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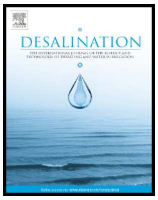

Impacts of tube bundle arrangement and feed flow pattern on the scale formation in large capacity MED desalination plants

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HIGHLIGHTS

- A new model of the seawater feed distribution is developed for MED evaporator.
- $CaCO_3$ scale deposit model is developed for triangle pitch tube bundle of MED.
- Tubes based on the 2nd row experience more $CaCO_3$ scale deposit of the 1st row.
- Modified feed flow and tube pitch increase reduce the scale precipitation thickness.

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ABSTRACT

The aim of the present work is to evaluate the effect of tube bundle arrangement and the seawater feed distribution on the dry zone and scale formation in the large sized Multiple Effect Distillation (MED) evaporator.

A mathematical model of the seawater feed distribution is developed and validated for a triangular pitch tube bundle of MED evaporator. The developed model includes $CaCO_3$ scale formation and CO_2 release. The simulation results showed that the dripping seawater flow rate on the column based on the 2nd row is lower than that of the 1st row. Consequently, the wetting rate of the tubes in the column based on the 2nd row is less than that based on the 1st row. This explains why the tubes based on the 2nd row experience more $CaCO_3$ scale deposit than that based on the 1st row.

The simulation results showed that increasing the feed seawater to twice that of the original flow will reduce the scale thickness by 15%. Increasing the tube pitch by twice the diameter will reduce the scale thickness by 30%. The combined effect of modified feed flow and increase in the tube pitch would significantly reduce the scale precipitation thickness.

1. Introduction

Thermal desalination based technologies including Multi Stage Flash (MSF) and Multi Effect Distillation (MED) make up 56% of the current desalination market share in GCC countries, while, 42% of the share is based on Reverse Osmosis (RO) membrane technology respectively [1]. Qatar however, pre-dominantly employs thermal desalination, making up 91% of the market, while RO taking only 8% [1]. This situation reflects the thermal process maturity for large capacity high purity production. The harsh gulf seawater conditions (high temperature, high salinity, high impurity, and sometimes red tide) increase the cost of RO membrane replacement and pretreatment.

Among thermal desalination technology, the MED is considered more energy-efficient and operates at lower specific power consumption than the MSF distillation. The prospective energy efficiency of the MED makes it a suitable option for hybrid thermal and membrane desalination based renewable energy [2]. The new record for MED evaporator unit capacity is 68,400 m^3/day (15 MIGD) developed and constructed by Doosan Heavy industries, which implements multiple tube bundles per effect [3]. The thermal design of the large-capacity unit is limited to certain design criteria in order to maintain a high-efficiency process, such as a minimum wetting rate to avoid dry patch and scale deposit at the lower tube bundle. Falling film evaporation has been widely studied in terms of liquid feed flow rate pattern, distribution method, tube surface structure & aging, tube spacing, heat flux, sub-cooling, and vapor cross-flow [4,5].

In horizontal tube falling-film evaporator, the physical form of the liquid film depends not only on the liquid flow rate leaving the tube row but also on the distance between the tubes in that row. For instance, at low flow rate and wide tube spacing, the liquid flow is usually in a form of droplets at discrete points along the underside of the tube. For the droplet and column flow modes, the liquid usually falls from fixed sites along the underside of the tube. Flow modes of a liquid film falling

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Nomenclature

A	Approach area	m^2
d	Tube diameter	m
D	Distillate flow rate	kg/h
L	Tube length	m
M	Flow rate per cell	kg/h
$m_{b,in}$	Brine mass flow rate inlet to one tube	kg/h
$m_{b,out}$	Brine mass flow rate outlet	kg/h
M_{ev}	Vapor mass flow rate	kg/h
nc	Number of tubes per row	
N_r	Number of tubes per column	
q	Heat flux	W/m^2
R	Recovery ratio	
R_f	Fouling rate	$m^2 \cdot k/w$
P	Flow density	$kg/(m^2 \cdot s)$
Re	Film Reynolds number	
x_b	Bottom brine salinity	kg/kg
x_f	Feed salinity	kg/kg
N_{CO_2}	The desorption rate of CO_2	$mol/(m^2 \cdot s)$
K_L	Mass transfer coefficient	m/s
K_f	Fouling thermal conductivity	w/m. k
k_R	Crystallization coefficient	m/s
k_{SP}	Solubility product constant	$(mol/kg)^2$
Greek symbol		
λ	Latent heat	kJ/kg
Γ	Liquid load	kg/m·s
μ	Seawater viscosity	kg/m·s
ϕ	Tube pitch	m
ρ_{SW}	Sea water density	Kg/m^3
ρ_f	Fouling density	Kg/m^3
ω	Deposition flux	Kg/m^2

on a vertical array of tubes depend principally on the flow rate and the physical properties of the liquid. Extensive studies focusing on the characterization and prediction of falling film flow modes were performed on plain tubes [6–8]. If the flow rate of the liquid film is reduced sufficiently, or if the amount of heat added to the surface is relatively high, the film will be too thin resulting in breakdown and dry patches will appear. These dry patches on the tube surface result in a steep decrease in the heat transfer coefficient. Liquid mal-distribution within the tube bundle can induce very poor performance locally on the lower part of the bundle by tripping the onset of dry-out. Reliable heat transfer data is usually limited to the top three tubes, as they are less affected by any non-ideal liquid distribution and perform relatively well [8]. A large number of influential parameters explain why the minimum flow rate obtained in one system must not necessarily be valid for another system under similar conditions.

The most general recommendation regarding the wetting of horizontal tube bundle evaporation seems to be that of Lorenz and Yung [9]. They used a bundle consisting of 30 horizontal tube rows and observed the film flow on the bottom bundle row. The minimum film Reynolds number required for wetting the bottom row was specified as a fixed number (Re = 300) without considering the liquid properties and system design. An expression for minimum flow rate is recommended by Fujita and Tsutusi [10]; this expression was deduced from experiments using refrigerant R-11 as a test fluid falling on only five vertical rows of horizontal tubes heated under a constant heat flux (q) condition as shown below.

$$\mathrm{Re}_{\mathrm{min.}} = \frac{q}{48}. \tag{1}$$

Another equation of minimum Reynolds number has been proposed by Roques and Thome for refrigerant R 134a [11] as shown below:

$$\mathrm{Re}_{\mathrm{min.}} = 164 + 6.8\frac{q}{1000}. \tag{2}$$

A number of equations for wetting rate are evaluated under different load conditions [12]. Some of these equations are independent of heat flux and are not valid for part load operation. The tube bundle pitch is increased up to double the tube diameter, in order to achieve even water distribution among tube bundle columns, consequently, avoiding dry patch phenomena [12]. There is a wide range of discrepancies among the equations, where a number of factors have not been considered such as the impact on the scale deposit.

In addition, the majority of the previous studies were carried out on a small number of tube rows which were mostly square-pitch type tube bundle. However, in the commercial MED evaporator, the tube bundle is arranged in a triangle-pitch. The flow rate distribution tends to be less uniform than a square-pitch arrangement which would be a severe condition due to scale deposition.

Scale deposition is a complex phenomenon that takes place at the same time as CO_2 release. In various investigations concerning scaling in MED distillers, it was found that the scale deposit on the tubes is mainly calcium carbonate $CaCO_3$ [13]. For this reason, a large part of the research based on scale deposition in MED Distillers focuses on calcium deposition. The fouling of this salt is the result of the mass transport of chemical species from the bulk to the liquid solid interface, followed by a crystallization reaction to form $CaCO_3$ scale [13]. However, the model is developed for a vertical tube configuration.

Glade and Al-Rawajfeh [14] developed a model for the prediction of CO_2 release rates for the individual effects of MED distillers at conventional temperature. In addition to the release rates the model allows for the calculation of the concentrations in the carbonate system of the brine. However their model does not take into account the variation of water properties across the bundle.

The various possibilities of coupling reaction kinetics with mass transfer involved in the release process of CO_2 have been modeled [15]. Glade carried an experimental investigation on a tube bundle [15]. It was observed that tube surfaces were completely covered with a thin liquid film, at the lowest wetting rate. However, the main part of the test rig is an evaporator with a bank of six horizontal tubes.

Therefore, the aim of the current work is to evaluate the minimum wetting rate Reynolds number under the operating conditions of a large scale MED. Furthermore, the proper seawater flow pattern distribution to reduce potential scale formation within the evaporator tube bundle is fully addressed. A mathematical model of mass and energy balance, including $CaCO_3$ scale deposit is developed. This model allows the determination of a number of parameters which vary along the different rows of the evaporator such as, PH, different species concentrations, total alkalinity (TA) and total carbon dioxide (TC). CO_2 release and the scale thickness deposit are also determined along the tube bundle.

2. Mathematical model and approach

2.1. Flow distribution on the tube bundle

In a commercial MED desalination plant, the evaporator consists of a multi effect. Each effect consists of tube bundle, demister, and spray nozzle. In order to have a compact size tube bundle, the triangle (staggered) pitch is adopted for the evaporator. Spray nozzles are used to distribute the seawater feed on the tube bundle as shown in Fig. 1. The uneven distribution among tubes in vertical columns of the tube bundle is a direct result of the conical shape of the spray nozzle which unevenly sprays the seawater. Also, the use of a triangle pitch tube bundle arrangement also contributes to this uneven distribution of flow across the tubes. Therefore, the present model is developed to consider only the effect of non-uniform flow distribution among tubes due to tube bundle arrangement. The model is developed under the following assumptions:

- The falling film does not intersect by vapor velocity crossover.
- The falling film deflection is within acceptable range.