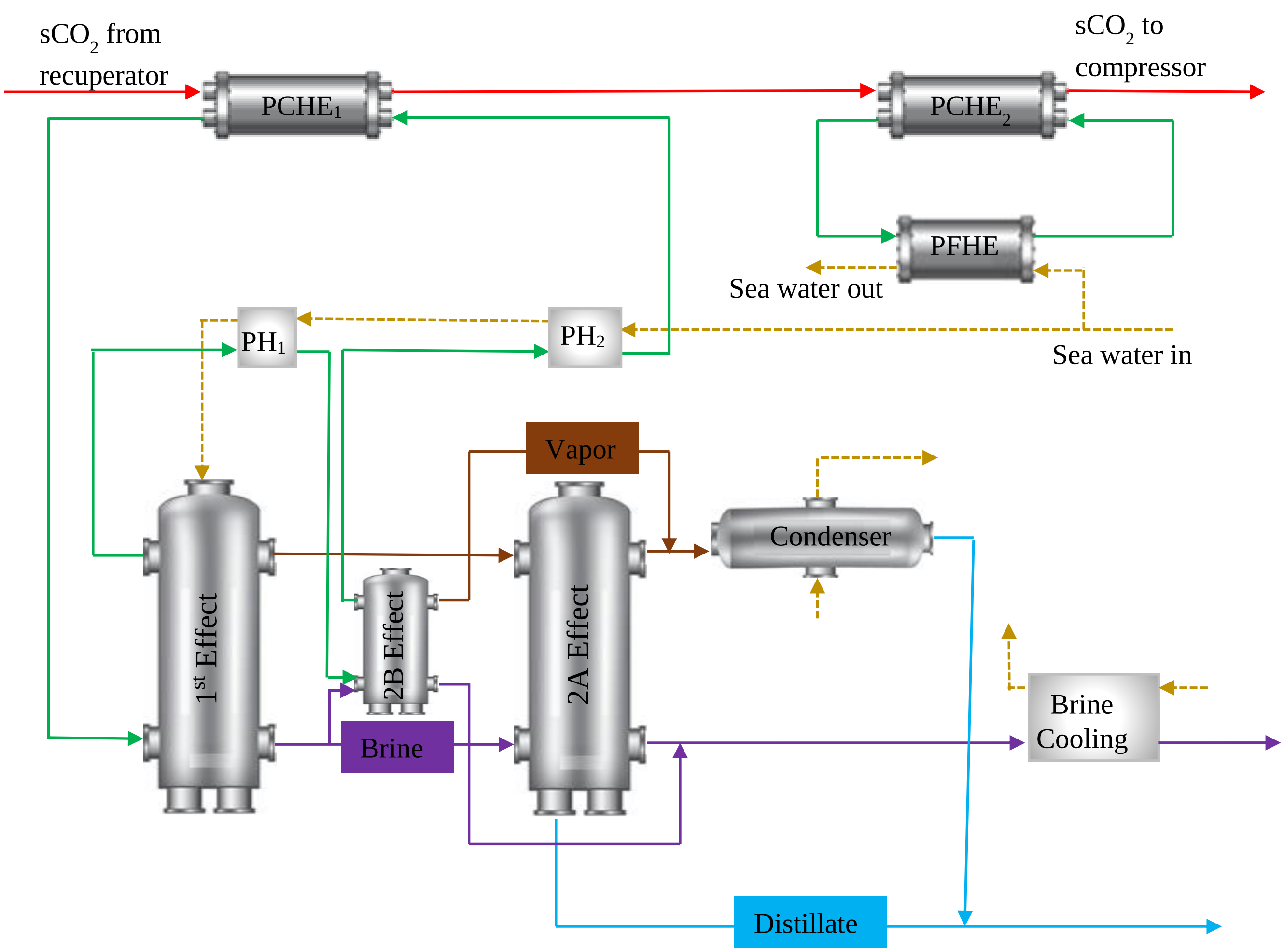

Figure 4: Integration of MED with sCO_2 Brayton cycle via intermediate sensible heating evaporators.

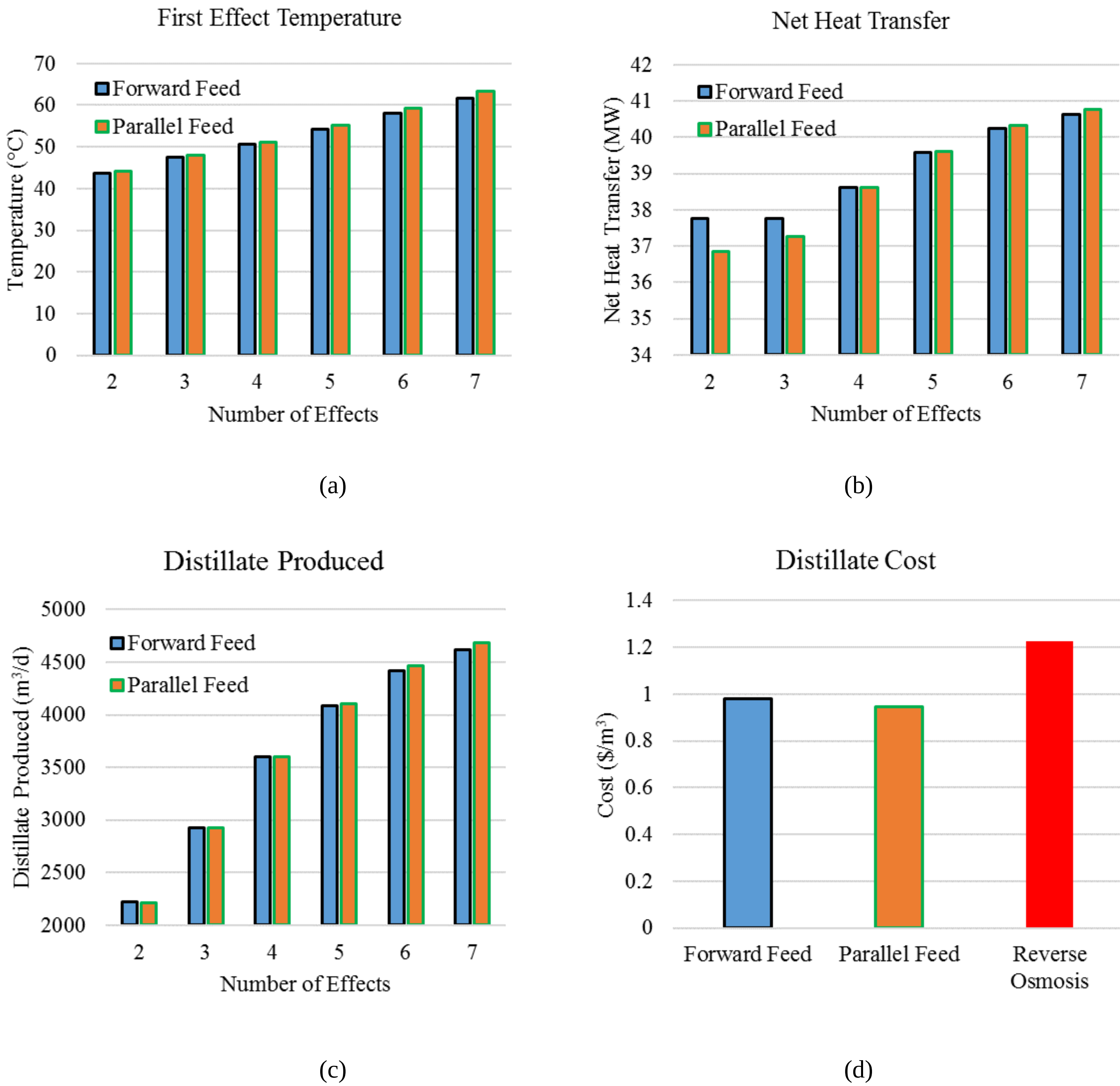

Figure 5: Results for variation in number of effects with intermediate sensible heating evaporators on (a) first effect operating temperature of forward feed and parallel/cross feed (b) net heat transfer for forward feed and parallel/cross feed (c) net distillate produced for forward feed and parallel feed (d) distillate cost based on maximum production for forward feed (7 effect), parallel/cross feed (7 effect) and reverse osmosis.

6. Conclusion

Integrating MED with a Rankine power cycle for distillate production decreases the power-plant efficiency because of higher operating condenser pressure, and it is a parasitic load for the power plant. The waste heat for a sCO_2 power cycle is sufficiently hot to run a thermal desalination system, which can be used efficiently for distillate production without being a parasitic load for the power plant. The maximum distillate produced from the system is around 3,165 m^3/day, and with intermediate sensible-heating evaporators, the net distillate produced is 4,681 m^3/day, for a 100 MW_e power plant. The optimal feed configuration for MED without intermediate sensible-heating evaporators is forward feed, which produces 10% additional distillate at 2.3% reduced cost. With sensible-heat evaporators, parallel/cross feed is the optimal feed configuration, with 1.4% additional distillate generation and 3.4% reduced distillate cost. Additionally, the cost of distillate produced from MED is 30% cheaper that RO, using system capital cost estimates from the literature.

References

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Acknowledgement

The research work was supported by Laboratory Directed Research & Development Program funding at the National Renewable Energy Laboratory. NREL operates under U.S. Department of Energy Contract No. DE-AC36-08GO28308.