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Optimum design of cogeneration for power and desalination to satisfy the demand of water and power



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HIGHLIGHTS

- A detailed mathematical model of the cogeneration for water and power is provided and described as a MINLP problem.
- The new mixed-coded genetic algorithm is put forward and used to solving the provided model.
- The optimization is performed from economic points of view to minimize the total annual cost (TAC).
- The optimal configuration and operation condition are obtained to satisfy electricity and fresh water demand simultaneously.

ARTICLE INFO

Article history:

Received 22 April 2013

Received in revised form 4 June 2013

Accepted 5 June 2013

Available online 6 July 2013

Keywords:

Cogeneration for power and desalination

Desalination

Genetic algorithm

Optimum design

ABSTRACT

Cogeneration for power and desalination could not only improve the economic benefit of the power plant, but also afford the high quality water to solve the freshwater shortage. Considering the demand of power and water, a detailed mathematical model of the cogeneration system targeting the minimum total annual cost (TAC), which includes the power plant, multistage flash (MSF) and reverse osmosis (RO), is proposed and described as a mixed integer nonlinear programming (MINLP) problem. The modified genetic algorithm (MGA) with mixed coding is put forward to solve the model developed by us. A case study, which is supposed to supply 250 MW of power and 12,000 m³/h of water for Huangdao District of Qingdao City, is analyzed in order to illustrate the model capabilities. The results show that the operation pattern of the cogeneration system could be varied in terms of the water demand. When the water demand is lower than 8000 m³/h, the combination of power plant associated with MSF is adopted and the condensing-extraction steam turbine is selected. When the water demand of water is higher than 8000 m³/h, the tri-combination of power plant, MSF and RO is the optimal choice, in which back pressure steam turbine is selected.

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1. Introduction

Cogeneration is defined as the combined production of two or more useful forms of energy from the same primary energy, thus allowing financial return and less impact with respect to the atmospheric emissions. The thermal power plants not only produce the electric energy, but also supply large amount low pressure steam. At the same time, the thermal power plants require a mass of freshwater to generate the high pressure and high temperature steam. The MSF and the RO are respectively driven by thermal energy and electricity

to produce freshwater. So the integrating thermal and membrane desalination process with power generation in the same site are currently considered as a viable alternative. The advantages of the triple hybrid power–MSF–RO over the dual power–MSF and single purpose MSF or RO plants were reported [1–3].

Many researchers have investigated in the cogeneration systems. A state-of-the-art review for simple and fully integrated hybrid desalination systems is presented in [4]. An overview of research endeavors carried out by hybrid desalination systems is also presented. A small-scale cogeneration system based on reciprocating engine is coupled in [5]. An exergoeconomic method is proposed in [6] for a combined gas/steam cycle associated with a MSF–RO desalination system. A thermodynamic model for integrated multi-effect evaporation thermal vapor compression (METVC) and humidified gas turbine cycle is presented in [7–9]. Nevertheless, there is no economic analysis and optimization approach in their researches. The performance of a cogeneration plant (combined power plant and desalination) is analyzed by R. Chacartegui [10] with a stationary lumped volume model and the design and optimization

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guidelines are presented. A dual purpose plant for supplying given amount of power and fresh water is modeled and optimized from thermodynamic and economic point of view [11]. The thermodynamic and economic aspect of METVC is studied without performing a complete economical analysis [12].

Some optimization models of combined desalination and cogeneration systems associated to the superstructure concept are presented in the literature [13–19]. An evolution of the modeling processes can be observed in the technical literature in which mixed integer non-linear programming technique is proposed for associating desalination systems and combined gas/steam cycles and culminates by presenting a disjunctive programming model for optimizing such systems.

Despite that many contributions dealing with the design of dual purpose desalination plants have been published, only few of them focus on the simultaneous optimization of the configuration and operating conditions.

Different arrangements are possible in order to satisfy electricity and freshwater demands and the selection of the optimal system is a difficult task because it depends strongly on many factors such as the power to water ratio, cost of fuel, capital cost and local requirements. Alternative configuration must be considered in order to select the most suitable cogeneration desalting plants. Therefore, the formulation of models for the synthesis and analysis of different design alternatives are very important and useful.

In this paper, the superstructure model of a triple hybrid power–MSF–RO system is developed and described as a MINLP problem, which contains all the potential interaction of material streams and energy streams involved in the combined systems. The optimization is performed based on economic points of view and a heuristic optimization algorithm, namely, modified genetic algorithm is applied. Afterward, the optimal configuration and operation condition is obtained to satisfy electricity and fresh water demand simultaneously.

2. The schematic of the cogeneration system

Fig. 1 illustrates the schematic of the combined power–desalination system for simultaneous generation of the electric power and fresh water. The power generation cycle includes boiler, steam turbine that produces the electric energy and the thermal energy. The desalination plant includes the MSF and RO. All parts of the cogeneration system were modeled and simulated to evaluate performance of the combined system.

The fuel is combusted in the boiler to produce the superheated steam. The steam is sent to the steam turbine to generate the electric

energy, which is used for MSF, RO and the grid. The whole or part steam extracted from turbine is feed to the brine heater of MSF and condensed to recycle the boiler. The seawater is sent to the MSF and heated as they flow through the pre-heater tubes of the heat rejection section. Subsequently, it is divided into two parts. One part is used as the makeup water to the heat recovery section and the other part is sent to RO as the feed water and return to the sea. The fresh water produced by MSF and RO are blended as the total water production. The blow-down brine of MSF and RO is feed to the common processing system.

3. Mathematical model

To simplify the cogeneration system, this model is based on the following assumptions:

- (1) Boiler, steam turbine and the MSF unit are adiabatic. The heat losses are neglected.
- (2) The isentropic efficiency of the steam turbine is calculated. The working mode of steam turbine could be selected back pressure or extracted steam based on the demand of desalination.
- (3) The cogeneration system for power and desalination, including steam turbine, MSF and RO, works in steady condition.
- (4) Physical properties of all streams, such as enthalpy, specific heat capacity and so on, are calculated in mean inlet and outlet temperatures.
- (5) Water is assumed as working fluid on the boiler and steam turbine.
- (6) The distillate product of MSF is assumed to be salt free.
- (7) The distillate of the MSF plant section can be blended with the RO permeate to obtain suitable water quality. So the single stage RO process can be used.

The plant consists of two desalination sections (MSF and RO). The energy demand is supplied by power plant where electric and thermal energy are co-produced. The detailed equations of the model are as the follows.

3.1. Co-generation plant

The co-generation plant consists of a boiler, a steam turbine, and an alternator. The superheated steam produced by boiler is sent to the steam turbine, which is connected with an alternator in order to produce electric energy. The outlet steam or extracted steam from steam turbine is feed to the brine heater of MSF. The electric energy produced is used for MSF, RO and grid.

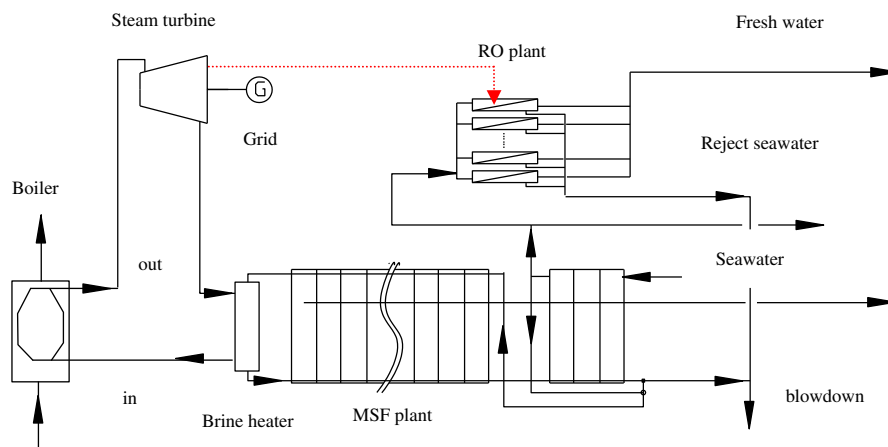


Fig. 1. Schematic of cogeneration of power and desalination.

3.1.1. Boiler

The water is heated to superheated steam in the boiler. The heat supplied by boiler is obtained from the following equation.

$$Q_{bo} = M_{s,bo} (h_{bo,out} - h_{bo,in}) \quad (1)$$

The necessary fuel mass to be admitted to the boiler is determined as:

$$M_c = \frac{Q_{bo}}{HC \cdot \eta_{bo}} \quad (2)$$

3.1.2. Steam turbine

The steam turbine comprises back pressure steam turbine and the condensing/extraction steam turbine. It should be realized that only one of the turbines would be selected to be used in the desalination. The mass and energy balance could be written as follows.

If the back pressure steam turbine is selected.

$$We_{BP} = M_{s,BP} (h_{bo,out} - h_{BP,out}) \cdot \eta_{BP} \quad (3)$$

$$M_{s,bo} = M_{s,BP} \quad (4)$$

Otherwise, the condensing/extraction steam turbine is selected.

$$M_{s,bo} = M_{s,co} + M_{s,ex} \quad (5)$$

$$We_{co} = (M_{s,bo} h_{bo,out} - M_{s,ex} h_{ex} - M_{s,co} h_{co}) \cdot \eta_{co} \quad (6)$$

Total electric energy produced by steam turbine can be defined as follows.

$$We = \gamma We_{BP} + \beta We_{co} \quad (7)$$

The steam flow rate from turbine to MSF can be described as Eq. (8).

$$M_{s,bh} = \gamma \cdot M_{s,bo} + \beta \cdot M_{s,ex} \quad (8)$$

$$\gamma + \beta = 1 \quad (9)$$

3.2. Desalination plant

The desalination plant considers the hybrid system of MSF and RO. The required energy is supplied by power plant with co-production of electric and thermal energy. The desalination plant model includes three parts: MSF unit, RO unit and the integration system of RO and MSF. The detailed equations of mass balance, energy balance and momentum balance for MSF and RO unit are described in paper [20]. Here, only the additional balance equations of hybrid desalination system are given as follows:

The total intake flow rate of seawater is equal to the sum of make-up flow rate, feed rate of RO and the blow-down brine.

$$M_F = M_m + M_{F,RO} + M_{bd} \quad (10)$$

The total freshwater product and the blow-down flow rate are obtained from Eqs. (11) and (12) respectively.

$$M_d = M_{d,MSF} + M_{d,RO} \quad (11)$$

$$M_{bd} = M_{bd,MSF} + M_{bd,RO} \quad (12)$$

The energy balance of MSF brine heater is given by Eq. (13).

$$M_{s,bt} h_s = M_R C_{PR} (T_{BT} - T_{MSF,out}) \quad (13)$$

The concentration of freshwater and blow-down brine is calculated by Eqs. (14) and (15).

$$M_d C_d = M_{d,MSF} C_{d,MSF} + M_{d,RO} C_{d,RO} \quad (14)$$

$$M_{bd} C_{bd} = M_{bd,MSF} C_{bd,MSF} + M_{bd,RO} C_{bd,RO} \quad (15)$$

The distillate product of MSF is assumed to be salt free. $C_{d,MSF} = 0$, so Eq. (14) could be simplified as follows:

$$M_d C_d = M_{d,RO} C_{d,RO} \quad (16)$$

The product ratio of MSF and RO is defined as follows.

$$R_{MSF,RO} = \frac{M_{d,MSF}}{M_{d,RO}} \quad (17)$$

The power/water ratio (PWR) indicates the ratio between the water produced and the electricity energy consumed, expressed in kWh/m³.

$$PWR = \frac{W_e}{M_d} \quad (18)$$

3.3. The economic model

The cost is calculated as the sum of the specific cost of the three sections presented in the cogeneration plant. The cost of each section includes the investment cost and operation cost, which is described as Eqs. (19), (20) and (21), respectively.

$$C_{power} = C_{cap,po} + C_{op,po} + C_c \quad (19)$$

$$C_{MSF} = C_{cap,MSF} + C_{op,MSF} \quad (20)$$

$$C_{RO} = C_{cap,RO} + C_{op,RO} \quad (21)$$

The optimization objective of the cogeneration system is to minimize the TAC while meeting the demand of electric energy and fresh water.

$$\text{Objective function : Min } TAC = C_{power} + C_{MSF} + C_{RO} \quad (22)$$

Where, TAC is the total annual cost of the cogeneration system. C_{power} , C_{MSF} , and C_{RO} is the cost of power plant, MSF plant and RO plant, respectively. The detailed description of the operation cost and investment cost can be found in [20].

The following limitations, which include the equipment and operation condition except equations of the material balance and energy balance, are considered for decision variable in the optimization study.

The production of power and fresh water for the cogeneration plant is described by Eqs. (23) and (24), respectively.

$$We_G \geq We_{dem} \quad (23)$$

$$M_d \geq M_{d,dem} \quad (24)$$

The restrictions defined in Eqs. (25) and (26) are included for the concentration of blow-down brine and fresh water.

$$C_{bd} \leq 70,000 \text{ mg/L} \quad (25)$$

$$C_d \leq 500 \text{ mg/L} \quad (26)$$

The difference temperature between intake seawater and blow-down brine of MSF is described by Eq. (27).

$$T_{bd,MSF} - T_0 \leq 10^\circ\text{C} \quad (27)$$

4. Modified genetic algorithm

The coding design for a special problem is the key to use genetic algorithm effectively. For the above problem, there exist three kinds of variables in the model: bool variable, integer variable and real variable, which are inconvenient to be coded using binary coding simultaneously. To overcome this problem, here a modified genetic algorithm featuring mixed coding, which uses different crossover and mutation operators for the above three kinds of variables, is shown as follows.

4.1. Coding

In the cogeneration system, the chromosome based on mixing coding can be described as:

$$\{(a_1, a_2), (z_1, z_2, \dots), (b_1, b_2, b_3, \dots)\}.$$

Where the bool coding (a_1, a_2) , the first part of chromosome, represents the equipment type of steam turbine, and the integer coding (z_1, z_2, \dots) , the second part of chromosome, represents stage number of MSF, module number of RO, etc. The real coding (b_1, b_2, b_3, \dots) , the third part of chromosome, represents the flow rate, operation pressure, production ratio of MSF and RO, and so on.

4.2. Initializing the population

For all independent variables, the initial values are generated within the feasible region randomly by the following five steps.

- Step 1 Initialize the population size L , population $Q = \{\Phi\}$ and let index $j = 1$.
- Step 2 Randomly generate the equipment type $A_j = (a_1, a_2)$, the integer string $Z_j = (z_1, z_2, \dots)$ and the real string $B_j = (b_1, b_2, \dots)$, thus the individual $Q_j = \{A_j, Z_j, B_j\}$.
- Step 3 If Q_j can meet the above constraints, then go to step 4, else go to step 2.
- Step 4 If Q_j is new individual different from all the previous individuals, then $Q = Q + \{Q_j\}$, and $j = j + 1$; else go to step 2.
- Step 5 If $j > L$, then $Q = \{Q_1, Q_2, \dots, Q_L\}$ and stop; else go to step 2.

The genetic algorithm performance is influenced heavily by the population size. It is possible to run the risk of serious under-covering the solution space and result in a local optimum when the population size is comparatively small, whereas it would increase the computation load when the population size is comparatively large. Consequently, the population size should be chosen according to the problem scale. In this paper, the population size is set to 50.

4.3. Crossover

The direct exchange is adopted for the bool and integer variable. The arithmetic crossover is used to real variable in solving process. Here the arithmetic crossover is only described.

The two individuals V_1 , and V_2 (two parents) are selected randomly and the offspring could be found as follows.

$$\text{offspring 1: } V'_1 = V_1 + (1-\lambda)V_2 \quad (28)$$

$$\text{offspring 2: } V'_2 = V_2 + (1-\lambda)V_1 \quad (29)$$

The λ is a random number between 0 and 1.

The arithmetic crossover could hold the diversity of offspring and avoid prematurely convergence and local optimum. The offspring generated by crossover replaced the parent regardless their fitness to maintain enough diversity in the population.

4.4. Mutation

The selection of mutation operator depended on the coding type. In this section, the mutation strategy for the mixed coding is adopted by the following step: if the selected gene is an integer, a new integer would be created to replace the old integer. If the selected gene is bool, the gene would be mutated 0 or 1. If the selected gene is real, the heteropic mutation is selected to solving process.

For example, first a random integer “temp” (0 or 1) would be created, then

If temp = 0

$$a = a + (a_{\max} - a) \cdot \text{temp} \cdot (1 - t/TT)^2. \quad (30)$$

If temp = 1

$$a = a - a \cdot \text{temp} \cdot (1 - t/TT)^2. \quad (31)$$

Where a represents the mutation gene, a_{\max} is the maximum of a ; the t is the iterative number, and TT is the total iterative number.

The structure of the MGA can be described as Fig. 2.

5. Case study

A plant consisting of power plant coupled with hybrid MSF/RO desalination has been considered. The water production is given 12,000 m³/h while the total demand electric energy of 250 MW must be satisfied. The blended water concentration of RO and MSF should be lower than 500 mg/L and the blow-down brine concentration is less than 70,000 mg/L. The main optimization variables are: the heat consumption of and the total transfer area of MSF, module

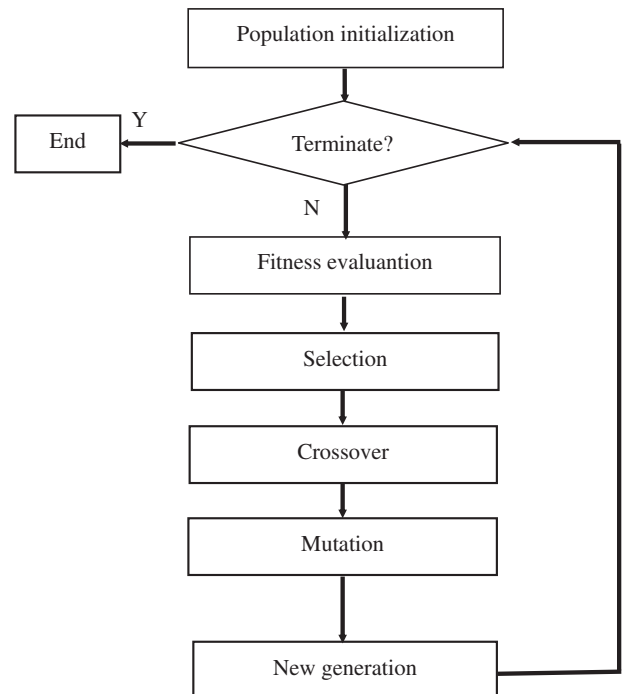


Fig. 2. Scheme of modified genetic algorithm.

Table 1
Input design parameter.

Parameter	Value	Parameter	Value
Power plant		Temperature of brine blow-down, °C	35
Outlet steam temperature of boiler, °C	566	Steam temperature of brine heater, °C	120
Outlet steam pressure of boiler, Mpa	24.2	RO plant	
Lower heat value of fuel, kJ·kg ⁻¹	25,200	Pure water permeability m·s ⁻¹ ·Pa ⁻¹	8.33 × 10 ⁻¹³
Efficiency of boiler	0.92	Solute transport parameter, m·s ⁻¹	3.51 × 10 ⁻⁸
Efficiency of steam turbine	0.97	Active area of membrane, m ²	34.5
MSF plant		Membrane lifetime, y	5
Stage number of MSF	21	Efficiency of HP pump	0.64
TBT, °C	110	Efficiency of energy recovery device	0.9
Feed concentration of seawater, mg·L ⁻¹	42,000	Price of membrane, \$	500
Feed temperature of seawater, °C	25	Total product of fresh water, m ³ /h	12,000

number of RO, and water production ratio of MSF and RO. The objective is to determine the optimal configuration of the cogeneration system and to select the optimal operation conditions of the cogeneration system in order to satisfy the water production and electric power demand while the total annual cost is minimal.

The main problem parameters are given in Table 1, and the optimal result is shown in Table 2.

As shown in Table 2 the optimal configuration is the combination of power plant, MSF and RO plant. The water production ratio of MSF and RO is 2.04. Namely, the water production of MSF is greater than that of RO. The steam flow rate from the boiler is equal to that feeding to the brine heater. Therefore the back pressure steam turbine is the optimal selection for the power plant. So MSF plant would be run on full load and the lacking amount of the total required water is made up by the RO plant.

In addition, the different demand of fresh water is considered. Here, four cases, 3000 m³/h, 5000 m³/h, 8000 m³/h, and 12,000 m³/h, are considered to observe the variation of the cogeneration system configuration. And the specific cost of the cogeneration system is compared with independent working MSF plant or RO plant. The result is showed in Table 3, and Figs. 3 and 1.

Figs. 1 and 3 show the optimal solutions for the case of the high demand of fresh water (more than 8000 m³/h) and the low demand of fresh water (lower than 8000 m³/h), respectively. When the demand of fresh water is low, the product of MSF plant is enough to satisfy the water demand and the RO plant is not a requisite (see Fig. 3). On the contrary, when the demand of fresh water is high, the MSF plant and RO plant run at the same to supply fresh water to consumer (see Fig. 1).

As shown in Table 3, the operation pattern of the cogeneration system converts from combination of power plant and MSF (Fig. 3) to the combination of power plant, MSF and RO (Fig. 1) when the water production increases from 3000 m³/h to 12,000 m³/h. At the same time, the water production ratio of MSF and RO is reduced and the cost of water production decreases gradually. On the one hand, it is caused by the scale effect

of the desalination plant. On the other hand, the cost of RO is lower than that of MSF commonly, the increasing of RO permeate flow rate results in the combined freshwater cost decreased. Although the required electric energy of the grid is constant, the more quantity of the required freshwater, the more the total electric energy produced by power plant and the fuel consume rate. So the TAC would be increased.

Any more, the production ratio between MSF and RO goes down gradually while the required freshwater increases. Therefore properly enhanced permeate rate of RO is advantageous for the cogeneration system when the demand of freshwater is increased.

In addition, when the required freshwater is comparatively small (3000 m³/h and 5000 m³/h), the demand steam of MSF is less than the steam flow rate of boiler. Consequently, the condensing-extraction steam turbine could be selected. As the required freshwater rate exceeds to 8000 m³/h, the demand steam of MSF is equal to the steam flow rate of boiler and the back pressure steam turbine is the optimal selection.

A comparison of fresh water cost for cogeneration plant, MSF plant and RO plant is shown in Fig. 4. The fresh water cost of the three independent systems reduces generally along with the increasing of fresh water production. The cost of MSF exceeds that of RO and cogeneration system at the same yield of fresh water. When the fresh water production is greater than 5000 m³/h, the cost of cogeneration system is superior to MSF and RO system. In other words, the optimal operation pattern is independent RO system or combination of power and MSF when the quantity demand of fresh water is lower. However, the combination of power and MSF not only satisfied quantity demand of the fresh water, but also supplied the electricity to consumers. So the combination of power and MSF is superior to alone RO system. Conversely, when the quantity demand of fresh water is high, the optimal operation pattern is the combination of power, MSF and RO.

6. Conclusions

In this paper, a cogeneration plant consisting of power, MSF and RO units was considered, which provides the required electricity

Table 2
Result of optimal design.

Parameter	Value	Parameter	Value
Power plant		RO plant	
Fuel consume rate, 10 ³ kg/h	125.8	Operation pressure, MPa	0.7
Steam flow rate of boiler, 10 ³ kg/h	787.7	Feed rate of RO, m ³ /h	12,980
MSF plant		W _{d,RO} , m ³ /h	3946
Stage number of MSF	21	Concentration of permeate, mg/L	788
Makeup seawater rate, m ³ /h	21,000	Module number	13,684
Concentration of blow-down, mg/L	68,093	Reject brine concentration, mg/L	60,000
W _{d,MSF} , m ³ /h	8054	Concentration of final fresh water, mg/L	259
Heat steam rate, 10 ³ kg/h	787.7	Total feed rate of seawater, m ³ /h	33,980
		Total recovery rate, %	35

Table 3
The optimal result of cogeneration system at different water products.

	Water production, m ³ /h			
	3000	5000	8000	12,000
W _{d,MSF} , m ³ /h	3000	5000	7290	8054
W _{d,RO} , m ³ /h	0	0	710	3946
W _{d,MSF} /W _d	1	1	0.91	0.67
Cost of water, \$/m ³	0.88	0.87	0.82	0.81
TAC, 10 ⁸ \$·y ⁻¹	1.35	1.49	1.70	1.99
W _c , 10 ³ kg/h	95.4	103.1	113.9	125.8
Steam flow rate of boiler, 10 ³ kg/h	597.3	645.5	713.2	787.7
W _s , 10 ³ kg/h	291.5	486.6	713.2	787.7
W _e , MW	254.8	258.0	267.4	295.4
Operating mode	MSF	MSF	MSF + RO	MSF + RO

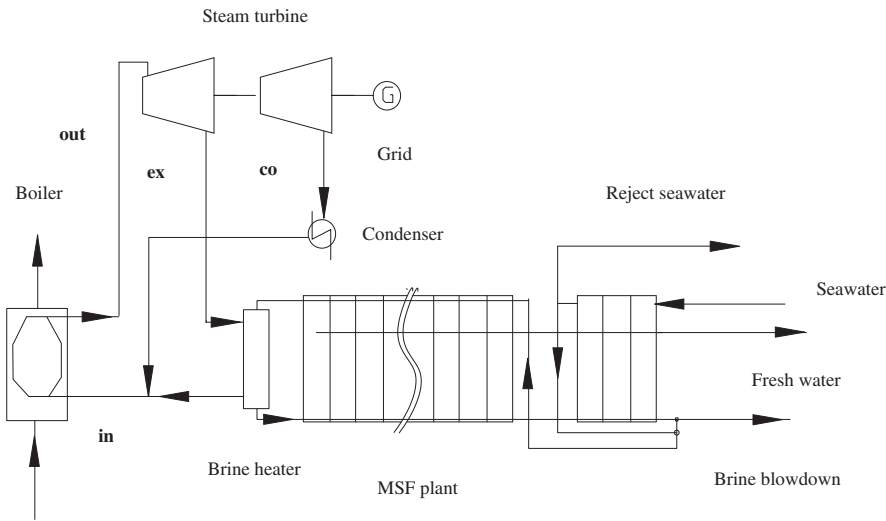


Fig. 3. Schematic of cogeneration of extra-condensed steam turbine with MSF.

and fresh water simultaneously. The superstructure of tri-function power-MSF-RO plant was developed as a MINLP model. The objective function is to minimize the TAC of cogeneration system. The proposed model was solved by the modified genetic algorithm featuring mixed coding, where bool variables were used to select the equipment type, integer variables were used to represent stage number of MSF, module number of RO, etc. and the real variables were used to represent the flow rate, operation pressure, production ratio of MSF and RO, and so on. An example, which is supposed to supply 250 MW power and 12,000 m³/h for Huangdao district of Qingdao City, has been successfully solved by applying the modified genetic algorithm. The optimization result showed: the optimal pattern of the cogeneration system for power and desalination could be varied in terms of the water demand. When the water demand is lower than 8000 m³/h, the combination of power plant associated with MSF is adopted, in which the condensing-extraction steam turbine is used for the power plant. But when the water demand of water is higher than 8000 m³/h, the tri-combination of power plant, MSF and RO is the optimal choice, in which back pressure steam turbine is used for the power plant.

Nomenclature

C	concentration, mg/L
C_p	specific heat capacity, $\text{kJ}\cdot\text{kg}^{-1}\cdot\text{K}^{-1}$
C_{power}	power plant cost, $\text{\$}\cdot\text{y}^{-1}$
C_{MSF}	MSF plant cost, $\text{\$}\cdot\text{y}^{-1}$
C_{RO}	RO plant cost, $\text{\$}\cdot\text{y}^{-1}$
H_c	lower heat value of coal, $\text{kJ}\cdot\text{kg}^{-1}$
h	enthalpy, $\text{kJ}\cdot\text{kg}^{-1}$
M	flow rate, $\text{kg}\cdot\text{h}^{-1}$
Q	heat duty, kW
T	temperature, K
T_0	seawater temperature, K
TAC	total annual cost, $\text{\$}\cdot\text{y}^{-1}$
TBT	the top brine temperature, K
We	the electricity generating capacity, MW
R	water product ratio
PWR	the power/water ration, kWh/m^3

Greek

η	efficiency
γ	bool variable, 0或1
β	bool variable, 0或1

Subscripts

MSF	multi stage flash
RO	reverse osmosis
out	outlet
in	inlet
F	seawater
s	steam
G	grid
dem	the demand
c	coal
ex	extraction steam turbine
bh	brine heater
cap	capital
bd	blow-down
m	makeup
d	desalination
po	power plant
BP	back pressure turbine

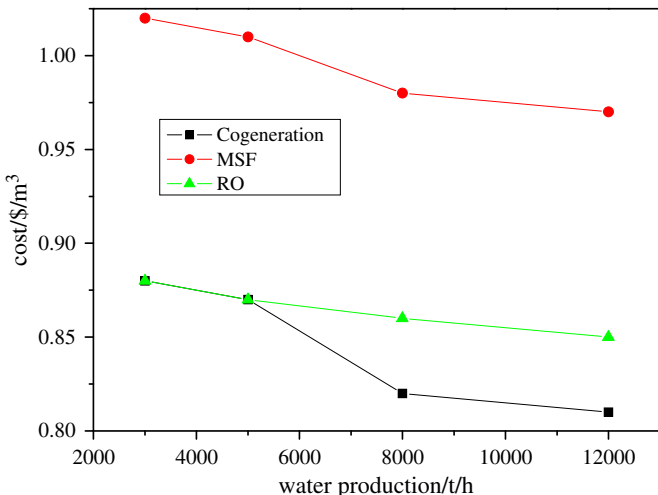


Fig. 4. Water cost of cogeneration system VS. MSF and RO.

R recycle brine
 co condense steam turbine
 bo the boiler
 op operation

Acknowledgments

This work was financially supported by the National Nature Science Fund Program of China (21076202). This is MCTL Contribution No. 19.

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