THERMAL PERFORMANCE OF MULTI-EFFECT DESALINATION SYSTEM ENERGIZED BY PARABOLIC TROUGH CONCENTRATING SOLAR SYSTEM

By

Eng. **Ahmed Yahia Youssef Abdel-Azim**

A Thesis Submitted to the
Faculty of Engineering at Cairo University
in Partial Fulfillment of the
Requirements for the Degree of
DOCTOR OF PHILOSOPHY
in
Mechanical Power Engineering

FACULTY OF ENGINEERING, CAIRO UNIVERSITY
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Title of Thesis:

Thermal Performance of Multi-Effect Desalination System Energized By Parabolic Trough Concentrating Solar system

Key Words:

Water Desalination, Parabolic Trough, Multi-Effect, CFD

Summary:

The present work will be divided into two main parts numerical study and experimental work these two parts will cover the modeling & sizing of Solar MED main components which include MED 6 effects unit, steam generator and three ejectors. The three ejectors are used to create the required vacuum within the MED unit. Second point for the numerical part is CFD simulation for the flow inside the three ejectors, the simulation is carried on (ANSYS Fluent 18.2). The experimental part starts with manufacturing of Solar MED main components, then installation of Solar MED plant and finally evaluation of the Solar MED plant thermal performance.

Performance ratio and recovery ratio is used to evaluate the thermal performance of the operating Solar MED plant, The system has variation of performance ratio from 1.5 and up to 4.3, while the achieved recovery ratio is (33.7 – 47)%.

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Nomenclature

A	Area	m^2
a	sonic velocity	m/s
Ar	Archimedes number of water outside tubes	---
C_b,	brine water salt concentration	ppm
C_f,	sprayed feed water salt concentration	ppm
C_p	specific heat of gas at constant pressure	kJ/kg.K
C_v	specific heat of gas at constant volume	kJ/kg.K
d_i	inner tube diameter	m
d_o	outer tube diameter	m
g	acceleration of gravity vector	m/s^2
G_{in}	inlet mass velocity of water inside tubes	m/s
G_{out}	outlet mass velocity of water inside tubes	m/s
$F_{env,n}$	Ratio of entrained vapor mass flow rate from the last effect to that of the last effect brine vapor	---
h_b	brine water enthalpy	kJ/kg
h_c	outlet water enthalpy	kJ/kg
h_d	distillate water enthalpy	kJ/kg
h_f	sprayed feed water enthalpy	kJ/kg
h_g	evaporated steam enthalpy	kJ/kg
h_i	inside hear transfer coefficient	$W/m^2.K$
h_v	motive steam inlet enthalpy	kJ/kg
$H_{e,b}$	brine well height	m
K	thermal conductivity	W/m.K
k_{fi}	inside tube water thermal conductivity	W/m.K
k_{fo}	outside tube water thermal conductivity	W/m.K
M	Mach number	---
$\dot{m}_b$	brine water mass flow rate	kg/s
$\dot{m}_c$	water mass flow rate inside tubes	kg/s
$\dot{m}_{ev}$	evaporated steam mass flow rate outside tubes	kg/s
$\dot{m}_f$	inlet feed mass flow rate	kg/s
$\dot{m}_s$	inlet steam mass flow rate	kg/s
N_{med}	MED number of tubes per pass	---
N_{uo}	Nusselt number of water outside	---
P_i	pressure inside tubes	Pa
$P_{o,i}$	pressure outside tubes	Pa
P_v	vertical tubes pitch	m
$Pr_{f,i}$	Prandtl number of water inside tubes	---
$Pr_{f,o}$	Prandtl number of water outside tubes	---
Q_{med}	Heat transfer rate to evaporator tubes	W
R	Gas constant	kJ/kg.K
Ra	The ratio of the motive steam mass flow rate to that of the entrained vapor from the last effect	---
Re_m	Reynolds number inside tubes	---

Re_o	Reynolds number outside tubes	---
S	Tubes total surface area	m^2
T_f	sprayed feed water temperature	^oC
T_i	temperature inside tubes	^oC
T_o	temperature outside tubes	^oC
V	Stream velocity	m/s
v_s	inlet steam velocity	m/s
X_{in}	inlet steam quality	---
X_{out}	outlet steam quality	---
Z	Number of passes	---

Greek letters

ω	entrainment ratio	---
γ	C_p/C_V	---
$\boldsymbol{\theta}$	Temperature difference	°C
$\boldsymbol{\theta}_{LMTD}$	Logarithmic mean temperature difference	°C
$\boldsymbol{\mu}_{f,i}$	dynamic viscosity inside tubes	Pa.s
$\boldsymbol{\mu}_{f,o}$	dynamic viscosity outside tubes	Pa.s
$\boldsymbol{\rho}_b$	brine density	kg/m^3
$\boldsymbol{\rho}_{f,i}$	Fluid density inside tube	kg/m^3
$\boldsymbol{\rho}_g$	Steam density	kg/m^3
$\boldsymbol{\tau}$	residence time	sec

Abbreviations

C.S.A	Constant Cross Section Area duct
CFD	Computational Fluid Dynamic
EES	Engineering Equation Solver
GOR	Gain Output Ratio
HRN	High Reynolds Number approach
LT-HT-MED	Low Temperature Horizontal Tube Multi-Effect Desalination
MED	Multi Effect Desalination
MEE	Multi Effect Evaporation
MSF	Multi-Stage Flash
NCG's	Non-condensable Gases
PCF	Motive Steam Pressure Correlation Factor
PPt	Par Per Thousands
PSA	Plataforma Solar de Almeria
PR	Performance Ratio
RO	Reverse Osmosis
RR	Recovery Ratio
TAC	Total Annual Cost
TVC	Thermal Vapour Compressor
TBT	Top Brine Temperature
TCF	Entrained Vapour Temperature Correlation Factor
UPC	Unit Product Cost

Abstract

Per the UN's Sustainable Development Resolution Report, 40% of the world's population already faces water stress and water scarcity. Water desalination is one of the solutions to overcome the global water shortage crisis and curb its emergence due to population growth and climate change. Multiple Effect Distillation (MED) is the oldest thermal water desalination process and it has typical plant capacities of 600 - 300,000 m^3/day. Because MED units do not use membranes, the investments, system complication, and operating costs are usually less than those for reverse osmosis (RO) units.

The present work will be divided into two main parts numerical study and experimental work these two parts will cover the modeling & sizing of Solar MED main components which include MED 6 effects unit, steam generator and three ejectors. The three ejectors are used to create the required vacuum within the MED unit. Second point for the numerical part is CFD simulation for the flow inside the three ejectors, the simulation is carried on (ANSYS Fluent 18.2). The experimental part starts with manufacturing of Solar MED main components, then installation of Solar MED plant and finally evaluation of the Solar MED plant thermal performance.

The novelty and originality of the present work is related to the ejector thermodynamic modeling since the present work will introduce the polytropic efficiencies instead isentropic efficiency for the primary nozzle and diffuser sections, additional to that is assuming that the mixing between the primary stream and secondary stream isn't done at single cross section but it occurs over length and it occurs at constant pressure. The final point related to the thermodynamic model of the ejector is that the mixing efficiency isn't not chosen arbitrarily, it is calculated from operating conditions. For the MED unit, the stack geometry will be used instead of the conventional geometry. As the work will be validated by experimental setup, a crucial issue is the matching between solar thermal system and the MED unit through the ejectors.

It is considered that this experimental setup (Solar MED Plant) is the first pilot in the Middle East, Thus components manufacturing and installation of the system is considered a big challenge also the installation and operation of the whole system and overcoming all problems during commissioning and operation.

It was concluded that using polytropic efficiency in the ejector 1-D thermodynamic model gives good matching with to reality except the no show of the shock-wave train. Also assuming mixing process occurred in the ejector at constant pressure gives consistent results with the CFD simulation. A change of 2% in the throat area of the steam ejector will affect its performance and the required target back pressure, this conclusion was done by simulating the flow using (ANSYS Fluent 18.2).

Using Stack MED type is efficient during operation with less needed space, less vacuum leakage, less investment and maximizes the thermal performance with lower evaporation temperature to decrease the fouling formation rate.

Performance ratio and recovery ratio is used to evaluate the thermal performance of the operating Solar MED plant, The system has variation of performance ratio from 1.5 and up to 4.3, while the achieved recovery ratio is (33.7 – 47)%.

The Solar MED plant which can meet daily demand of distilled water of average 10 m^3 was installed in Sheikh Zaid branch of the Faculty of Engineering, Cairo University. A parabolic trough solar collector with 135 m^2 aperture area is used to heat thermal oil to around 140 ^0C to be stored in 2.2 m^3 storage tank. Then steam generator is generating saturated steam at 2 bar for the three ejectors to create the needed vacuum for the 6 effects MED unit. Currently the plant is working with fully automated tracking system and control system to optimize its thermal performance. The 1st trail has been done by distilling 750 ppm water to reach product with 150 ppm. Over 95 % of the Solar MED system components were locally manufactured.

Keywords: Thermal vapor compression; Desalination; Multi-effect, Parabolic Trough, Entrainment Ratio