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Steady state optimization of design and operation of desalination systems using Aspen Custom Modeler

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ABSTRACT

In this paper Multistage flash (MSF), Reverse Osmosis (RO) and hybrid MSF/RO desalination systems are optimized. A superstructure is set up for analyzing various process configurations in a single flowsheet. Detailed steady state models for MSF and RO sections of the superstructure are developed incorporating comprehensive physio-chemical properties and design characteristics. The model for the hybrid system combines individual models of MSF and RO systems and additional separators and mixers. The optimization variables consist of the operating and design variables, and the objective function is developed on the basis of economic and technical performance indicators. Primary results show that the hybridization of MSF and RO systems sharing common intake-outfall facilities presents lower cost with the additional benefits of higher overall recovery than MSF system and higher product quality than RO system. The sensitivity analysis of the cost parameters is performed to realize their effects on the selection of process configuration.

1. Introduction

Water is the most abundant compound on the surface of the earth but a very small portion of it is suitable for human needs. The water that can be used for human consumption is called fresh water which comprises only 3% of the total water capacity (Bielik et al., 2010). The steady depletion of natural water resources has increased the demand of freshwater than its supply in many countries and this depletion is expected to continue. This shortage of water is known as water stress. Global population growth and increased industrial activities are the main reasons for the expected increase in water stress (Hawlader et al., 2000; Liu et al., 2016). According to the reports of United Nations, more than half of the world will experience water stress by 2025 (UN-Water, 2007; UNDP, 2006). Water is a renewable resource and the overtaking demand can be fulfilled through innovative and adaptive technologies such as desalination processes. The desalination market is growing fast all around the world and is forecasted to expand further (Kesieme et al., 2013; Mehdizadeh, 2006; Mezher et al., 2011).

Among all desalination processes Multistage flash (MSF) and Reverse Osmosis (RO) are the well-established technologies leading the desalination industry. MSF is a thermal based desalination process and is expected to remain the first choice in the desalination industry in the future in the areas where the fuel prices are low. The benefits of MSF such as large production capacity, proven reliability, higher product quality and well-developed construction and operation experience have kept the process more favorable in the future desalination over other competitive thermal desalination methods (El-Dessouky and Ettouney, 2002; Mezher et al., 2011). RO on the other hand is a pressure driven membrane process which is the second choice of consumers. The major producer countries are the Gulf countries which face harsh water conditions (high salinity range) and RO is not feasible for these conditions. Moreover with the higher salt concentration in the seawater the quality of fresh water produced is low. Therefore in these countries MSF is preferred over RO for seawater desalination. RO requires much less energy as compared to all other thermal desalination processes. Moreover RO has a higher product recovery and quality than other membrane based processes and is simple in terms of automation and control. An RO plant is often more compact, can be easily scaled up and more quickly installed than alternative plants (El-Dessouky and Ettouney, 2002; Mezher et al., 2011).

A lot of efforts have been made in the past three decades to reduce the cost of a MSF plant. Considering the advantages of a RO plant, it is believed that one possible way to reduce the cost of the MSF plant is to hybridize the MSF and RO systems (Helal et al., 2003; Marcovecchio et al., 2011). Another significant advantage of

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Nomenclature for MSF

Abh	Total heat transfer area of brine heater
Ar_j	Total heat transfer area of stage j
A_T	Total heat transfer area
BD	Flow rate of brine blow down
B_j	Flow arte of flashing brine leaving stage j
B_{j-1}	Flow rate of flashing brine entering stage j
BN	Flow rate of flashing brine leaving last stage
BO	Flow rate of flashing brine entering first stage
BPEj	Boiling point elevation
C	Concentration
$C_{B,j}$	Salt concentration of flashing brine leaving stage j
$C_{B,j-1}$	Salt concentration of flashing brine entering stage j
CBN	Salt concentration of flashing brine leaving last stage
CBO	Salt concentration of flashing brine entering first stage
CF	Salt concentration of feed
CR	Salt concentration of recycle brine
CW	Flow rate of reject seawater
D	Flow rate of distillate
$D^i{}_H$	Internal diameter of brine heater tubes
$D^\circ{}_H$	External diameter of brine heater tubes
$D^i{}_j$	Internal diameter of tubes at stage j
$D^\circ{}_j$	External diameter of tubes at stage j
D_j	Flow rate of distillate leaving stage j
D_{j-1}	Flow rate of distillate entering stage j
f_H	Brine heater fouling factor
f_j	Fouling factor at stage j
Fm	Flow rate of makeup seawater
Fsea	Flow rate of feed seawater
H_j	Height of brine pool at stage j
h_j	Specific enthalpy of flashing brine leaving stage j
h_{j-1}	Specific enthalpy of flashing brine entering stage j
hm	Specific enthalpy of makeup stream
hR	Specific enthalpy of recycle stream
hw	Specific enthalpy of cooling brine entering heat recovery section
hv_j	Specific enthalpy of flashing vapor at stage j
$(LMTD)_{bh}$	Log mean temperature difference for brine heater
$(LMTD)_j$	Log mean temperature difference for stage j
NEAj	Non-equilibrium allowance in temperature for flashing brine for stage j
R	Flow rate of recycle brine
S_{bh}	Specific heat capacity of brine in brine heater
SB_j	Specific heat capacity of flashing brine leaving stage j
SB_{j-1}	Specific heat capacity of flashing brine entering stage j
SD_j	Specific heat capacity of distillate leaving stage j
SD_{j-1}	Specific heat capacity of distillate entering stage j
Src_j	Specific heat capacity of cooling brine leaving stage j
T	Temperature
TB_j	Temperature of flashing brine leaving stage j
TB_{j-1}	Temperature of flashing brine entering stage j
TBO	Temperature of flashing brine leaving brine heater
TD_j	Temperature of distillate leaving stage j
TD_{j-1}	Temperature of distillate entering stage j
TF1	Temperature of cooling brine leaving stage 1
TF_j	Temperature of cooling brine leaving stage j
TF_{j+1}	Temperature of cooling brine entering stage j
Tref	Reference temperature
Ts_j	Temperature of flashed vapor at stage j
T_{steam}	Steam temperature
Ubh	Overall heat transfer coefficient at the brine heater
U_j	Overall heat transfer coefficient at the brine heater at stage j
W	Flow rate of cooling brine in heat recovery section
w_j	Width of stage j
Ws	Flow rate of steam

Symbols for MSF

λs	Latent heat of vaporization of water in brine heater
Δj	Temperature drop in demister in stage j
ρ_b	Brine density
ρ_w	Pure water density

Nomenclature for RO

Amem	Area of membrane
As	Salt permeability constant
Aw	Water permeability
C	Concentration
Cb	Bulk concentration
Cf	Feed concentration
C_{mem}	Membrane cost
Cp	Permeate concentration
C_{pv}	Pressure vessel cost
Cr	Reject concentration
Cw	Wall concentration
d	Diameter of element
df	Feed spacer thickness
Ds	Solute diffusivity
f_c	Plant load factor
hsp	Height of spacer channel
Js	Salt flux
Jw	Water flux
k	Mass transfer coefficient
Lm	Length of membrane element
Lpv	Length of pressure vessel
m	No of membrane element in a pressure vessel
N1	Number of leaves in a membrane element
N_{pv}	Number of pressure vessels
Pf	Feed pressure
Pp	Permeate pressure
Pr	Reject pressure
Qb	Bulk flow rate
Qf	Feed flow rate
Qp	Permeate flow rate
Qr	Reject flow rate
Re	Reynolds no
Sc	Schmidt no
SR	Salt rejection
T	Temperature
w	Membrane width
V	Average axial velocity in the feed channel

Symbols for RO

μ	Brine viscosity
π	Osmotic pressure
πf	Osmotic pressure of feed
πp	Osmotic pressure of permeate
πr	Osmotic pressure of reject
$\Delta\pi$	Osmotic pressure drop
ΔP	Pressure drop
ΔPf	Pressure drop on the feed side
ϵ	Feed spacer void fraction
ρ	Brine density
ρ_w	Pure water density

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