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Operational analysis of the coupling between a multi-effect distillation unit with thermal vapor compression and a Rankine cycle power block using variable nozzle thermocompressors

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HIGHLIGHTS

- Variable nozzle steam ejectors are used for operation flexibility of MED plants.
- The power block breaking points have been investigated by simulations in Thermoflex.
- An operational model of the MED-TVC process is developed for part load operation.
- Efficiency and fresh water production are studied at nominal and partial loads.

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ABSTRACT

In Multi-Effect Distillation with Thermal Vapor Compression (MED-TVC) plants, fixed steam ejectors are usually designed for constant motive steam pressures. When these distillation units are integrated into Concentrating Solar Power (CSP) plants, the available motive steam pressure is normally lower than the design value (due to the partial load operation of the power cycle under different solar radiation conditions), being the efficiency of the steam ejectors drastically reduced. Also, it has a negative impact on the fresh water production from the desalination plant because of a decrease in the mass flow of the motive steam. All this can be avoided by using variable nozzle steam ejectors, which can adjust the mass flow rate of steam according to the variable pressure so that they are always operating with the maximum efficiency and therefore they can maintain the freshwater production of the desalination plant near to the nominal value. This work presents a study of the coupling between CSP plants and MED-TVC units using variable nozzle steam ejectors in a wide range of operating conditions (on and off-design). For this purpose, simulations of a Rankine cycle power block in a typical commercial CSP plant have been firstly performed at different thermal loads to investigate the operational limits that allow keeping the motive steam mass flow rates constant. Then, the efficiency and fresh water production of an MED-TVC unit coupled to the different extractions available at the CSP plant have been studied in a wide range of operating conditions, covering both nominal and partial loads. To this end, an operational model of the MED-TVC unit has been developed based on a design model previously published by the authors.

1. Introduction

The water shortage is becoming a more serious threat to many countries. Even regions that had not severe water scarceness are now struggling to have a fresh water supply. Industrial desalination plants are among the best technological solutions to provide fresh water from seawater. Regions as the Middle East and North Africa have been solving the water scarcity by thermal desalination plants driven by fossil fuels so far, which is neither sustainable nor economically feasible in a long-term perspective, as fuels are increasingly becoming expensive and scarce [1–5]. Although the case of South of Europe is not as drastic as the Middle East, it increasingly suffers from a severe lack of fresh water supplies, and it depends all the more on seawater desalination to solve this problem. Approximately 39% of the population in these regions lived within 100 km of the coast in 2010 [6], and many locations are good candidates for the development and installation of solar

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Nomenclature

Variables

A	area, m^2
k_s	heating steam constant
p_m	motive steam pressure, bar
q_{comp}	compressed steam mass flow rate, kg/s
q_{cw}	cooling seawater mass flow rate, T/h
q_D	flow rate of distillate produced, m^3/d
q_F	feedwater mass flow rate, T/h
q_{in}	intake seawater mass flow rate, T/h
q_{LP1}	mass flow rate of steam in FWH LP1, kg/s
q_m	motive steam mass flow rate, kg/s
Ra	entrainment ratio
sA	specific heat transfer area, $m^2 \cdot s/kg$
T_s	heating steam temperature, °C
X_1	brine salinity in the first effect, ppm

Acronyms and abbreviations

CR	Compression Ratio
CSP	Concentrating Solar Power
DEA	Deaerator
EES	Engineering Equation Solver
ER	Expansion Ratio
FHW	Feedwater Heater
GOR	Gain Output Ratio
HP	High Pressure
LP	Low Pressure
LT	Low Temperature
MED	Multi-Effect Distillation
PB	Power Block
PBBP	Power Block Breaking Point
PBML	Power Block Minimum Load
RR	Recovery Ratio
TC	Thermocompressor
TVC	Thermal Vapor Compression

Subscripts

act	actual
bef	before
c	end condenser
comp	compressed
cw	rejected cooling seawater
D	distillate
F	feedwater
in	intake or inlet
lim	limit
m	motive steam
nom	nominal
opt	optimum
preh	preheater

Greek

β	Reduction of evaporator area
Δ	Variation step

energy plants due to the high values of solar irradiation available [7,8]. Therefore, it is clear that there is a nexus between energy and water that makes the coupling between desalination processes and solar energy technologies, such as Concentrating Solar Power (CSP) plants, a real alternative for fossil fuel powered desalination.

Among the different thermal desalination technologies suitable for coupling with a Rankine cycle power block of a CSP plant, Multi-Effect Distillation (MED) represents the most efficient one from a thermodynamic point of view [9]. One of the most viable coupling arrangements is the integration of a Low-Temperature MED (LT-MED) unit replacing the condenser of the power block, which uses heating steam from the outlet of the turbine at a maximum temperature of 70 °C to reduce the risk of scale formation on the tubes of the evaporators. However, in this case, the freshwater production cannot be decoupled from the load of the turbine, and there are not possibilities of regulation according to the electricity and water demands of the location. The increase in the energetic performance of MED plants can make this CSP + D concept even more reliable and sustainable. This increase can be achieved by the coupling with absorption heat pumps or a Vapor Compression (VC) system, which recover part of the thermal energy rejected by the distillation process. The hybridization of LT-MED and adsorption systems has been investigated through several research works [10–14], which proved the potential to increase the thermal efficiency of the desalination plant. The Adsorption/Desorption (AD) cycle permits to decrease the temperature of the last stage to values as low as 5–10 °C allowing for a larger total driving force and/or for a greater number of effects.

The coupling of Thermal Vapor Compression (TVC) systems with MED units (MED-TVC) is more extended and implemented in the industry. It has been proved that it can increase the energetic performance of the plant by 30–40% on the conventional LT-MED process. The integration of MED-TVC units into Rankine cycle power blocks of CSP plants, where the thermocompressor or steam ejector is fed by one of the steam extractions of the turbine, has been proposed as a preferable option to the use of the LT-MED units. This is due to the possibility of decoupling the fresh water and power productions. It thus provides more flexibility to the operation of the plant and permits to adapt both productions to the daily or seasonal demands. Also, there is no need to replace the condenser of the power cycle as in the case of the LT-MED, and it allows the steam to be expanded completely through the turbine. Moreover, the thermal efficiency of the MED-TVC unit is significantly increased in comparison with the LT-MED plants [7,15].

Most of the MED-TVC plants use conventional thermocompressors, which are designed for a fixed motive steam pressure and can only operate at an acceptable efficiency with motive steam pressures close to the design value. When these plants are integrated into the power block of a CSP plant, it is needed to adapt the steam ejectors to the operation under variable ambient conditions (the part load operation of the power block due to variable solar radiation leads to changes in the pressure of the steam extractions from the turbine). This is only possible with the use of variable nozzle thermocompressors because they can modify the motive steam mass flow rate with a spindle located inside the nozzle, which changes its cross-sectional area. Thus, the mass flow rate of motive steam can be kept constant or varied for convenience when the motive steam pressure changes at part load conditions, always operating with the maximum possible efficiency.

Although the literature related to the use of variable nozzle thermocompressors is scarce, the advantages of this kind of ejectors in MED desalination plants using steam from a power plant have been already pointed out by several authors. Desportes [16] showed its use in the Huanghua Project in China. In that project, which was aimed to produce both power and water, a combined cycle power plant with two generation blocks of 600 MW fed two MED-TVC units with four effects and a capacity of