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A rigorous, mixed-integer, nonlineal programming model (MINLP) for synthesis and optimal operation of cogeneration seawater desalination plants

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Abstract

This paper presents a rigorous mixed-integer nonlinear programming (MINLP) model for optimal synthesis and design of dual-purpose seawater desalination plants. The proposed superstructure considers more alternative configurations than the model recently proposed by Mussati et al. [1] and all process equipment is modelled in a rigorous way. The MINLP model introduces binary variables in order to select equipment for the cogeneration plant. The detailed model for the MSF desalter developed by Mussati et al. [2] was considered. The MSF mathematical model involves the real-physical constraints for the evaporation process. Nonlinear equations are used to model all plant equipment rigorously in terms of chemico-physical properties (enthalpies, entropies, vapor pressure) and design equations (efficiencies, NEA, BPE, heat transfer coefficients, momentum balances, among others). The proposed model is not only useful for synthesis, but also for analyzing different design alternatives. The model has been implemented in a general algebraic modelling system [4]. Several study cases were successfully solved by applying the MINLP model. A case study is presented in order to illustrate the model's capabilities.

Keywords: MINLP programming; Dual-purpose desalination systems; Multi-stage flash desalination (MSF) systems

1. Introduction

Desalination processes are energy intensive, and the cost of energy can account for up to 50% of overall water production. Thermal desalination plants combined with power generation result in appreciable economics compared with separate, single-purpose power generation and desalination installations.

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The selection of optimal cogeneration systems for a certain application requires the analysis of their thermodynamics parameters and the minimization of the production cost of their output. Electric power demands and fresh water production depend strongly on each region of the world. In order to select the most suitable cogeneration desalting plants, different potential structures at the same time have to be considered. For this reason, the formulation of models for synthesis and analysis of different design alternatives is very important.

Even though some works related to the desalination process have been published, they do not present a systematic methodology for achieving an optimal structure [5–7]. Instead, the analysis is carried out for each fixed structure, and then the structures are compared (see [5]).

Several authors [8,9] evaluated and compared different energy allocation methods for different configurations. El-Nashar [8] compared the exergy method with calculations of available energy in studying the optimum design for adding distillers to generating units 9 and 10 at Umm Al Nar, Abu Dhabi. The results show that the available energy method gives slightly higher energy costs for the process steam than would be determined by exergy considerations.

Wade et al. [9] reviewed different energy allocation methods. Also a pricing model for a range of power and desalination options with sensitivity analysis to fuel cost variations was developed and applied. Energy consumption has been parametrically evaluated for five schemes, covering MSF with four different power plants and also RO. The authors concluded that MSF with a combined cycle is the least expensive distillation scheme with low energy costs. Increasing energy cost favours RO with the lower prime energy consumption needed for the process.

Mussati et al. [1] presented a mathematical model for a superstructure for dual-purpose seawater desalination plants. The mathematical model was based on the following hypothesis: the MSF system was modeled in simplified way considering the heat capacity (C_p), boiling point elevation (*BPE*), heat transfer coefficients (*U*) and latent heat of evaporation (λ_v) as constant values for each stream in the process. Hydraulic equations and recycle streams were not taken into account, and the number of stages was considered as a continuing variable. The following hypotheses were assumed for the power generation cycles: constant values for the chemico-physical properties for air, fuel gas and working fluid. Only the evaporator was taken into account in the model of the boiler.

In the present paper, the model proposed by Mussati et al. [1] has been properly modified to develop a new mathematical formulation for the optimal synthesis and design of dual-purpose plants. A large number of different possible configurations have been included in the superstructure for the MINLP model (additional burners, air pre-heater, stream splitters, among others). Also, a more detailed description of the different equipment (gas turbine, high-pressure and back-pressure steam turbines, deareator) and rigorous chemico-physical properties of the streams have been introduced. Finally, the mathematical model for MSF desalter developed by Mussati et al. [2], which considers a detailed description of the process, has been introduced into the present model.

This work is organized as follows. Section 2 introduces the problem formulation. Section 3 briefly describes the process and the proposed superstructure. Section 4 summarizes the hypothesis assumptions and the mathematical model. Section 5 presents the resolution procedure. Section 6 presents a case study. Finally, Section 7 presents the conclusions of the paper.

2. Definition of the problem

Different combinations of power–desalination systems are possible in order to satisfy the production of both electric power and water demands. The preference of one scheme over another depends mainly on many factors such as the required power to water ratio, cost of fuel energy charged to the desalting process, electricity sales, capital costs, and local requirements. The problem to be addressed in this paper is stated as follows: Given (1) different local electric power requirements, (2) different local water productions and, (3) different seawater temperatures and compositions, the goal is to determine the optimal configuration and design of a dual-purpose plant at the minimal total annual cost. For this purpose, it is mandatory to develop robust and flexible models as well as efficient resolution procedures.

3. Process description: superstructure for dual-purpose desalination plants

In this section a brief description of the process under analysis is presented. Fig. 1 depicts the superstructure proposed for a DDD desalination plant.

An air compressor (AC) compresses the inlet air raising its pressure and temperature. In order to increase efficiency, the compressed air would be pre-heated in a heat exchanger (PHE) by exhaust gases from the gas turbine. After the air is compressed and eventually pre-heated, it enters the combustor (CC) to be mixed with fuel and then burned. The resulting hot gas then enters the turbine (EXT) where some of the thermal energy of the gas is converted into mechanical energy to drive the compressor as well as the electricity generator. The temperature of the exhaust gas from the gas turbine is typically in the range of 500°C to 640°C, depending on the design of the gas turbine and the fuel used. As previously mentioned, the heat energy in this gas can be used in a PHE to pre-heat the air incoming from the air compressor and/or it can be used in a heat recovery steam generator (HRSG1) to produce steam. Also the fuel gases can be used in a Heat Recovery Steam Generator HRSG2. The produced steam is directed to the steam turbine HPT where the steam's thermal energy is converted into mechanical energy to produce electricity.

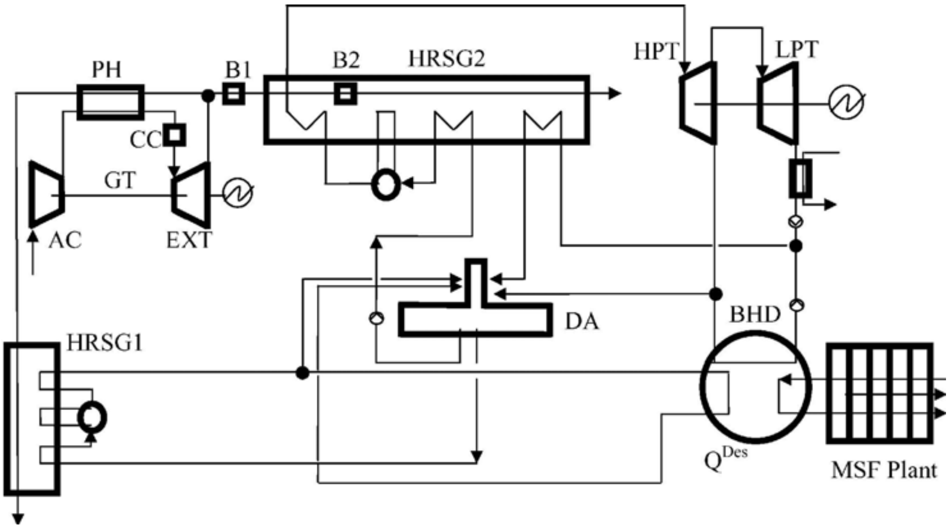

Fig. 1. Superstructure of a dual-purpose desalination plant.

Then, part of the steam is derived to the brine heater (Q^{Des}) and to the deareator (DA). Also, part of the steam can optionally be directed to the low-pressure turbine (LPT) to produce electricity. Two optional burners (B1 and B2) are considered in the heat recovery steam generator (HRSG2). The steam produced in HRSG1 or HRSG2 is used in the brine heater (BHD) to heat the seawater at the admissible temperature. It is important to note that only one heat recovery boiler will be selected (HRSG1 or HRSG2).

4. Process model

The dual-purpose plant model is formulated as a MINLP model where binary variables are related to process configuration and the continuous variables are temperatures; pressures; flow rates (fuel, working fluid, fuel gas); compositions; heat loads; dimensions of the desalter (length, height and width); heat transfer areas; and stage areas, among others. The binary variables are used to select the following equipment: air re-heater exchanger (PHE), heat recovery boilers (HRSG1 or HRSG2), burners (B1 and B2), gas turbine (GT) and a low-pressure turbine (LPT). According to this, the model has seven binary variables.

All hypotheses assumed in the model recently proposed by Mussati et al. [4] were relaxed in order to derive the rigorous MINLP model. Thus, the following hypotheses have been assumed to formulate the model.

Gas turbine:

- Rigorous chemico-physical properties (enthalpy and entropy) for fuel, air and fuel gas are are considered
- Isoentropic efficiency is taken into account.
- Chen's approximation is used to calculate the logarithmic mean temperature difference in the optional pre-heater.

Heat recovery boiler and steam turbines:

- Water is assumed as working fluid.
- Rigorous chemico-physical properties (specific volume, enthalpy and entropy) for working fluid, fuel and fuel gas are considered.
- Isentropic efficiency is taken into account.
- Chen's approximation is used to calculate the logarithmic mean temperature difference in order to compute the heat transfer area on the boilers.

MSF evaporator:

- The functionality of heat capacity (C_p), boiling point elevation (*BPE*), and latent heat of evaporation (λ_v) with the temperature and concentration are considered.
- A specific correlation developed by Griffin and Keller [10] is adopted to compute the overall heat transfer coefficient (U). The correlation depends on the velocity of brine, brine temperature, and diameter tube.
- The non-equilibrium allowance (NEA), which represents a measure of the flashing process thermal efficiency, is considered according to the correlation proposed by Helal et al. [11]. The NEA depends on the stage flashing temperature, the liquid level inside the flashing chamber and the brine flow rate per unit of chamber width.
- The hydraulic correlation proposed by El-Dessouky et al. [6] is adopted. These equations describing the inter-stage transport flowrate of the flashing brine are considered.
- The condenser tube configuration in the preheaters is arranged perpendicular to the direction of brine flow.
- The geometric design for the chamber of each stage (length, width and height) has been considered.
- The model assumes 20 flashing stages.

Based on the above hypothesis, the mathematical model was derived. The mathematical model involves material, energy and momentum balance constraints. Also, detailed design equations for the heat recovery boiler, gas turbine and desalter have been considered. Binary variables appear on linear constraints and an objective function.

The proposed mathematical model (to be published at a later date), was implemented in a general algebraic modelling system GAMS [4]. In order to solve model, the following algorithms were used: the outer-approximation algorithm with the DICOPT equality relaxation strategies algorithm as MINLP solver, the generalized reduced gradient algorithm CONOPT as NLP solver and the OSL algorithm as the MIP solver.

5. Resolution procedure

The solution strategy proposed in Mussati et al. [3] has been extended to solve the present model. A simplified model is solved in a preprocessing phase providing the initial values and bounds for the MINLP model. Then, from these values the rigorous MINLP model is solved. The systematic way to initialize the variables of the rigorous model increases the robustness of the optimization algorithm and the convergence is guaranteed. However, global optimality for the rigorous model cannot be guaranteed because of the presence of nonconvexities in the model. The advantages of using a simplified model have been analyzed in detail in [3,12].

6. Case study

In this section the proposed model and resolution method are presented in order to illustrate the application of the model. In this case study, only water production is given while power generation is considered as variable for the problem. As was mentioned in Section 2, the objective is to determine the optimal configuration and design in order to satisfy the water production and electric power demand.

The credit method is adopted to calculate the total annual cost. This method allocates a predetermined value to one of the products. The cost of the other product is determined by subtraction from the total cost of the dual-purpose plant. In this way, according to the power credit method, the total annual cost is calculated in the following way: $C_{\text{water}} = C_{\text{total}} - W$, where W is the benefit of the net electricity generated.

The problem parameters are given in Table 1. Fig. 2 illustrates the configuration obtained for the present case. The optimal con-figuration for the given data is composed of the GT, the HRSG2 and the HPT coupled to a MSF desalter, and Table 2 reports the mean values of the solution.

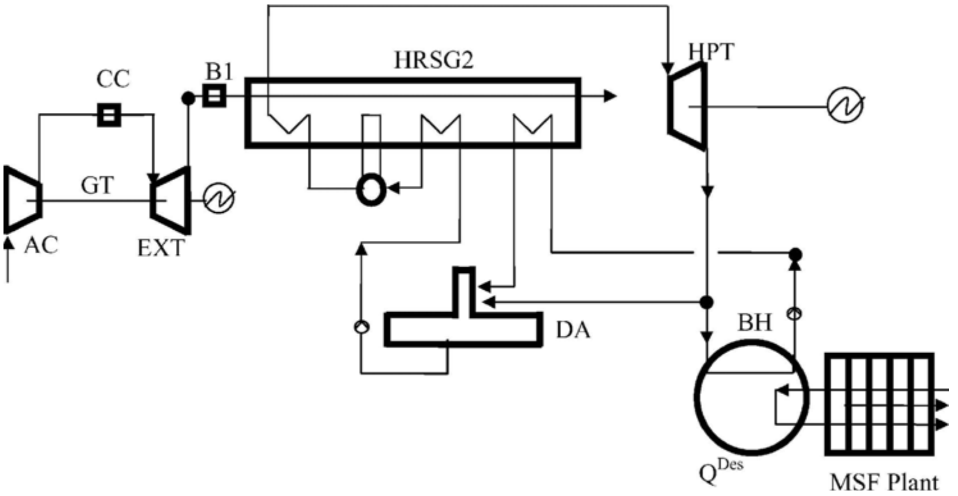

Fig. 2. Optimal configuration for DDP.

Table 1
Problem parameters

Evaporator EFME:	
Seawater salinity, ppm	45,000
Seawater temperature, K	298
Maximum operating temperature, K	390
Water production, t/h	1000
Tube diameter, m	0.030
Pitch, m	1.25
Steam turbines:	
Turbine efficiency (HPT, LPT)	0.95
Maximum inlet temperature (GT), K	1600
Maximum inlet temperature (HPT), K	870
Maximum inlet pressure (HPT), bar	140

Table 2
Optimal values for case study

Variable	Values
Process heat (desalter) (Q^{Des}), Gcal/h	58.972
Fuel consumption by GT (M_{fuel_CC}), Kmol/s	0.1386
Fuel consumption by B1 (M_{fuel_B1}), Kmol/s	0.0426
Power consumed by AC, MW	16.769
Power produced by GT, MW	50.102
Net power produced by GT, MW	33.333
Power produced by HPT, MW	17.010
Working fluid flow (Vap_{HRSG2}), kg/s	32.711
Objective function value, $/s	0.8446

Also, the MINLP model has been successfully solved for different configurations. For this, the binary variables have been fixed and the optimization problem has been solved. In other words, the optimization problem has been solved by fixing the configuration (binary variables) of the system.

From the results, we conclude that a combined cycle including gas turbine, heat recovery steam generator and steam turbines coupled to MSF are more convenient for high power/water ratios. Structures including gas turbine and a heat recovery steam generator coupled to MSF are preferred for low ratio values.

7. Conclusions

A MINLP model for optimal synthesis and design of a dual-purpose desalination plant system has been developed by modifying the previous model developed by Mussati et al. [1]. A large number of different possible configurations were included in the superstructure for the MINLP model (additional burners, air pre-heater, stream splitters, among others). Also, a more detailed description of the different equipment (gas turbine, high-pressure and back-pressure steam turbines, deareator) was introduced. The mathematical model for an optimal MSF desalter design developed by Mussati et al. [2] has been introduced in the rigorous model.

The resulting MINLP model is not only useful for synthesis, but also for analyzing different configurations. Different examples have been successfully solved (not presented in this paper). The proposed MINLP model is characterized by its robustness and flexibility.

The same qualitative results presented in Mussati et al. [1] have been obtained in this paper. However, in all cases, more detailed designs for the power generation cycle and desalter were achieved. The preference of one scheme over another would depend mainly on many factors such as the required power to water ratio, cost of fuel energy charged to the desalting process, electricity sales, capital costs, and local requirements. The costs have a strong influence in selecting the structure.

It is not possible to establish a generally valid economical viability of configurations. A very detailed analysis must be done for each situation. For example, back-pressure or/and extraction/condensation steam turbines coupled to a MSF desalter are preferred for low power/water ratios whereas combined cycles (gas turbine + back-pressure steam turbine and/or gas turbine+back-pressure steam+low-pressure steam turbines) coupled to a MSF desalter are preferred for high ratio values.

7. Symbols

Fg — Fuel gas
H — Enthalpy
Inl — Inlet
Iso — Isentropic
Mfg — Fuel gas flow
*Mfg*_PHE — Fuel gas flow to PHE
Mfg_HRSG2 — Fuel gas flow to HRSG2
S — Entropy
T — Temperature

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