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A composite desirability function-based modeling approach in predicting mass condensate flux of condenser in seawater greenhouse

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HIGHLIGHTS

- A new empirical model is introduced for predicting mass condensate flux.
- Composite desirability function methodology is implemented for modeling purpose.
- Various descriptive statistical indicators are tested for the prediction accuracy.
- Proposed formulation showed adequate performance and produced small residual errors.
- Condenstation process is reformulated as a novel and practical manner.

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ABSTRACT

The main aim of this paper was the development of a new empirical model based on the composite desirability function methodology for predicting mass condensate flux of a condenser in a seawater greenhouse located at Al-Hail, Muscat, Oman. The computational analyses were conducted for simulating relative humidity of inlet dry air, inlet temperature of humid air (dry bulb temperature), temperature of the seawater at the inlet, mass flow of humid air input, and mass flow of seawater at the inlet. The performance of the proposed empirical model was assessed by means of various descriptive statistical indicators. The comparison of the proposed approach with existing condensation data exhibits very good precision of the developed composite desirability function-based model in predicting the mass condensate flux for the condenser process. The proposed mathematical formulation eliminated the various complex variable interactions and many unit conversions usually carried out in the theoretical approach.

1. Introduction

Providing water for agriculture is the primary stressor in arid regions [1]. This is because these areas are already struggling with a shortage of fresh water, high salinity soil, high temperatures, and increased shortage of groundwater [2].

Seawater greenhouses are a type of technology that offers sustainable solutions to these problems by providing desalination and cooling in one structure. Hence, the technology can be used to enable the growth of the plants in arid coastal regions by providing the fresh water together with the cooler climate that is required to restore active agriculture. The technology depends on the sun, the sea, the atmosphere, and the greenhouse structure. The result is the generation of fresh water and conditions of high humidity and cool air in the greenhouse, thereby allowing plants to be grown. The technology is unique and impressive, as it operates entirely on seawater rather than ground water.

The use of greenhouse-type structures brings about the need to provide properly-designed and efficient installations that are appropriate for the operating conditions and the desalination limits. However, an extensive, published database, much of which is conflicting and incomplete, has caused greenhouse-equipment engineers to greatly misinterpret the operational parameters in their specific condenser designs. In practice, engineers, designers, researchers, manufacturers, and end-users may not have ample time to calculate all the variables of different functions and control complex iterative calculations typically performed using conventional methods [3]. Hence, to respond to these needs, the complicated thermodynamic inter-relationships among a number of system factors in the process may be explicated through a number of attempts to develop a representative prediction model allowing for the investigation of the key variables in greater detail. For this reason, an appropriate data set that depends on the suitable

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Nomenclature

a	coefficient of non-linear power-law correlations
CWOA	closed-water open-air
D	diameter of vertical tubes in the condenser (m)
E	energy (kWh/day)
EC	energy consumption (kWh/m^3 or kWh/day)
h	heat transfer coefficient
I	importance of non-linear independent parameter equations
L	length of seawater greenhouse (m)
m	mass flow rate (kg/s or kg/h)
MSF	multi-stage flash
n	number of data
N	number of longitudinal or transverse tubes
O	observed value
P	predicted value
Re	Reynolds number
RH	relative humidity of inlet dry air (kg of water vapor/kg of dry air)
RO	reverse osmosis
S	pitch value (mm)
T	temperature (°C)
W	width of seawater greenhouse (m)
WP	water (condensate) production (m^3/day)
x	x-axis of non-linear power-law correlations

Greek symbols

η	efficiency (%)
σ	standard deviation

Subscripts

air	air
c	condensate
cce	corrected combined equation
ce	combined equation
cor	corrected
D	diagonal
dbin	dry bulb inlet
dbout	dry bulb outlet
i	data number
in	inlet
L	longitudinal
m	model
min	minimum
out	outlet
p	particular value
R	ratio
S	systematic
sat	saturation
sw	seawater
swin	seawater inlet
swout	seawater outlet
t	theoretical
T	transverse
TE	thermal energy
TOT	total
U	unsystematic

ranges of input variables should be considered to obtain good performance and yield reliable outputs for the proposed model. Furthermore, verification should be conducted for the validity of the model predictions for a reasonable amount of testing data taken from different outputs. A representative mathematical formulation can provide a significant potential for solving operational problems and testing control strategies in order to meet effluent quality requirements at a reasonable cost. Moreover, model results can also be appraised for various operating scenarios before transferring the design concepts to a full scale plant [3].

Modeling and simulation of the condenser process that occurs in a seawater greenhouse has been considered by many investigators to enhance the performance of the greenhouse [4–12]. However, there are very few systematic papers regarding the implementation of different mathematical analogies that lead to the formulation of novel prediction models that can directly be used to design a condenser in a seawater greenhouse. To the best of the authors' knowledge, the present work is the first study primarily devoted to a study of composite desirability function-based empirical modeling for the prediction of mass condensate flux in a seawater greenhouse. It is expected that this kind of approach, in a straight forward manner, will meet the multi-objective criteria by building a composite response surface, either as a composite or combined function, from individual response surfaces of each independent operating variable. The present technique is flexible and also allows the incorporation of new operating parameters concerning a specific problem [3].

The main objective of this study was to develop a simple tool for researchers, engineers, and students, which makes it possible to efficiently determine the mass condensate flux in a seawater greenhouse without the use of the theoretical procedure given in the literature. The main objectives of this study were: (1) to demonstrate a novel application of composite desirability function-based empirical modeling to the general condenser design problem; (2) to make available a newly developed mathematical formulation in order to eliminate different complicated interactions of process variables, time-consuming calculations, and conversion of units usually carried out in the theoretical approach; (3) to confirm if the proposed model is valid by various performance indicators; and (4) to ensure that practical novel references are provided to the designers of the condenser, the researchers, the manufacturers, the greenhouse-equipment engineers, and the industries that are the end-users making use of the most common operating parameters, which include relative humidity of inlet dry air, inlet temperature of humid air, temperature of the seawater at the inlet, mass-flow rate of humid air input, and mass-flow of seawater at the inlet.

2. Methodology

2.1. Description of seawater greenhouse process

The seawater greenhouse is a desalination process that uses air humidification and dehumidification. The idea of its operation simulates the hydrological cycle of water in nature. First, the seawater is heated by the sun. Next, it evaporates. Third, it cools to form clouds. Finally, it returns to the earth in the form of rain and fog. Therefore, the process of the seawater greenhouse depends on the initiation of a natural hydrological cycle within the actual environs of the greenhouse (Fig. 1) [13]. The greenhouse offers desalination, cooling, and humidification in one integrated structure.

The Oman seawater greenhouse has dimensions of 4.8 m high, 16 m wide, and 45 m long. The cycle of the seawater begins by supplying the cold storage tank with incoming seawater. The seawater is then passed through the tubes of the condenser, where it is sent to the first cooling evaporator at the front wall of the greenhouse. In this first evaporator, the seawater will flow from top to bottom, whereas the air will flow in a perpendicular direction. This air will be introduced into the seawater greenhouse and controlled by two fans that are installed on the opposite side (back side) of the greenhouse. The evaporation of the seawater in the first evaporator allows the air leaving it to be relatively cold and humid (i.e., first humidification process of the air). This greenhouse