Applied Energy 224 (2018) 448–468

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

# Synthesis and dual-objective optimization of industrial combined heat and power plants compromising the water–energy nexus

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## HIGHLIGHTS

- A novel water desalination method and a novel water-energy system are proposed.
- A synthesis and dual-objective optimization framework is developed.
- A solution strategy is proposed for the dual-objective optimization problem.
- The superiority of the proposed novel water–energy system is validated.
- Sensitivity analysis of key parameters on the water-energy system is conducted.

## ARTICLE INFO

*Keywords:*
Water–energy nexus
Utility plant
Reverse osmosis
Thermal membrane distillation
Integration and optimization

## ABSTRACT

Water and energy are inextricably linked in various industrial applications. In a Rankine cycle-based combined heat and power plant, water is used as a working fluid for power generation and as a heat carrier. The water used as heat carrier is typically incompletely recovered. Therefore, a considerable amount of make-up water is required. Energy-intensive water treatment technologies are typically used given the strict quality requirements for boiler feed water. Thus, a systematic approach is required for the synthesis and optimization of water desalination and energy conversion processes. In this study, a novel water desalination system that couples thermal membrane distillation and reverse osmosis is proposed. A water–energy integration system that features strong nexus of water and energy is then developed. A dual-objective mathematical model is also formulated for the thermodynamic analysis and optimization of the novel system to minimize fuel and freshwater consumption. Furthermore, a case study is elaborated to validate the proposed novel integration system and optimization methodology. A sensitivity analysis of the key parameters on the performance of the novel system is also conducted. The water consumption objective optimization results show that the freshwater consumption of the proposed novel water–energy integration system is reduced by 54.8% compared with the conventional system. Similarly, the results achieved from minimizing the fuel consumption show that the fuel and freshwater consumptions of the proposed novel water–energy integration system are reduced by 1.7% and 21.0%, respectively, compared with those of the conventional system. The Pareto frontier achieved from the dual-objective optimization offers a trade-off between water and fuel consumption for the proposed water–energy integration system.

## 1. Introduction

Water and energy are two critical resources for human life. The consumption of fossil fuels has dramatically increased with the development of society [1–3]. Only 2.5% is usable freshwater, although most of the Earth's surface is covered by water [4]. Energy shortage and water crisis, together with their associated environmental pollutants, are the most serious problems currently faced by the world [5]. Energy and water are fundamentally linked to each other. Water is used in energy transportation and conversion processes while energy is used in

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https://doi.org/10.1016/j.apenergy.2018.04.095
Received 22 January 2018; Received in revised form 6 April 2018; Accepted 28 April 2018
Available online 11 May 2018

## Nomenclature

| | |
|---|---|
| A | membrane pure water permeability, $kg\,m^{-2}\,s^{-1}\,Pa^{-1}$ |
| $A_{ref}$ | reference permeability, $kg\,m^{-2}\,s^{-1}\,Pa^{-1}$ |
| $a_b$ | boiler model coefficients |
| $ais_z$ | model coefficients for isentropic enthalpy difference of subsection z |
| $Ais_z$ | model coefficients for isentropic efficiency of subsection z |
| B | slat permeability constant, $kg/m^2s$ |
| $b_b$ | boiler model coefficients |
| $B_{wb}$ | temperature independent base value for the permeability, $kg\,m^{-2}\,s^{-1}\,P_a{}^{-1}\,K^{-1.334}$ |
| $bis_z$ | model coefficients for isentropic enthalpy difference of subsection z |
| $Bis_z$ | model coefficients for isentropic efficiency of subsection z |
| CpBFW | heat capacity of boiler feed water, kJ/(kg °C) |
| $Cp_{b,RO}$ | heat capacity of RO bine water, kJ/(kg °C) |
| $Cp_{B,BLD,FW}$ | heat capacity of flashed water, kJ/(kg °C) |
| $Cp_{CW,\ BLD}$ | heat capacity of cooling water blowdown, kJ/(kg °C) |
| $Cp_{f,\ raw}$ | heat capacity of TMD raw water, kJ/(kg °C) |
| $Cp_{w,f}$ | heat capacity of feed water to TMD, kJ/(kg °C) |
| $Cp_{brine}$ | heat capacity of TMD brine water, kJ/(kg °C) |
| $Cp_{p,TMD}$ | heat capacity of TMD permeate water, kJ/(kg °C) |
| $Cp_f$ | heat capacity of TMD feed water, kJ/(kg °C) |
| $Cp_{TMD,MKW}$ | heat capacity of TMD make-up water, kJ/(kg °C) |
| $Cp_{p,RO}$ | heat capacity of RO permeate water, kJ/(kg °C) |
| $Cp_{cw}$ | heat capacity of cooling water, kJ/(kg °C) |
| $D_w$ | diffusion coefficient for water in air |
| FF | fouling factor |
| HBGen | enthalpy of steam generated in boiler, kJ/kg |
| K | constant with the value of 0.7 |
| LHVF | low heat value of fuel, kJ/kg |
| $M_{NaCl}$ | molar mass of NaCl, g/mol |
| $MM_{NaCl}$ | molecular weight of NaCl |
| tBFW | temperature of boiler feed water, °C |
| HBSat | enthalpy of boiler water, kJ/kg |
| $H_{B,BLD}$ | enthalpy of boiler blowdown, kJ/kg |
| $H_{B,BLD,FSTM}$ | enthalpy of flashed steam, kJ/kg |
| $H_{B,BLD,FW}$ | enthalpy of flashed water, kJ/kg |
| $H_{z,de}$ | process heat demand under the pressure rating in subsection z, kW |
| $HW_{DEA}$ | enthalpy of water in deaerator supplied to boiler, kJ/kg |
| r | pore radius, mm |
| Ru | universal gas constant, J/kmol |
| S | membrane active surface area, $m^2$ |
| $SP_{fan}$ | unit power consumption of draft fan, kW |
| $T_{cw,in}$ | inlet temperature of cooling water, °C |
| $T_{cw,out}$ | outlet temperature of cooling water, °C |
| $T_{TMD,MKW}$ | temperature of TMD make-up water, K |
| $T_{B,BLD,FW}$ | temperture of flashed water, K |
| $T_{CW,BLD}$ | temperture of cooling water blowdown, K |
| TCF | temperature correction factor |
| $WT_{de}$ | process power demand, kW |
| $X_{B,BLD,FSTM}$ | ratio of blowdown water flashed into steam |
| $y_{TMD,MKW}$ | concentration of TMD make-up water, g/L |

*Greek letters*

| | |
|---|---|
| $\delta$ | membrane thickness, mm |
| $\eta_b$ | boiler efficiency |
| $\eta_{pump}$ | efficiency of pump in the cooling tower |
| $\eta_{cond}$ | efficiency for conduction in the membrane of TMD |
| $\eta_{thermal}$ | thermal efficiency of TMD |
| $\rho_{cw}$ | density of cooling water, $kg/m^3$ |
| $\rho$ | density of feed water in RO, $kg/m^3$ |
| $\varphi$ | boiler blowdown ratio |
| $\nu$ | ratio of recyled to raw water |
| $\xi$ | water recovery of TMD |
| $\eta_{pump,RO}$ | efficiency of pump in the RO |
| $\Delta P_{cw}$ | cooling water pressure drop in the cooling tower, kPa |
| $\Delta H_{vw}$ | latent heat of water in the feed side of the membrane, kW |
| $\Delta T_{cw}$ | temperature difference of cooling water, °C |
| $\Delta p$ | trans-membrane pressure, Pa |
| $\Delta p_{drop}$ | pressure drop along the membrane channel, Pa |
| $\Delta\pi$ | trans-membrane osmotic pressure, Pa |
| $\gamma_{w,f}$ | activity coefficient of the water in the feed |
| $x_{w,f}$ | mole fraction of the water in the feed |
| $x_{NaCl}$ | molar concentration, mol/L |
| $\tau$ | pore tortuosity |
| $\theta$ | temperature polarization coefficient |

*Variables*

| | |
|---|---|
| $B_w$ | membrane permeability, $kg/(Pa\,m^3)$ |
| $DLTHis_z$ | isentropic enthalpy difference of turbine subsection z, kJ/kg |
| $EFFis_z$ | isentropic efficiency of turbine subsection z, kJ/kg |
| $E_p$ | power of pump in RO, kW |
| $F_B$ | flow rate of fuel, kg/s |
| $F_B{}^{max}$ | the maximum value of the fuel consumption, kg/s |
| $F_B{}^{min}$ | the minimum value of the fuel consumption, kg/s |
| $HT_{z,in}$ | inlet enthalpy in subsection z, kJ/kg |
| $HT_{z,out}$ | outlet enthalpy in subsection z, kJ/kg |
| $HT_{LP,out}$ | enthalpy of LP extraction steam, kJ/kg |
| $HT_{CONDS,out}$ | outlet enthalpy of turbine, kJ/kg |
| $J_{w,RO}$ | water flux, $kg/(s\,m^2)$ |
| $J_{w,TMD}$ | water flux, $kg/(s\,m^2)$ |
| $J_{s,RO}$ | salt flux, $kg/(s\,m^2)$ |
| $K_m$ | heat transfer coefficient of membrane, kW/(m K) |
| $M_B$ | steam generation flow rate of boiler, kg/s |
| $M_B{}^{max}$ | maximum steam generation flow rate in boiler, kg/s |
| $M_{B,BLD}$ | flow rate of boiler blowdown, kg/s |
| $M_{BFW}$ | flow rate of boiler feed water, kg/s |
| $M_{B,BLD,FSTM}$ | flow rate of flashed steam, kg/s |
| $M_{B,BLD,FW}$ | flow rate of flashed water, kg/s |
| $M_{p,TMD}$ | flow rate of TMD permeate water, kg/s |
| $M_{f,RO}$ | flow rate of RO feed water, kg/s |
| $M_{f,raw}$ | flow rate of TMD raw water, kg/s |
| $M_{w,f}$ | flow rate of TMD feed water, kg/s |
| $M_{p,RO}$ | flow rate of RO permeate water, kg/s |
| $M_{b,RO}$ | flow rate of RO brine, kg/s |
| $M_{b,RO,MK}$ | flow rate of TMD makeup water from RO brine, kg/s |
| $M_{brine}$ | flow rate of brine in TMD, kg/s |
| $M_{cw}$ | flow rate of cooling water, kg/s |
| $M_{CW,MKW}$ | mass flow rate of make-up water in cooling tower, kg/s |
| $M_{TMD,MKW}$ | mass flow rate of make-up water in TMD, kg/s |
| $M_{RO,MKW}$ | mass flow rate of make-up water in RO, kg/s |
| $M_{CW,EVAP}$ | mass flow rate of evaporation water in cooling tower, kg/s |
| $M_{CW,BLD}$ | mass flow rate of cooling tower blowdown, kg/s |
| $M_{CW,BLD,MK}$ | mass flow rate of TMD makeup water from cooling tower blowdown, kg/s |
| $M_{FW}$ | flow rate of freshwater, kg/s |
| $MT_{1,in}$ | inlet steam flow rate of turbine, kg/s |
| $MT_{z,in}$ | inlet steam flow rate of turbine in subsection z, kg/s |
| $MT_{z,\ ext}$ | outlet steam flow rate of turbine in subsection z, kg/s |
| $MT_{LP,ext}$ | extraction flow rate of LP steam, kg/s |
| $MT_{CONDS,out}$ | outlet flow rate of turbine, kg/s |
| P | total pressure inside the membrane pores, Pa |
| $p_a$ | air pressure in the membrane pores, Pa |
| $P_{f,RO}$ | applied feed pressure, Pa |