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Solar assisted multiple-effect evaporator

Prashant Sharan, Santanu Bandyopadhyay*

Department of Energy Science and Engineering, Indian Institute of Technology Bombay, Powai, Mumbai 400 076, India

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ABSTRACT

Multiple-effect evaporator (MEE) is used for concentrating the liquor. A substantial energy saving can be achieved by integrating MEE with a thermo-vapor compressor (TVC). TVC is a device in which the low-pressure vapor produced from MEE is compressed with the help of the high-pressure motive steam supplied externally, to produce a medium pressure vapor. This medium pressure vapor acts as a heat source for MEE. The high-pressure motive steam can be produced from concentrating solar thermal system, which is a renewable and non-polluting source of energy. The present study deals with the integration of linear Fresnel reflector (LFR) with MEE-TVC system. The objective of the present work is to minimize the total annual cost for the integrated MEE-TVC and LFR system. The important parameters affecting the annual cost for the integrated system are solar design radiation and temperature of the motive steam. A methodology is developed to determine the optimal solar radiation and steam temperature. The proposed methodology is demonstrated through a case study for manufacturing of corn glucose. The annual cost for the system is 87,106 \$/y, with optimal steam temperature 250 °C and optimal design radiation 600 W/m^2. Sensitivity analysis is also carried out for the selection of the optimal operating parameters. The cost of the auxiliary heating source plays a dominating factor on the economic feasibility of the integrated system.

1. Introduction

Solar thermal systems are useful in reducing the fossil fuel consumption and green-house gasses emission (Desai and Bandyopadhyay, 2015a). Flat plate collector and evacuated tube collector are commonly used for low temperature process heat applications, like water heating (Sánchez-Bautista et al., 2014), desalination (Ranjan and Kaushik, 2014), etc. For high operating temperature range, concentrating solar thermal (CST) systems are preferable. The CST technologies can be classified as paraboloid dish, solar power tower, parabolic trough collector (PTC) and linear Fresnel reflector (LFR) (Desai and Bandyopadhyay, 2015b). Paraboloid dish, solar power tower are point focusing type solar concentrator. They are used for very high temperature application, in the range of 500 °C (Avila-Marin et al., 2013). PTC and LFR are line focusing type solar concentrator. PTC is ideal for process heat in the temperature range of 120–250 °C (Fernández-García et al., 2015).

The solar thermal system can also act as a heat source for multiple-effect evaporator (MEE). MEE is used for increasing the concentration of the solution. MEE finds its application in various industries like food processing, desalination, pulp and paper, etc. In MEE the vaporization takes place in stages. The steam coming from a solar thermal system can act as a heat source for the first effect of MEE, and the feed liquor gets partially concentrated and produces vapor. This vapor acts as a heat source for the second effect of MEE, where the liquor gets further concentrated and the process continues until the last effect of MEE. El-Nashar (2001) studied the economic feasibility of using solar energy over conventional energy source for MEE based desalination system for the remote area. They concluded that with decreasing solar cost and increasing local cost for procuring conventional fuel, solar energy based MEE system can be economical. Souza et al. (2008) integrated flat plate collector with MEE for concentrating the industrial effluents. The performance of the system was dependent on the inclination of the collector and the feed flow rate. Jiang et al. (2009) used the solar collector to heat the seawater up to 78 °C. The heated seawater was flashed in a flash tank to produce vapor, which acted as a heat source for MEE. Joo and Kwak (2013) developed an experimental setup to produce 3 m^3 per day of desalinated water from 3-effect MEE system. The hot water coming from the solar collector acts as a heat source for the first effect of MEE. Results showed with an increase in hot water temperature the energy required to produce a

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* Corresponding author.
E-mail address: santanub@iitb.ac.in (S. Bandyopadhyay).

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Nomenclature

A	Area (m^2)
C	cost ($)
Cp	specific heat (kJ/kgK)
CR	compression ratio
CRF	Capital recovery factor (y)
CU	cold utility (kW)
d	Discount rate (%)
DF	dryness fraction (%)
DNI	Direct normal irradiance (W/m^2)
E	amount by which each effect is shifted away from pinch (kW)
ER	expansion ratio
f	fraction of annual energy supplied by solar
$f(I_C)$	cumulative hours corresponding to cut of radiation
$f(I_D)$	cumulative hours corresponding to design radiation
h	liquor enthalpy (kJ/kg)
H	vapor enthalpy (kJ/kg)
HU	hot utility (kW)
I	Radiation (W/m^2)
IAM	Incident angle modifier
L	life of equipment (y)
M	Mass flow rate of water (kg/s)
n	effect under consideration
P	Pressure (Pa)
R	mixing ratio
Q	heat (kW)
SPP	simple payback period (y)
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
Y	yearly operating hours (h)
Yr	yearly auxiliary heating required (kWh)
z	ratio of maintenance cost to capital cost ($/y)
i, ii … …x	state points

Subscript

a	ambient
avg	mean temperature difference between ambient and solar collector
annual	annualized cost
aux	auxiliary heating
C	cut off point
capital	capital cost for the integrated system
cond	condenser
D	design point
e	extracted vapor
elec	cost of electricity
evap	evaporator
feed	feed flowing into the MEE
H/E	heat exchanger
in	inlet
l	loss from solar collector
land	land requirement for LFR
m	medium pressure vapor
max	maximum
min	minimum
mt	maintenance
solar	solar collector
op	operating
out	outlet
pump	cost of pumping
product	concentrated liquor coming out from MEE
0	motive steam

Superscript

new	updated value
*	non-dimensionalized parameter

Greek Letter

Δ	change
η	efficiency
λ	latent heat of vaporization (kJ/kg)
ρ	density of water (kg/m^3)

Abbreviations

CSP	Concentrating solar power
CST	Concentrating solar thermal
GCC	Grand composite curve
GOR	Gain output ratio
LFR	Linear Fresnel reflector
MEE	Multiple-effect evaporator
MVC	Mechanical vapor compression
PTC	Parabolic trough collector
TVC	Thermo-vapor compressor

unit amount of distillate decreased. Sharan and Bandyopadhyay (2015) integrated the MEE with evacuated tube collector. A methodology to calculate the optimal operating temperature was proposed to minimize the initial investment cost, for a given solar radiation. Ghaffour et al. (2015) carried out an extensive literature survey on the use of solar energy as a heat source for desalination system. Frantz and Seifert (2015) integrated multiple-effect desalination system with solar tower power plant. The freshwater production increased by 50% by increasing the heat transfer area by 30%. Prado et al. (2016) integrated solar dish collector with thermal desalination system. The maximum freshwater production achieved was 4.95 kg per day per unit solar collector area. It might be noted that the standalone MEE is an energy intensive process (Sogut et al., 2010), resulting in higher solar collector area requirement. A solution to this can be integration of MEE with a thermo-vapor compressor (TVC).

TVC is a device in which the low-pressure vapor coming from MEE is compressed with the help of the high-pressure external motive steam. Resulting in the production of a medium pressure vapor, which acts as a heat source for the MEE. Integration of MEE with TVC leads to a simultaneous reduction in cold and hot utility requirement. Hamed and Ahmed (1994) showed that by integrating MEE with TVC system, the gain output ratio (GOR) for 4-effect desalination system can be increased by 70%.GOR is defined as the ratio of mass of vapor produced by MEE to the mass of external motive steam supplied. GOR is the measure of the energy efficiency of MEE. The pressure of motive steam used for compressing the low-pressure vapor in TVC plays an important role in the thermal performance of MEE. Al-Juwayhel et al. (1997) found that the performance of TVC increases with increase in pressure of motive steam for a single effect evaporator.

The temperature of motive steam required in TVC is in the range