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Analysis of a single-effect mechanical vapor compression desalination system using water injected twin screw compressors

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HIGHLIGHTS

- A single-effect MVC system using a water-injected twin screw compressor was proposed.
- A mathematical model was developed for analysing the performance of such an MVC system.
- The operational characteristics of the twin screw compressor were investigated.
- The single-effect MVC performance was compared with data reported in literature.
- The effect of key parameters on system performance was investigated.

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ABSTRACT

The mechanical vapor compression (MVC) desalination system is very attractive and competitive for small and medium scale water production. This paper presents a comprehensive analysis of a single-effect MVC desalination system using water injected twin screw compressors. The operational characteristics of the twin screw compressor including inlet volume flow rate, compressor pressure ratio, and mass fraction of injected water are investigated. The specific power consumption and the specific heat transfer area of the MVC system are then analyzed based on these characteristics. The results are comparable with data reported in literature for similar single-effect MVC desalination systems. Further comparison is performed for a single-effect MVC system using a twin screw compressor with/without water injection. The results demonstrate that the single-effect MVC desalination system using water injected twin screw compressor is a very promising technology for water production capacities less than 600 m^3/d. It also shows that the temperature difference between boiling vapor and compressed vapor at compressor exit can be as high as 10 °C.

1. Introduction

Global water scarcity has increased substantially in past decades due to continuous population growth, decreasing rainfall, improved living conditions and increasing industrial pollution of existing water resources. It is a serious and urgent problem worldwide. Eighty eight developing countries that are home to half of the world's population are experiencing water scarcity. In these places, 88–90% of all diseases and 30% of all deaths result from poor water quality [1]. The number of people affected is expected to increase fourfold over the next 25 years [2]. Desalination of seawater or brackish water is one of the possible solutions to assist in alleviating this problem.

Desalination can be achieved by many techniques which can be classified into two main categories: Membrane processes such as reverse osmosis (RO) and thermal processes including multi-stage flash distillation (MSF), multi-effect distillation (MED), thermal vapor compression (TVC) process, mechanical vapor compression (MVC) process and thermally driven adsorption desalination. Among the thermal processes, the MVC process is one of the promising, low temperature desalination methods. It is considered a viable desalination option to replace RO systems due to advantages such as: compactness; efficient utilization of energy; easy integration with conventional desalination systems such as MSF or MED and other renewable systems such as solar, geothermal and waste thermal system; the small amount of civil work and limited erection requirements; low capital cost; high level of water quality; ease of operation and transportability [3]. It is very attractive and competitive for water production capacities less than 5000 m^3/d [4,5]. Market data shows the rapid progress and expansion of MVC systems, especially in the single effect configuration [6,7].

The MVC desalination system has been experimentally and theoretically studied over the past few decades. In the experimental research, Lucas and Tabourier [8] reported design and performance data for a 1500 ton/day MVC system installed in the nuclear power

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Nomenclature

A	Heat transfer area, m^2
BPE	Boiling point elevation, °C
C_p	Specific heat at constant pressure, kJ/(kg·K)
d	Tube diameter, m
h	Heat-transfer coefficient, kW/(m^2·°C)
H	Enthalpy, kJ/kg
k	Thermal conductivity, kW/(m^2·K)
$LMTD$	Logarithmic mean temperature difference, °C
m	Mass flow rate, kg/s
Q	Heat transfer rate, kW
r	Fouling resistance, (m^2K)/kW
s	Salinity, g/kg
S	Entropy, kJ/(kg K)
T	Temperature, °C
$\triangle T$	Temperature difference, °C
U	Overall heat transfer coefficient, kW/(m^2·K)
W	Power consumption of compressor, kW
X	Salinity, ppm
x	Mass fraction of injected water

Greek symbols

η_c	Transmission efficiency of compressor
η_{ad}	Adiabatic efficiency of compressor
λ_s	Latent heat of steam condensation, kJ/kg
λ_v	Latent heat for evaporation, kJ/kg

Subscripts

1	Inlet of compressor
2	Outlet of compressor
B	Brine
C	Condensate
cw	Intake seawater
D	Distillate
f	Feed
HEX	Heat exchanger
i	Inject
o	Outlet
S	Steam for condensing
trans	Heat transfer

Superscripts

vap	Vapor
liq	Liquid water

plant of Flamanville, France. Average energy consumption was about 11 kWh/m^3. Veza [9] reported on the reliability of two single effect MVC units installed in the Canary Islands in 1987 and 1989. The water production rate of these two units is 500 m^3/d and the plant factor is 90% with a low temperature operation around 60 °C. The specific power consumption is between 10.4 and 11.2 kWh/m^3. Aly and Fiqi [10] investigated thoroughly the thermal performance of a 5 m^3/d MVC system. The experimental and theoretical results indicated that water production rate increases with increasing operating temperature from 70 to 90 °C, and evaporator temperature has a large effect on the heat transfer coefficient. Bahar et al. [11] conducted an experimental study on a 1 m^3/d MVC desalination plant. They evaluated the performance of the MVC system under variable conditions including brine flow rate, compressor rotational speed, and feed concentration. The results showed that system performance increased with lower salinity concentration and high compressor speed. Water production increased with low feed concentration and high brine flow rate. The highest performance ratio obtained was 2.52.

A number of mathematical models of the MVC system have been developed. Darwish [12] developed a simple mathematical model which provides a useful and quick estimation of various system properties. Al-Juwayhel et al. [13] improved the model to provide performance evaluations for various single-effect MVC systems. Ettouney et al. [14] further improved the model by incorporating more details for calculating the heat transfer area of the evaporator, the plate preheaters, and the compressor power. Aybar [15] developed a mathematical model using mass and energy balance equations in addition to an LMTD method for heat transfer analysis. The study focused on the operational characteristics of low temperature MVC systems. It mainly included three independent parameters – evaporation side pressures, condensation side pressure and water inlet temperature – and their effects on compressor work. Recently, Ettouney et al. [16] developed a more detailed design model which studied the characteristics of the MVC system as a function of design and operating parameters. It investigated specific power consumption and specific heat transfer area, in addition to new design features such as dimension of evaporator, demister and ventilating orifice. The results showed a noticeable decrease in specific power consumption and heat transfer area at elevated MVC inlet temperatures. It also showed that the specific power consumption decreases when a low temperature difference exists between the boiling brine and steam condensate, while the specific heat transfer area increases. Desportes and Scharfe [17] presented another design model which investigated the basic design parameters of MVC systems. They compared the design of two 1500 m^3/d units and highlighted key parameters that improve the energy efficiency in the range 14 – 17 kWh/m^3 to below 9 kWh/m^3. More recently, Alasfour et al. [18] theoretically studied the thermal performance of the MVC desalination system using a steady state mathematical model based on the first and second laws of thermodynamics. Results showed that as temperature drop across the compressor stage increases, the specific power consumption increases, and water production decreases. On the other side, as the MVC brine temperature increases, the specific heat transfer area decreases.

Although the MVC system has been widely studied, it has not been widely applied in industry due to various technical barriers. One of the most pressing problems is the absence of a purpose-built steam compressor. There are three different ways to compress steam, as shown in Fig.1. Line 1 represents dry steam compression in which the

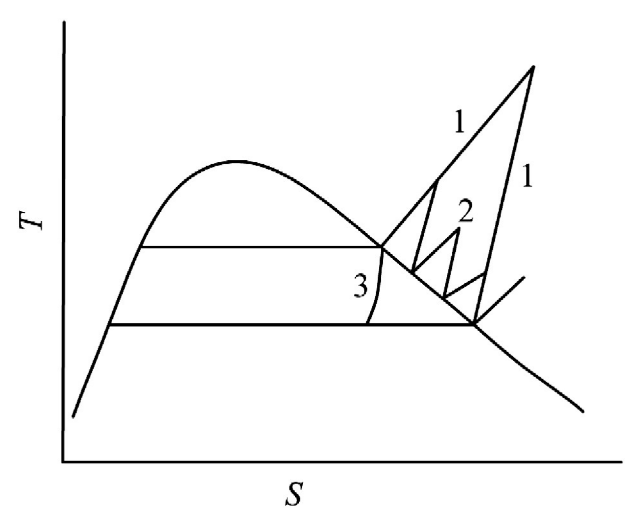

Fig. 1. Three different steam compression processes plotted in a T–S diagram.