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A dynamic model for MED-TVC transient operation

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HIGHLIGHTS

- An equation-based dynamic model for MED-TVC has been implemented.
- It also accounts for non-condensables, partial condensation & brine level variation.
- Transient operations due to disturbances are analysed.
- Critical transitory conditions have been identified.
- Strategies for process control under variable regime are discussed.

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ABSTRACT

The Multi Effect Distillation (MED) process is often proposed as a key technology for the construction of new thermal desalination plants, especially within solar-powered cogeneration schemes. With this respect, the need for transient behaviour analysis requires the development of dynamic models for the MED process. Only a few have been presented so far in the literature, in which, however, several simplifying assumptions and constrains are still limiting their potential use.
The model here proposed addresses most of the aspects still limiting previous models formulations. The powerful equation-based process simulator gPROMS® was chosen for the implementation of the model, developed on the basis of available data from a MED-TVC plant located in Trapani, Sicily (Italy). After validation, the model was used for some preliminary analysis of system behaviour under transient conditions, artificially generated starting from steady state by implementing specific disturbances such as the variation in the motive steam pressure, seawater feed flow rate and temperature. This demonstrates the model capability to describe in detail the dynamic response of the system with respect to all its variables, thus representing a useful tool for the prediction of transient operations and control system design purposes of MED-TVC plants.

1. Introduction

Nowadays, the desalination market is experiencing a continuous growth due to the increasing water demand and reduced fresh water availability especially in warm and arid areas of the planet. Among desalination technologies, membrane processes, such as Reverse Osmosis, have achieved a dominant role in terms of production capacity. Nevertheless, thermal processes still play a fundamental role in locations where seawater quality is poor, salinity is high or with a strong potential for the integration of desalination facilities with power plants, aiming at highly effective co-generation schemes. Among thermal desalination processes, the Multi Effect Distillation (MED) technology is currently leading the trend of new plants construction. This is due to the higher energetic performances achieved and the larger flexibility compared to the traditionally preferred Multi-Stage Flash (MSF) technology [1]. For the same reasons, MED technology is considered the best selection for the coupling with solar energy plants, as stand-alone or, much more frequently, in combination with Concentrated Solar Power co-generation schemes. In this latter case, MED units are often equipped with Thermal Vapour Compression (TVC) systems, able to increase the energetic performance of the plant by 30–40% with respect to the standard MED process. Other methods for increasing the thermal efficiency of the MED plants have been proposed, which can present even higher enhancement factors compared to standard TVC units. These are mainly based in extending the number of effects, by the increase of the first

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Abbreviations: AD, adsorption/desorption; BPE, Boiling Point Elevation; FF, forward feed; HX, heat exchanger; MED, Multiple Effect Distillation; NCG, non-condensable gas; NEA, Non-Equilibrium Allowance; SE, single evaporation effect; PF, parallel feed; PC, parallel/cross; RR, Recovery Ratio; sA, specific area; TVC, Thermal Vapour Compression.

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Nomenclature

A	surface [m^2]
B	mass of brine [kg]
BPE	Boiling Point Elevation [°C]
Cd	brine discharge coefficient [s/m$^{1/2}$]
C_G	Gas Solubility [micro-mol/kg]
Cp	specific heat [kJ/(kg·°C)]
D	Diameter of the effect [m]
D_{tot}	total distillate production [kg/s]
g	specific gravity [m/s^2]
GOR	Gain Output Ratio [−]
G_{pool}	gain of brine flow-rate control law [kg/(m·s)]
H	enthalpy [kJ]
H_c	Henry-like constant [Pa]
h	specific enthalpy [kJ/kg]
L	length of the effect [m]
LMTD	logarithmic mean temperature difference [°C]
L_{pool}	Brine level [m]
M	Mass flow rate [kg/s]
NCG	mass of non-condensable gas [kg]
P	pressure [Pa]
PM	molar weight [kg/kmol]
Q	heat [kW]
R	universal gas constant [kJ/kmol K]
S	auxiliary salinity [kg ppm]
T	temperature [°C]
U	overall heat coefficient [kJ/m^2 °C]
Vap	mass of the vapour phase [kg]
Vol	volume [m^3]
X	mass fraction of non-condensable gas in the liquid phase $\left[\frac{\text{kg of NCG}}{\text{kg of liquid}}\right]$
x	salt concentration expressed as [ppm]
Y	mass fraction of non-condensable gas in the vapour phase $\left[\frac{\text{kg of NCG}}{\text{kg of gaseus phase}}\right]$

Greek symbols

α	vapour discharge coefficient [m^2]
Δ	difference
ε	condensation ratio in the tube bundle [−]
θ	release coefficient of non-condensable gasses [−]
λ	latent heat [kJ/kg]
ρ	density [kg/m^3]

Subscript

air	air
br_in	brine stream arriving from the previous effect
br_out	brine stream leaving the effect to the following one
br_shell	dispersed liquid reaching the brine pool from the tube bundle
cond	condenser
d	condensed vapour exiting the tube bundle
ds	condensate extracted from the 1st effect for the de-super-heater
eff	effective quantity of heat transferred
eq	equilibrium
evap	vapour generated from tube bundle evaporation surface;
f	seawater entering into the effect
flash	vapour generated by the flashing of brine arriving from previous effect
in	inlet
mix	vapour and non-condensable gas mixture
mol	molar fraction (instead of mass fraction)
ms	motive steam (i.e. condensing vapour) entering the tube bundle
NCG	non-condensable gas
	NCG_entrained NCG arriving to the effect from the previous effect
	NCG_pool NCG released from the brine arriving from the previous effect
	NCG_shell NCG released from the dispersed brine around the tube bundle
out	outlet
p	motive steam to the TVC ejector
pe	primary energy
ph	vapour condensing inside the pre-heater
pipe	tube connection between two effects
pool	brine accumulated in the pool
ref	reference state for calculation
SE	evaporation effect
shell	brine around tube bundle
sp	set point fixed for the brine pool level
sw_in	seawater entering the condenser
	sw_in_ph seawater entering the pre-heater
sw_out	seawater exiting from the condenser
	sw_out_ph seawater exiting from the pre-heater
tubes	tube bundle
vap	vapour phase
vap_out	gas mixture exiting from the effect

effect temperature and/or the decrease in the last effect temperature [2]. On one hand, the introduction of pre-treatments such as nano-filtration, which dramatically reduce bivalent ions concentration thus avoiding scaling problems, allows higher top brine temperatures. On the other hand, the condensation of the last effect vapour at a much lower temperature through the coupling with Adsorption/Desorption (AD) cycles permits to decrease the temperature of the last stage to values as low as 5 °C–10 °C allowing for a larger total driving force and/or for a larger number of effects. This latter method has been specifically studied by Shahzad et al. in several research works [3,4,5]. For this purpose, a 3-stages MED pilot system was designed, fabricated, installed and coupled with an existing AD system, which allows the last stage of the MED plant to operate at temperatures as low as 5 °C. The experimental results showed a significant increase in the distillate production (up to 2.5 to 3 folds compared to the stand-alone evaporator) and in the Performance Ratio (defined as the ratio of the energy of the distillate produced to the power input) from 0.52 to 1.0 when the evaporator is coupled with AD. The same authors also predicted by simulations that PR of almost 5 could be achieved with an 8-stages MED unit. Also the combination of both methods (nanofiltration + AD) for MED processes has been proposed in [6], leading to specific thermal consumptions as low as 12.5 kW$_{pe}$/m^3.

In all these combinations, the design and optimisation of MED units require advanced modelling tools able to predict the behaviour of a plant under the planned operating conditions. Moreover, when transitory operations are foreseen, such as in the case of solar-powered plants, dynamic modelling tools are strongly required for the design of the system, its relevant control loops and for the optimisation of coupling strategies with the solar energy integrated system.

This paper presents a novel and comprehensive dynamic model for the MED-TVC process aiming at filling the gaps of previous research