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Integration of thermo-vapor compressor with multiple-effect evaporator

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HIGHLIGHTS

- Energy integration of thermo-vapor compressor with multiple-effect evaporator.
- Proposed a new methodology for optimal placement of thermo-vapor compressor.
- Extended Pinch Analysis for overall energy conservation.
- Obtained simultaneous reduction in evaporator area requirement and energy consumption with optimal integration.

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ABSTRACT

Thermo-vapor compressor (TVC) is used for compressing the low-pressure vapor with the help of the high-pressure motive steam, to produce the medium pressure vapor. A substantial portion of energy may be conserved by integrating TVC with the multiple-effect evaporator (MEE). The common practice in desalination industry is to compress the vapor produced in the last effect of a MEE using TVC to reduce the overall motive steam requirement. Such integration does not necessarily guarantee energy optimality. The objective of the present work is to optimally integrate TVC with a MEE system to maximize the gain output ratio (GOR). GOR is defined as the ratio of the mass flow rate of vapor produced in MEE to the mass flow rate of the motive steam supplied to TVC. GOR is the measure of the energy efficiency of MEE system. Using the principles of Pinch Analysis and techniques of mathematical optimization, a new methodology for integration of TVC with MEE is proposed in this paper. This is the first analytical methodology to optimally integrate TVC with MEE, avoiding multiple simulations of the overall system. A Theorem is proposed to directly calculate the optimal location of TVC suction position. The proposed methodology gives the designer the freedom to design an MEE-TVC with minimum energy consumption and without carrying out the detailed simulation of the entire system. The methodology is demonstrated through the illustrative case studies for concentrating corn glucose, and freshwater production through thermal desalination. In the case of corn glucose, the optimal integration of TVC with 2-effect MEE resulted in the increase in GOR by 10.1% with a decrease in the specific area requirement by 4.1%. For a desalination system with 11-effect MEE, the optimal integration of TVC improves the GOR by 1.5% and reduces the specific area by 4.3%. Furthermore, sensitivity analysis is carried out to determine the optimal operating parameters for both case studies.

1. Introduction

Multiple-effect evaporator (MEE) is used for increasing the concentration of a solution. In MEE, the vaporization takes place in stages. In freshwater production through desalination, the energy cost for the MEE is about 20–30% of the total water cost [1]. Similarly, energy consumption in MEE for tomato industry is about 60% [2]. Therefore, a standalone MEE is an energy intensive device. A substantial amount of energy can be recovered by integrating MEE with a thermo-vapor compressor (TVC) [3]. The vapor produced in the last effect of MEE needs to be cooled before being discharged. Generally, a large portion of the last effect vapor goes out as waste, even after heat recovery through feed preheating. Instead, this vapor can be recompressed in a thermo-vapor compressor (TVC) with the help of the high-pressure motive steam, to produce the medium pressure vapor that can act as a heat source for MEE. Basically, TVC is thermodynamically equivalent to a heat pump. Recompression of vapor gives two benefits; the decrease in external hot utility requirement for MEE and the decrease in the cold utility requirement. Apart from TVC mechanical vapor compressor can also be used for reducing the energy

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Nomenclature

A	area (m^2)
CR	compression ratio
CU	cold utility (kW)
dV	change in vaporization (kg/s)
E	distance by which effect is shifted away from pinch (kW)
ER	expansion ratio
$f(TVC)$	ratio signifying the GOR for MEE-TVC system
F	feed flow rate (kg/s)
h	liquor enthalpy (kJ/kg)
H	vapor enthalpy (kJ/kg)
HU	hot utility (kW)
K	total number of effects
l	liquor flow rate (kg/s)
n	effect under consideration
P	pressure (MPa)
R	mixing ratio
S	salinity (g/kg)
T	effect temperature (°C)
U	heat transfer coefficient (W/m^2 K)
V	vapor flow rate (kg/s)
W	total amount of vapor produced by MEE (kg/s)
X	concentration

Greek letter

δ	desired accuracy
Δ	change
λ	latent heat of vaporization (kJ/kg)

Subscript

Cond	condenser
conden	condensate
e	extracted vapor
evap	evaporator
f	feed
H/E	heat exchanger
i	effect number
j	effect number
in	inlet
m	medium pressure vapor
max	maximum
min	minimum
out	outlet
p	product
s	specific
sat	saturation
0	motive steam

Superscript

new	updated value
′	modified value

Abbreviations

BPR	boiling point rise
GCC	grand composite curve
GOR	gain output ratio
MEE	multiple-effect evaporator
MOO	multi-objective optimization
MPTA	modified problem table algorithm
TBT	top brine temperature
TVC	thermo-vapor compressor

consumption of MEE [4]. Mechanical vapor compressor uses electrical energy for compressing the low-pressure vapor [5].

Hamed and Ahmed [6] carried out simple energy analysis and showed that by integrating TVC with MEE system, the gain output ratio (GOR) can be increased up to 70%. GOR is defined as the ratio of mass flow rate of vapor produced by MEE to the mass flow rate of motive steam supplied. GOR is the measure of the energy efficiency of MEE. Higher the GOR, more energy efficient is the MEE. Darwish and El-Dessouky [7] demonstrated that by integrating TVC with a 4-effect MEE, the GOR becomes almost equal to an 11-effect standalone MEE and 24-stage flash desalination system. Chun-hua [3] showed that with the integration of TVC the GOR for desalination system increases, and so does the freshwater production rate.

The performance of an integrated MEE-TVC system is dependent on operating parameters (temperature, pressure, etc.) of vapor and steam. Al-Juwayhel et al. [8] showed that the GOR for TVC integrated with single effect desalination system increases with increase in pressure and temperature of the motive steam. Similar results were reported for MEE-TVC system by El-Dessouky et al. [9]. Kamali et al. [10] showed that with variation in motive steam flow rate with respect to design point, the GOR for MEE-TVC system decreases. Bin Amer [11] calculated optimal design parameters of TVC, to maximize the GOR for the system. Optimal values for operating temperatures were also suggested. Samake et al. [12] suggested operating TVC at a high compression ratio (ratio of the discharge pressure to the suction pressure of a TVC) which was contrary to the existing result [11]. It was found that with the increase in compression ratio the exergy efficiency increases, without any penalty on freshwater flow rate. Han et al. [13] preheated the low-pressure vapor extracted from MEE to improve the performance of MEE-TVC system. Due to preheating of low-pressure vapor, the chances of vapor condensation in TVC reduced. It may be noted that in all these studies, the low-pressure vapor produced from the last effect of MEE is compressed using TVC.

Location of TVC vapor suction position from MEE plays an important role in minimizing the overall energy consumption in MEE-TVC system. Alasfour et al. [14] studied three different configurations for 6-effect MEE: MEE-TVC without heater, MEE-TVC with heater, and MEE-TVC with vapor extraction from the third effect. The second configuration was more energy efficient due to the presence of heater, whereas the third configuration gave the minimum area requirement. Kouhikamali et al. [15] studied the effect of a change in the location of the TVC vapor suction position for a desalination system. GOR for the system increased from 9 to 9.3, as the suction pressure of entrained vapor was moved from the last to the middle effect [15]. Galván-Ángeles et al. [16] found that the GOR for 4-effect MEE for milk processing plant was higher when TVC was placed after the second effect in comparison to other effects. Sayyaadi et al. [17] used multi-objective optimization (MOO) to simultaneously minimize the cost of distillate produced and to maximize the exergy efficiency for a desalination system and concluded that the last effect is the optimal location for TVC vapor suction. Similarly, Dadhah and Mitsos [18] used MOO to minimize the specific area for a 12-effect MEE and to maximize the GOR for the system. It was observed that by varying the TVC suction position from the last to an intermediate effect, GOR