Desalination 394 (2016) 30–43

Contents lists available at ScienceDirect

Desalination

journal homepage: www.elsevier.com/locate/desal

Global optimization of MSF seawater desalination processes

Chandra Sekhar Bandi, R. Uppaluri *, Amit Kumar

Department of Chemical Engineering, Indian Institute of Technology Guwahati, North Guwahati, Assam 781039, India

HIGHLIGHTS

- For MSF-BR and MSF-M processes, DE provided global optimal solutions.
- Cost based MSF process ranking is MSF-BR > MSF-M > MSF-OT* (* refers solution with penalty).
- For important MSF process parameters, obtained solutions improved by 2.31%, 3.9%, 2.92%, 20.24%, 3.53% and 5.2%.

ARTICLE INFO

Article history:
Received 2 February 2016
Received in revised form 5 March 2016
Accepted 6 April 2016
Available online 12 May 2016

Keywords:
Differential evolution algorithm
Global optimization
Seawater desalination
Multi stage flash (MSF)
MSF-BR
MSF-OT
MSF-M
SQP
Modeling
Optimization

ABSTRACT

This article addresses the global optimal design of multi-stage flash desalination processes. The mathematical formulation accounts for non-linear programming (NLP) based process models that are supplemented with the non-deterministic optimization algorithm. MSF-once through, -simple mixture (MSF-M) and -brine recycle (MSF-BR) process configurations have been evaluated for their optimality. While freshwater production cost has been set as the objective function for minimization, mass, energy and enthalpy balances with relevant supplementary equations constitute the equality constraints. Differential evolution algorithm (DE/rand/bin) was adopted to evaluate the global optimal solutions. Further, obtained solutions have been compared with those obtained with MATLAB optimization toolbox solvers such as SQP and MS-SQP. The global optimal solution corresponds to a variable value set of [2794.4 m^3/h, 1.0499, 7.62 m, 3.359 kW/m^2·K, 3.297 kW/m^2·K, 3.042 kW/m^2·K and 22] for decision variables [W_M, R_H, L_T, U_B, U_R, U_j, N_R] in the MSF-BR process to yield an optimal freshwater production cost of 1.0785 \$/m^3. Compared to the literature, the obtained global solution from DE is 2.31% better. Further, inequality constraint resolution has been excellent for DE but not other methods such as MS-SQP, SQP and DE-SQP.

1. Introduction

Among several technologies viable for potable water production, the desalination of sea and brackish water is an established technology in several countries including the USA, Persian Gulf and European countries [15,35]. Based on the working energy principle, desalination processes are further classified primarily into two classes namely thermal processes that involve phase change due to addition of heat and membrane processes that involve pressure energy. While thermal processes are primarily classified into multi-effect evaporation (MEE), MSF and vapor-compression (VC) processes, membrane processes are primarily classified into RO and electrodialysis (ED) processes. Among various alternate technologies for sea water desalination, MSF processes have the promising features of large scale operation and ability to deliver good quality potable water (5–50 ppm total dissolved solids).

A typical MSF process involves brine heating followed with flash distillation in multiple stages and subsequent heat recovery. Thereby, a MSF process plant has three important sections namely brine heater, heat rejection and heat recovery sections. Design variations in the MSF process systems refer to either once through (OT) or simple mixer (M) or brine recirculation (BR) process configurations to yield MSF-OT or MSF-M or MSF-BR processes respectively. Among these, while MSF-OT is the simplest in design, it is not as efficient as the MSF-BR system.

The design of efficient MSF processes invariably requires simulation and optimization studies. Several researchers have conducted simulation studies to obtain insights upon the process performance of MSF processes. These have been contributed by Mandil and Abdel Ghafour [19], Helal et al. [2], Al-Mutaz and Soliman [14], Rossol et al. [26], Thomas et al. [29], Abdel-Jabbar et al. [28], Hawaidi and Mujtaba [6], and Tayyebi and Alishiri [34]. Many of these literatures emphasized upon

* Corresponding author.
E-mail address: ramgopalu@iitg.ernet.in (R. Uppaluri).

http://dx.doi.org/10.1016/j.desal.2016.04.012
0011-9164/

stage-to-stage calculations and deployed Newton–Raphson method or tridiagonal matrix (TDM) formulations solved with Thomas algorithm (TA) for evaluation of MSF process performance.

Further, optimization studies have also been conducted by several researchers. These include MSF-OT processes [3–5,21–23]; MSF-M processes [20] and MSF-BR processes [1,3–5,6,7,8,9,16,18,24,25,31,32,33]. Considering the minimization of water production cost as objective function, the literature refer to the deployment of either one of the following methods: genetic algorithm (GA) [24,32]; sequential quadratic programming (SQP) method [22,23], deterministic optimization methods built in gPROMS [6,25], generalized reduced gradient (GRG) [1,3–5,20] and in DICOPT++ [22,23]. Further, MATLAB programming environment has also been used in several engineering applications as a competent modeling tool for simulation and optimization studies [36,37,38,39].

A critical analysis of the available literatures in optimization studies refers to the following. Firstly, earlier research works mostly addressed either MSF-BR or MSF-M or MSF-OT processes for process optimization based insights. Only [3–5] addressed MSF-OT and MSF-BR process optimization but not the MSF-M process. The authors adopted GRG optimization method which is a local optimization tool. It is well known that GRG might provide local solutions whose quality could not be judged in conjunction with the global optimality. Further, GRG is well known to be non-rigorous and fails to solve problems with larger number of inequality constraints, as the method needs the satisfaction of all inequality constraints in each iteration. While SQP method foregoes such limitation, the SQP also could not provide insights upon the quality of generated optimal solutions. On the other hand, non-deterministic models such as GA were only investigated for the MSF-BR but not MSF-OT and MSF-M processes. Thus, it is apparent that global optimization methods have not been applied till date for the comparative assessment of MSF-BR, MSF-M and MSF-OT processes.

Secondly, a critical issue with respect to alternate optimization methods such as GRG, SQP, and GA, is with respect to the satisfaction of inequality constraints. The traditional approach to couple a penalty function with cost function may or may not yield feasible solutions using GRG and SQP methods, given the fact that these algorithms may require additional fine tuning of optimization algorithm parameters such as maximum number of iterations, maximum function evaluations, and penalty parameters, to obtain feasible solutions. Thus, it might be the case that an engineer may have to spend a significant amount of time in fine tuning these parameters for the deterministic optimization methods. On the other hand, such insights may not be applicable for the non-deterministic optimization methods due to random nature of solution search. Therefore, an important issue that also needs to be addressed is the ability to fetch feasible solutions with similar penalty function parameters for both deterministic and non-deterministic optimization methods.

A third and essential insight is to visualize upon the sensitivity of process and operating parameters using global optimization approaches. While such sensitivity analysis might be possible with local optimization methods, they may not provide the most stringent sensitivity analysis. Therefore, the sensitivity analysis conducted with non-deterministic methods needs to be judged with that conducted with deterministic methods.

In summary, this work addresses three major objectives. The first objective refers to comparative assessment of MSF-M, MSF-OT and MSF-BR processes using non-deterministic optimization. The second objective refers to the evaluation of inequality constraint resolution ability for both deterministic and non-deterministic methods. The final objective is to conduct sensitivity analysis of all MSF processes in the light of global and local optimization. Differential evolution (DE) has been chosen as the global optimization tool as it has not been studied for MSF process optimization despite being proven effective for other engineering optimization problems. Thereby, suitable benchmarks are expected to be set for the engineering optimization of MSF processes.

2. Process configurations

A schematic representation of the MSF-OT, MSF-M and MSF-BR process configurations is presented in Fig. 1(a)–(c). Among these processes, while MSF-OT limits the temperature of the last stage to 30–40 °C for winter and summer operations, the flashing operation on several flash stages requires vacuum pressure conditions to achieve operating temperatures below 100 °C. As indicated in the figure, the common features of these process configurations are briefly summarized as follows:

– The feed seawater (W_{MF}) at temperature T_{Sea}, is de-aerated and chemically treated before being introduced into the condenser/preheater tubes of the last flashing stage in the heat recovery section.
– The preheated feed seawater at temperature T_2 enters the brine heater tubes, where the heating steam (W_S) is condensed on the outside surface of the tubes. Eventually, the seawater reaches the maximum design temperature value also known as the top brine temperature (T_3).
– The feed seawater finally enters the flashing stages, where a small amount of fresh water vapor is generated by brine flashing in each stage. In each stage, the flashed off vapor condenses on the outside surface of the condenser tubes, where the feed seawater (W_{MF}) flows inside the tubes from the cold to the hot side of the plant. Thereby, the heat recovery process enables an increase in the feed seawater temperature. The condensed fresh water vapor outside the condenser tubes accumulates across the stages and forms the distillate product stream (W_{MD}).

Fig. 1(b) illustrates that the MSF-M process essentially consists of a brine heater, heat recovery section and brine recycle mixing tank. Hence, the MSF-M process configuration facilitates a brine recycle stream to reduce fresh seawater requirements and associated chemical pretreatment costs. This is achieved by mixing part of the blowdown brine stream (W_{MR}) with the feed stream (W_{MSC}), thereby generating a mixed stream (W_{MF}) with higher salinity than that of the fresh seawater (set as 70,000 ppm for the upper bound according to El-Dessouky et al. [11].

It can be further observed in Fig. 1(c) that the MSF-BR desalination plant has heat rejection, recovery section and brine heater section. The final reject stream from the heat recovery section is being split into two streams which serve as cooling seawater stream (W_{MCW}) and makeup stream (W_M). The makeup stream is further chemically treated and mixed in the brine pool of the last flashing stage in the heat rejection section. The mixed stream is sent to blowdown splitter S_2 from which the brine recycle stream (W_{MR}) is introduced into the condenser tubes of the last stage in the heat recovery section. The stream after absorbing the latent heat of condensation from flashing vapor in several stages leaves the last stage and enters the brine heater, where its temperature is enhanced to saturation temperature (i.e., top brine temperature) at the prevalent system pressure.

3. Methodology

Process optimization of alternate MSF configurations has been targeted by coding a competent simulation model that is supplemented with a non-deterministic optimization algorithm. For comparison purposes, deterministic optimization algorithms have also been considered to evaluate upon the efficacy of the non-deterministic optimization algorithm. The following sub-sections summarize the simulation and optimization models.

3.1. Simulation model

The simulation models for MSF-OT and MSF-BR processes were adopted from Helal et al. [3]. For the MSF-M process, the simulation