Desalination and Water Treatment
www.deswater.com

1944-3994 / 1944-3986
doi: 10.5004/dwt.2010.1312

22 (2010) 371–378
October

Thermoeconomic analysis of a CHP-based dual-purpose power plant

Luopeng Yang*, Xue Chen, Shengqiang Shen, Huawei Hu

Key Laboratory of Ocean Energy Utilization and Energy Conservation of Ministry of Education, School of Energy and Power Engineering, Dalian University of Technology, Dalian, 116024, China
Tel. +86 (411) 82903997; Fax +86 (411) 84707963; email: yanglp@dlut.edu.cn, michale_ylp@yahoo.com.cn

Received 1 May 2009; Accepted in revised form 26 March 2010

ABSTRACT

China faces severe water shortages due to the rapid growth of population and fast development of the economy. Especially in northern coastal cities where China's population and economy are concentrated, the poor water condition has become a critical constraint factor for socio-economic development in the long run. A combined heat-and-power (CHP)-based dual-purpose power plant with low-temperature multi-effect distillation (LT-MED) is a viable answer to the problem for this zone. This paper presents an economic analysis of it based on the cyclical function method, the equivalent enthalpy drop theory, and the analytical theory on steam turbines in off-design working conditions. By solving the matrix calculation models of the cyclical function method and the equivalent enthalpy drop theory, the thermal generating efficiency, the heat and power generation rate (HPGR) and the electricity-equivalent consumption rate (EECR) are analysed to explore the effect of extraction for desalination on the CHP system and the energy cost for water production. The study indicates that utilizing surplus heating extraction load in summer for desalination improves thermal generating efficiency and HPGR of extraction and reduces the fuel cost for water production. It is also shown that EECR is more accurate to evaluate the performance of the desalination process than GOR that is widely used to evaluate the performance of desalination process. It is concluded that the CHP-based dual-purpose power plant is a suitable way to economically provide fresh water resource in northern coastal zone of China.

Keywords: Combined heat-and-power; Dual-purpose power plant; Equivalent enthalpy drop theory; Cyclical function method; Electricity-equivalent consumption rate; Desalination

1. Introduction

Due to the population growth, industrialization and urbanization, a severe fresh water shortage has become a major concern in China. China's average amount of freshwater resource is approximately one fourth that of the world. The poor water situation is more serious in northern coastal cities where China's population and economy are concentrated. So the water shortage has become a critical constraint factor restricting socio-economic development. In order to mitigate the shortage problem in the northern coastal zone, desalination has been a good alternative source for fresh water.

A CHP-based dual-purpose power plant with LT-MED can pave the way to more accessible water in China. As coal is the primary energy source in China, the coal-fired power plant is the dominant form in electric power industry. The installed capacity of coal-fired power plants accounted for more or less 74.4% of the total installed capacity and produced about 82.2% of the total electric

* Corresponding author.

power in 2000 [1]. Among various available desalination technologies for big scale desalination plants, including LT-MED, multi-stage flash (MSF) and reverse osmosis (RO), LT-MED is superior in utilizing low-grade heat available through cogeneration to minimize the energy cost component as its top brine temperature is below 65°C. What's more, several dual-purpose power plants built in China have demonstrated that the coal-fired steam turbine combined with LT-MED is an efficient and economical solution for water scarcity in China.

An accurate calculation for energy requirement of water production in a CHP-based dual-purpose power plant is of great importance to determine desalination decisions since the cost of energy requirement accounts for the foremost part of the water production cost. Several methods have been proposed to estimate the energy cost of water production. A brief description of different concepts was reported, which could be applied to estimate the energy cost for water prodyction in a cogeneration system [2]. El-Nashar [4] approached two methods for cost allocation in a dual-purpose power plant, which are the exergy cost accounting method and one in-directed cost allocation method. El-Nashar [5] further developed the thermoeconomic method for incorporating equipment reliability consideration into the design of the cogeneration system. Darwish [3] outlined the MSF desalting method and its power consumption, together with the rating method of power-desalting plants and the energy charged to the desalter methods. Darwish [6], based on the second law of thermodynamics efficiencies, investigated the efficient use of fuel in a dual-purpose power plant as compared to separate desalting desalting and power plants. Darwish [7] compared the energy consumption of different desalting systems by the use of the concept of exergy to bring different kinds of energy to a common basis. A method was presented to compare these energies in terms of available energy, i.e. maximum theoretical work that can be obtained from that energy [8]. But the above mentioned methods were used to analyse the steam turbines and desalting units separately, thus the effect of the extraction for desalination on the steam turbine was neglected. As a result the exact energy cost for water production can't be calculated accuratedly by these methods. This paper presents a new method to analyse a CHP-based dual-purpose power plant with LT-MED grounded on the cyclical function method, the equivalent enthalpy drop theory and the analytical theory on steam turbines in off-design working conditions.

2. Mathematical models

2.1. Brief description of the CHP plant with LT-MED

A process schematic for a CHP-based dual-purpose power plant with LT-MED is shown in Fig. 1. In the CHP power plant, there are two kinds of extraction which are extraction Π and extraction T. Hight pressure extraction Π is supplied for industrial production, thus its flow rate usually keeps invariable. The flow rate of low pressure extraction T varies with seasons as it is used for civil and industrial heating. A portion of extraction T is used as the motive steam of thermal vapour compression (TVC) to compress part of the saturation steam produced in the last effect of LT-MED. The discharged steam of TVC drives LT-MED to produce fresh water.

2.2. Cyclical function method

It is possible to divide the whole complicated cogeneration circle into several sub-cycles by the cyclical function method. As a result each circle has its own formula in

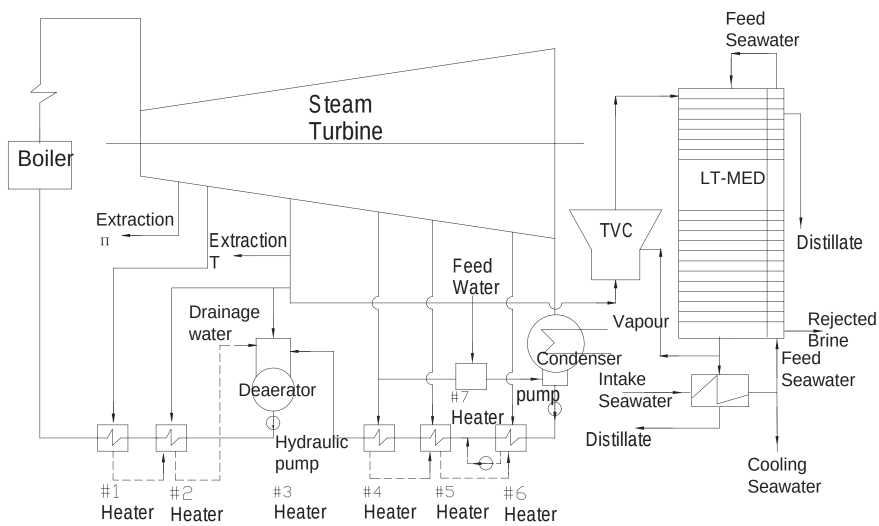

Fig. 1. Schematic diagram of a CHP-based dual-purpose power plant with the LT-MED process.

express that is versatile and suitable for computerization. The circles can be associated with each other by the characteristic coefficient and equation of CHP turbine. With the cyclical function method [9], the cogeneration shown in Fig. 1 can be divided into the main condensing circle, extraction Π circle and extraction T circle. Two assumptions are made in the cyclical function method. The first assumes that the heat sink loss is the only irreversible loss. The second assumption is that the heat sink loss solely includes the exhaust steam loss.

The exhaust coefficient, α represents the exhaust flow when the inlet steam flow of the steam turbine is 1 kg. In light of mass conservation, the exhaust coefficient of the main condensing circle αk is expressed as

$$\alpha_k = 1 - \sum_{i=1}^{6} \alpha_i \tag{1}$$

α_k can be given in the form of matrix equation as

$$\alpha_k = 1 - \begin{bmatrix} 1 \\ 1 \\ 1 \\ 1 \\ 1 \\ 1 \end{bmatrix} \begin{bmatrix} \alpha_1 \\ \alpha_2 \\ \alpha_3 \\ \alpha_4 \\ \alpha_5 \\ \alpha_6 \end{bmatrix} \tag{2}$$

Based on the energy conservation, the q–γ–τ matrix equation for the schematic diagram in Fig. 1 is expressed by

$$\begin{bmatrix} q_6 & & & & & \\ \gamma_6 & q_5 & & & & \\ \gamma_6 & \gamma_5 & q_4 & & & \\ \tau_6 & \tau_5 & \tau_4 & q_3 & & \\ \tau_6 & \tau_5 & \tau_4 & \gamma_3 & q_2 & \\ \tau_6 & \tau_5 & \tau_4 & \gamma_3 & \gamma_2 & q_1 \end{bmatrix} \begin{bmatrix} \alpha_1 \\ \alpha_2 \\ \alpha_3 \\ \alpha_4 \\ \alpha_5 \\ \alpha_6 \end{bmatrix} = \begin{bmatrix} \tau_1 \\ \tau_2 \\ \tau_3 \\ \tau_4 \\ \tau_5 \\ \tau_6 \end{bmatrix} \tag{3}$$

Combining Eq. (2) with Eq. (3), the matrix model of α_k is expressed by

$$\begin{bmatrix} q_6 & & & & & & \\ \gamma_6 & q_5 & & & & & \\ \gamma_6 & \gamma_5 & q_4 & & & & \\ \tau_6 & \tau_5 & \tau_4 & q_3 & & & \\ \tau_6 & \tau_5 & \tau_4 & \gamma_3 & q_2 & & \\ \tau_6 & \tau_5 & \tau_4 & \gamma_3 & \gamma_2 & q_1 & \\ \tau_6 & \tau_5 & \tau_4 & \tau_3 & \tau_2 & \tau_1 & 1 \end{bmatrix} \begin{bmatrix} x_6 \\ x_5 \\ x_4 \\ x_3 \\ x_2 \\ x_1 \\ \alpha_k \end{bmatrix} = \begin{bmatrix} 1 \\ 1 \\ 1 \\ 1 \\ 1 \\ 1 \\ 1 \end{bmatrix} \tag{4}$$

The matrix model of the exhaust coefficient of extraction T circle, α_T is

$$\begin{bmatrix} q_7 & & & & & & & \\ \tau_7 & q_6 & & & & & & \\ \tau_7 & \gamma_6 & q_5 & & & & & \\ \tau_7 & \gamma_6 & \gamma_5 & q_4 & & & & \\ \tau_7 & \tau_6 & \tau_5 & \tau_4 & q_3 & & & \\ \tau_7 & \tau_6 & \tau_5 & \tau_4 & \gamma_3 & q_2 & & \\ \tau_7 & \tau_6 & \tau_5 & \tau_4 & \gamma_3 & \gamma_2 & q_1 & \\ \tau_7 & \tau_6 & \tau_5 & \tau_4 & \tau_3 & \tau_2 & \tau_1 & 1 \end{bmatrix} \begin{bmatrix} x_7 \\ x_6 \\ x_5 \\ x_4 \\ x_3 \\ x_2 \\ x_1 \\ \alpha_T \end{bmatrix} = \begin{bmatrix} 1 \\ 1 \\ 1 \\ 1 \\ 1 \\ 1 \\ 1 \\ 1 \end{bmatrix} \tag{5}$$

The steam consumption rate of the main condensing circle, d_k, is equal to

$$d_k = \frac{3600}{\left[\left(i_0 - \bar{t}_1\right) - \alpha_k\left(i_k - \bar{t}_k\right)\right]\eta_M \eta_G} \tag{6}$$

The work of the main condensing circle for 1 kg exhaust, W_k can be expressed by

$$W_k = \frac{1}{\alpha_k}\left(i_0 - \bar{t}_1 + \Delta\bar{t}_f\right) - \left(i_k - \bar{t}_k\right) \tag{7}$$

The work of extraction T circle for 1 kg extraction T, W_T, is expressed as

$$W_T = \frac{1}{\alpha_T}\left(i_0 - \bar{t}_1 + \Delta\bar{t}_f\right) - \left(i_T - \bar{t}_T\right) \tag{8}$$

The thermal generating efficiency, η_e, is expressed by

$$\eta_e = \frac{3600\eta_b\eta_p}{d_k\left(i_0 - \bar{t}_1\right)} \tag{9}$$

The heat and power generation rate of extraction T, ω_T, can be given by

$$\omega_T = \frac{\left(i_o - \bar{t}_1 + \Delta\bar{t}_f\right) - \alpha_T\left(i_T - \bar{t}_T\right)}{\alpha_T\left(i_T - \bar{t}_T\right)} \times \frac{\eta_m\eta_g \times 10^6}{3600} \tag{10}$$

The normal-coal consumption of power unit hourly, B_0, is

$$B_0 = \frac{D_0\left(i_0 - \bar{t}_1\right) \times 1000}{\eta_b\eta_{gd}Q_d^y} \tag{11}$$

The specific fuel cost (defined as the cost in $ for 1 ton of distilled water production), C_W, is obtained as

$$C_W = \frac{\Delta B \times \text{cost}}{\Delta D_T \times \text{GOR}} \tag{12}$$

2.3. *Equivalent enthalpy drop theory*

The equivalent enthalpy drop theory is a partial quantitative analytical method for analyzing and calculating the thermodynamic system [10]. The equivalent enthalpy drop demonstrates the real work ability of 1 kg extraction when it returns to the turbine from the extraction point and also indicates the grade energy of the extraction steam. It is assumed in the equivalent enthalpy drop theory that the fresh steam flow rate of the turbine and the beginning and ending steam parameters keep invariant and the eigenvalue of heat-cycle system is constant. The equivalent enthalpy drop is determined only by the parameters of the entrance, exit and extraction steam of the turbine and is independence of the amount of extraction steam. When there is some variation in the thermal system, the effect of variation on the system efficiency can be conveniently obtained by the partial quantitative calculation instead of the complex calculation of the whole system. This theory has already been widely used to do research on the analysis of energy saving of both condensing and CHP steam turbines.

The equivalent enthalpy drop of extraction j for power unit, H_j^e, is expressed by

$$H_j^e = i_j - i_k - \sum_{r=j+1}^{z} \frac{A_r}{q_r} H_r^e \tag{13}$$

The efficiency of extraction j, η_j, is

$$\eta_j = \frac{H_j^e}{q_j} \tag{14}$$

The matrix model of the extraction efficiency of the unit shown in Fig. 1 can be calculated as

$$\begin{bmatrix} q_1 & \gamma_2 & \gamma_3 & \tau_4 & \tau_5 & \tau_6 \\ & q_2 & \gamma_3 & \tau_4 & \tau_5 & \tau_6 \\ & & q_3 & \tau_4 & \tau_5 & \tau_6 \\ & & & q_4 & \gamma_5 & \gamma_6 \\ & & & & q_5 & \gamma_6 \\ & & & & & q_6 \end{bmatrix} \begin{bmatrix} \eta_1 \\ \eta_2 \\ \eta_3 \\ \eta_4 \\ \eta_5 \\ \eta_6 \end{bmatrix} = \begin{bmatrix} i_1 - i_k \\ i_2 - i_k \\ i_3 - i_k \\ i_4 - i_k \\ i_5 - i_k \\ i_6 - i_k \end{bmatrix} \tag{15}$$

or

$$[A][\eta] = [\Delta h] \tag{16}$$

where A_r equals to τ_r or γ_r according to the type of the heater [10], the matrix A is determined by the structure and parameters of power unit.

After extraction T condenses in the desalination system, the condensate of extraction T and the supply water are mixed, heated and returned to feed water from No. j heater. In terms of the rule that working fluid and heat entering and leaving the thermal system, the work loss, ΔH, due to the extraction for heating desalination system is given by

$$\Delta H = n_T\left[\left(t_T - i_k\right) + \Delta\alpha_i\left(i_i - i_k\right) - \left(1 + \Delta\alpha_i\right)\right] \left[\left(\bar{i}_l - \bar{i}_{i+1}\right)\eta_j + \sum_{r=z}^{j+1} \tau_r \eta_r\right] \tag{17}$$

The portion of No. i extraction that is used to heat the mixture is

$$\Delta\alpha_i = \frac{\bar{t}_L - \bar{t}_m - \varphi\left(\bar{t}_T - \bar{t}_m\right)}{i_T - \bar{t}_L} \tag{18}$$

The matrix model of ΔH can be given by

$$\Delta H = n_T\left[\left(h_T - h_k\right) + \Delta\alpha_i\left(h_i - h_k\right)\right] - [\eta^T][A_r][\alpha_f]$$

$$A_r = \begin{bmatrix} 0 & & & & & \\ \tau_2 & 0 & & & & \\ \tau_3 & \tau_3 & 0 & & & \\ \vdots & \vdots & \vdots & \vdots & & \\ \tau_j & \tau_j & \tau_j \ldots (\bar{i}_l - \bar{i}_{j+1}) & & & \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ \tau_Z & \tau_Z & \tau_Z \ldots & \ldots\ldots\ldots 0 & & \end{bmatrix} \quad \alpha_f = \begin{bmatrix} 0 \\ 0 \\ 0 \\ \vdots \\ (1+\Delta\alpha_i)n_T \\ \vdots \\ 0 \end{bmatrix} \tag{19}$$

where n_T is the share of the extraction for heating the desalination system, ϕ is the rate of condensate that returns to power unit, $\bar{t}_m$ is the enthalpy of the supply water and $\bar{t}_L$ is the enthalpy of the mixture after being heated by No. i extraction.

The EECR defined as the electricity loss in kWh for 1 ton of distilled water production can be used to evaluate the energy cost for water production. EECR can be calculated as

$$\text{ELWP} = \frac{\Delta H}{n_T \times \text{GOR} \times 3.6} \tag{20}$$

2.4. Mathematical model of off-design working conditions

The economical operation of the unit in the power plant is closely related to its operating parameters. Flugel formulation is the basic fundamental of off-design working condition calculation of cogeneration. It expresses that the steam flow varies with steam temperature and pressure in contiguous units of steam turbine. Flugel formulation is based on these conditions in each unit which are invariable flow path area, flow rate and homogeneous steam flow.

Flugel formulation is expressed as

$$\frac{D_{01}}{D_0} = \sqrt{\frac{p_{01}^2 - p_{21}^2}{p_0^2 - p_2^2}} \sqrt{\frac{T_0}{T_{01}}} \tag{21}$$

where D is the steam flow, the first subscripts of 0 and 2 represent the parameters of the previous and posterior unit respectively, and the second subscripts of 1 represents the parameter of varying working conditions.

Flugel formulation is derived from condition that the steam flow and flowing area of units keep constant. As to the extraction steam regulation turbine, both the flow and flowing area change. In order to satisfy the stipulation of the formulation, the extraction steam regulation turbine should be divided into different units in terms of heating extraction, thus Flugel formulation can be used in each unit.

2.5. LT-MED combined with thermal vapour compression

The equations describing LT-MED are developed by applying mass balance, energy balance and heat transfer equations to evaporators, flash boxes, pre-heaters and the final condenser [11]. The features of LT-MED mathematical models are constant and equal heat transfer area in all effect, thermodynamic losses including boiling point elevation, temperature depression in the demister and vapour transmission passage etc. The simulation model of the thermal vapour compression is developed by application of the equations of continuity, momentum and energy to individual operation of the nozzle, mixing chamber and diffuser [12]. Therefore the gained output ratio (GOR) of LT-MED combined with TVC can be expressed as:

$$\mathrm{GOR} = f(D_d, P_m, T_0, T_n, X_0, X_n, N) \tag{22}$$

2.6. Solution algorithm

The solution algorithm stars with the definition of the following parameters:

- The number of evaporator effects is 12
- The intake seawater temperature is 25°C
- The evaporation temperature in the last effect is 40°C
- The heating steam temperature varies over a range of 60–75°C
- The salinity of seawater has the value of 3.4%
- The outer diameter of tubes is 25.4 mm and the inside diameter is 24 mm

The detail solution algorithm is shown in Fig. 2.

3. Results and discussion

A 12-effect LT-MED combined with TVC is driven by extraction T of the CHP plant shown in Fig. 1. By solving matrix models of the cyclical function method and the equivalent enthalpy drop theory, it is analysed that the extraction used for desalination has effect on the CHP plant and the specific fuel cost of water production at different working conditions.

Although investment and O&M cost are important in the analysis of the cost of water production, they are not analysed hereinto due to the following reasons. It is concentrated on the thermoeconomic analysis rather than the economic analysis. Besides, as the design condlition contributes the equipments of a power plant steady and long-term running, O&M expense in a CHP-based dual-purpose power plant reduces compared with a CHP power plant at part-loads. In addition, due to the improvement of the efficiency of equipment utilization at the design condition, the effect of investment is apt to under-estimating the produced water cost qualitatively.

3.1. Analysis based on the cyclical function method

Table 1 shows the effect of extraction T on the CHP. It can be seen that thermal generating efficiency and HPGR decrease with a reduction in extraction T flow rate when the power production and extraction Π keep invariant. As the CHP plant supplies heating by adjusting the diaphragm, the steam flow path of CHP is different from that of condensing steam turbine (CST). Thus the generating efficiency of the main condensing circle of the CHP is lower than that of CST that produces the same amount of power. The generating efficiency of CHP for the extraction circle is higher than that of CST due to heating extraction being utilized for desalination. Thus with the decrease of extraction T, the proportion of power production generated by the main condensing circle increases while that generated by the extraction circle decrease, which results in the reduction in the generating efficiency of CHP.

HPGR precisely calculated by the cyclical function method is an important economic index of the CHP plant, which denotes the efficiency of the heat to power output process and economics of CHP. When it is lower than the critical value, the economics of cogeneration is inferior to the independent heat and power system. So the heat and power generation rate of extraction can be used as the criterion of energy saving to calculate the minimal heating extraction.

The load of extraction T is relatively unstable compared with that of extraction Π, as it varies with seasons. It reaches maximum in winter while being minimum in summer. Thus a CHP plant works in an off-design condition, which results in a decrease in power production. However the power demand increases in summer due to an increase in the air-conditioning load. A CHP-based dual-purpose power plant satisfies the power and water demand simultaneously. The generating efficiency can be improved and the fuel cost for water production can be reduced if the surplus heating load in summer is utilized for desalination. For Case 1 and Case 2 in Table 1, it is possible to make both of them work at the designed condition by increasing the load of extraction T. When the price of norm-coal cost is 37 $/t that is obtained according to the calorific value and price of fired-coal, the fuel cost for water production is about 0.3$/t. Such low fuel cost is nearly equal to the energy cost of reverse osmosis (6 kWh/t × 0.06$/kWh = 0.36 $/t). However the quality of water produced by LT-MED is much higher than that produced by reverse osmosis, the former being 5 ppm, the latter being 150–300 ppm. So it is an economic and effective way to reduce the energy requirement of water production and increase the thermal efficiency of the CHP by utilizing the extraction load to heat LT-MED system in summer.

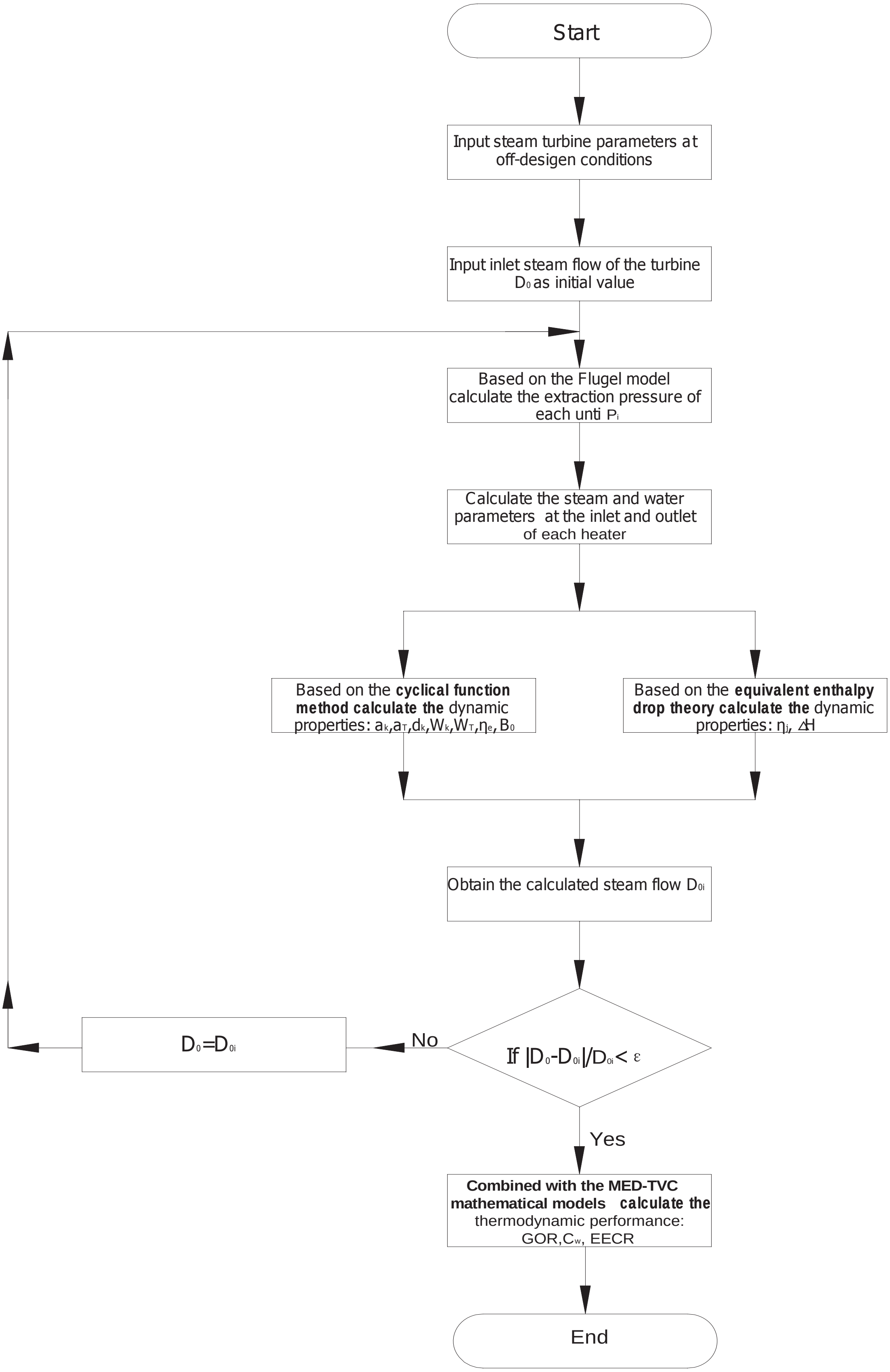

Fig. 2. Flow chart of the solution algorithm.

Table 1
The performance of the CHP plant at different working conditions

	Design condition	Case 1	Case 2
Power production P, MW	52	52	52
Extraction Π flow D_{Π}, t/h	75	75	75
Extraction T flow rate D_{T}, t/h	120	60	0
Steam consumption rate for main condensate steam circle dk, kg/kWh	3.89	4.03	4.07
Work of extraction Π circle for 1 kg extraction W_{Π}, kJ/kg	388.4	359.9	332.9
Work of extraction T circle for 1 kg extraction W_{T}, kJ/kg	592.7	537.1	503.3
Thermal generating efficiency ηe	0.3216	0.3044	0.3039
Heat and power generation rate of extraction T ω_{T}, kWh/GJ	53.0	47.4	44.1
Heat and power generation rate of extraction Π ω_{Π}, kWh/GJ	32.5	29.9	27.7
Normal-coal consumption of power unit hourly B0, t/h	36.935	33.287	29.59
Specific fuel cost for water production C_{W}, $/t		0.299	0.301

3.2. Analysis based on the equivalent enthalpy drop theory

Figs. 3 and 4 demonstrate the effect of the heating steam temperature and extraction pressure on EECR and GOR. It can be seen that EECR and GOR increase with an increase in the extraction pressure. With an increase in the extraction pressure, the performance of the LT-MED desalination process improves according to the widely used evaluation criterion of GOR, while it reduces in terms of EECR. The reason is that GOR does not take into account the grade energy of the extraction, regarding the extraction T and Π as the same grade energy, while EECR reveals the real work ability of extraction. So the accurate calculation for energy requirement of water production can be done by EECR.

As Fig. 3 indicates, the value of EECR in the range of 12–20 kWh/t is high. One reason is that the pressure of extraction is higher than the required heating steam pressure of LT-MED, thus the energy can't be utilized according to its grade. The most common way to solve the problem is to adopt TVC to match the extraction parameters to that of LT-MED. As the efficiency of TVC is low in transforming available energy into pressure energy, which is about 30%, a great deal of energy is lost during the process. The other reason is that the energy-saving benefit of the CHP is allocated to power share for calculating EECR, while the coal-saving benefit due to an increase in extraction is allocated to the specific fuel cost for water production in Table 1. So the specific fuel cost for water production in Table 1 is obviously lower than EECR in Fig. 3.

4. Conclusion

The following conclusions are made:

(1) For a CHP-based dual-purpose power plant with LT-MED, it is possible to calculate the effect of the heating extraction for desalination process on the power and heat of the CHP, and accurately assess the energy requirement of water production based on the equivalent enthalpy drop theory and cyclical function method.

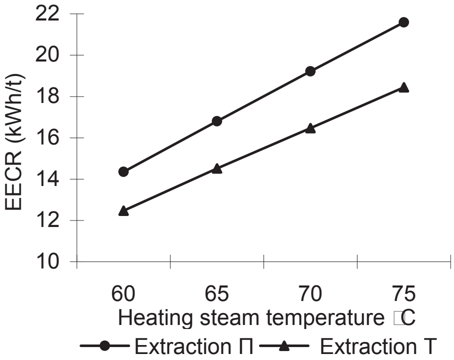

Fig. 3. Effect of heating steam temperature and extraction pressure on EECR.

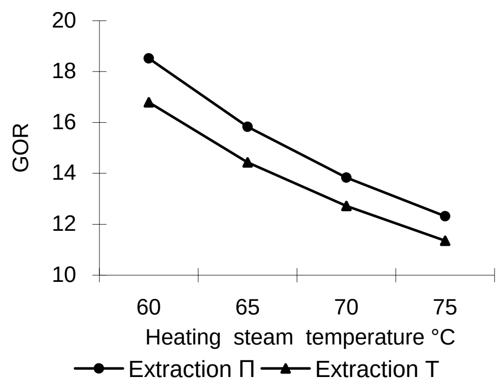

Fig. 4. Effect of heating steam temperature and extraction pressure on GOR.

(2) Utilizing surplus heating extraction load in summer for desalination contributes to improving thermal generating efficiency and HPGR and reducing the fuel cost of water production.
(3) The matrix calculation models of the equivalent enthalpy drop theory and cyclical function method are established, which are easy to be computerized and have features for universal purpose.
(4) EECR is more accurate to evaluate the performance of the desalination process than GOR that is widely used.

Symbols

B_0 — Normal coal consumption of power unit hourly, t/h
ΔB — Increment of norm-coal due to augmenting extraction T, t/h
C_W — Specific fuel cost, \$/t
Cost — Price of norm coal, \$/t
d_k — Steam consumption rate of the main condensing circle, kg/kWh
D_0 — Flow rate of fresh steam, kg/s
D_d — Flow rate of distillate, kg/s
ΔD_T — Flow of extraction for LT-MED, kg/s
GOR — Gained output ratio of LT-MED combined with TVC
H_j^e — Equivalent enthalpy drop of extraction j for power unit, kJ/kg
ΔH — Work loss, kJ/kg
i_0 — Enthalpy of fresh steam for the turbine, kJ/kg
i_k — Enthalpy of the exit steam of the turbine, kJ/kg
i_T — Enthalpy of extraction T, kJ/kg
n_T — Share of the extraction for heating the desalination system
N — Number of effects
p — Steam pressure, MPa
P_m — Extraction pressure, MPa
q_i — Amount of the release heat of extraction for No. i heater, kJ/kg
Q_d^y — Calorific value of normal-coal, MJ/kg
$\overline{t}_m$ — Enthalpy of the supply water, kJ/kg
$\overline{t}_L$ — Enthalpy of the mixture after being heated by No. i extraction, kJ/kg
$\Delta\overline{t}_f$ — Increment of enthalpy of 1 kg feed water in feed water pump, kJ/kg
T — Steam temperature, K
T_0 — Heating steam temperature, K
T_n — Saturated steam temperature in the last effect, K
W_k — Work of the main condensing circle for 1 kg exhaust, kJ/kg
W_T — Work of extraction T circle for 1 kg extraction T, kJ/kg
X_0 — Intake seawater salinity
X_n — Rejected brine salinity

Greek

α_i — Exhaust coefficient of No. i extraction
α_k — Exhaust coefficient of the main condensing circle
α_T — Exhaust coefficient of extraction T circle
$\Delta\alpha_t$ — Portion of No. i extraction that is used to heat the mixture
ϕ — Rate of condensate that returns to power unit
γ_i — Release heat of 1 kg drainage in No. i heater, kJ/kg
η_b — Thermal efficiency of the boiler
η_e — Thermal generating efficiency
η_f — Efficiency of extraction j
η_G — Efficiency of the power generator
η_{gd} — Thermal efficiency of the feed heating pipe
η_M — Mechanical efficiency of the steam turbine
τ_i — Increment of enthalpy of 1kg feed water in No. i heater, kJ/kg
ω_T — Heat and power generation rate of extraction T, kWh/GJ

References

[1] Z. Wang, The present status and future development of cogeneration in China, China Power, 32 (1999) 10–13.
[2] G.P. Maheshwari Smith and M. Al-Ramadhan, Energy requirement of water production in dual-purpose plant, Desalination, 101 (1995) 133–140.
[3] M.A. Darwish, Fuel cost charged to desalters in co-generation power-desalting plants, Heat Recovery Systems CHP, 15(4) (1995) 357–368.
[4] A.M. El-Nashar, Cost allocation in a cogeneration plant for the production of power and desalted water comparison of the exergy cost accounting method with the WEA method, Desalination, 122 (1999) 15–34.
[5] A.M. El-Nashar, Optimal design of a cogeneration plant for power and desalination taking equipment reliability into consideration, Desalination, 229 (2008) 21–32.
[6] M.A. Darwish, Cogeneration power–desalination plants, Desalination, 69 (1988) 27–46.
[7] M.A. Darwish, F.A. Yousef and N.M. Al-Najem, Energy consumption and costs with a multi-stage flashing (MSF) desalting system, Desalination, 109 (1997) 285–302.
[8] M.A. Danish, F. Al Asfour and N. Al-Najem, Energy consumption in equivalent work by different desalting methods: case study for Kuwait, Desalination, 152 (2002) 83–92.
[9] F.-l. Ma, The Principle of Saving Energy Analysis of Thermodynamic Systems in Power Plants, Beijing Hydraulic and Electric Power Press, Beijing, 1992, pp. 29–83.
[10] W.-c. Lin, The Systemic Energy-Saving Theory of Power Plants, Xi'an Jiaotong University Press, Xi'an, 1994, pp. 22–43.
[11] H.T. El-Dessouky and H.M. Ettouney, Performance of parallel feed multiple effect evaporation system for seawater desalination, Appl. Thermal Eng., 20 (2000) 1679–1706.
[12] N.H. Aly, A. Karameldin and M.N.Shamloul, Modelling and simulation of steam jet ejectors, Desalination, 123 (1999) 1–8.