Desalination and Water Treatment
www.deswater.com

18 (2010) 38–45
June

1944-3994 / 1944-3986 © 2010 Desalination Publications. All rights reserved.
doi: 10.5004/dwt.2010.1310

Energy-consumption analysis of a configuration of an absorption vapor compression coupled to MED in a dual-purpose power plant

Luopeng Yang*, Huawei Hu, Xue Chen

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, People's Republic of China
Tel.: +86 (411) 84707963; email: yanglp@dlut.edu.cn; michale_ylp@yahoo.com.cn

Received 1 May 2009; Accepted 9 February 2010

ABSTRACT

A dual-purpose power plant that produces heating-water-cooling-power cogeneration is presented. It comprises LiBr-H_2O absorption vapour compression (ABVC), low-temperature multi-effect distillation (LT-MED) and combined heat and power plant (CHP). The low grade extraction or discharged steam from the steam turbine is used for heating as well as motive steam to drive LT-MED combined ABVC that produces fresh water and cooling. Based on the second law of thermodynamics, it is used to analyze the energy consumption of the dual-purpose power plant that the energy with different grades can be evaluated by the equivalent raw energy consumption. The effect of turbine's steam parameter on the specific raw energy consumption of water production is explored and the comparison of energy consumption between the dual-purpose power plant and CHP plant for different heating load is done. The results indicate that it is favourable to increase the parameter of fresh steam and reduce the parameters of the exit steam for reducing the energy consumption of water production. It is also shown that with the reduction in heating load, the raw energy consumption rate of generation and heating increases for the CHP plant and the specific raw energy consumption of water production reduces for the dual-purpose power plant. It is concluded that the dual-purpose power plant extends the evaporating temperature range by dramatically reducing evaporating temperature in the bottom evaporator, which results in effectively reducing the cost of water production, and contributes to alleviating the power load for refrigeration in summer, increasing the power production, and reducing the cost of heating by using surplus heating load for desalination.

Keywords: Low-temperature multi-effect distillation; Absorption vapor compression; Raw energy consumption rate; Dual-purpose power plant

1. Introduction

The fresh water shortage in northern coastal regions has become a critical constraint factor for sustainable development. The average freshwater amount of China is approximately one fourth of that of the world. The water shortage is particularly serious in the northern coastal where the population accounts for 40% of the total, but the area is only 13% of the country. The fast development of the process of industrialization and urbanization, together with the rapid increasing population, deteriorates the severe water condition in the past 30 years.

In order to mitigate the water shortage problem several methods are considered, which include enactment of laws and regulations on water conservation, exploitation of groundwater, inter-basin water transfer and desalination. But the practical results have proved that

---

*Corresponding author.

desalination may pave the way to more accessible water while the rest methods are not able to effectively solve the problem of water scarcity.

The dual-purpose power plant integrated with LT-MED proves to be a viable way to reduce energy cost of desalination. As seawater desalination is a kind of technology gaining freshwater from seawater which needs to consume a large amount of energy, minimization of energy consumption is one of the most important factors determining desalination decisions. The available thermal desalination technologies used in the dual-purpose power plant are multi-stage flash (MSF) and low temperature multi-effect distillation. MSF process has been the mainstay for the large-scale desalination plant in the word, especially in the Middle East countries. But with the latest developments in LT-MED technology, LT-MED changes the dominant MSF. Compared with the equivalent capacity high efficiency MSF plants, a number of LT-MED plants have been built with lower costs [1-2], which proves that LT-MED emerges as a candidate for providing water supply.

The dual purpose power plant integrated with LT-MED is an efficient and economical solution for water scarcity in Chinese northern coastal zone. To begin with, the present energy state in China demands the dual purpose power plant. For the present energy state, on the one hand the average energy resource per capital is short, on the other hand the efficiency of energy utility is low. As China is populous, its average energy resource per capital is 45% of the average of the world while the efficiency of energy utility accounts for 32% of the average of the world [3]. The coal-fired power plant is the dominant contributor to power production. The installed capacity of coal-fired power plants will account for more or less 71% of the total installed capacity, and they produced about 78.3% of the total electric power by 2010 [4]. The dual-purpose power plant integrated with LT-MED contributes to utilizing low-grade heating resource, which improves the efficiency of energy utility. Besides, the dual-purpose power plant makes for improving the economic performance of the power plant. For the combined heat-and-power (CHP) plant the load of heating extraction varies with seasons, which reaches maximum in winter while minimum in summer. As a result the CHP works at not design but off-design working condition, which leads to reducing the thermal generating efficiency of CHP. It improves thermal generating efficiency and reduces the fuel cost for water production when the surplus heating extraction is used to heat LT-MED. The dual purpose power plant integrated with LT-MED is a viable way for special situation in China.

In attempt to reduce the energy cost in desalination, heat pumps have been coupled to LT-MED to increase the thermal performance. Heat pumps are devices that receive energy from a low-pressure source and upgrade to a high-pressure source. For the process of pressure transfer an energy input in form of either work or heat is required. The thermal efficiency is enhanced by compressing the vapor from the last effect to increase its saturated pressure to drive the first effect. Several forms of heat pumps are suitable for thermal desalination including mechanical vapor compression (MVC), thermal vapor compression (TVC) and absorption vapor compression (ABVC).

Most of the MVC plants work in the single-effect mode with unit capacities up to 5000 m^3/d [5] and specific power consumption, 6 kWh/m^3 [6–8]. The MVC process has high reliability, inexpensive seawater pretreatment and long lifetime. The main disadvantage is that it consumes electricity which is high-grade energy compared with saturated steam used in other thermal desalination process. Besides, the mechanical compressor requires frequent maintenance due to its moving parts. In addition, the capacity of MVC is confined to the increasing in the compression range. Therefore MVC is mainly limited to the operation of small and medium scale units in remote areas where steam is not available.

TVC-LT-MED is widely used in practice among the desalination processes of combining heat pumps with LT-MED. The outstanding feature is absence of moving parts, which makes it easy operation and maintenance. Another important feature is that its thermal performance is high. Temster [9] reported a thermal performance ratio of 16 for a twelve-effect TVC-LT-MED. Michles [10] reported a GOR of 8 for a four-effect system. Two of LT-MED desalination plants with a capacity of 1000 m^3/d and a GOR of 8.33 were installed in northern coastal areas of China in 2006 and One LT-MED desalination unit with a capacity of 12 500 m^3/d has successfully been operating in 2009 [29]. The main drawback of TVC-MED lies in that it does not permit a precise matching of the power demand curve. The performance of TVC is very sensitive to the motive steam pressure. When the power plant operates at partial load, the pressure of motive steam reduces, which results in the ejecting coefficient of TVC reducing sharply. Thus TVC-MED does not permit to match the power demand exactly although TVC-MED is the industrial standard.

ABVC-LT-MED has been proposed to be one of the best options for thermal desalination to be competitive with reverse osmosis [11]. The significant advantage of the ABVC-LT-MED is that it is able to operate at partial load. The reduction in the pressure of motive steam caused by the power demand curve has less effect on ABVC-LT-MED than TVC-LT-MED. Compared with the widely used TVC-LT-MED system, ABVC-LT-MED has higher performance ratio for the same pressure motive steam. For TVC-LT-MED, a GOR of 16 is normally the maximum whereas a GOR of 21 was attained for the ABVC-LT-MED at Plataforma Solar de Almeria (PSA), Spain [12]. The heat rejection is able to be recovered in ABVC-LT-MED while that is partially recovered in TVC-LT-MED. In addition, since the steam produced in the last effect is condensed by ABVC, the ABVC-LT-MED system avoids the requirement of cooling seawater. Thus the electric power of the pumping consumption and intake seawater costs are decreased. Moreover, the evaporation temperature in the last effect is not limited to fresh seawater temperature. For ABVC-LT-MED the evaporation temperature in the last effect may be decreased below the ambient temperature. Thus a higher number of the effect is possible to be attained, corresponding to higher thermal performance. Aly [13] proposed the lowest evaporation temperature of 6°C with a 20-effect distillation plant. Some researches have done on development, innovation and performance evaluation of ABVC for desalination [14–21]. Mandani [20] gave a detailed thermodynamic model of ABVC-LT-MED. Nguyen [18] proposed a system driven by a hybrid gas and solar system. Siquiers [21] presented a small demonstration plant.

The experiments on double effect ABVC for LT-MED [12, 22–24] have proven its technical feasibility at PSA. The experimental researches show that the ABVC-LT-MED is competitive if a thermal energy resource with high exergy has to be consumed. Thus the CHP integrated with ABVC-LT-MED seems to be the most suitable dual-purpose power plant configuration for the above-mentioned special situation in China. On the one hand in summer the CHP works at partial load due to the reduction in heating extraction load, which leads to decreasing the thermal efficiency of power plants, on the hand there is more electric demand for air-condition and fresh water. However, most of the above researches are about solar-powered ABVC-LT-MED.

A dual-purpose power plant that produces heating-water-cooling-power cogeneration is presented. It comprises LiBr-H_2O ABVC, low-temperature multi-effect distillation (MED) and combined heat and power plant (CHP). The low grade extraction or discharged steam from the steam turbine is used for heating as well as motive steam to drive ABVC-LT-MED that produces fresh water and cooling. Based on the second law of thermodynamics, it is used to analyze the energy consumption of the dual-purpose power plant that the energy with different grades can be evaluated by the equivalent raw energy consumption.

2. Process description

Fig. 1 shows a schematic diagram for a back-pressure power plant integrated with ABVC-LT-MED. The dual purpose power plant has the following advantages. Firstly, the condenser and evaporator in the standard ABVC are replaced by the LT-MED unit. Secondly, the rejected brine about 7°C as a by-product of the proposed system can be used as cooling medium for water chiller of air-condition, which contributes to relieving the high electric demand in summer. Thirdly, the extraction steam of high pressure and temperature matches the heating steam of low pressure and temperature of MED by adopting ABVC. Lastly, the systemic performance is further improved by addition of a second generator, known as double-effect ABVC.

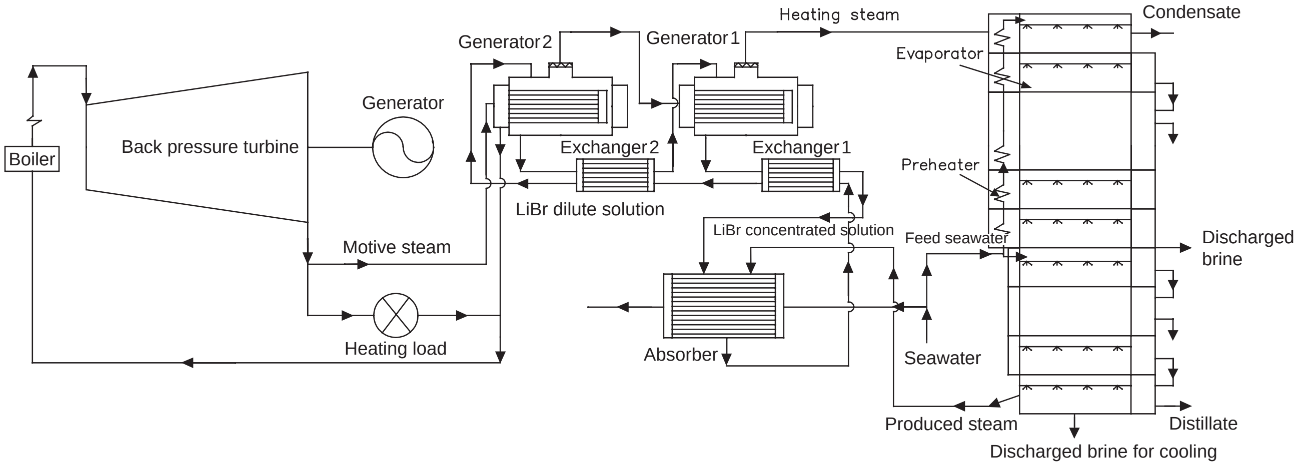

Fig.1. Schematic diagram for a back-pressure power plant integrated with ABVC-LT-MED.

The proposed dual-purpose power plant in Fig. 1 consists of three sub-systems which are a back-pressure power plant, an ABVC of the LiBr-H_2O type and a MED unit of stack flow. The steam drives the back-pressure turbine to generate power after it is heated in the boiler. The extraction is divided into two parts. Part of it is used for heating load which varies with seasons. The rest is motive steam to supply thermal energy to the sub-system of ABVC which utilizes the surplus heating load in summer. In the case of lithium and bromide absorption sub-system, water acts as refrigerant and lithium as absorbent. In Generator 2, the LiBr-H_2O dilute solution absorbs the latent heat of motive steam that condenses on the tube side. The condensate of motive steam goes back to the feed-water system of the boiler. The temperature of solution is increased to saturation by the heating process, and part of the refrigerant is evaporated as heating source for Generator 1. The concentration of LiBr-H_2O solution and the saturated steam temperature defined the equilibrium conditions in the generator. The dilute solution from Generator 2 gives away a fraction of its sensible heat through Exchanger 2 to the influent flowing to Generator 2, then enters Generator 1 where it is sprayed on the outside surface of the tubes. The steam produced in Generator 2 is used to heat the LiBr-H_2O solution in Generator1 at lower temperature, thus the LiBr-H_2O solution is concentrated twice. The steam released in Generator 1 is supplied as the heating steam to the MED top effect and its condensate is withdrawn outside the plant in order to avoid possible polluting the produced water by the chemical component of LiBr. After the concentrated solution from Generator 1 flows through Exchanger 1, it is introduced to the shell side of the absorber where it absorbs the vapour produced in the last effect of the MED sub-system. The dilute solution leaves the absorber to repeat the cycle. The heat produced during the process of absorption is cooled by fresh seawater.

The LT-MED sub-system in Fig.1 is similar to that of Aly [13], which is stacked vertically one on top of the other. As the evaporation range of LT-MED is extended due to the cold end not being restricted to the temperature of cooling seawater, it comprises an upper section of effects 1–12 and lower section of effect 13–18. The preheated seawater in the absorber is divided into three parts. The first part is allowed to pass successively through pre-heaters of the upper section to increase temperature close to the saturated in the first effect. The second is directly fed to the evaporators of the lower section. The rest is rejected back to the sea, known as the cooling seawater. On leaving the topmost pre-heater, the warm feed seawater is sprayed in the form of thin film on the outside of the succeeding rows of tubes arranged horizontally. The brine is heated to its saturated temperature before a small portion of it is evaporated. The vapour produced in each effect is condensed in the next effect after being passed through a demister to remove the entrained brine droplet. The rest part of brine is introduced into the next effect. As different effects are stacked vertically, brine cascades downwards by gravity, which can save a substantial pumping power. The processes of spray, evaporation and condensation are repeated in successive effects. The brine in effect 12 is divided into two parts. One enters the succeeding evaporator directly with the second part of the preheated seawater in the absorber, the other is rejected. The low temperature brine of 7°C in the last effect can be used for cooling. The steady-state conditions require the control between the rejected brine from effect 12 and the feed seawater to effect 13 to balance the produced steam in the last effect and the heating steam in the first effect.

3. Mathematical models

Some constructive studies have done on the economic analysis of the ABVC-LT-MED system based on the First Law of Thermodynamic [14–16,18,20]. But as most of the ABVC-LT-MED systems in these studies are driven by solar energy, the economic analysis does not include the effect of the desalination unit on the power plant. What's more, the grade of in-put energy is not taken into account in these studies. Thus the research does not reveal the qualitative performance, but the quantitative. In order to reflect the difference of the energy grade among heating, power, cooling and input energy, it is used to analyze the energy consumption of the dual-purpose power plant that the energy with different grades can be evaluated by the equivalent raw energy consumption based on the second law of thermodynamics [22].

According to the theory of the equivalent raw energy consumption, the high-grade heat energy combusted by 1kJ fuel in the boiler corresponds to μkJ low-grade heat energy of extraction which is expressed by

$$\mu = 1/(T - \omega\upsilon), \tag{1}$$

where ω is the work that the extraction as motive steam driving the ABVC-LT-MED has done before it exits from the steam turbine in kWh, υ is the heat energy consumed in the steam turbine to generate 1kWh work in kJ/kWh. T is the equivalent raw energy corresponding to the extraction of 1kJ heat energy in kJ/kJ.

3.1. Raw energy consumption rate of the dual-purpose power plant

The raw energy consumption rate of produced water (RECTW) defined as the raw energy in kW for 1kg/s produced water is used to evaluate the cost for water production. Based on the equivalent raw energy consumption, the RECTW can be calculated as

$$\text{RECTW} = \frac{\dfrac{Q_h \times (1-x)}{\mu \times \eta_p} - W_c}{M_m \times \text{GOR}}, \tag{2}$$

where x is the ratio between the part heating load and the rating heat load, Q_h, η_p, is the transportation efficiency of steam pipe, W_c is the raw energy consumption for the cooling load of the low-temperature discharged brine from the last effect of LT-MED, M_m is the mass flow rate of motive steam in kg/s, and GOR is the gained output ratio.

When the same amount of cooling load Q_c is generated by the ABVC refrigeration system, the Eq. (2) can be given by

$$\text{RECTW} = \frac{\dfrac{Q_h \times (1-x)}{\mu \times \eta_p} - \dfrac{Q_c}{\xi \times \mu \times \eta_p}}{M_m \times \text{GOR}}. \tag{3}$$

When the same amount of cooling load Q_c is generated by the compression refrigeration system, the Eq. (2) can be expressed as

$$\text{RECTW} = \frac{\dfrac{Q_h \times (1-x)}{\mu \times \eta_p} - \dfrac{W_e}{\eta_e \times \eta_n}}{M_m \times \text{GOR}}, \tag{4}$$

where ξ is the COP of ABVC, η_e is the thermal efficiency of the power plant, and η_n is the efficiency of power grid.

The special raw energy cost defined as the cost in $ for 1kg/s of produced water C_w is given as

$$C_w = \frac{\cos t \times \text{RECTW}}{Q_d^y}, \tag{5}$$

where Q_d^y is the calorific value of normal-coal and cos t is the price of norm-coal.

3.2. Comparison of raw energy consumption between the dual-purpose power plant and the CHP plant

In order to compare the raw energy consumption between the dual-purpose power plant and the CHP plant, it is assumed that the reduction in power due to the partial heating load is compensated by the power grid, and the surplus heating load is used to drive the ABVC-LT-MED system. Thus the RECTW is given by

$$\text{RECTW} = \frac{\left(\dfrac{Q_h \times (1-x)}{\mu\eta_p} + \dfrac{W}{\eta_m\eta_g\eta_b\eta_p\eta_{ih}}\right) - \left(\dfrac{XQ_h}{\mu'\eta_p} + \dfrac{W'}{\eta_m\eta_g\eta_b'\eta_p\eta_{ih}'} + \dfrac{W - W'}{\eta_n\eta_e}\right) - \dfrac{Q_c}{\xi\mu\eta_p}}{M_m\text{GOR}}, \tag{6}$$

where $\left(\dfrac{Q_h \times (1-x)}{\mu\eta_p} + \dfrac{W}{\eta_m\eta_g\eta_b\eta_p\eta_{ih}}\right)$ is the raw energy consumption of the dual-purpose power plant, $\dfrac{XQ_h}{\mu'\eta_p} + \dfrac{W'}{\eta_m\eta_g\eta_b'\eta_p\eta_{ih}'}$ is the raw energy consumption of the back pressure power plant at partial heating load, $\dfrac{W - W'}{\eta_n\eta_e}$ is the raw energy consumption of power compensated by the power grid due to the partial heating load, $\dfrac{Q_c}{\xi\mu\eta_p}$ is the raw energy consumption for the cooling load of the low-temperature discharged brine from the last effect of LT-MED, W is the rating power load, η_b is the boiler efficiency, η_{oi} is the steam turbine efficiency, η_m is the mechanical efficiency of the generator, and η_g is the efficiency of the generator. The superscript of ′ demonstrates partial load.

3.3. LT-MED combined with ABVC

The mass balance, energy balance and heat transfer equations for evaporators, flash boxes and pre-heaters in LT-MED system are developed simultaneous [23]. The thermodynamic losses from one effect to another are calculated in this mathematical model, which include temperature depression in the demister and vapour transmission lines, boiling point elevation and non-equilibrium allowance inside evaporators and flashing boxes. The model also considers the effect of water temperature and salinity on water physical properties such as density latent heat of evaporation, and the specific volume.

The simulation models of the double-effect ABVC is developed by applying the conservation equations of mass and energy and the mass concentration of LiBr concentrated solution is 55% provided that crystallization is avoided of the concentrated LiBr-H_2O in the generators [24].

Combined LT-MED and ABVC mathematical models, the gained output ratio (GOR) of desalination process can be expressed as the function of the flow rate of the distillate, the extraction pressure, the heating steam temperature, the saturated steam temperature in the last effect, the intake seawater salinity, the rejected brine salinity and the number of effect.

The GOR of LT-MED combined with ABVC is expressed as

$$GOR = GOR_{MED} \times COP, \quad (7)$$

where COP is the coefficient of ABVC performance.

4. Results and discussion

A 18-effect LT-MED combined with ABVC is driven by extraction of a back-pressure power plant as is shown in Fig.1. The extraction acts as the motive steam of the double-effect ABVC to produce heating steam of 70°C to heat the LT-MED unit with capacity of 5000 t/d. The low-temperature produced steam in the last effect is absorbed by the concentrated LiBr-H_2O in the absorber, the discharged brine of 7°C is used for cooling.

Table 1 shows the effect of steam parameters on the raw energy consumption rate of produced water. The steam parameters include both inlet steam pressure and extraction pressure of back-pressure turbine. It is assumed that the price of norm-coal cost is 114 $/t that is obtained according to the calorific value and price of fired-coal, the COP of the compression refrigeration amounts to 0.98 [25], the COP of the ABVC refrigeration system equals to 1.29 [26]. The value of μ in Table 1 depends on the steam parameters of the steam turbine [25,27].

It can be seen that RECTW and C_w decrease with an increase in inlet steam pressure and reduction in extraction pressure. Compared with steam parameters of B6-3.43/0.49, the inlet steam pressure, 8.83 MPa of B50-8.83/0.294 is high and the extraction pressure, 0.294 MPa is low. Thus inlet steam of B50-8.83/0.294 does more work than that of B6-3.43/0.49, and the extraction grade of B50-8.83/0.294 is lower than that of B6-3.43/0.49. Therefore the equivalent raw energy consumption of motive steam for B50-8.83/0.294 is lower than for B6-3.43/0.49. Although the COP of ABVC increases with an increase in extraction pressure, corresponding to an increase in the GOR of ABVC-LT-MED system, the effect of the raw energy consumption increasing with extraction pressure weighs more than that of COP of ABVC. As a result the raw energy consumption rate of produced water for B50-8.83/0.294 is lower than for B6-3.43/0.49.

Table 1 also illustrates that it is of importance to reduce the power load for air conditioning and mitigate the shortage of power in summer that the by-product of low-temperature brine can be used as the cooling medium for air-condition. As a result, the dual-purpose's economy is improved.

Table 2 shows the comparison of the raw energy consumption of B6-3.43/0.49 between the dual-purpose power plant and the back-pressure power plant for different heating load ratio. The boiler efficiency and the steam turbine efficiency change with the heating load ratio [28]. It can be seen from Table 2 that with a reduction in heating load the production power reduces, and

Table 1
Raw energy consumption rate of produced water for different steam parameters.

Steam turbine	μ	Compared with ABVC refrigeration system		Compared with compression refrigeration		Specific cooling power of produced water (kW/kg/s)
		RECTW (kW/kg/s)	C_w($/t)	RECTW (kW/kg/s)	C_w($/t)	
B6-3.43/0.49	1.86	93.89	0.37	90.13	0.35	6.58
B50-8.83/0.294	3.20	62.43	0.24	58.25	0.23	6.58

Table 2
Comparison of the raw energy consumption between the dual-purpose power plant and the back-pressure power plant for different heating load ratio.

x	Back-pressure power plant					Dual-purpose power plant			
	P (MW)	RECP (MW)	RECRP (MW/MW)	RECH (MW)	P_g (MW)	RECP (MW)	RECRP (MW/MW)	RECH (MW)	RECTW (kW/kg/s)
0.9	5.18	24.69	4.76	19.15	0.82	26.89	4.48	18.72	65.31
0.8	4.42	22.40	5.07	17.41	1.58	26.89	4.48	16.64	72.77
0.7	3.70	20.23	5.47	15.79	2.30	26.89	4.48	14.56	73.99
0.6	2.95	18.12	6.14	14.04	3.05	26.89	4.48	12.48	74.48

x : heat load ratio; P: power production; RECP: raw energy consumption of power; RECRP: raw energy consumption rate of power; RECH: raw energy consumption of heating; Pg: power from power grid.

the raw energy consumption rate of power increases obviously for the back-pressure power plant. For the dual-purpose power plant the raw energy consumption rate of produced water increases with the reduction in heating load ratio. When the heating load ratio reduces the inlet steam flow rate decreases, which results in the reduction in the production power, the boiler efficiency and the back-pressure turbine efficiency for the back-pressure power plant. The back-pressure steam turbine works at designed condition as the surplus heating load is used for desalination. Thus the raw energy consumption rate of power and the raw energy consumption of heating for the back-pressure power plant are higher than those of the dual-purpose power plant. Besides, combined with Eq. (6), the RECTW increases with the decrease in heating load ratio.

Table 2 also illustrates that the RECTW increases slowly with the reduction in the heating load ratio. On the one hand the raw energy consumption of heating load is proportional to the heating load ratio. On the other hand the raw energy consumption of power from power grid is lower t han that of the back-pressure turbine due to the higher average power efficiency of power grid. As a result the RECTW in Eq. (6) does not increase proportionally with the heating load for desalination.

5. Conclusions

A configuration of a two-effect absorption heat compression coupled to MED in a dual-purpose power plant is presented and analyzed. The following conclusions are made in light of the results and analysis.

- Compared with the widely used hybrid process TVC-LT-MED, the combining of ABVC with LT-MED offers important advantages: high thermal performance at the same steam parameters and fitting to the partial load.
- The ABVC-LT-MED system offers a possibility of extend evaporation rang by reducing the evaporation temperature in the last effect and increase the number of effect.
- The presented dual-purpose power plant can improve the efficiency of the power and heating load for the CHP plant in summer and effectively reduce the cost of produced water by means of utilizing the surplus heating load for desalination and cooling.
- Based on the theory that the energy with different grades can be evaluated by the equivalent raw energy consumption, the energy cost of power, heating and produced water is able to be accurately assessed for different heating load.
- It is favourable to increase the parameter of inlet steam and reduce that of extraction for reducing the energy consumption of water production. It is also shown that with the reduction in heating load, the raw energy consumption rate of power and heating increases and that the specific raw energy consumption of water production reduces.

References

[1] J.W. Vermey, Taweelah-Al, Makes breakthrough in large-scale MED plants, Desalination Water Reuse, 12 (4) (2003) 10–13.
[2] G. Canton, The recent progress and next generation of MED plants, Proceedings of the IDA International Water Forum, Dubai, UAE, March 5–6, 2006.
[3] Dai Yande, The energy issues for China's sustainable development, Energy Conserv., 2 (2003) 17–20.
[4] W. Jingru and C. Jiaobo, Problems of development planning for electric power industry in China, China Power, 38 (2005) 11–14.
[5] H.M. Ettouney, H.T. El-Dessouky and W. Abou Waar, Separation Characteristics of Ternary Gas Mixtures in Serial Cells of Polysulfone Hollow Fibre Membranes, Chem. Eng. Res. Des., 77(5) (1999) 395–404.
[6] M.A. Darwish and H. E1-Dessouky, Proc., IDA World Congress on Desalination and Water Sciences, Abu Dhabi, 2 (1995) 219–223.
[7] Z. Zimerman, Development of large capacity high efficiency mechanical vapor compression (MVC) units, Desalination, 96 (1994) 51–58.
[8] G. Piernavieja, J. M. Veza and J. M. Padrón, Experience in desalination training and know-how in the Canary Islands, Desalination, 141 (2001) 205–208.
[9] C. Temstet, G. Canton, J. Laborie and A. Durante, A large high-performance MED plant in Sicily, Desalination, 105 (1996) 109–114.
[10] T. Michels, Recent achievements of low temperature multiple effect desalination in the western areas of Abu Dhabi UAE, Desalination, 93 (1993) 111–118.
[11] J. de Gunzbourg and D. Larger, Cogeneration applied to very high efficiency thermal seawater desalination plants, Desalination, 125 (1999) 203–220
[12] J. de Gunzbourg and D. Larger, Cogeneration applied to very high efficiency thermal seawater desalination plants, Desalination, 125 (1999) 203–208.
[13] S. E. Aly, A study of a new thermal vapor compression/multi-effect stack (TVC/MES) low temperature distillation system, Desalination, 3 (1995) 257–263.
[14] S. E. Aly, Analysis of a fuel-solar assisted central DPP, Desalination, 82 (1991) 245.
[15] K. Fathalah and S. E. Aly, Theoretical study of a solar powered absorption/MED combined system, Energy Convers Manage., 31(6) (1991) 529–544.
[16] F. Al-Juwayhel, H. El-Dessouky and H. Ettouney, Analysis of single-effect evaporator desalination systems combined with vapor compression heat pumps, Desalination, 114 (1997) 253–275.
[17] S. Elshamarka, Absorption heat pump for a potable water supply in a solar house, Applied Energy, 40(1) (1991) 31–40.
[18] M. Nguyen, S. B. Riffat and D. Whitman, Solar/gas-driven absorption heat-pump systems, Appl. Therm. Eng., 16 (4) (1996) 347–356
[19] A. Huicochea, J. Siqueiros and R.J. Romero, Portable water purification system integrated to a heat transformer, Desalination, 165 (2004) 385–391.
[20] F. Mandani, H. Ettouney and H. El-Dessouky, LiBr–H_2O absorption heat pump for single-effect evaporation desalination process, Desalination, 128 (2000) 161–176.

[21] J. Siqueiros and F. A. Holland, Water desalination using heat pumps, Energy, 25(8) (2000) 717–729.

[22] C. Junyan, Energy estimation of combined heating and cooling systems, Heating Ventilating & Air Conditioning, 2 (2002) 120–124.

[23] L. Yang and S. Shen, Thermal analysis of low temperature seawater multi-effect distillation system, Chem. Eng., 34(11) (2006) 20–24.

[24] L. Yang and S. Shen, Thermal analysis of multi-effect distillation desalination system combined with absorption vapor compression, Acta Energiae Solaris Sinica, 28(06) (2007) 210–214.

[25] D. Yan and J. Wei, Energy conservation conditions on the CHP-combined with cooling, China Energy, 16(4) (1996) 29–33.

[26] Y. Dai, Technology and application of LiBr-H_2O absorption refrigeration [M], Mechanical industry Press, Bejing, 2001.

[27] K. Du, R. Qian and S. Yang, Appling analysis of the CHP combine with cooling, Power Eng., 18(2) (1998) 55–59.

[28] H. Jin and H. Guo, Load ratio and economic benefit of CHP, Energy Res. Util., 9(5) (1997) 8–12.

[29] R. Deng, L. Xie, H. Lin, J. Liu and W. Han, Integration of thermal energy and seawater desalination, Energy, (7) (2009) 1–7 (Contents lists available at ScienceDirect).