A Method for Analyzing the Thermodynamic System of Feedwater Heating Type Combined Cycle Unit

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***Abstract*—This paper introduces a novel matrix method for calculating the efficiency of the feedwater heating type combined cycle unit. The structure of this matrix has a mapping relationship with the thermodynamic system of the feedwater heating type combined cycle unit, and it can simplify the thermal economic analysis of the feedwater heating type combined cycle unit. An example was given to illustrate the validity of the method.**

Keywords-feedwater heating type; combined cycle; thermal economic analysis; matrix

I. INTRODUCTION

The feedwater heating type combined cycle unit is one of the most popular generating combined cycle units. Analysis the thermal system of the feedwater heating type combined cycle unit are of great scientific interest and also essential for the efficient utilization of energy resources. The most commonly-used method for analysis of an energy-conversion process is the first law of thermodynamics and the second law of thermodynamics. This paper presents a matrix method of analyzing the thermal system of the feedwater heating type combined cycle unit.

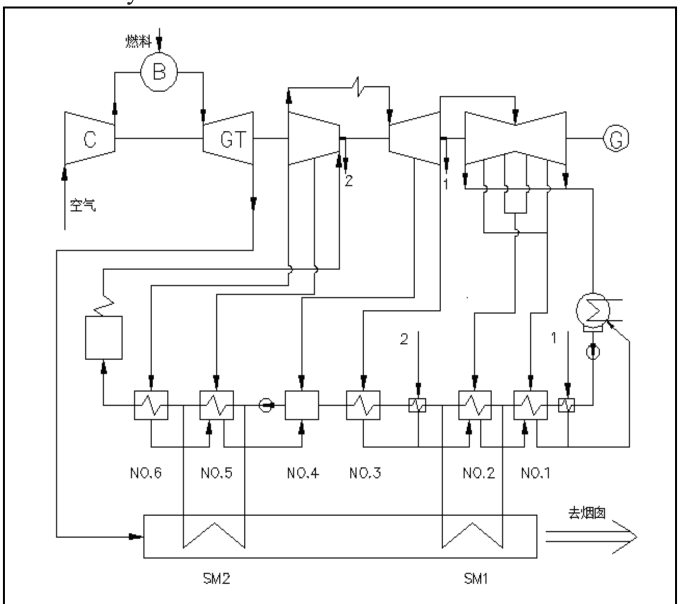

Figure 1. Schematic diagram of feedwater heating type combined cycle unit

II. UNIT DESCRIPTION

This paper introduces a feedwater heating type combined cycle unit, which total installed power capacity of 350 MW. It started to produce power in the 2000s. The schematic diagram of the unit's thermal system is shown in Fig.1. This unit employs regenerative feed water heating system. Feed water heating is carried out in two stages of high pressure heaters (HPH5, HPH6) and three stages of low pressure heaters (LPH1, LPH2, LPH3) along with one deaerating heat exchanger (PH4).

III. MATRIX METHOD AND MODELING

In this study, a matrix method[1] has been used to model the thermal system of the feedwater heating type combined cycle unit. This model performs on analyzing the economics of the thermal system of the feedwater heating type combined cycle unit.

The relations used to analyze the performance of the feedwater heating type combined cycle unit under consideration are the steady state, steady flow expressions of the continuity equation, the first laws of thermodynamics, the second laws of thermodynamics and matrix method. Thus feedwater heating type combined cycle unit's Steam-Water Distribute State Equation can be expressed by

$$[\mathbf{A}^{\mathbf{v}}][\boldsymbol{\alpha}] = [\boldsymbol{\tau}] \tag{1}$$

$$[\mathbf{A}^{\mathbf{v}}] = [\mathbf{E} - [\mathbf{A}_{\mathbf{f}}][\boldsymbol{\alpha}_{\mathbf{f}}]_{\mathbf{D}} - [\mathbf{A}_{\boldsymbol{\tau}}][\boldsymbol{\alpha}_{\boldsymbol{\tau}}]_{\mathbf{D}} - [\boldsymbol{\Delta}\mathbf{q}]_{\mathbf{D}}]^{-1}[\mathbf{A}] \tag{2}$$

Where $[\boldsymbol{E}]$ is a z order unit matrix; $[\boldsymbol{\alpha}_f]_{\boldsymbol{D}}$ is a z order matrix, its elements on the diagonal is α_{fi} / τ_i; $[\boldsymbol{\alpha}_\tau]_{\boldsymbol{D}}$ is a z order matrix, its elements on the diagonal is $\alpha_{\tau i} / \tau_i$; $[\boldsymbol{\Delta q}]_{\boldsymbol{D}}$ is a z order matrix, its elements on the diagonal is $\Delta q_i / \tau_i$.

1kg new steam's capacity of a turbine to do work can be expressed by:

$$\begin{aligned} H_0 &= h_0 + \sigma - h_n - \sum_{i=1}^{z} \alpha_i \Delta \tilde{h}_i \\ &= h_0 + \sigma - h_n - [\alpha]^T [\Delta \tilde{h}_i] \end{aligned}$$

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Nomenclature

		Subscripts	
h	specific enthalpy (J/ kg)	1,2,…,m,…,z	stages of steam extraction
H	enthalpy drop (J/ kg)	D	elements on the diagonal
A	structure matrix	f	auxiliary steam
q	heat release of steam in heater (J/kg)	gs	feed water
q_0	heat absorption (J/ kg)	i	stages of heaters
Δq	quantity of heat (J/ kg)	n	inlet of condenser
Π	loss of energy (J/ kg)	o	outlet of steam generator
Greek symbols		t	throat
		v	virtual system
α	steam extraction factor	zr	reheat
γ	heat release of drain in heater (J/kg)		
τ	heat absorption of feed water in heater (J/kg)		
η	efficiency (%)		

$$= h_0 + \sigma - h_n - [\tau]^T [A^T]^{-1} [\Delta \tilde{h}_i]$$

$$= h_0 + \sigma - h_n - [\tau]^T [\varphi]$$

$$= h_0 + \sigma - h_n - \sum_{i=1}^{z} \varphi_i \tau_i \qquad (3)$$

Where $[\varphi] = [A^T]^{-1} [\Delta \tilde{h}]$

Before reheater: $\Delta \tilde{h}_i = h_i - h_{zri} + \sigma$

After reheater: $\Delta \tilde{h}_i = h_i - h_n$

The thermal efficiency of the feedwater heating type combined cycle unit can be expressed by the following formulas:

$$\eta_{ccf}^0 = \frac{p_{gt}^0 + p_{st}^0}{Q_{ar,net,p}^G + A^S Q_{ar,net,p}^S}$$

$$= \frac{\eta_{gt}^0 Q_{ar,net,p}^G + p_{st,G} + p_{st,S}}{Q_{ar,net,p}^G + A^S Q_{ar,net,p}^S} \qquad (4)$$

Where: $p_{st,S} = k \times H_0$;

Because of (3), this efficiency is also given by the following expression:

$$\eta_{ccf}^0 = \frac{\eta_{gt}^0 Q_{ar,net,p}^G + p_{st,S}}{Q_{ar,net,p}^G + A^S Q_{ar,net,p}^S}$$

$$= \frac{\eta_{gt}^0 Q_{ar,net,p}^G + n*(h_0 + \sigma - h_n - \sum_{i=1}^{z} \alpha_i \Delta h_i)}{Q_{ar,net,p}^G + A^S Q_{ar,net,p}^S}$$

$$= \frac{\eta_{gt}^0 Q_{ar,net,p}^G + n*[h_0 - h_n - \sum_{i=1}^{z} \varphi_i \tau_i]}{Q_{ar,net,p}^G + A^S Q_{ar,net,p}^S} \qquad (5)$$

Equation (5) can also convert into matrix versions:

$$\begin{bmatrix} & & & 0 \\ & & & 0 \\ & [A^v]^T_{z\times z} & & \vdots \\ & & & 0 \\ & & & 0 \\ & & & \vdots \\ & & & 0 \\ \tau_1 & \tau_2 & \cdots \quad \tau_z & Q \end{bmatrix} \begin{bmatrix} \varphi_1 \\ \varphi_2 \\ \vdots \\ \varphi_{m-1} \\ \varphi_m \\ \vdots \\ \varphi_z \\ \eta_{ccf}^0 \end{bmatrix} = \begin{bmatrix} h_1 - h_n \\ h_2 - h_n \\ \vdots \\ h_{m-1} - h_n \\ h_m + \sigma - h_n \\ \vdots \\ h_z + \sigma - h_n \\ h_0 + \sigma + \omega - h_n - \prod \end{bmatrix} \qquad (6)$$

Where $Q = \frac{Q_{ar,net,p}^G + A^S Q_{ar,net,p}^S}{n}$; $\omega = \frac{\eta_{gt}^0 Q_{ar,net,p}^G}{n}$.

This expression is used as a criterion either to evaluate the interest of the auxiliary system or impact of modifying the operating conditions of the power plant on its performance.

IV. AUXILIARY SYSTEM ANALYSIS

Based on this matrix method, if users fill in the matrix element according to the drawings of the principle heating system, it can calculate the efficiency (η_t) of the feedwater heating type combined cycle unit by MATLAB tools. The water or steam flow into or out, of any component of the systems under consideration, using the matrix method by set the matrix element zero, variety in the thermodynamic system, which has a mapping relationship with real thermal system, the following equations can be obtained:

$$\Delta\eta_t = \eta_t^{'} - \eta_t \tag{6}$$

$$\delta\eta_t = \frac{\eta_t^{'} - \eta_t}{\eta_t^{'}} \times 100\% \tag{7}$$

$\delta\eta_t$ is the interest of the auxiliary system or impact of modifying the operating conditions of the feedwater heating type combined cycle unit on its performance.

Fig. 1 shows the schematic diagram of the unit's; Table 1 shows main original datum of the unit's; Table 2 shows auxiliary original datum of the unit's.

TABLE I. MAIN ORIGINAL DATUM OF THE UNIT'S

Heater	q_i/ (J·kg-1)	τ_i / (J·kg-1)	γ_i / (J·kg-1)
1	2335800	147200	———
2	2342300	129800	211.0
3	2198400	60200	105.9
4	2215500	106000	———
5	2387000	87500	129.3
6	2389000	170800	186.8
	2327500	121000	———

TABLE II. THE AUXILIARY ORIGINAL DATUM OF THE UNIT'S

Auxiliary Water-Steam Flow	symbol	value	h_{fi}/(J·kg-1)	q_{fi}/(J·kg-1)
1	α_{f1}	0.00378	2970300	2390800
2	α_{f2}	0.00541	2515700	2379400

By combining (2) and (5), using these expressions fill in the element of the matrix. The example's matrix can be expressed, respectively, by

$$\begin{bmatrix} & & & & 0 \\ & & & & 0 \\ & [A^v]^T_{z\times z} & & & 0 \\ & & & & 0 \\ & & & & 0 \\ & & & & 0 \\ & & & & 0 \\ \tau_1 & \tau_2 & \cdots & \tau_z & Q \end{bmatrix} \begin{bmatrix} \varphi_1 \\ \varphi_2 \\ \varphi_3 \\ \varphi_4 \\ \varphi_5 \\ \varphi_6 \\ \varphi_7 \\ \eta_{ccf}^0 \end{bmatrix} = \begin{bmatrix} h_1 - h_n \\ h_2 - h_n \\ \vdots \\ h_4 - h_n \\ h_5 - h_n \\ h_6 + \sigma - h_n \\ h_7 + \sigma - h_n \\ h_0 + \sigma + \omega - h_n - \prod \end{bmatrix}$$

$$[A] = \begin{bmatrix} q_1 & \tau_1 & \tau_1 & \tau_1 & \tau_1 & \tau_1 & \tau_1 \\ & q_2 & \gamma_2 & \tau_2(1-X_1) & \tau_2(1-X_1) & \tau_2(1-X_1) & \tau_2(1-X_1) \\ & & q_3 & \gamma_3 & \tau_3 & \tau_3 & \tau_3 \\ & & & q_4 & \tau_4 & \tau_4 & \tau_4 \\ & & & & q_5 & \gamma_5 & \gamma_5 \\ & & & & & q_6 & \gamma_6 \\ & & & & & & q_7 \end{bmatrix}$$

$$[A_f] = \begin{bmatrix} q_{f2} & \tau_1 & \tau_1 & \tau_1 & \tau_1 & \tau_1 & \tau_1 \\ & 0 & \gamma_2 & \tau_2(1-X_1) & \tau_2(1-X_1) & \tau_2(1-X_1) & \tau_2(1-X_1) \\ & & 0 & \gamma_3 & \tau_3 & \tau_3 & \tau_3 \\ & & & 0 & \tau_4 & \tau_4 & \tau_4 \\ & & & & q_{f1} & \gamma_5 & \gamma_5 \\ & & & & & 0 & \gamma_6 \\ & & & & & & 0 \end{bmatrix}$$

$$[\alpha_f]_D = diag[\alpha_{f2}/\tau_1, 0, 0, 0, \alpha_{f1}/\tau_5, 0, 0]$$

$$[A_\tau][\alpha_\tau]_D = \vec{0}$$

$$[\Delta q_f]_D = diag[0, 0, 0, 0, 0, \tau_b/\tau_6, 0]$$

$$[\Delta q_{sm}] = [0, \tau_2 X_1, 0, 0, 0, \tau_6 X_2, 0]^T$$

$$\prod = \tau_b + \alpha_{f1}(h_{f1} - h_n) + \alpha_{f2}(h_{f2} - h_n)$$

Solving these matrix, we can obtain the thermal efficiency η_{ccf}^0 and η_{ccf}^{0} '. We also calculate the interest of the auxiliary system by the first law method. Calculation results were summarized in table 3.

TABLE III. CALCULATING RESULTS

Results		Matrix method	First law method
Thermal efficiency/%		42.221105983765	42.221105983765
interest of the auxiliary system	1	0.1026224	0.1026224
	2	0.0273341	0.0273341

V. CONCLUSIONS

In this paper, we proposed a novel and method of analyzing the feedwater heating type combined cycle unit An example is given to illustrate validity of the method, as a thermal economics diagnostic method, which is easy to be used in system design and operation diagnosis.

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