Desalination of brackish water using cascade Rankine cycle based reverse osmosis system

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Abstract. The desalination of brackish ground water using cascade Rankine cycle is proposed. A pair of a Rankine cycle like steam Rankine cycle (SRC) and organic Rankine cycle (ORC) as a waste heat recovery. The single stage steam turbine for the SRC unit while the scroll expander for ORC unit is selected. Simulation of cascade RO system performance is considered using R245fa as a working fluid for ORC unit. The saturated steam from solar Scheffler disc will expand into steam turbine, where the reject heat from steam turbine will utilize for evaporation of ORC working fluid. The high-pressure RO pumps integrated with SRC and ORC turbines to provide net driving pressure to the RO module. This type of system is well suitable for desalination of brackish water due to moderate working temperature & pressure. Result shows that the pair of Rankine cycle will increase the overall (cascade) efficiency of the system. The basic input parameters are optimised with Taguchi approach. The performance of the system shows a good agreement with variation of mass flow rate of the steam in which the permeate flow rate from RO will increase along with the cycle efficiencies.

1. Introduction
Water scarcity does not occur in arid areas but also, it unbalanced the demand & supply of drinking water. The pollution and exploitation of aquifers may affect quality of natural water resources. The population growth, agriculture, and industries trends towards the increasing demand of water led to increase the per capita consumption of water. The desalination of water is one of the promising techniques towards water shortage in countries. It becomes an alternative solution otherwise the water is not accessible for irrigation, industrial and municipal application. [1]. There are various techniques for water desalination includes thermal desalination like multi-stage flash (MSF), multi-effect distillation (MED), vapour compression (VC), etc and membrane desalination processes like reverse osmosis (RO), reverse electro-dialysis (EDR), etc [2]. Amongst all of them, the reverse osmosis process is one of the key techniques for desalination [1]. According to water salinity, the required pressure to pass through porous membrane of RO which can generate from high-pressure pump. The required energy to drive RO pump can provide through various technologies. The Rankine cycle is one technique to provide required energy by coupling turbine with the RO pump. It increases the power transmission efficiency instead of driving RO pump through an electric source.

The small capacity steam Rankine cycle is the most promising technique to produce the work output from turbine which shows low thermal efficiency. The organic fluid is one which evaporates at low temperature. Therefore, the combination of steam Rankine cycle along with organic Rankine
cycle is one technique to produce almost twice of permeate water from a single heat input which may increase the overall efficiency of the system. As comparison of rotary expander with the turbo-expanders, rotary expander can handle the liquid, binary, and vapour phase of the working fluid. The thermal power generation using the solar collector will utilise by the steam Rankine cycle can eliminate the super-heating and operate at moderate temperature and pressure [3]. The direct steam generation (DSG) through the Scheffler disc or solar concentrators can avoid to use of boiler which may reduce the future cost of the system [4]. However, boiler can be used for alternative heating source during cloudy weather or night. The major advantage of solar Scheffler disc for constant heating temperature during pick time and highly efficient for evaporation of water. The demonstration of the Scheffler disc at PDPU, Gandhinagar is used for direct steam generation through the parabolic shaped mirror disc to generate steam at >160 °C temperature. The plant is developed for desalination of water by batch RO system [5].

![Figure 1 T-S diagram of cascade (pair of steam & organic) Rankine cycle.](image)

A pair of steam Rankine cycle along with organic Rankine cycle is proposed. The T-S diagram of a Rankine cycle for water and R245fa working fluid saturation curve (refer Figure 1) with a basic cycle flow process in which the water shows negative saturation slope while R245fa showing positive saturation slope. The evaporation temperature of steam is higher than R245fa. For the high temperature difference of hot and cold side, the cascading of Rankine cycle is preferred in which the steam Rankine cycle at top cycle while the organic Rankine cycle to be at bottom cycle. It will be more beneficial for single stage small steam turbine and expander showing the pressure ratio of about 2.5 - 8. The low boiling point temperature of the R245fa advantage to evaporate at the saturation temperature of steam during condensation. The bottoming of the organic Rankine cycle allows to design the system at smaller size in terms of power capacity.

In this work, solar powered cascade Rankine cycle-based water desalination process is proposed. A novel design guarantees the continuous water purification at a low consumption of specific energy. The thermodynamic performance of the system is examined by using R245fa with variation of different parameter of the system.

2. System description
The schematic diagram of the cascade-RO system (refer Figure 2) comprises with the steam Rankine cycle & organic Rankine cycle. The turbine shafts are directly integrated with the high-pressure pump of RO unit. The evaporative temperature of organic fluid is lower than the water so that organic Rankine intimate as a bottom cycle in the cascade system. The water is considered as a working fluid of steam Rankine cycle and R245fa for organic Rankine cycle. The generated steam from solar Scheffler disc, or by additional biomass boiler, will be expanded into steam turbine. The rejected heat from the steam turbine will be condensed by an organic fluid of the organic Rankine
cycle. This organic fluid will be evaporated up to 100 °C temperature & 11 bar pressure. The superheated vapour will be expanded into the ORC expander & recirculated by condensing into the ORC condenser. In this manner, the cascading of Rankine cycle will increase the overall efficiency of the system by utilising the rejected heat of steam Rankine cycle. The produced power from the steam turbine & ORC expander will be utilised by the high-pressure RO pump. The bypass line from steam separator can balance the energy (enthalpy) at evaporative condenser to provide constant vapour generation of Organic fluid.

![Schematic diagram of cascade RO system](image)

**Figure 2** Schematic diagram of cascade RO system.

Reverse osmosis unit is integrated with both Rankine cycles. The recycling of concentrate water is proposed to increase the overall recovery rate of the permeate water. The osmotic pressure of feed water can estimate by considering impurities in feed water. The required feed pressure or net driving pressure of feed water can calculate based on the osmotic pressure to allow salt rejection from water by passing it into the RO module. This net driving pressure can be generated by utilising turbine energy (shaft power) coupled with the high-pressure RO pump. Because of the net driving pressure more than osmotic pressure, the permeate water will separate out and concentrate will be rejected from the RO module. Apart from concentrate water, fractional amount of water will be recycled with the feed water.

In RO unit-2, the feed water from ground or surface will be passed into the ORC condenser as a cooling liquid. It can eliminate the cost of cooling tower and due to this, pump work of circulating water will also reduce.

2.1. **Mathematical model**

The SRC, ORC along with Cascade efficiencies are defined by:

\[
\eta_{SRC} = \left( \frac{(h_{3S} - h_{4S}) - (h_{2S} - h_{1S})}{(h_{3S} - h_{2S})} \right) \times 100
\]

\[
\eta_{ORC} = \left( \frac{(h_{3O} - h_{4O}) - (h_{2O} - h_{1O})}{(h_{3O} - h_{2O})} \right) \times 100
\]

\[
\eta_{Cascade} = \left( \frac{(h_{3S} - h_{4S}) - (h_{3O} - h_{4O})}{(h_{3S} - h_{2S})} \right) \times 100
\]

The performance formula of Scheffler disc type solar collector is:
Where $\eta_{col}$ is collector efficiency is calculated by [6]:

$$\eta_{col} = \eta_0 - (0.0000045(T_{co} - T_a)) - 0.039 \left(\frac{T_{co} - T_a}{G_b}\right) - 0.0003 \left(\frac{T_{co} - T_a}{G_b}\right)^2$$

(5)

The enthalpy balance of evaporative condenser is based on:

$$m_{SRC}(h_{4S} - h_{1S}) = m_{ORC}(h_{3O} - h_{2O})$$

(6)

The net flow rate by RO pump is defined by:

$$\text{work}_{pump-RO} = \frac{Q_{net} * H_S * SG_{water}}{367 * \eta_{pump}}$$

(7)

Where, $H_S$ is the suction head of water and $SG_{water}$ is the specific gravity of feed water.

The salt rejection from RO module is defined by [7]:

$$X_{concentrate} = \frac{(Q_{net} * X_{net}) - (Q_{permeate} * X_{permeate})}{Q_{concentrate}}$$

(8)

Where, $Q_{permeate}$ is the permeate flow can calculated by:

$$Q_{permeate} = Q_{net} * RR_{membrane}$$

(9)

Where $RR_{membrane}$ is the recovery rate of RO membrane.

3. Assumptions

Some assumptions for cascade Rankine cycle RO system are proposed for mathematical model may listed as:

- The work produce by the turbine and expander will be consumed by the RO pump, i.e., the mechanical efficiency of $\eta = 100\%$ [8].
- The evaporative-condenser and ORC condenser is well-insulated compact heat exchangers having zero heat loss to surrounding i.e. $\epsilon = 1$ [9].
- Isentropic efficiency of steam turbine, expander, & pump assumed to be $\eta_{isentropic} = 75\%$.
- The inlet temperature of the cooling water into the condenser is 25 $^\circ$C whereas the flow rate and the outlet temperature of the cooling water can be adjusted according to achieve 48.5 $^\circ$C ORC fluid temperature during condensation.
- The ambient temperature for the system assumed to be 25 $^\circ$C.
- A constant solar radiation assumed to be 850 W/m$^2$ during sunshine hour.
- A constant salinity of feed water is assumed to be 1000 ppm.

4. Result and discussion

Both Rankine cycles are working under the subcritical cycle where the hottest temperature of the cycle is the evaporation temperature of steam at turbine inlet & coldest temperature is the condensation temperature of the organic fluid. The thermodynamic design of the cascade RO is examined based on the mathematical model. The output parameters of the system are determined using the engineering equation solver software [10]. The inlet variables of the cascade cycle are listed in Table 1.

| Term                          | Unit | Value |
|-------------------------------|------|-------|
| Evaporation temperature of SRC, ($T_{3S}$) | $^\circ$C | 190   |
| Evaporation pressure of SRC, ($P_{3S}$)    | bar  | 11    |
| Condensation temperature of SRC, ($T_{4S}$) | $^\circ$C | 133   |
| Condensation pressure of SRC, ($P_{4S}$)    | bar  | 2.9   |
| Mass flow rate of SRC, ($m_S$)              | kg/hr | 19.67 |
4.1. Thermodynamic parameters of optimum cascade power conversion condition for RO

Based on the mathematical model of cascade RO, the optimum output results are listed in Table 2. The cycle efficiencies depending on the temperature of the steam at turbine inlet. Based on feed water salinity of 1000 ppm into the RO, the required specific energy consumption, i.e., power required to drive RO pump is determined. The output results for RO permeate are shown in Table 2. The area of collector is also calculated based on equation (4) & (5). The system may dynamically unbalance due to the variation of solar irradiation during sunshine hours can interrupt the permeate water from RO.

| Term                        | Unit   | Value |
|-----------------------------|--------|-------|
| Evaporation temperature of ORC, \( T_{3S} \) | °C     | 100   |
| Evaporation pressure of ORC, \( P_{3S} \)   | bar    | 11    |
| Condensation temperature of ORC, \( T_{4O} \) | °C     | 67    |
| Condensation pressure of ORC, \( P_{4O} \)   | bar    | 3.4   |
| Mass flow rate of ORC, \( m_{0} \)           | kg/hr  | 216   |
| Reference Solar radiation, \( G_{p} \)        | W/m²   | 850   |

| Term                        | Unit   | Value |
|-----------------------------|--------|-------|
| SRC efficiency \( \eta_{SRC} \) | %      | 7.74  |
| ORC efficiency \( \eta_{ORC} \)  | %      | 7.23  |
| Cascade Efficiency \( \eta_{cascade} \)  | %      | 14.07 |
| Heat input \( Heat_{input,S} \)           | kW     | 13.66 |
| Pump Work SRC \( Work_{pump-S} \)     | kW     | 0.01  |
| Pump Work ORC \( Work_{pump-O} \)      | kW     | 0.5   |
| Turbine Power \( Power_{Turbine} \)   | kW     | 0.99  |
| Expander Power \( Power_{expander} \)  | kW     | 0.98  |
| SRC RO Permeate \( Permeate_{S-RO} \) | m³/hr  | 0.98  |
| ORC RO Permeate \( Permeate_{O-RO} \)  | m³/hr  | 0.98  |
| Area of collector \( A_{col} \)        | m²     | 34    |

The Taguchi method is examined for optimize input parameters to achieve maximum output from the system [11]. There are 3 different input parameters along with 4 levels are preferred for the orthogonal array (refer Table 3) as evaporation temperature (190, 200, 210, & 220 °C), mass flow rate (0.0054, 0.0055, 0.0056, & 0.0057 kg/sec), & evaporation pressure (9, 10, 11 & 12 bar) are considered. According to the array, there are 16 experiment to be examined by arranging these parameters and levels in different sequences (refer Table 4).

| Experiment No. | Evaporation Temperature, \( T_{3S} \) (°C) | Mass flow rate, \( m_{SRC} \) (kg/hr) | Evaporation Pressure, \( P_{3S} \) (bar) |
|----------------|-------------------------------------------|----------------------------------------|----------------------------------------|
| 1              | 190                                       | 19.44                                  | 9                                      |
| 2              | 190                                       | 19.80                                  | 12                                     |
| 3              | 190                                       | 20.16                                  | 10                                     |
| 4              | 190                                       | 20.52                                  | 11                                     |

Table 2 Thermodynamic parameter results.

Table 3 Number of variable (parameters) along with levels (values).

| Number of Levels | 1 | 2 | 3 | 4 |
|------------------|---|---|---|---|
| Number of parameters | 1 | 2 | 3 | 4 |
| 1 | Evaporation Temperature, \( T_{3S} \) (°C) | 190 | 200 | 210 | 220 |
| 2 | Mass flow rate, \( m_{SRC} \) (kg/hr) | 19.44 | 19.80 | 20.16 | 20.52 |
| 3 | Evaporation pressure, \( P_{3S} \) (bar) | 9 | 10 | 11 | 12 |

Table 4 Experiment sequence based of orthogonal array.
| Exp. No. | Heat In (kW) | \( W_{\text{turbine}} \) (kW) | \( W_{\text{exp}} \) (kW) | \( Q_{S-RO} \) (m³/hr) | \( Q_{O-RO} \) (m³/hr) | \( \eta_{\text{SRC}} \) (%) | \( \eta_{\text{ORC}} \) (%) | \( \eta_{\text{Cascade}} \) (%) |
|---------|-------------|----------------|----------------|-----------------|-----------------|----------------|----------------|----------------|
| 1       | 13.52       | 0.84           | 0.98           | 0.84            | 0.98            | 6.18           | 7.37           | 13.10          |
| 2       | 13.66       | 1.05           | 0.98           | 1.05            | 0.98            | 7.68           | 7.37           | 14.49          |
| 3       | 13.98       | 0.94           | 1.01           | 0.94            | 1.01            | 6.73           | 7.36           | 13.60          |
| 4       | 14.2        | 1.03           | 1.02           | 1.03            | 1.02            | 7.23           | 7.36           | 14.05          |
| 5       | 13.62       | 0.92           | 0.99           | 0.92            | 0.98            | 6.76           | 7.37           | 13.64          |
| 6       | 13.84       | 1.01           | 0.99           | 1.01            | 1.00            | 7.25           | 7.37           | 14.09          |
| 7       | 14.05       | 1.08           | 1.00           | 1.08            | 1.00            | 7.70           | 7.37           | 14.50          |
| 8       | 14.41       | 0.90           | 1.04           | 0.89            | 1.04            | 6.22           | 7.34           | 13.11          |
| 9       | 13.71       | 1.00           | 0.99           | 1.00            | 0.98            | 7.29           | 7.37           | 14.13          |
| 10      | 14.00       | 0.96           | 1.01           | 0.95            | 1.01            | 6.81           | 7.36           | 13.67          |
| 11      | 14.28       | 0.90           | 1.03           | 0.89            | 1.03            | 6.26           | 7.35           | 13.16          |
| 12      | 14.58       | 1.14           | 1.04           | 1.13            | 1.03            | 7.78           | 7.35           | 14.56          |
| **13**  | **13.82**   | **1.08**       | **0.99**       | **1.07**        | **0.99**        | **7.78**       | **7.37**       | **14.58**      |
| 14      | 14.15       | 0.90           | 1.02           | 0.89            | 1.02            | 6.32           | 7.36           | 13.21          |
| 15      | 14.36       | 1.06           | 1.03           | 1.05            | 1.02            | 7.34           | 7.35           | 14.16          |
| 16      | 14.64       | 1.01           | 1.05           | 1.00            | 1.05            | 6.86           | 7.34           | 13.69          |

Based on the sequence of experiments, output parameters are examined (refer Table 5). The heat input of 13.52 to 14.58 kW will be required to achieve cascade efficiency of 13.1 to 14.58%. The work output of 0.838 to 1.1377 kW will be achieved along with 0.836 to 1.134 m³/hr of permeate water from the RO. The lowest heat input of 13.52 kW will be achieved in experiment 1. While the experiment 12 shows highest work output of the steam turbine & ORC expander. The experiment 13 show significant output parameter with highest system efficiencies & balanced heat input and turbine works.

Based on the optimized result, with a variation of mass flow rate of steam with constant input parameters (such as heat input & evaporation pressure of steam \( P_{3S} \)) shows improvement in performance in which evaporation temperature of ORC \( T_{5O} \) become increase along with work output from both SRC & ORC cycle. Due to this, the performance of both cycles advantage to production of permeate water from RO.
Figure 3 System efficiencies with variation of mass flow rate of steam.

As shown in graph (refer Figure 3), the super-heating of R245fa from its saturation temperature of 93°C shows an increase in SRC efficiency $\eta_{\text{SRC}}$ along with variation of mass flow rate ($m_{\text{SRC}}$) of steam. The ORC efficiency $\eta_{\text{ORC}}$ is reduced due to heat reject by ORC condenser will be increased. However, the ORC work output from expander become improve with variation of mass flow rate ($m_{\text{SRC}}$) of steam along with high-pressure pump shows an increase in net driving pressure of feed water, resulting high permeate water (refer Figure 4) from both RO systems is achieved.

5. Conclusion
The proposed cascade Rankine cycle driven RO system comprises two Rankine cycle along with individual RO systems. The good applicability in RO system with a pair of cycle makes the utilisation of solar energy at low or medium heat source temperature. The Scheffler disc-based cascade cycle has advantage to lower temperature and pressure in solar field. The thermodynamic analysis is performed with different input parameters and values. The mathematical model is simulated using the EES software. The investigation performs based on Taguchi approach to optimise the system for suitable output. Based on the analysis, the conclusion remarks:

- By using EES software, the mathematical model is investigated with variation of mass flow rate of steam. The cycle integrates with the RO shows significant performance.
- The literature shows R245fa is suitable working fluid for ORC. The critical temperature is less than the condensing temperature of steam at turbine exit.
- The Taguchi approach for optimising the output parameters is applied. The experiment 13 shows a good agreement of system efficiency along with work output from turbine.
- The variation of mass flow rate of steam $m_{\text{SRC}}$ will improve the overall efficiency and performance of the system along with permeate water form RO. The super-heating of the R245fa will increase the work output from the expander but, the ORC efficiency will be reduced because of the increase in heat rejects during condensation of working fluid at expander exit.

It is clear for this analysis that a pair of Rankine cycle can increase in overall performance of the system. However, water need wet expansion turbine because of negative slope of water in saturation curve. Otherwise, the super-heating of steam is required, which increase size of the solar collector. The super-heating of steam required highly stable piping and equipment to sustain which impact on capital cost of the system. The normal boiling point of R245fa is 15 °C will advantage to evaporate at the condensing temperature of steam at turbine exit. The R245fa working fluid is the best alternative to replace with chlorine based working fluid in nowadays. Overall, the solar energy-based cascade RO shown good agreement towards the desalination of brackish water.

6. Future Work
Thermo-economic analysis of the system will be investigated by considering the capital cost of turbine, solar collector, RO pump, RO module, etc along with different working fluids. The experimental investigation will be examined at PDEU, Gandhinagar.

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References

[1] Fritzmann C, Löwenberg J, Wintgens T, Melin T. State-of-the-art of reverse osmosis desalination. Desalination. 2007;216(1–3):1–76.

[2] Nafey AS, Fath HES, Mabrouk AA. A new visual package for design and simulation of desalination processes. Desalination. 2006;194(1–3):281–96.

[3] Li J, Li P, Gao G, Pei G, Su Y, Ji J. Thermodynamic and economic investigation of a screw expander-based direct steam generation solar cascade Rankine cycle system using water as thermal storage fluid. Appl Energy [Internet]. 2017;195:137–51. Available from: http://dx.doi.org/10.1016/j.apenergy.2017.03.033

[4] Li J, Li P, Pei G, Alvi JZ, Ji J. Analysis of a novel solar electricity generation system using cascade Rankine cycle and steam screw expander. Appl Energy. 2016;165:627–38.

[5] Mudgal A, Davies PA. A cost-effective steam-driven RO plant for brackish groundwater. Desalination [Internet]. 2016;385:167–77. Available from: http://dx.doi.org/10.1016/j.desal.2016.02.022

[6] Blanco et al. J. Technical Comparison of different solar-assisted heat supply systems for a multi-effect seawater distillation unit. Sol World Congr. 2003;(May 2014):14–9.

[7] El-Dessouky HT, Ettouney HM. Chapter 7 - Reverse Osmosis. In: El-Dessouky HT, Ettouney HMBT-F of SWD, editors. Amsterdam: Elsevier Science B.V.; 2002. p. 409–37.

[8] Nafey AS, Sharaf MA. Combined solar organic Rankine cycle with reverse osmosis desalination process: Energy, exergy, and cost evaluations. Renew Energy [Internet]. 2010;35(11):2571–80. Available from: http://dx.doi.org/10.1016/j.renene.2010.03.034

[9] Liu H, Shao Y, Li J. A biomass-fired micro-scale CHP system with organic Rankine cycle (ORC) - Thermodynamic modelling studies. Biomass and Bioenergy. 2011;35(9):3985–94.

[10] SA. K. Engineering equation solver (EES). Madison USA: Klein SA.;

[11] Ivens GP. Chemical process dynamics. Chem Eng J. 1983;27(2):120–1.