An Optimization Study on Energy Consumption Benchmarks for Boilers and their Auxiliary Systems

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***Abstract* — The energy consumption decision rules of power plant boiler and its auxiliary system are difficult to determine. Using unit consumption analysis, an optimization method of energy consumption benchmark is proposed in this paper. By calculating the correlation degree between the operation parameters and decision attributes, the key energy consumption characteristic variables are selected. The operation conditions are divided by fuzzy c-means clustering algorithm (FCM). Aimed at the best historical operation data, the decision rules of the energy consumption benchmark in different conditions are determined by combining the rules of the key energy consumption characteristics. The analytical results show that the energy consumption benchmark is between the actual operation value and the design value. The energy consumption level of the boiler and auxiliary system can be further reduced by adjusting the operation parameters.**

Keywords: boiler; energy consumption decision rule; the decision variables; energy consumption optimization

I. Introduction

At present, the key and difficult point of the decision rules of the energy consumption of fossil fuel power generation units are determined by the target value. The target value, also known as norm value, is refers to the current operation boundary corresponding to the optimal unit condition. It generally refers to the operation parameters and unit comprehensive performance index. Therefore, the scientific determination of the operation parameters reference value is the core and difficult problem in the energy consumption optimization of the boiler and its auxiliary system [1].

Traditional target value determination methods include:(1) For main steam's pressure, main steam's temperature, reheat steam's temperature and other parameters which can't be determined by experiment , the design values of the parameters are used as far as possible; (2) In general, the parameters that can be determine by experiment should be used directly such as amount of oxygen; (3) For the vacuum and other parameters which can be calculated by using variable conditions calculation, the calculation values are taken as the target value; (4) For the Flow of reheat or overheated desuperheating water that the ash of boiler heating area and operation level has a great influence on, it usual is determined by combustion adjustment test results or reference operation data. The four methods have their own characteristics, but they have different shortcomings [2]. Determine the target values of power plant operation optimization plays an important role in the optimization of thermodynamic system of the power plant operation's research. And the target values determined should consider the feasibility, accuracy and real-time property. If unit operation optimization target values did not match with actual operation values, the target values are not useful.

In this paper, we use the fuzzy C means clustering algorithm (FCM) to divide the operation conditions, and the energy consumption decision attributes are determined by the second law of thermodynamics. The key energy consumption characteristic variables are selected by calculating the correlation degree between the operation parameters and the decision attributes. All these works are based on the acquisition of units' massive historical data. For the four key energy consumption characteristic variables that are main steam's pressure, main steam's temperature, reheat steam's temperature and feed-water temperature, the different combinations of these four parameters are obtained. Taken the best combination as the optimal operation mode, the final energy decision rules are acquired. This paper determines the energy consumption benchmark from a large number of historical data through data mining, and provides the basis for reducing the energy consumption level in the actual operation.

II. Selection of Energy Consumption Decision Attributes According to the Unit Consumption Analysis

The decision attribute of energy consumption decided the actual operation state of the units. Based on the unit consumption analysis theory and second law of thermodynamics, the energy "quantity" and "quality" are analyzed, and the boiler additional unit consumption is used to characterize the overall operation condition of boiler. The lower additional unit consumption is, the higher the level of energy efficiency is. Therefore, this paper will use it as the decision-making attributes to evaluate the boiler overall energy consumption level.

According to the second law of thermodynamics, the exergy balance of any energy use process can be described as "fuel exergy = product exergy + exergy loss + exergy run off". If there is no exergy run off, the exergy balance equation can be written as:

$$Fe_f = Pe_p + \sum E_{D,I} \tag{1}$$

In above-mentioned equation: e_f , e_p is the exergy of fuel and product; F , P Respectively are the fuel quantity and the amount of product; $\sum E_{D,I}$ is the sum of exergy loss of the system.

The above-mentioned equation also can be rewritten as a general expression of unit consumption theory:

$$b = \frac{F}{P} = \frac{e_p}{e_f} + \sum \frac{E_{D,I}}{Pe_f} = b_{\min} + \sum b_{aux,I} \tag{2}$$

In the equation (2): $b_{\min}$ is the minimum fuel unit consumption of the product. Namely, fuel unit consumption in the absence of any exergy loss; $\sum b_{aux,I}$ is additional fuel consumption caused by each part of the system.

Boiler exergy loss is:

$$I_b = D_f e_f + D_a e_a - (D_b e_b - D_{fw} e_{fw}) - D_{rh}(e''_{rh} - e'_{rh}) \tag{3}$$

In the equation (3):

D_f —Coal Consumption（kg/s）

e_f —the exergy of standard coal（kj/kg）

D_a —the flow of reheat or overheated desuperheating water（kg/s）

e_a —the exergy of reheat or overheated desuperheating water（kj/kg）

D_b —the flow of main steam（kg/s）

e_b —the exergy of main steam（kj/kg）

D_{fw} —the flow of feed-water（kg/s）

e_{fw} —the exergy of feed-water（kj/kg）

D_{rh} —the flow of reheat steam（kg/s）

e''_{rh} —Reheat steam inlet exergy value（kj/kg）

e'_{rh} —Reheat steam exit exergy value（kj/kg）

The additional unit consumption of boiler:

$$b_b = (I_b / e_f) / (P / e_p) \tag{4}$$

In the equation (4)：

e_f —Specific electric exergy of standard coal（kj/kg）

P —unit power（KW）

e_p —Exergy of unit product（kj/kg）

Taken a 600MW boiler as the object, the calculation results of additional unit consumption under design conditions are shown in table I.

TABLE I. THE ADDITIONAL UNIT CONSUMPTION UNDER DESIGN CONDITIONS OF A 600MW BOILER (UNIT: G / KWH)

load	100%THA（kj/kg）	75%THA（kj/kg）	60%THA（kj/kg）	50%THA（kj/kg）	40%THA（kj/kg）
boiler	145.79	151.53	157.08	164.72	174.00

III. SELECTION OF THE CHARACTERISTIC VARIABLES OF KEY ENERGY CONSUMPTION

The characteristics variables of key energy consumption refer to the steam parameters which had main effect on the energy consumption characteristics of the boiler, the equipment parameters or their combination. Based on the grey relation analysis method, the correlation degree between the operation parameters and boiler additional unit consumption are analyzed. And the characteristic variables of key energy consumption are acquired.

According to the influence of the index change on the decision attributes, the indexes are firstly to be classified before the grey relation is analyzed: the positive indexes are that increase the energy efficiency level with the increase of the parameter values; the negative indexes are that decrease the energy efficiency level with the increase of the parameter values; the interval indexes are that have the best energy efficiency level with the parameter values in a certain range. The operation adjustable parameters of boiler are shown in Table II.

TABLE II. THE OPERATION ADJUSTABLE PARAMETERS OF BOILER

category	Parameter name
negative indexes	the flow of reheat or overheated desuperheating water
positive indexes	main steam pressure、main steam temperature、reheat steam temperature、feed-water temperature
interval indexes	excess air factor、combustion chamber draft、primary air temperature、second air temperature、primary air volume、second air volume

The most important of the grey relation analysis method is the calculation of the correlation degree. The calculation method and steps are as follows:

The first step: to determine the primary sequence, that is, the reference sequence and the comparison sequence. The reference sequence is the additional unit consumption of boilers. The comparison sequence is the operation parameters.

The reference sequence:

$$X_0(k) = \{x_0(1), x_0(2), x_0(3), \ldots x_0(n)\} \in X, \ k=1, 2, 3, \ldots n \tag{5}$$

The comparison sequence:

$$X_i(k) = \{x_i(1), x_i(2), x_i(3), \ldots x_i(n)\} \in X, \ i=1, 2, 3, \ldots m \tag{6}$$

The second step: calculating correlation coefficient

$$\gamma_{0i}^{0}(k)=\frac{\min_{i}\min_{k}\left|x_0(k)-x_i(k)\right|+\rho\max_{i}\max_{k}\left|x_0(k)-x_i(k)\right|}{\left|x_0(k)-x_i(k)\right|+\rho\max_{i}\max_{k}\left|x_0(k)-x_i(k)\right|} \quad (7)$$

In the equation (7): ρ is the resolution coefficient, the range is between 0-1, the smaller the value of ρ , the greater the resolution, usually, ρ =0.5, correlation coefficient $\gamma_{0i}^{0}(k)$ is the relative difference between the comparison sequence X_i and the reference sequence X_0 at k point(or index, space). $\min_{i}\min_{k}\left|x_0(k)-x_i(k)\right|$ and $\max_{i}\max_{k}\left|x_0(k)-x_i(k)\right|$ represent the minimum and maximum difference of two levels, $\min_{k}\left|x_0(k)-x_i(k)\right|$ and $\max_{k}\left|x_0(k)-x_i(k)\right|$ represent the minimum difference and the maximum difference of the first level, represents the minimum and maximum difference that is selected in different time (or index, space); The second levels of the minimum and maximum difference are the minimum and maximum difference of the first level.

The third step: The calculation of relationship degree, generally using average value method

$$\gamma_{0i}^{0}=\frac{1}{m}\sum_{i=1}^{m}\gamma_{0i}^{0}(k) \quad (8)$$

In the equation (8): Correlated Degree γ_{0i}^{0} represents the correlation degree between the comparison sequence X_i and the reference sequence X_0, the bigger the value of γ_{0i}^{0}, the closer that the curve of the sequence X_i is close to the reference sequence X_0 . It shows that their development trend is closer, or sequence X_i is the main factor that affects the development of sequence X_0 .

The fourth step: List associated sequence

According to the size of the degree of correlation, the greater the correlation is, the more closely the relationship between the two is.

To a 600MW boiler, the boiler operation parameters and the additional unit consumption of grey relation analysis results are shown in table III.

TABLE III. GREY RELATION ANALYSIS BETWEEN BOILER OPERATION PARAMETERS AND ADDITIONAL CONSUMPTION

parameter	R	parameter	R
main steam pressure	0.86	excess air factor	0.71
main steam temperature	0.73	primary air volume	0.64
reheat steam temperature	0.72	second air volume	0.70
feed-water temperature	0.74	combustion chamber draft	0.64
the flow of over-heated desuperheating water	0.71	primary air temperature	0.70
the flow of reheated desuperheating water	0.70	second air temperature	0.69

The results show that the relation degree between the operation parameters and the additional unit consumption are big and almost the same. The selected characteristic variables of key energy consumption are the four parameters which grey relation degree are max. That is: main steam pressure, main steam temperature, reheat steam temperature, feed-water temperature. Based on the analysis of the four characteristic variables of energy consumption, the energy consumption benchmark of the boiler and its auxiliary system are determined.

Ⅳ. OBTAINING THE OPERATION PARAMETERS BENCHMARK BASED ON DATA MINING

A. Fuzzy C Means Clustering Algorithm

Fuzzy C means clustering algorithm (FCM) obtained the different clustering centers of training samples by calculation. The object is divided into clustering, which makes the similarity between different cluster is minimum, and the similarity among the same cluster is the largest [3].

$X=\{x_i, i=1,2,...,n\}$ is a sample before cluster, $X\subseteq R^p$,c is the setting number of cluster categories, $v_i\,(i=1,2,3,...,c)$ is the i-th cluster center, $u_{ik}\,(i=1,2,...,c;k=1,2,...,n)$ is the membership functions of k-th samples relative to the i-th cluster, and $0\le u_{ik}\le 1$, $0\le\sum_{i=1}^{n}u_{ik}\le n$. FCM's objective function is:

$$J_m(U,v)=\sum_{i=1}^{cv}\sum_{k=1}^{n}u_{ik}^{m}\left\|x_k-v_i\right\|^2 \quad (9)$$

In the equation (9): $U=\{u_{ik}\};v=\{v_1,v_2,...,v_c\}$; m is the weighted coefficient of membership, which constraint is:

$$\sum_{i=1}^{c}u_{ik}=1,\forall k=1,2,...,n \quad (10)$$

The membership function of k-th samples relative to the i-th cluster is:

$$u_{ik}=\frac{\left(1/\left\|x_k-v_i\right\|^2\right)^{1/(m-1)}}{\sum_{j=1}^{c}\left(1/\left\|x_k-v_j\right\|^2\right)^{1/(m-1)}},\forall i=1,2,...,c;k=1,2,...,n \quad (11)$$

$$v_i=\frac{\sum_{k=1}^{n}v_{ik}^{m}x_k}{\sum_{k=1}^{n}u_{ik}^{m}},\forall i=1,2,...,c \quad (12)$$

The fuzzy partition matrix of $c*n$ and c clustering center point vectors can be calculated by FCM algorithm. Matrices show that the sample points' support for each

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clustering class. According to the partition matrix, the sample points have high support degree for a cluster mean that the sample points belong to the cluster. Each cluster has a clustering center, which means the central point of each cluster or the average point.

B. Access to Operation Parameter Benchmark Range

Based on the one year's operation historical data of power plant (covering all load range and environmental temperature range), the operation parameter benchmark range are selected in different operation conditions [4].

1) The processing of historical data

a) Obtain stable operation condition data

For a large number of historical data, this paper uses two stability algorithm to remove the data of the unstable condition[5] Taking the main steam pressure parameters as an example, the first step is to determine the appropriate change magnitude (-1%~1%) and the corresponding stability index S=95%; the second step is to calculate the average value of the time period data V_{avg} ; And the third step, the fixed time in the process is to determine the shortest time, making 5min for the shortest time, and add a little time to the first stable basis by the search algorithm, then continue to judge the stability of the data in this period and extend to the entire historical data.

b) Dividing the working condition

Making the Fuzzy clustering from one-year historical record data of the active power and the environmental temperature of the power plant, the clustering number of active power is 10, and the clustering number of environmental temperature is 6. So the clustering number of Unit operation condition is 6*10=60. The categories are shown in Table IV.

TABLE IV. CONDITIONS CLASSIFICATION CATEGORIES

The number of working condition		environmental temperature(℃)					
		[-8,1]	[1, 7.5]	[7.5, 12.8]	[12.8, 17.7]	[17.7, 22.3]	[22.3, 33]
Active power(MW)	[250,351]	11	12	13	14	15	16
	[351,406]	21	22	23	24	25	26
	[406,431]	31	32	33	34	35	36
	[431,454]	41	42	43	44	45	46
	[454,479]	51	52	53	54	55	56
	[479,506]	61	62	63	64	65	66
	[506,533]	71	72	73	74	75	76
	[533,560]	81	82	83	84	85	86
	[560,585]	91	92	93	94	95	96
	[585,600]	101	102	103	104	105	106

2) Acquisition of excellent historical data

Taking 1613 historical data of 600MW unit under working condition of active power range [560MW-585MW] and the environmental temperature range[12.8□-17.7□] as example, Firstly the boiler additional unit consumption is clustering. And the clustering number is divided into 3 categories. The clustering results are shown in Table V.

TABLE V .THE CLUSTERING RESULTS OF BOILER ADDITIONAL UNIT CONSUMPTION

Sequence number	Clustering center/(g/(kW.h))	Interval /(g/(kW.h))	D	number
1	149.62	141.06—151.89	a	566
2	154.16	151.90—156.91	b	186
3	159.68	156.92—169.32	c	861

The data of additional unit consumption in category A is chosen as excellent sample data.

3) Access to the operation parameters benchmark interval

The four key energy consumption characteristic, that are the main steam pressure, the main steam temperature, the reheat steam temperature and the feed-water temperature, are fuzzy clustering respectively. Assuming the clustering numbers are n_1、n_2、n_3、n_4 , the number of category combinations will be $n_1 \times n_2 \times n_3 \times n_4$. Each moment of historical data correspond to a category combination. And each category combination represents an operation mode. The operation mode represented by the category combination which is most frequently occurring in the excellent historical data is considered as the optimal operation mode [6-8].

TABLE VI. CATEGORIES COMBINATION EXAMPLE

P1	Category	P2	Category	P3	Category	P4	Category	combination
16.75	2	539.8	2	540.0	3	270.84	2	2232
16.76	2	540.6	2	537.7	2	270.99	2	2222
16.78	2	539.4	3	536.3	2	270.85	2	2322
16.80	3	538.0	2	535.5	1	270.91	2	3212
…	…	…	…	…	…	…	…	…
16.70	1	538.9	3	539.3	3	270.63	2	1332
16.49	2	538.9	3	537.9	2	270.36	2	2322
16.49	3	539.0	3	538.9	3	270.33	2	3332
16.56	2	538.5	2	539.2	3	271.36	3	2233

P1:main steam pressure（MPa）; P2:main steam temperature（℃）; P3:reheat steam temperature（℃）; P4:supplied water temperature（℃）; P5: combination.

The above 566 excellent sample data is taken out, the main steam pressure, the main steam temperature, the reheat steam temperature and the feed-water temperature are fuzzy clustered. Set the cluster number to 3 classes, the results are shown in Table VI.

Statistics show that there are 47 kinds of category combinations, and the number of each type is shown in Table VII.

TABLE VII. NUMBER OF EACH CATEGORY COMBINATION

Category combination	occurrence number
2232	1
2222	3
2322	1
3212	2
…	…
1332	3
2322	9
3332	4
2233	2

The category combination with the most occurrence number is 3213. And the occurrence number is 49. The data in this category combination is the optimal operation mode, and the parameters benchmark interval is obtained from these data.

For the positive parameters, the maximum value of sample is set as the upper bound of the interval, and it makes sure that the probability that the sample falls within the interval is 80% by finding the lower bounds. Those are the bounds of positive parameters.

For the negative parameters, the minimum value of sample is set as the lower bound of the interval, and it makes sure that probability that the sample falls within the interval is 80% by finding the upper bounds. Those are the bounds of negative parameters.

For the Interval parameter, the sample mean is set as the interval center, and it makes sure that probability that the sample falls within the interval is 80% by finding the upper and lower bounds. Those are the bounds of Interval parameter.

V. CASE ANALYSIS

One year's historical data of a 600MW air cooling unit which basically covers all the operation load and environmental temperature are selected. The stability of the main steam pressure is judged. And the continuous and stable operation data is acquired. On the basis of stable operation data, Taking 1613 historical data of 600MW unit under working condition of active power range [560MW-585MW] and the environmental temperature range[12.8□-17.7□] as example, the decision rules of unit energy consumption are acquired , which are shown in table VIII.

TABLE VIII. DECISION RULES OF UNIT ENERGY CONSUMPTION

Adjustable parameter name	Parameter reference value
The additional consumption of boiler(g/kwh)	150.38
Main steam pressure（MPa）	16.71
Main steam temperature（℃）	539.17
Reheat steam temperature（℃）	539.21
Furnace negative pressure（Pa）	-65.44
Primary air volume（t/h）	551.04
Primary air temperature（℃）	288.49
secondary air volume（t/h）	1583.37
secondary air temperature（℃）	297.42
Feed-water Temperature（℃）	270.66
excess air factor	1.4470
Overheated desuperheating water flow（t/h）	153.31
Reheated desuperheating water flow（t/h）	20.33

The reference values of the parameters in table 8 are the adjusted target values for each operation condition. In this time, the decision variable of the operation condition which is the additional consumption of boiler is 150.3843g/kwh.

From the historical data under the operation condition, one of the data is randomly selected as the actual operation data. The design value and the target value of parameters shown in the table 8 are compared and analyzed and the results are shown in the table IX.

TABLE IX. ACTUAL VALUE, REFERENCE VALUE AND DESIGN VALUE

Adjustable parameter name	Actual value	reference value	design value
the additional consumption of boiler(g/kwh)	155.65	150.38	145.79
Main steam pressure（MPa）	16.55	16.71	17.29
Main steam temperature（℃）	539.44	539.17	541
Furnace negative pressure（Pa）	-50.29	-65.44	-60~-80
Primary air volume（t/h）	550.21	551.05	440.28
Primary air temperature（℃）	287.79	288.49	323.3
secondary air volume（t/h）	1586.06	1583.37	1518.90
secondary air temperature（℃）	296.76	297.42	332.2
Feed-water Temperature（℃）	270.66	270.66	272.1
excess air factor	1.51	1.44	1.2
Overheated desuperheating water flow（t/h）	163.89	153.32	66
Reheated desuperheating water flow（t/h）	24.81	20.33	/

As it is shown in the table, the energy consumption benchmark is between the actual operation value and the design value. The energy consumption level of the boiler and auxiliary system can be further reduced by adjusting the operation parameters. The results provide the basis for reducing the energy consumption level in the actual operation.

VI CONCLUSIONS

In this paper, the method combining data mining algorithm and comparable historical boundary conditions to determine the unit optimal target value is put forward. Using unit consumption analysis theory, the energy consumption decision variable is the boiler additional unit consumption which can measure the overall operation efficiency of the boiler. For the four key energy consumption characteristic variables that are main steam's pressure, main steam's temperature, reheat steam's temperature and feed-water temperature, the different combinations of these four parameters are obtained. Taken the best combination as the optimal operation mode, the final energy decision rules are acquired. This paper determines the energy consumption benchmark from a large number of historical data through data mining, and provides the basis for reducing the energy consumption level in the actual operation.

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