

Economic Analysis of Energy Requirement of Water Production in the Cogeneration with Low-Temperature Multi-Effect Distillation Plants

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Abstract: An accurate estimate for energy requirement of water production is of great importance in the cogeneration with low-temperature multi-effect distillation plants since the cost of energy requirement accounts for the foremost part of the water production cost. This paper presents an economic analysis of the energy cost of water production by the equivalent enthalpy drop theory that is proven to be an effect method for partial quantitative analysis. The theory can be used to accurately calculate both the energy requirement of water production and the influence of extraction on the turbine's efficiency. The electricity loss for water production (ELWP) and the specific fuel cost for water production are analysed as the function of the pressure of the extraction and the heating steam temperature. The results indicate that ELWP and the specific fuel cost are more accurate to evaluate the performance of the desalination process than gained output ratio (GOR) that is widely used to evaluate the performance of MED. It is also shown that the energy requirement of water production is favoured at lower heating steam temperature and extraction pressure. It is concluded that the cogeneration with LT-MED plant not only adequately utilizes the capacity of power plant, but also economically and efficiently resolves the problem of supply water for coastal power plants.

Keywords: Cogeneration with low-temperature multi-effect distillation plants; Equivalent enthalpy drop theory; Electricity - equivalent consumption rate; Specific fuel cost

1. INTRODUCTION

Water shortage in China, especially in north coastal regions, has become a critical constraint factor for socioeconomic development in the long run. To solve or eliminate water shortage problems, seawater desalination draws more and more attention as an alternative water supply source. At present there are various desalination technologies, including low-temperature multi-effect distillation (LT-MED), multi-stage flash (MSF), reverse osmosis (RO) and electrodialysis (ED). Among them, LT-MED is superior in utilizing low-grade heat available through cogeneration to minimize the energy cost component. So cogeneration with the LT-MED plant is an efficient and economical way to resolve the water supply for the power plant itself since the power plant consumes huge quantity of water.

It is very necessary to accurately estimate for the energy requirement of water production in the cogeneration with LT-MED plants. Many methods have been proposed to estimate the energy cost of water production^[1-2], but the effect of the extraction for LT-MED on the efficiency of turbine is neglected. So the exact energy cost for water production can't be calculated by the method. This paper presents a new method to analyse the cogeneration with LT-MED plants by the equivalent enthalpy drop theory.

2. MATHEMATICAL MODELS

2.1 Brief Description of The Cogeneration with LT-MED Plant

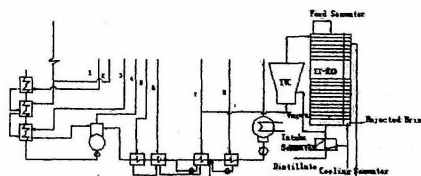


Figure 1: Flow chart of cogeneration with the LT-MED plant

A process schematic for the cogeneration with LT-MED plant is shown in Fig.1. As the top brine temperature of LT-MED is below 75°C, the parameter of extraction does not match to that of the desalination process. The most common way to solve the problem is to adopt thermal vapour compression (TVC) that uses extraction as motive steam to compress part of the saturation steam produced in the last effect of LT-MED. The condensation of the extraction returns to feed water of the power plant from No. j heater.

2.2 Equivalent Enthalpy Drop

The equivalent enthalpy drop theory is a partial quantitative analytical method for analysing and calculation the thermodynamic system [3]. The equivalent enthalpy drop demonstrates the real work ability of 1kg extraction when it returns to the turbine from the extraction point and also indicates the quality of the extraction steam. The equivalent enthalpy drop is determined only by the parameter of the entrance steam, exit steam and extraction of the turbine and is independence of the amount of extraction steam. When there is some variation in the thermal system, the effect of the 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 energetic saving of steam turbines.

(1) Equivalent enthalpy drop of extraction for power unit with re-heat

As the extraction from the hot head of re-heater to the condenser doesn't flow by the re-heater, the equivalent enthalpy drop of extraction is the same as the one for power unit without re-heater.

Equivalent enthalpy drop of extraction for power unit without re-heater is expressed by

$$H_j^e = h_j - h_k - \sum_{r=j+1}^z \frac{A_r}{g_r} H_r^e \quad (1)$$

Where h_j , h_k and g_r are the enthalpy of extraction for No. j heater, the enthalpy of the exit steam of the turbine and the amount of the release heat of extraction for No. j heater. A_r is equal to τ_r or γ_r according to the type of the heater [3]. τ_r is the increment of enthalpy of 1kg feed water in No. j heater, γ_r is the release heat of 1kg drainage in No. j heater.

The real work ability of the extraction from the fresh steam to the cool head of re-heater also includes the increment of work due the absorbed heat Δq_{rh} . The equivalent enthalpy drop of extraction from the fresh steam to the cool head of re-heater is given by

$$H_j^e = h_j - h_k - \sum_{r=j+1}^z \frac{A_r}{g_r} H_r^e + \Delta q_{rh} \quad (2)$$

The efficiency of extraction is

$$\eta_i = \frac{H_j^e}{g_j} \quad (3)$$

(2) Equivalent enthalpy drop of the fresh steam for power unit with re-heater

When the total work loss $\sum L_i$ is calculated, the net equivalent enthalpy drop of the fresh steam is defined as

$$H_0^e = h_0 - h_k - \sum_{r=1}^z \tau_r \eta_r - \sum L_i + \Delta q_{rh} \quad (4)$$

The absorbed heat of system is given by

$$Q_0 = h_0 - \bar{h}_{fw} + \alpha_{rh} \Delta q_{rh} \quad (5)$$

So the efficiency of turbine is expressed as

$$\eta_0 = \frac{H_0^e}{Q_0} \quad (6)$$

Where $\bar{h}_{fw}$ and α_{rh} are the enthalpy of the feed water and the share of the re-heat steam.

2.3 Partial Quantitative Analysis

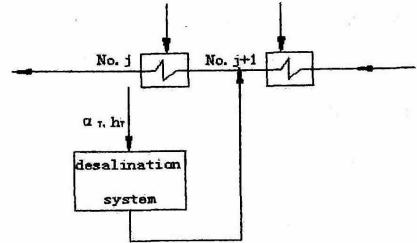


Figure 2: Diagram of the extraction for heating desalination system

2.3.1 work loss of extraction

As is shown in Fig.2, the condensation returns to feed water from No. j heater after the extraction condenses in the desalination system. In terms of the rule that working fluid and heat enter and leave the thermal system, the work loss ΔH due to the extraction for heating desalination system is given by

$$\Delta H = \alpha_T (h_T - h_k - (\bar{h}_T - \bar{h}_{j+1}) \eta_j - \sum_{r=z}^{j+1} L_r \eta_r) \quad (7)$$

Where h_T , $\bar{h}_T$ and $\bar{h}_{j+1}$ are the enthalpy of extraction for heating the desalination system, condensation and the exit feed water, and α_T is the share of the extraction for heating the desalination system.

2.3.2 Partial quantitative analysis for constant fresh steam Flow

When the flow of fresh steam D_0 keeps constant, according to the work loss in Eq. (7), the electricity loss for water production (defined as the electricity loss in kWh for 1ton of distilled water production) can be used to evaluate the energy cost for water production. ELWP can be calculated as

$$ELWP = \frac{\Delta H}{\alpha_T \times GOR \times 3.6} \quad (8)$$

Where GOR (defined as the distillation product divided by the extraction) is the gained output ratio of LT-MED, ΔD is the flow of extraction for LT-MED. Both of them can be obtained by the calculation of LT-MED combined with thermal vapour compression.

2.3.3 Partial quantitative analysis for constant power

To keep the power of the turbine invariant, the equivalent enthalpy drop and the flow of fresh steam are both variant. So the power equation of the turbine is given by

$$P_0 = D_0(H_0^e + t_p) = (D_0 + \Delta D_0)(H_0^e + \Delta H + t_p) \quad (9)$$

The increment of norm-coal consumption of power generation Δb can be derived from eq. (9)

$$\Delta b = b \times \frac{\Delta D_0}{D_0} = b \times \frac{\Delta H}{H_0^e + \Delta H + t_p} \quad (10)$$

Where t_p is the augment of the enthalpy of 1kg feed water due to the feed water pump, ΔD_0 is the increment of the flow of fresh steam. And b is the norm-coal consumption of power generation.

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

$$C_w = \frac{\Delta b \times P_0 \times \text{cost } t}{\text{GOR} \times \Delta D} \quad (11)$$

where $\text{cost } t$ is the price of norm-coal.

2.4 LT-MED Combined with Thermal Vapour Compression

The equations describing LT-MED are developed by applying material balance, energy balance and heat transfer equations to the evaporator, flash box, pre-heater and end condenser [4]. The simulation model for thermal vapour compression is developed by application of the equation of continuity, momentum and energy to individual operation of the nozzle, mixing chamber and diffuser [5]. So the distillation in each effect, the motive steam of TVC and the gained output ratio (GOR) can be expressed as the function of the flow 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 effects.

3. RESULTS AND DISCUSSION

It is supposed that the 12-effect LT-MED combined with TVC that produces 2000 ton distillation per day is driven by the extraction of N200—12.74/535/535 power unit. Based on the partial quantitative analysis, the ELWP and the specific fuel cost are performed as a function of the heating steam temperature and the extraction pressure.

Figure 3 and Figure 4 show the effect of the heating steam temperature and extraction pressure on ELWP and GOR for constant fresh steam flow. It can be seen that ELWP increases at higher heating steam temperature and higher extraction pressure while GOR increases with extraction pressure and decreases with heating steam temperature. At lower heating steam temperature the thermal vapour compression consumes less extraction, to induce the vapour generated in the last effect of LT-MED for the same extraction pressure, which results in the increment of GOR and the decrease of work loss of

extraction decrease. Combined with Eq. (8) it can prove that ELWP reduces. Figure 5 also shows that the specific transfer area of the distillate increases drastically at lower heating steam temperature, which causes the increase in the production cost.

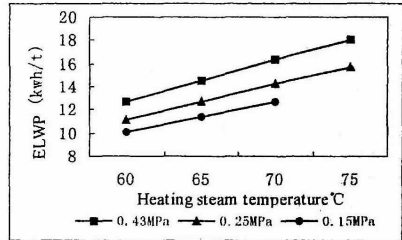


Figure 3: Effect of heating steam temperature and extraction pressure on the ELWP

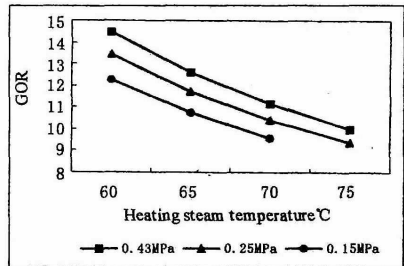


Figure 4: Effect of heating steam temperature and extraction pressure on the GOR

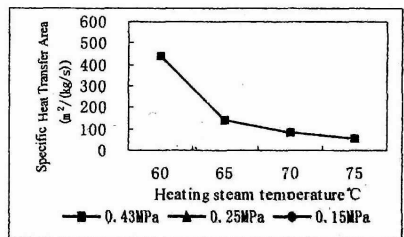


Figure 5: Effect of heating steam temperature and extraction pressure on the specific heat transfer area

With the increment of the extraction pressure the enthalpy of the extraction augments causing the increase in the work loss, and GOR increases due to the reduction of the extraction. As the effect of the increment of work loss on the ELWP weights more than that of the increase in GOR, the ELWP increases.

From the above analysis it can be seen that the variation of ELWP doesn't accord with that of GOR. The reason is that the quality of the extraction isn't

taken into account when GOR is widely used to evaluate the performance of LT-MED. So the accurate estimate for energy requirement of water production can be done by ELWP as ELWP reflects the real work ability of extraction.

As Figure 3 demonstrates, the value of ELWP that is in the range of 10-19 kWh/t is high compared with around 6 kWh/t of the reverse osmosis system. What's more, the quality of the distillate is much higher than the production of reverse osmosis system. However the quality of the distillate is much higher than the production produced by reverse osmosis. The distillate can even be used directly for the boiler supply water.

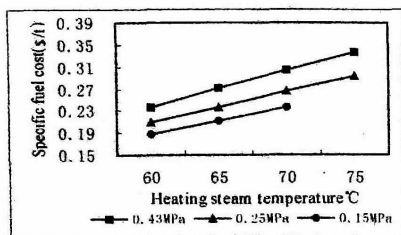


Figure 6: Effect of heating steam temperature and pressure on the specific fuel cost

The effect of heating steam temperature and the extraction pressure on the specific fuel cost is presented in Fig. 6 for constant power when the price of norm-coal cost is 62\$/t. The specific fuel cost in Figure 6 varies between 0.19-0.33\$/t that is even lower than the cost of supplying boiler water from surface and ground water in the coastal region where the condition of water scarcity is very severe. So the cogeneration with LT-MED can effectively resolve the problem of water supply for power plants

4. CONCLUSION

The following conclusions are made:

(1) In the cogeneration with LT-MED plants, the specific electricity loss of water production for constant fresh steam and the specific fuel cost for constant power based on the equivalent enthalpy drop theory provide an accurate assessment of the realistic energy cost of water production.

(2) The energy requirement of water production is favoured at lower heating steam temperature and extraction pressure. However, at lower heating steam temperature the specific heat transfer area increases drastically causing increase in the production cost. So selection of the most efficient operating condition and the least expensive system necessitate systemic optimisation.

(3) ELWP and the specific fuel cost are more accurate to evaluate the performance of the desalination process than GOR T power plants.

(4) The cogeneration with LT-MED not only adequately utilises the capacity of power plants, but also economically and efficiently resolves the problem of supply water for coastal

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