Investigation on the performance evaluation of gas-fired combi-boilers with factor analysis and cluster analysis

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Abstract

This study presents a performance evaluation method of gas-fired heating and hot water combi-boilers. Seven factors related to the operation performance are selected. Twenty combi-boilers of different brands and heat input are selected randomly and tested according to GB25034-2010. The factor analysis and cluster analysis method are selected to evaluate the performance of combi-boilers. Analysis results show that, the evaluation model $F = 0.652F_1 + 0.190F_2 + 0.158F_3$ is achieved, and the combi-boilers can be ranked with the evaluation model. The gas-fired combi-boilers selected can be copolymerized into 3 classes. The thermal efficiency at rated input in heating mode, thermal efficiency at 50% of the nominal input in hot water mode, concentration of O₂ and CO₂ of dry combustion products have the greatest impact on the operation performance of combi-boilers. This study provides a method for quantitative evaluation of the operation performance of combi-boilers and a clear direction for product optimization.

Keywords Gas-fired heating and hot water combi-boilers · Evaluation model · Factor analysis · Cluster analysis

1 Introduction

The haze pollution in winter in northern China has become more and more serious since 2013, and studies found that coal combustion has a great impact on haze. Haze is mainly composed of sulfur dioxide, nitrogen oxides and inhalable particles. In order to reduce the haze pollution, China has proposed the “coal-to-gas project” to convert coal-fired to gas-fired. The core of the coal-to-gas project is the change of heating mode, the coal-fired boiler is replaced with gas-fired boiler in the urban centralized heating zone and the domestic gas-fired combi-boiler is used instead of the bulk coal in the rural areas. With the advancement of coal-to-gas project, the sales of gas-fired combi-boilers have reached 2.1 million, 5.5 million and 3.2 million in 2016–2018. Therefore, for such a large number of

combi-boilers, it is necessary to quantitatively evaluate the performance of combi-boilers comprehensively.

However, the research of gas-fired boilers is mostly focused on the industrial boilers with high heat input and the boilers are used only for heating, while the research of gas-fired heating and domestic hot water boilers below 40 kW is relatively few. As a kind of gas-fired boiler, the difference between gas-fired heating and hot water combi-boilers and industrial gas-fired boiler is that, the heat input of gas-fired combi-boilers is generally below 40 kW, and mainly for domestic use, while the industrial gas-fired boilers are generally used for industrial or urban central heating. Both of them are consistent in the principle of gas combustion, so the research of combi-boilers can be learned from the research of industrial gas-fired boiler.

In the latest research on the performance evaluation of boiler, the operation performance mainly focuses on

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the evaluation of thermal efficiency, for example, a performance evaluation model was established based on energy-efficiency mechanism modeling [1], and performance evaluation model was established based on heat loss method [2]. Failure analysis was carried out on a prematurely failed tertiary super heater tube used in gas-fired boiler [3]. For the operational performance boilers, the performance of a very common commercial premixed boiler setup with cylindrical premixed burners has been studied, the aim is to generate knowledge on applied premixed combustion and find the contribution of metal fiber combustion action [4]. With the investigation of denitration efficiency of transition metal oxide oxygen carriers for the gas-fired boiler flue gas, the results showed that with the reduced oxygen carriers, NO can be reduced to N_2 with direct reaction and the carriers can also be converted to the oxidized oxygen carriers at the same time [5]. The study of heat transfer efficiency, emission concentrations of CO and NO_x of a heat exchanger by an efficiency bench test of the gas-fired boiler has been carried out, and results showed that the excess air coefficient has a significant effect on the heat efficiency, CO and NO_x emission concentrations of the water heater [6]. The development of visualisation and measurement of multi-burner flame in an instrumentation system is introduced, and the size, temperature and oscillation frequency of flame were quantitatively determined with the flame images obtained [7]. An improved methodology to compare a traditional natural gas combined cycle plant with a distributed energy resource combined heat and power system has been put forward [8]. With a given exhaust gas temperature, the operation regulation of coupled high–low energy flue gas waste heat recovery system was carried out to maintain the exhaust gas temperature under different flue gas flow, flue gas temperature and air temperature conditions [9].

By choosing several relevant influencing factors, an evaluation model can be established to evaluate the performance of boilers comprehensively. Principal component analysis, as a basic mathematical analysis method, is widely used in practice. In terms of energy, the analysis method is widely used in building energy. Principal component analysis was used for plugging detection and identification for final super heater tube banks with tube temperature data, which show that the method can detect and identify plugged tubes successfully, and categorical principal components analysis has been used to examine the views of people involved in ground source heat pump sector [10, 11]. Based on principal component analysis, the model built for automatic online fault detection, diagnose and sensor reconstitution scheme, that captures the correlation among the flow meters and

temperature sensors installed in the chilling systems has been presented [12]. The principal component analysis is used to select the significant modeling inputs and simplify the artificial neural network model for hourly prediction of building electricity consumption, the proposed prediction model obtained can be used for building electricity consumption online prediction [13]. Three regression variables including synthetic data sequences, outdoor specific humidity and solar radiation were selected for regression analysis, and the principal component analysis seemed to perform better than multiple regression analysis [14]. In addition, the principal component analysis method is also used in botany, medicine, ocean, groundwater and other aspects of evaluation and analysis, for example, evaluation of catalytic pyrolysis of cassava rhizome, evaluation of the partial organ tolerance of normal tissues to radiation and evaluation of ground water quality have all been analyzed by principal component analysis [15–18].

At present, the evaluation of the gas-fired combi-boilers is only based on China national product standards “GB 25034-2010” to determine whether it is qualified, and cannot comprehensively and quantitatively determine the performance of the combi-boilers or give the ranking of combi-boilers. In the previous studies, factor analysis and cluster analysis are rarely used to evaluate the operation performance of boilers. Therefore, combined with the above analysis, the performance of gas-fired heating and hot water combi-boilers can be evaluated and analyzed by factor analysis and cluster analysis, which can be provided as a method for quantitative evaluation of boilers.

The main performance of the combi-boilers includes economic performance and safety performance, among which the economic performance is mainly reflected in the level of useful efficiency, while the safety performance is mainly reflected in the concentration of dry combustion products. Compared with the combustion characteristics of gas-fired combi-boilers, seven indicators including useful efficiency at rated input in heating mode, exhaust temperature, concentration of O_2 , CO, CO_2 of the dry combustion products, useful efficiency at 50% of the nominal input in hot water mode and weighted value of the NO_x concentration have been selected for performance evaluation.

The purpose of this study presented here is to provide a quantitative evaluation method for the operation performance of the combi-boilers. For performing this aim, few combi-boilers have been tested, and the evaluation model are developed with factor analysis method. Then, the key factors affecting the evaluation of operation performance are determined with cluster analysis method.

2 Experiment and method

2.1 Sample selection

Taking 20 gas-fired heating and hot water combi-boilers as an example, the operation performance is evaluated by principal component analysis.

The selected samples have a rated heat input distribution of 20–40 kW and closed heating system structure. The burners are atmospheric burners, and the structure and head of burner are grate structure and harmonica structure, which made of stainless steel. The heat exchanger is made of finned copper coil. The fan type includes fixed frequency and variable frequency fan. The heat exchange methods include plate heat exchanger heat transfer and casing heat transfer. The gas type used during the test is natural gas (12 T).

2.2 Test rig

Figures 1 and 2 are the system schematic and interior structure of the gas-fired heating and hot water combi-boiler,

2.3 Test method

- (1) Useful efficiency at the rated heat input in heating mode

The boiler is installed on the insulated test rig (see Fig. 2), and the measurement of the efficiency may begin once the boiler, with the control thermostat put out of action, is at thermal equilibrium and the return and flow temperatures are constant. The hot water is passed into a vessel placed on scales (suitably tared before the test) and at the same time measurement of the gas rate (reading the meter) is started. Reading of the water return and flow temperatures are taken periodically so as to obtain a sufficiently accurate average.

Mass m_1 of water is collected during the 10 min of the test. A further 10 min wait is required in order to evaluate the evaporation corresponding to the test period. Mass m_2 is obtained. $m_1 - m_2 = m_3$, the quantity of which note has to be taken in order to increase m by the value corresponding to the evaporation, whence the corrected water mass $m = m_1 + m_3$. The quantity of heat transferred by the boiler to the water collected in the vessel is proportional to the corrected mass m and to the difference between temperature T_1 at the cold water inlet and T_2 at the boiler outlet. The useful thermal efficiency is determined by means of the following formula:

Fig. 1 Schematic diagram of test system

Fig. 2 Test rig

$$\eta_u = \frac{4.186 \times m \times (T_2 - T_1) + D_p}{10^3 \times V_{r(10)} \times H_i} \times 100 \quad (1)$$

where η_u is the useful efficiency in percent, m is the corrected quantity of water expressed in kg, 4.186 is the specific heat of water in kJ/(kg °C), T_1 is the temperature at the cold water inlet at 60 ± 1 in °C, T_2 is the temperature at the boiler outlet at 80 ± 1 in °C, $V_{r(10)}$ is the fuel gas flow consumption in m^3 measured during the test corrected to 15 °C, 101,325 mbar, H_i is the net calorific value of the gas used, in MJ/ m^3 at 15 °C, 101,325 mbar, dry gas, D_p is the heat loss from the test rig corresponding to the mean water flow temperature, expressed in kJ, taking into account the heat loss from the circulation pump, by calculating the heat loss of the experimental device, the heat loss is generally 0.5 kW.

(2) Combustion products sampling

The sample of the combustion products is taken in the plane perpendicular to the direction of flow of the combustion products, and a distance from the extreme end of the combustion products duct is equal to the internal diameter of the combustion products evacuation duct, the distance is generally 60 mm. The other end of the sampling probe is connected to the ZSU-BY3000-4 flue gas analyzer.

(3) Useful efficiency at 50% of the nominal heat input in hot water mode

The inlet water temperature is kept constant at 20 ± 1 °C, the outlet temperature of hot water is adjusted to be

20 K higher than the inlet water temperature, and the useful efficiency test is started when the thermal equilibrium state is reached and the outlet temperature remains constant.

$$\eta_s = \frac{4.186 \times m' \times (T'_2 - T'_1)}{10^3 \times V_{r(10)} \times H_i} \times 100 \quad (2)$$

where η_s is the useful efficiency in percent, 4.186 is the specific heat of water in kJ/(kg·°C), m' is the quantity of domestic hot water produced expressed in kg, T'_1 is the inlet domestic hot water temperature at 20 ± 1 in °C, T'_2 is the outlet domestic hot water temperature at 40 ± 1 in °C.

(4) Weighted value of NO_x concentration

The test method of weighted value of NO_x concentration is in accordance with the China national standard GB 25034-2010 “Gas-fired heating and hot water combi-boilers”.

The return water temperature T_r is calculated as a function of the particular heat input using the following formula:

$$T_r = 0.4Q + 20 \quad (3)$$

where T_r is the return water temperature expressed in °C, Q is the partial heat input expressed in percent of nominal heat input.

The NO_x value is specified below:

$$(\text{NO}_x)_0 = (\text{NO}_x)_m + \frac{0.02(\text{NO}_x)_m - 0.34}{1 - 0.02(h_m - 10)} \times (h_m - 10) + 0.85 \times (20 - T_m) \quad (4)$$

where $(\text{NO}_x)_m$ is the concentration of NO_x in the dry flue gas at h_m and T_m in mg/kWh, h_m is humidity of the air in g/kg; T_m is wet bulb temperature of air in °C; $(\text{NO}_x)_0$ is the corrected value of NO_x expressed in mg/kWh.

The weighted value of the NO_x concentration is calculated as follows:

$$(\text{NO}_x)_{\text{pond}} = 0.15(\text{NO}_x)_{m(70)} + 0.25(\text{NO}_x)_{m(60)} + 0.60(\text{NO}_x)_{m(40)} \quad (5)$$

where $(\text{NO}_x)_{\text{pond}}$ is the weighted value of the NO_x concentration in milligram per kilowatt-hour (mg/kWh), $(\text{NO}_x)_{m(70)}$, $(\text{NO}_x)_{m(60)}$, $(\text{NO}_x)_{m(40)}$ are the measured value at the partial heat input.

3 Results and analysis

3.1 Test results

The useful efficiency at rated input in heating mode, the exhaust temperature, the concentration of O_2 , CO, CO_2 of the dry combustion products, the useful efficiency at 50% of the nominal input in hot water mode and the weighted

Table 1 Test results of 20 samples

Sample	Efficiency at rated input (%)	Exhaust temperature (°C)	O_2 (%)	CO	CO_2 (%)	Efficiency at 50% nominal input (%)	$(\text{NO}_x)_{\text{pond}}$ (mg (kWh))
1#	91.65	126	10.8	37×10^{-6}	5.9	88.25	133
2#	89.40	128	11.7	10×10^{-6}	5.2	88.71	132
3#	93.43	123	5.7	122×10^{-6}	8.8	92.98	142
4#	89.64	147	11.8	28×10^{-6}	5.0	88.29	125
5#	93.96	122	6.8	128×10^{-6}	7.8	92.20	147
6#	92.41	139	9.7	58×10^{-6}	6.4	91.01	153
7#	92.18	124	9.8	12×10^{-6}	6.2	91.62	130
8#	90.70	129	11.8	18×10^{-6}	5.1	87.38	175
9#	92.02	115	10.7	38×10^{-6}	6.1	89.96	136
10#	91.48	135	8.8	55×10^{-6}	7.3	89.36	162
11#	91.76	124	9.5	53×10^{-6}	6.9	91.94	127
12#	91.96	132	10.7	13×10^{-6}	5.9	91.33	131
13#	92.24	122	10.9	43×10^{-6}	5.9	90.94	130
14#	93.25	120	8.9	21×10^{-6}	7.1	90.10	132
15#	93.04	124	8.2	93×10^{-6}	7.3	89.33	148
16#	91.72	143	10.1	69×10^{-6}	6.0	88.73	139
17#	90.00	142	11.7	20×10^{-6}	5.3	88.63	136
18#	92.44	121	10.4	37×10^{-6}	5.9	90.77	136
19#	90.64	137	10.5	54×10^{-6}	5.9	87.71	147
20#	91.34	120	11.9	12×10^{-6}	5.0	88.09	172

Table 2 Correlation coefficient matrix

Index	Efficiency at rated input	Exhaust temperature	O_2	CO	CO_2	Efficiency at 50% nominal input	$(\text{NO}_x)_{\text{pond}}$
Efficiency at rated input	1.000	0.564	0.796	-0.628	0.785	0.709	-0.014
Exhaust temperature	0.564	1.000	0.286	-0.090	0.323	0.399	-0.020
O_2	0.796	0.286	1.000	-0.853	0.983	0.684	-0.010
CO	-0.628	-0.090	-0.853	1.000	-0.806	-0.463	0.104
CO_2	0.785	0.323	0.983	-0.806	1.000	0.691	0.021
Efficiency at 50% nominal input	0.709	0.399	0.684	-0.463	0.691	1.000	0.357
$(\text{NO}_x)_{\text{pond}}$	-0.014	-0.020	-0.010	0.104	0.021	0.357	1.000

value of the NO_x concentration of the 20 gas-fired heating and hot water combi-boilers have been tested respectively. 20 samples of different production enterprises and different heat input are selected randomly. The test results of 20 samples are shown in Table 1.

3.2 Correlation analysis

The test indicators have been standardized with SPSS software. The correlation between the evaluation indicators is analyzed, and the correlation coefficient matrix between the evaluation indexes is expressed in tabular form as shown in Table 2.

According to the criterion of correlation, the closer the absolute value of the correlation coefficient is to 1, the stronger the correlation. It can be seen from Table 2 that there is a significant correlation between the efficiency and combustion exhaust gas, and the correlations between O_2 and CO_2 is more significant. It can be known that there is a certain correlation between the seven indexes, and some of the correlations are high. Therefore, it is reasonable to extract the principal component common factor for principal component analysis from the seven independent indicators.

According to the KMO metric given by Kaiser, the factor analysis can be performed if the KMO value is above 0.5, and the output of this analysis is 0.748, so the selected variable is suitable for factor analysis. The Bartlett's test of sphericity has completed the independence test between the variables by converting to the χ^2 test. According to the analysis output, Bartlett's sphericity test statistic is 121.665, and the Sig. is 0.00, which is significantly less than the significance level of 0.005, so the null hypothesis of the Bartlett's sphericity test is rejected, indicating that the correlation coefficient matrix is significantly different from the identity matrix, and the selected variable can be performed with factor analysis.

3.3 Principal components analysis

3.3.1 Principal components extraction

Taking Table 2 as a correlation coefficient matrix, with the data analysis software SPSS, the eigenvalues and eigenvectors can be obtained by solving the coefficient matrix. The number of eigenvalues is the number of components. The variance contribution rate of the k principal component is the ratio of the eigenvalue of the k principal component and the sum of all eigenvalues. The cumulative variance contribution rate of the k principal components is the sum of the first k variance contribution rate. The data processing results are shown in Table 3

Principal component analysis is the method that using few variables to reflect the information of the original variables as much as possible. It is generally believed that most important information can be retained while the cumulative variance contribution rate is greater than 85%. It can be seen from Table 3 that the cumulative contribution rate of the first three main components is 91.118%

Fig. 3 Scree plot of component factor

Table 3 Total variance explained

Component	Initial eigenvalues			Extraction sums of squared loadings			Rotation sums of squared loadings		
	Total	% of Variance	Cumulative %	Total	% of Variance	Cumulative %	Total	% of variance	Cumulative %
1	4.160	59.425	59.425	4.160	59.425	59.425	1.109	15.847	15.847
2	1.210	17.279	76.704	1.210	17.279	76.704	1.089	15.555	31.401
3	1.009	14.414	91.118	1.009	14.414	91.118	1.054	15.054	46.455
4	0.284	4.059	95.178	0.284	4.059	95.178	1.012	14.456	60.912
5	0.173	2.477	97.654	0.173	2.477	97.654	0.947	13.533	74.445
6	0.152	2.173	99.827	0.152	2.173	99.827	0.916	13.087	87.532
7	0.012	0.173	100.000	0.012	0.173	100.000	0.873	12.468	100.000

and greater than 85%. Figure 3 is the gravel map of the eigenvalue. The abscissa is the number of components, and the ordinate is the eigenvalue of the component. The figure shows that the amplitude of variation of eigenvalues varies greatly in the first 3–4 component and tends to be stable after fourth component, which indicates that it is reasonable to extract three indicators as the main components, which can summarize most of the information.

3.3.2 Principal components loading

It can be seen from Tables 3 and 4 that the indicators of useful efficiency at rated input in heating mode, concentration of O_2 and CO_2 have a greater loading on the first principal component, and the corresponding loadings are 0.902, 0.958 and 0.952, respectively, and the contribution of the first principal component to the comprehensive evaluation index is reached 59.425%. The indicator of weighted value of NO_x concentration has the largest loading on the second principal component, the corresponding loading is 0.885 and the contribution is 17.279%. The indicator of concentration of CO has the largest loading on the third principal component, the corresponding loading is 0.806 and the contribution is 14.414%. Combined with the cumulative and the loading corresponding to the principal component, it can be seen that useful efficiency at rated input in heating mode and concentration of O_2 and CO_2 has a greater impact on performance evaluation.

3.4 Factor analysis

3.4.1 Factor loading

Seven indicators of 20 gas-fired heating and hot water combi-boilers are analyzed with factor analysis, three principal components have been extracted and the cumulative contribution rate of the first three main components is 91.118%, so it can be known that the three principal components can reflect 91.118% information of the seven indicators, which is highly representative. In order to obtain a more independence between the seven indicators, the factors have been rotated with the maximum variance method. With the rotation, the factor loading is concentrated to both ends, which can better explain the common factors. The results are shown in Table 5.

3.4.2 Factor scores and ranking

Taking the contribution rate of each component as the weight, the function of comprehensive performance evaluation score is constructed:

$$F = 0.652F_1 + 0.190F_2 + 0.158F_3 \quad (6)$$

The performance scores of each combi-boiler can be calculated with Eq. (6), and the comprehensive ranking of the operation performance of 20 gas-fired combi-boilers can be obtained with the values sorted from large to small in descending order. The rankings of the 20 samples are shown in Table 6. It can be seen that the comprehensive

Table 4 Component matrix

Index	Component						
	1	2	3	4	5	6	7
Efficiency at rated input	0.902	0.026	0.237	0.081	−0.328	0.124	−0.006
Exhaust temperature	0.469	0.268	0.806	−0.211	0.091	−0.075	0.004
O_2	0.958	−0.158	−0.162	−0.036	0.107	0.107	0.084
CO	−0.809	0.361	0.310	0.217	0.088	0.252	0.011
CO_2	0.952	−0.110	−0.133	−0.047	0.173	0.164	−0.069
Efficiency at 50% nominal input	0.802	0.431	−0.043	0.367	0.075	−0.166	−0.003
$(NO_x)_{pond}$	0.060	0.885	−0.402	−0.218	−0.050	0.037	0.002

Table 5 Rotated factor loading matrix

Index	Component						
	1	2	3	4	5	6	7
Efficiency at rated input	−0.340	0.250	0.029	0.318	0.747	0.278	0.291
Exhaust temperature	0.963	0.010	−0.019	−0.146	−0.194	−0.085	−0.081
O_2	0.094	−0.432	−0.020	−0.297	−0.334	−0.503	−0.594
CO	0.033	0.824	0.082	0.161	0.254	0.330	0.338
CO_2	−0.134	0.369	−0.009	0.293	0.307	0.642	0.504
Efficiency at 50% nominal input	−0.197	0.150	−0.262	0.818	0.285	0.243	0.246
$(NO_x)_{pond}$	−0.020	0.049	0.988	−0.142	0.013	0.003	0.006

Table 6 Factor scores and comprehensive scores

Sample	F ₁	F ₂	F ₃	Score	Ranking
1#	-0.823	0.357	0.217	-0.434	13
2#	-2.455	0.828	-0.016	-1.446	17
3#	4.738	-0.436	-0.669	2.901	1
4#	-2.855	0.470	-1.974	-2.084	20
5#	4.057	-0.729	-0.135	2.486	2
6#	0.512	-0.788	-0.670	0.078	10
7#	0.360	1.512	0.412	0.587	6
8#	-2.402	-1.959	1.329	-1.728	18
9#	0.124	0.862	1.265	0.445	8
10#	0.501	-1.731	-0.375	-0.061	12
11#	1.167	1.265	-0.244	0.963	5
12#	-0.374	1.263	-0.192	-0.034	11
13#	0.179	1.235	0.490	0.429	9
14#	1.251	0.916	0.786	1.114	3
15#	1.968	-1.037	0.123	1.105	4
16#	-0.523	-0.696	-1.497	-0.710	14
17#	-2.464	0.113	-1.139	-1.765	19
18#	0.295	0.903	0.795	0.489	7
19#	-1.347	-1.059	-0.735	-1.195	16
20#	-1.909	-1.292	2.229	-1.138	15

Table 7 Correlation analysis

Index	F ₁	F ₂	F ₃	F
F ₁	1.000	-0.001	0.001	0.981
F ₂	-0.001	1.000	-0.001	0.153
F ₃	0.001	-0.001	1.000	0.118
F	0.981	0.153	0.118	1.000

evaluation index value of sample 3 is 2.901, which is the highest of the 20 samples, so the comprehensive ranking is first, and the index value of sample 4 is -2.084, which is the lowest of the 20 samples, so the ranking is 20th.

3.4.3 Correlation analysis of scores

The correlation analysis between the index comprehensive score and factor score is shown in Table 7. The comprehensive score and factor score 1 are significantly positively correlated ($P < 0.01$), and the correlation coefficient is 0.981, indicating that the comprehensive score and factor score 1 have a good correlation; while the correlation between the three factor scores are all 0, indicating that the performance evaluation information of combi-boilers represented by the three principal components does not overlap, which is consistent with the requirements for factor analysis.

3.5 Cluster analysis

As the factor score 1 has a good correlation with the comprehensive score, the system cluster analysis is carried out for 20 gas-fired combi-boilers based on the factor score 1, and the analysis results are shown in Fig. 4. When the class distance is 5, 20 gas-fired combi-boilers are copolymerized into 3 classes (see Table 8). The first category is the samples with a comprehensive score range of 2.486–2.901, which can be regarded as "products with high operation performance"; the second category is the samples with a comprehensive score range of -0.710–1.114, which can be regarded as "products with general operation performance"; the third category is the samples with a comprehensive score range of -2.084 to -1.138, which can be regarded as "products with low operation performance".

Combined with Tables 8 and 9, it can be seen that the combi-boilers with higher operation performance have the higher thermal efficiency at rated input in heating mode and thermal efficiency at 50% of the nominal input in hot water mode and concentration of CO₂ of dry combustion products, and lower concentration of O₂ of dry combustion products, while the exhaust gas temperature, concentration of CO of dry combustion products and weighted value of NO_x concentration of the three types of products are not significantly different. Therefore, it is known that under the premise of the qualified gas-fired combi-boilers, the thermal efficiency at rated input in heating mode and thermal efficiency at 50% of the nominal input in hot water mode and concentration of O₂ and CO₂ of dry combustion products have the greatest impact on the comprehensive operation performance evaluation of combi-boilers, which is in accordance with the indicators with higher loading in the first principal component.

4 Discussions

With factor analysis, the evaluation model is obtained and can be used to quantitatively determine the quality of boilers. With cluster analysis, the key factors influence evaluation model are determined. The results of factor analysis and cluster analysis show that thermal efficiency, concentration of O₂ and CO₂ are the most significant factors that influence the performance of combi-boilers.

Thermal efficiency is the proportion of heat effective heating circulating water to the heat released by gas combustion. In terms of economy, for the same heat required, the higher the thermal efficiency is, the less gas consumption is. In this way, a low gas cost and higher economy can be obtained. Therefore, the higher the thermal efficiency, the better the combi-boilers performance, and the combi-boiler has a high ranking.

Fig. 4 Cluster analysis dendrogram **Table 8** Results of operation performance evaluation with cluster analysis

Product category	Comprehensive score range	Average score	Sample number
High operation performance	2.486–2.901	2.693	3#, 5#
General operation performance	− 0.710–1.114	0.331	1#, 6#, 7#, 9#, 10#, 11#, 12#, 13#, 14#, 15#, 16#, 18#
Low operation performance	− 2.084— 1.138	− 1.559	2#, 4#, 8#, 17#, 19#, 20#

Table 9 Value range of evaluation index in different combi-boilers

Product category	x_1 (%)	x_2 (°C)	x_3 (%)	x_4	x_5 (%)	x_6 (%)	x_7 (mg (kWh)
High operation performance	93.43–93.96	123–122	5.7–6.8	122–128	8.8–7.8	92.98–92.2	142–147
General operation performance	91.48–93.25	115–143	8.2–10.9	12–93	5.9–7.3	88.25–91.94	127–162
Low operation performance	89.40–91.34	120–147	10.5–11.9	10–54	5.0–5.9	87.38–88.71	125–175

O_2 is the air that needed for gas combustion, so the higher the concentration of O_2 in the dry flue gas, the less O_2 concentration involved in gas combustion. With the same volume of gas, the higher the O_2 concentration in the flue gas, the less O_2 concentration involved in gas combustion, and the less the gas combusted. According to the chemical reaction equation of gas combustion, a large amount of CO will be generated while the gas is not completely burned. Similarly, the higher the content of CO_2 , the lower the co generated and the better the combustion effect. Therefore, the lower the concentration of O_2 and the higher the concentration of CO_2 in flue gas, the better the operation performance of combi-boilers.

Thermal efficiency is regarded as an important factor affecting boiler performance [2], and thermal efficiency is the base for the performance of the reheat boiler design [19]. The performance of circulating fluidized bed boiler has been evaluated and results showed that the improved efficiency can improved performance of the boiler [20]. O_2 and CO_2 are mainly reflected in excess air coefficient, the optimization of excess air level in combustion process is one of the improving performance methods, and also can increase the efficiency of boiler [21]. The optimization of excess air also can improve the environment performance in a 150 MW boiler [22]. Therefore, compared with the work published previously, it can be seen thermal efficiency,

concentration of O₂ and CO₂ are the most significant factors that influence the performance of combi-boilers.

5 Conclusions

In this study, performance of gas-fired heating and hot water combi-boilers has been evaluated by factor analysis method. In the analyses, the evaluation model for the combi-boilers using the thermal efficiency, concentration of O₂, CO, CO₂ and weighted value of NO_x concentration has been determined. With the evaluation model, the performance of combi-boilers can be determined quantitatively, and the ranking of combi-boilers can be given. Also in this study, the combi-boilers can be copolymerized into 3 classes with cluster analysis method, and the key factors affecting the evaluation of operation performance are also determined. The purpose of this paper is to provide a quantitative evaluation method for the operation performance of the combi-boilers, so the data used in this paper is mainly the test results. In the future research, the feedback of users using the boiler for a long time can be increased, in this way, the operation performance evaluation model of the whole life cycle of the combi-boiler can be obtained.

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Compliance with ethical standards

Conflict of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

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