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A general calculation model on the effect of main steam pressure variation on the coal consumption rate of steam turbines

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ABSTRACT

Based on the unified physical model and mathematical model of the heat economic analysis of thermal power generating units, this paper employs the partial differential theory and gradient operator to construct a calculation model for the strength coefficient of the effect of main steam pressure variation on the economical efficiency of the unit. Under each working condition, the strength coefficient greatly reduced the main steam pressure on the impact of change on the unit coal consumption rate calculation workload. A case study on the typical working condition of a 600MW unit reveals that the proposed model for the strength coefficient boasts a small computational load and high accuracy when it is applied to calculate the effect of main steam pressure variation on the coal consumption rate. Moreover, the concept of a strength coefficient provides a new way of energy saving for the thermal power generating unit and the quantitative analysis of a thermal system.

Keywords: Main Steam Pressurem, Heat Economy, Coal Consumption Rate, Heat Coefficient.

1. INTRODUCTION

The rated main steam pressure of stream turbines is the optimal choice after considering various factors like the safety of material utilization and economy of unit operation. To achieve the best economic efficiency in actual operation, the main steam pressure should be maintained as close to the design value as possible [1]. Nevertheless, the economy of the unit is often dampened by a deviation from the rated main steam pressure because the actual operation is affected by load changes, the level of operators, and other factors [2]. As a result, it is necessary to analyze the effect of main steam pressure variation on the coal consumption rate, an effective aid for relevant personnel to make an intuitive judgment of the operational economy of the unit.

The conventional mathematical model for the effect of main steam pressure variation on the coal consumption rate is based on the equivalent enthalpy drop method. The application of the model is greatly limited due to its heavy computational load and complicated analysis process, which are only mastered by professionals. When the model is used, a slight fluctuation of the main steam pressure would require re-calculation [3-4]. To make up for the shortcomings, this paper establishes a calculation model for the general strength coefficient of the effect of main steam pressure variation on the coal consumption rate of thermal power generating units. Following the basic principle of variable working conditions of steam turbines and in view of the change relations among the parameters, the model is derived from the steam-water distribution general matrix equation, specific internal power equation, cyclic heat absorption equation, and the formula of standard coal consumption rate of power generation in the unified physical model and mathematical model of heat economic analysis of thermal power units. The strength coefficient greatly facilitates the analysis of the effect of main steam pressure variation on the coal consumption rate.

2. HYPOTHESIS FOR MODEL DERIVATION AND GRADIENT OPERATOR

Aiming at analyzing how the heat economy is effected by the main stream pressure deviations from the target value under various working conditions, the author assumes that the main steam temperature, reheated steam temperature, and steam turbine exhaust pressure all remain the same under the corresponding working conditions. Besides, the admission status of the steam turbine changes with the deviations of main steam pressure, which in turn results in changes to the steam inflow, extraction pressure of each stage, extraction steam enthalpy, and exhaust steam enthalpy of the steam turbine, as well as the feed-water enthalpy and drain-water enthalpy at the outlet of the heater at each stage. In this case, the flows of various auxiliary steam-water systems, the temperature difference between the upper and lower ends of the heater at each stage, the extraction pressure loss, and the feed power will remain unchanged.

As a sign of function operation, an operator acts on a function to generate a new function according to a certain rule. In this paper, a gradient operator is defined for the function $f(x_1, x_2, \cdots, x_n)$, $\nabla f|_{x_i} = \left[\frac{\partial f}{\partial x_1}\frac{\partial f}{\partial x_2}\cdots\frac{\partial f}{\partial x_n}\right]$, to express the influence of each component, whose physical meaning falls within $[x_i]$, over function f. If x_i has an actual influence on f, the influence equals $\frac{\partial f}{\partial x_i}$; otherwise, the influence equals 0. Applying the function operator to any matrix $\boldsymbol{F}$, the author defines a matrix operator $\nabla\boldsymbol{F}$, i.e.: $\nabla\boldsymbol{F}|_{x_i} = \left[\frac{\partial \boldsymbol{F}}{\partial x_1}\frac{\partial \boldsymbol{F}}{\partial x_2}\cdots\frac{\partial \boldsymbol{F}}{\partial x_n}\right]$

On this basis, the author defines the "□" operation of the matrix operator $\nabla\boldsymbol{F}|_{x_i}$ and the column matrix $\boldsymbol{B}$ as follows: $\nabla\boldsymbol{F}|_{x_i} \square \boldsymbol{B} = \left[\frac{\partial \boldsymbol{F}}{\partial x_1}\boldsymbol{B}\frac{\partial \boldsymbol{F}}{\partial x_2}\boldsymbol{B}\cdots\frac{\partial \boldsymbol{F}}{\partial x_n}\boldsymbol{B}\right]$

3. STEAM-WATER DISTRIBUTION EQUATION AND DIFFERENTIAL EXPRESSION OF EXTRACTION COEFFICIENT

The model derivation is based on the unified physical model and mathematical model of heat economic analysis of the thermal power generating unit. The proposed model involves an n-stage extraction steam turbine, which is segmented into a number of n+1 small steam turbines by the n extraction ports. Each of the small steam turbines has a small boiler to provide it with the working medium. The steam-water distribution equation, cyclic heat absorption equation, and specific internal power equation are involved in the model. Please refer to references [5-13] for the specific meanings of the model and the symbols included in it. Formula (1) is the steam-water distribution general matrix equation of the heat system of the thermal power generating unit:

$$\boldsymbol{A}\cdot\boldsymbol{D} + \boldsymbol{Q} = \boldsymbol{\tau}\cdot\boldsymbol{G} \tag{1}$$

Where:

$\boldsymbol{A}$—thermal system structure matrix

$\boldsymbol{D}$—nominal extraction volume matrix

$\boldsymbol{Q}$—nominal auxiliary heat matrix

$\boldsymbol{\tau}$—main feed-water specific internal power rise matrix

$\boldsymbol{G}$—nominal water flow matrix

The author divides Formula (1) on both sides by the main steam flow D_0, seeks partial derivatives of the extraction steam enthalpy of each extraction port and the feed-water and drain-water enthalpies at the outlet of each heater, and introduces the operator to sort out the differential relationship between the coefficients of different stages: [5]

$$\mathrm{d}\alpha_i = A^{-1}(d\tau_i g_i - dA\alpha_i) \tag{2}$$

where $\alpha_i = D/D_0$ and $g_i = G/D_0$. In light of the hypothesis for model derivation and the discussion on the physical meaning of the matrix operator, it is obtained that: $dA\alpha_i = \nabla A|_{h_{ii}} \square \alpha_i dh_{ii} + \nabla A|_{h_{wi}} \square \alpha_i dh_{wi} + \nabla A|_{h_{di}} \square \alpha_i dh_{di}$ $\quad d\tau_i g_i = \nabla\tau_i|_{h_{wi}} \square g_i dh_{wi}$, where $\nabla A|_{h_{ii}}$, $\nabla A|_{h_{wi}}$ and $\nabla A|_{h_{di}}$ are respectively the effects on the thermal system structural matrix from the variation of extraction steam enthalpy of each stage, from the variation of feed-water enthalpy at the outlet of each heater, and from the variation of drain-water enthalpy at the outlet of each heater. $\nabla\tau_i|_{h_{wi}}$ stands for the effect of variation of feed-water enthalpy at the outlet of each heater on the main feed-water enthalpy rise matrix. $dh_{ii} = [dh_{11}dh_{22}\cdots dh_{nn}]^T$, $dh_{wi} = [dh_{w1}dh_{w2}\cdots dh_{wn}]^T$, and $dh_{di} = [dh_{d1}dh_{d2}\cdots dh_{dn}]^T$ are respectively the column matrices of the extraction steam enthalpy at each stage, the feed-water enthalpy at the outlet of each heater, and the drain-water enthalpy at the outlet of each heater when the main steam pressure changes. The unit is kJ/kg.

4. EQUATION AND DIFFERENTIAL EXPRESSION OF CYCLIC HEAT ABSORPTION

In the unified physical model, the matrix form of the cyclic heat absorption equation is: [5]

$$Q = H_{bi}D_{bi} + IQ_{bi} \tag{3}$$

H_{bi}—the heat absorption matrix of the working medium in each small boiler, kJ/kg;

D_{bi}—the relative flow column matrix of the working medium in each small boiler;

Q_{bi}—the heat absorption column matrix of the auxiliary steam-water in each small boiler, kJ/kg;

I— (n+1) row matrices in which the value of elements is 1.

In light of the hypothesis for derivation, the author takes the differential on both sides of the formula.

$$dQ = H_{bi}dD_{bi} + dH_{bi}D_{bi} \tag{4}$$

After introducing the gradient operator, it is obtained that: $dD_{bi} = \nabla D_{bi}|_{\alpha_i}d\alpha_i + \nabla D_{bi}|_{D_0}\nabla D_0|_{p_0}dp_0$ $\quad dH_{bi}D_{bi} = \nabla H_{bi}|_{h_{ii}} \square D_{bi}dh_{ii_b} + \nabla H_{bi}|_{h_i} \square D_{bi}dh_{i_b}$

The author substitutes the above two formulas into Formula (4) to obtain the following:

$$dQ = H_{bi}\left(\nabla D_{bi}|_{\alpha_i}d\alpha_i + \nabla D_{bi}|_{D_0}\nabla D_0|_{p_0}dp_0\right) + \nabla H_{bi}|_{h_{ii}} \square D_{bi}dh_{ii_b} + \nabla H_{bi}|_{h_i} \square D_{bi}dh_{i_b} \tag{5}$$

where the operator $\nabla D_{bi}|_{\alpha_i}$ refers to the influence on the working medium flow in each small boiler (of the n-stage extraction thermal system) from the variation of the extraction volume of each stage:

$$\nabla D_{bi}|_{\alpha_i} = \begin{bmatrix} 0 & & & & \\ -1 & 0 & & 0 & \\ -1 & -1 & 0 & & \\ -1 & -1 & -1 & \ddots & \\ \vdots & \vdots & \vdots & \ddots & 0 \\ -1 & -1 & -1 & -1 & -1 \end{bmatrix}_{(n+1)\times n};$$

$\nabla D_{bi}|_{D_0}$ refers to the effect of steam flow variation on the working medium flow in each small boiler; $\nabla D_0|_{p_0}$ refers to the main steam pressure variation on the main steam flow; dp_0 refers to the variation of main steam pressure; $\nabla H_{bi}|_{h_{ii}}$ and $\nabla H_{bi}|_{h_i}$ respectively refer to the influences on the heat absorbed by the working medium in each small boiler from the enthalpy variations of the working medium at the inlet and outlet of the small boiler; $dh_{iib} = [dh_{00}dh_{11}dh_{22}\cdots dh_{nn}]^T$, and $dh_{ib} = [dh_0 dh_1 dh_2 \cdots$

$dh_n]^T$ respectively refer to the column matrices of the variations of the working medium at the inlet and outlet of each small boiler when the main steam pressure changes; kJ/kg.

5. EQUATION AND DIFFERENTIAL EXPRESSION OF SPECIFIC INTERNAL POWER

In the entire cycle of the unit, the matrix form of the specific internal power is:[5]

$$N = H_{ti} \cdot D_{ti} \quad (6)$$

N—the specific internal power of the unit, kJ/kg;

H_{ti}—the row matrix of the ideal specific internal power drop of the steam in each small turbine, kJ/kg;

D_{ti}—the column matrix of the relative flow of the working medium in each small turbine.

In light of the hypothesis, the author takes the differential on both sides of the formula:

$$dN = dH_{ti} \cdot D_{ti} + H_{ti} \cdot dD_{ti} \quad (7)$$

After introducing the gradient operator, it is obtained that:

$$dH_{ti} \cdot D_{ti} = \nabla H_{ti}|_{h_i} \square D_{ti} dh_{ib} + \nabla H_{ti}|_{h_{ii}} \square D_{ti} dh_{iit}, dD_{ti} = \nabla D_{ti}|_{\alpha_i} d\alpha_i + \nabla D_{ti}|_{D_0} \nabla D_0|_{p_0} dp_0$$

The author substitutes the above formula into Formula (7):

$$dN = \nabla H_{ti}|_{h_i} \square D_{ti} dh_{ib} + \nabla H_{ti}|_{h_{ii}} \square D_{ti} dh_{iit} + H_{ti}(\nabla D_{ti}|_{\alpha_i} d\alpha_i + \nabla D_{ti}|_{D_0} \nabla D_0|_{p_0} dp_0) \quad (8)$$

where $\nabla D_{ti}|_{\alpha_i} = D_{bi}|_{\alpha_i}$ stands for the effect of the steam extraction volume of each stage on the flow of the working medium in each small turbine; $D_{ti}|_{D_0}$ stands for the effect of the main steam flow variation on the relative flow of the working medium in each small turbine; $\nabla H_{ti}|_{h_i}$ and $\nabla H_{ti}|_{h_{ii}}$ respectively stand for the influences on the specific internal power drop of each small turbine from the enthalpy variation at the outlet of each boiler and of the exhaust working medium of each small turbine, kJ/kg; $dh_{iit} = [dh_{11} dh_{22} \cdots dh_{(n+1)(n+1)}]^T$ stands for the column matrix of the exhaust steam enthalpy variation of each small turbine when the mains steam pressure changes, kJ/kg.

6. DETERMINATION OF THE PARAMETERS WHEN THE MAIN STEAM PRESSURE CHANGES

When the main steam pressure changes, the main steam enthalpy and reheat steam enthalpy will change accordingly. Meanwhile, the steam extract pressure of each stage also changes, resulting in a variation of the steam-side saturation temperature in the heater of each stage, which, in turn, causes changes to the feed-water enthalpy rise and drain-water enthalpy of heat of each stage.

6.1 Determination of enthalpy at the outlet of each small boiler

With the changing main steam pressure, the reheat pressure changes but the main steam temperature and reheat steam temperature remain the same. In light of the hypothesis for derivation and the gradient operator, it is obtained that:

$$dh_0 = \nabla h_0|_{p_0} \cdot dp_0 \quad (9)$$

where $\nabla h_0|_{p_0}$ is the effect of main steam pressure variation on the main steam enthalpy.

$$dh_{zr} = \nabla h_{zr}|_{p_{zr}} \cdot \nabla p_{zr}|_{p_0} \cdot dp_0 \quad (10)$$

$\nabla h_{zr}|_{p_{zr}}$ is the effect of reheat steam pressure variation on the reheat steam enthalpy; $\nabla p_{zr}|_{p_0}$ is the main steam pressure variation on the reheat steam pressure.

6.2 Feed-water enthalpy variation at the outlet of the heater of each stage

As the extraction pressure of each extraction port changes with the main steam pressure, the saturated temperature of each heater changes at the steam-side but remains the same at the water-side. If the upper limit of the temperature difference is unchanged, the variation of the feed-water enthalpy at the outlet of the stage *i* heater is:

$$dh_{wi} = \nabla h_{wi}|_{t_{bi}} \cdot \nabla t_{bi}|_{p_i} \cdot \nabla p_i|_{p_0} \cdot dp_0 \quad (11)$$

where $\nabla h_{wi}|_{t_{bi}}$ is the effect of the saturated temperature variation of the stage *i* steam extraction on the feed-water enthalpy at the outlet of stage *i* heater; $\nabla t_{bi}|_{p_i}$ is the effect of pressure variation of the stage *i* steam extraction on the saturated temperature of the stage *i* steam extraction.

6.3 Drain-water enthalpy variation of the heater at each stage

If the lower limit of the temperature difference of the heater at each stage is unchanged when the main steam pressure changes, the variation of the drain-water enthalpy of the heater at each stage is:

(1) If the *i*-th heater does not have a drain-water cooler, the variation of the drain-water enthalpy at the outlet of each heater is: [14]

$$dh_{di} = \nabla h_{di}|_{p_i} \cdot \nabla p_i|_{p_0} \cdot dp_0 \quad (12)$$

where $\nabla h_{di}|_{p_i}$ represents the effect of stage *i* extraction pressure on stage *i* drain-water enthalpy; $\nabla p_i|_{p_0}$ represents the effect of main steam pressure variation on stage *i* extraction pressure.

(2) If the *i*-th heater has a drain-water cooler, the variation of the drain-water enthalpy at the outlet of each heater is:

$$\Delta d_{d(i-1)} = \Delta h_{wi} \quad (13)$$

6.4 Exhaust steam enthalpy variation of each small steam turbine

According to the variable working conditions of steam turbines, when the main steam pressure of steam turbines changes, the relative internal efficiency at the middle stages (save the wet steam stage) is basically unchanged, and the exhaust enthalpy of each small steam turbine is as follows [15]:

$$h_{ii} = h_0 - (h_0 - h_{i,t}) \cdot \eta_{ti} \tag{14}$$

where
h_{ii}—the exhaust steam enthalpy of the i-th small steam turbine, kJ/kg;
h_0—the main steam enthalpy, kJ/kg;
$h_{i,t}$—the isentropic enthalpy of the i-th small steam turbine, kJ/kg;
η_{ti}—the relative internal efficiency of the stage i group.

In light of the hypothesis for derivation, the author takes the differential on both sides of the above formula and introduces the gradient operator to sort it out as:

$$dh_{ii} = (\nabla h_0|_{p_0}(1 - \eta_{t_i}) + \eta_{t_i} \cdot \nabla h_{it}|_{p_i} \cdot \nabla p_i|_{p_0}) \cdot dp_0 \tag{15}$$

where η_{t_i} illustrates the relative internal efficiency of the stage i group between the admission of steam and the reheating of the steam turbine; $\nabla h_{it}|_{p_i}$ illustrates the effect of exhaust steam pressure variation of the i-th small steam turbine on the exhaust steam isentropic enthalpy of the i-th small steam turbine. After reheating, the section between the MP cylinder's steam inlet and each extraction port is taken as a group and is calculated in accordance with the rules before the reheating.

At the end stages of the steam turbine, the steam parameters enter the wet steam zone of the water vapor. The relative internal efficiency changes due to the loss of wet steam. The author adopts the following empirical formula to correct how much the relative internal efficiency is affected by the loss of wet steam: [16]

$$\eta_{0i}^1 = \eta_{0i}(1 - \alpha\bar{y}) \tag{16}$$

where
η_{0i} and η_{0i}^1—the group efficiency acting on dry steam and wet steam zones, respectively;
$\bar{y}$—relative humidity of the group;
α—Baumann factor.

7. DIFFERENTIAL EQUATION OF THE POWER GENERATION'S STANDARD COAL CONSUMPTION RATE

The standard coal consumption rate of the power generating unit should be calculated by the following formula:

$$b_s = 3600Q/(7000 \times 4.1868\eta_b\eta_m\eta_g N) \tag{17}$$

where b_s is the standard coal consumption rate of the power generating unit, g/kw.h; η_b is the boiler efficiency; η_m is the mechanical efficiency of the steam turbine; η_g is the efficiency of the power generator; Q is the cyclic heat absorption, kJ/kg; N is the cyclic internal power of the unit, kJ/kg. The author takes the natural logarithm and differential on both sides of Formula (17):

$$db_s/b_s = dQ/Q - dN/N \tag{18}$$

The operating procedures only allow a small difference between the operating and design values of the main steam pressure at corresponding load points. Therefore, as the main steam pressure deviates from its design value, the η_b, η_m, and η_g vary only in a small range. That is why the author holds that the parameters are of fixed values near specific load points and do not vary with the main steam pressure.

The author substitutes Formula (2) into Formulas (5) and (18) and substitutes the results into Formula (18). The final results are sorted out as follows:

$$db_s/b_s = m \cdot dp_0 \tag{19}$$

where m is the strength coefficient of the effect of main steam pressure on the coal consumption rate of the power generation; dp_0 is the difference between the operation value and design value of the main steam pressure under the load, MPa.

8. CASE STUDY AND ANALYSIS OF CALCULATION RESULTS

The object is a domestic 600MW condensing steam unit (model: N600-16.67/537/537). The heat system is shown in Figure 1. Table 1, Figures 2 and 3 list the results of the calculation of the typical working conditions of the unit.

As shown in Table 1, the coal consumption variation calculated by the strength coefficient obtained by the proposed model (Coal Consumption 1) is very close to the corrected coal consumption variation provided by the manufacturer. With a relative error of no more than 3%, the proposed model is proved to be correct. Figure 2 shows that the absolute value of the strength coefficient increases with the decrease of the load. For each unit of main steam pressure variation, the influence on the unit's coal consumption rate is bigger at a low load than it is at a high load. Besides, the influence grows as the load decreases. For each unit of main steam pressure variation, the coal consumption rate for the change order is THA condition < 75% condition < 50% condition. The trend is also demonstrated in Figure 3.

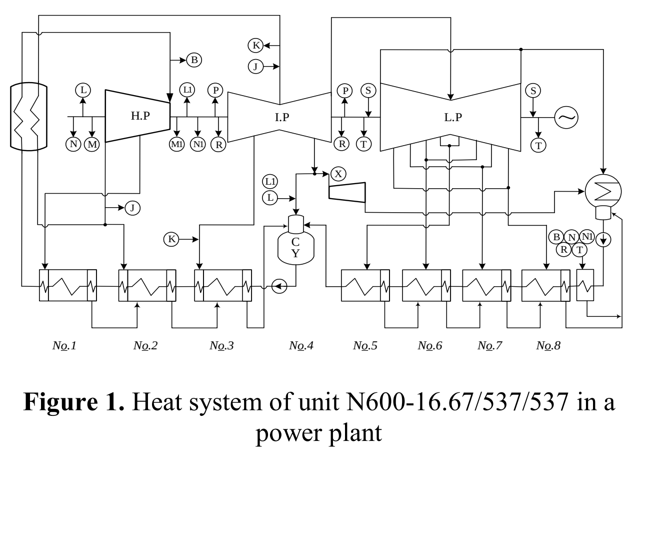

Figure 1. Heat system of unit N600-16.67/537/537 in a power plant

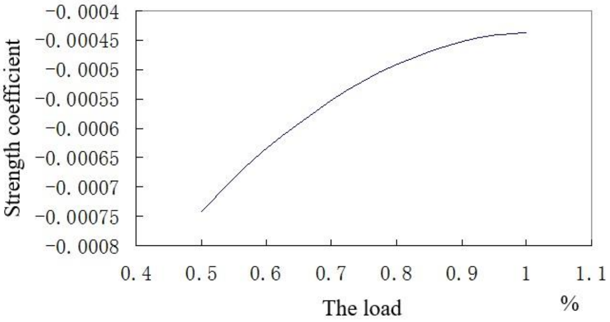

Figure 2. Strength coefficient under different conditions

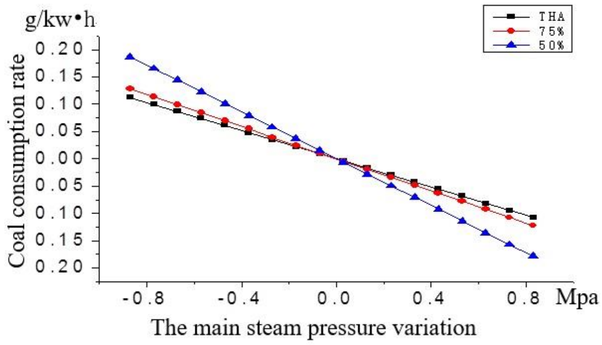

Figure 3. Influence on the unit's coal consumption rate from main steam pressure disturbances under different working conditions

Table 1. Calculation results of the effect of main steam pressure variation on the unit's coal consumption rate under the THA working condition

ΔP_0(MPa)	-0.37	-0.27	-0.17	-0.07	0.03	0.13	0.23	0.33	0.43
Coal consumption 1 (g/kw.h)	0.467 7	0.341 3	0.214 9	0.088 5	-0.037 9	-0.164 3	-0.290 8	-0.417 2	-0.543 6
Coal consumption 2 (g/kw.h)	0.479 7	0.348 9	0.218 1	0.087 2	-0.037 1	-0.163 5	-0.287 8	-0.414 3	-0.534 2
│Relative error│(%)	2.5	2.17	1.44	1.46	2.31	0.49	1.02	0.70	1.75
│Absolute error│(g/kw.h)	0.012	0.007 6	0.003 1	0.001 3	0.000 9	0.000 8	0.002 9	0.002 9	0.009 4

Therefore, more attention should be paid to the influence of main steam pressure variation on the unit's coal consumption efficiency. Timely adjustments should be made to lower the coal consumption of the unit. For a specific unit, the strength coefficient and the load have a fixed relationship. Through the fitting relationship, one can easily obtain the strength coefficient at a specific load, and, on this basis, acquire the effect of main steam pressure variation on the unit's coal consumption rate.

9. CONCLUSIONS

(1) On the basis of the unified physical model and mathematical model of the heat economic analysis of the thermal power generating unit, which makes clear physical meaning, in the derivation process is simple, and derive the calculation of the model is applied to any form of condensing thermal power unit, the practicability of the model is very wide. The author obtains the general strength coefficient of the effect of main steam pressure variation on the unit's coal consumption rate by introducing the gradient operator, and verifies the correctness and simplicity of the calculation through a case study.

(2) The strength coefficient itself reflects the effect of main steam pressure variation on the powerr generation's coal consumption rate.This proves that the strength matrix can be applied directly to the qualitative and quantitative analysis of the effect of main steam pressure variation on the unit's coal consumption rate. After getting the strength coefficient under different loads, the author has obtained the intensity coefficient and the relation between the load of the fitting. Afterwards the relation analysis is used to multiply the main steam pressure change amount by the coefficient of the intensity of the corresponding load, thus the impact on the coal consumption can be easily obtained, and a greatdeal of complicated calculation can be avoided, and its use is very convenient.

(3) The case study indicates that the effect of main steam pressure on the economic efficiency not only depends on the level of pressure, but also on the working condition of the unit. The relation is reflected by the value of the strength coefficient. The absolute value of the strength coefficient grows with the decrease of the load. That is to say, the pressure variation has a higher impact on the coal consumption at a low load. During the operation, one should pay more attention to the effect of the main steam pressure on the economic efficiency at a low load.

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