FAULT DIAGNOSIS ANALYSIS AND HEALTH MANAGEMENT OF THERMAL PERFORMANCE OF MULTI-SOURCE DATA FUSION EQUIPMENT BASED ON FOG COMPUTING MODEL

by

Miao WANG[a*], Zhenming ZHANG[a], Yun XIE[b], Can SI[a], Long LI[a], Yanxi CHEN[a], and Bo ZHAI[a]

[a] Northwestern Polytechnical University, Xi'an, China
[b] Lanzhou Lanshi Group Co., Ltd., Lanzhou, China

Original scientific paper
https://doi.org/10.2298/TSCI200621318W

Waste heat boiler will be restricted by the exhaust parameters of gas turbine, at the same time, it will affect the thermal characteristics of steam side, and its flue gas resistance will directly affect the power and efficiency of gas turbine cycle, which will have an important impact on the efficiency of combined cycle system. Therefore, it is necessary to monitor the running status of the equipment in time, identify the early signs of faults, and make accurate judgments on fault location, fault degree and development trend, so as to improve the reliability and availability of the unit. The thermal system is the main part of thermal power plant production, so the fault diagnosis of this part is particularly important. In this paper, a method of thermal performance fault diagnosis and health management for multi-source data fusion equipment based on fog computing model is proposed. Using the theory of multi-source data fusion analysis, the qualitative values of the parameters of the fog computing model are marked, and the causes of the failure of the failure variables are obtained. Complete the fault subspace identification, and comprehensively evaluate the equipment status according to multi-attribute decision. This method is conducive to the accurate identification of early faults and the accurate judgment of fault degree and fault trend

Key words*: fog computing, multi-source data fusion, waste heat boiler, fault diagnosis, health management*

Introduction

With the gradual improvement of science and technology, the scale of industrial boilers is expanding day by day, the internal capacity of the boiler system is expanded, the functions are gradually powerful, and the complexity of working conditions is also increasing. Once the boiler equipment fails, its impact and losses are enormous, so it is necessary to monitor the operation status of the equipment in time, identify the early signs of the failure, and make accurate judgments on the fault location, fault degree and development trend, so as to improve the reliability and availability of the unit [1]. It is of great significance to guide the optimized and economical operation of equipment, avoid sudden failure, arrange maintenance reasonably and improve the performance of equipment. This knowledge is often uncertain, inaccurate and incomplete, and is generally expressed in natural language. Uncertainty is an inherent property of natural language, and this uncertainty is mainly manifested as fuzziness [2]. For example,

[*] Corresponding author, e-mail: wmiao@mail.nwpu.edu.cn

the boiler output is insufficient, the exhaust temperature is too high, and the furnace air leakage is serious. However, for the boiler feed water pump system [3, 4], which is composed of many equipments and has the characteristics of changeable working conditions, because various working parameters of the system vary widely between different working conditions, it is impossible to simply adopt a single threshold control method.

Fog computing is a new type of network computing mode that focuses on providing services for mobile smart terminal users. It has gradually emerged in China in recent years. At present, some scholars have carried out research on the architecture [5], network application [6], and system security [7] in this new network computing paradigm. Multi-source information fusion is to make full use of multi-sensor information resources in different time and space, and automatically analyze, synthesize and dominate the multi-sensor observation information obtained according to time series by computer technology under certain criteria, so as to obtain the consistent interpretation and description of the measured object, so as to complete the required tasks and make the system obtain better performance than its various components. According to the characteristics of multi-information in thermal system fault diagnosis of thermal power plants, multi-source information fusion technology is introduced into equipment fault diagnosis and health management based on fog computing model. By fusing the information of fault symptom detection sensors, the system fault can be accurately judged.

Related work

In the operation of boiler equipment, the phenomenon that the boiler, its auxiliary machines and accessories lose their specified functions due to the defects of prior operation, illegal operation and poor maintenance is called fault. With the development of large-scale circulating fluidized bed boiler, its part-load performance has been paid more and more attention. Based on the deposition rate and denudation rate of ash layer, Pan and Zhang [8] deduces the prediction model of ash layer growth on convection heating surface of coal-fired utility boiler, and analyzes the variation law of ash thermal resistance with ash deposition time and flue gas velocity. At present, the main technical index for evaluating the thermal performance of waste heat boiler is the thermal efficiency of waste heat boiler, that is, how much waste heat discharged by gas turbine is absorbed by the boiler and generates steam [9, 10]. In modern equipment management, advanced and complex diagnostic equipment and analytical instruments are used to complete condition monitoring, and some characteristic parameters (such as vibration, noise, temperature*, etc.*) of the equipment can be measured, and then the measured values are compared with the specified normal values, so as to judge whether the working state of the equipment is normal. He *et al.* [11] calculated the performance of the influence of the change of cleaning factors on the main operating parameters of the boiler, and concluded that the soot blowing effect and effect of the heating surfaces in different parts of the boiler are different, which can provide guidance for the optimal operation of soot blowing. Li *et al.* [12] introduced a systematic method based on artificial neural network to predict soot deposition in coal-fired boilers.

Methodology

In the fault diagnosis system, the uncertainty is caused by many reasons, which generally includes three fundamentals: the uncertainty of diagnosis information, the uncertainty of knowledge, and the uncertainty of reasoning process. The temperature level of exhaust gas of modern gas turbine can be well matched with that of steam process of modern steam turbine, which makes gas turbine cycle and steam turbine cycle become a pair of pre-cycle and post-cycle which are naturally matched [13, 14]. For the industrial boiler system, it is necessary to ensure the safety, accuracy and reliability of the control system while realizing high automation. Therefore, higher requirements are put forward for the process monitoring and fault diagnosis of the industrial boiler system. Fog computing edge storage node or fog computing server is a miniaturized hardware device which is arranged locally and provides localized services for mobile terminal users through wireless access. The device integrates high-density wireless network access technology, big data low-delay channel transmission technology, localized storage and computing technology, and cloud computing front-end hardware equipment. Detection data of sensors such as data link. Fusion processing fuses the data generated by sensor sensing simulation and records the time consumption of related processing. In multi-sensor system, the information provided by various sensors may have different characteristics, such as time-varying or non-time-varying, real-time or non-real-time, definite or random, accurate or fuzzy, mutually exclusive or complementary*, etc.*

When the i^{th} node is added to the fog computing network at time, t, the degree change rate $v(i, t)$ of the network [15] can be expressed as:

$$\frac{\delta v(i,t)}{\delta t} = mp_1 \prod_i \tag{1}$$

Assume that at t the probability of adding an edge in the fog computing network is p_2. If one node of the newly added edge is selected from N fog nodes, the probability of selecting another node is $\prod_i$. Then the change rate equation of $v(i, t)$ is:

$$\frac{\delta v(i,t)}{\delta t} = p_2 \left(\frac{1}{N} + \prod_i \right) \tag{2}$$

When the intelligent terminal leaves the fog computing network environment or runs out of energy and leaves the fog computing environment, the fog computing network will delete the corresponding nodes. It is assumed that at t, the probability of deleting a fog node with degree m_2 in the fog computing network is p_3. If the deleted fog node is equal to the m_2 in the network with probability $\prod_i$, Nodes are disconnected. then the rate of change equation of $v(i, t)$ is:

$$\frac{\delta v(i,t)}{\delta t} = -m_2 p_3 \prod_i \tag{3}$$

In fog computing environment, due to energy or network bandwidth, there are two fog nodes canceling communication. It is assumed that at t, the probability of deleting an edge in fog computing network is p_4. If one node with deleted edge is randomly selected from N fog nodes, the probability of choosing another node is $\prod_i$. Then the change rate equation of $v(i, t)$ is:

$$\frac{\delta v(i,t)}{\delta t} = -p_4 \left(\frac{1}{N} + \prod_i \right) \tag{4}$$

Through the aforementioned analysis of fog computing network evolution model, it is obvious that there is $p_1 + p_2 + p_3 + p_4 = 1$. By summing eqs. (1)~(4), the system equation of fog computing network evolution model based on complex network can be obtained:

$$\begin{aligned} \frac{\delta v(i,t)}{\delta t} &= m_1 p_1 \prod_i + p_2 \left(\frac{1}{N} + \prod_i \right) - m_2 p_3 \prod_i - p_4 \left(\frac{1}{N} + \prod_i \right) = \\ &= (m_1 p_1 + p_2 - m_2 p_3 - p_4) \prod_i + (p_2 - p_4) \frac{1}{N} \end{aligned} \tag{5}$$

Using bond graph model to provide information such as system structure, function, characteristics and relationships among elements, a complex causal reasoning fault tree is established [16]. Because the fault diagnosis is developed by causal reasoning of bond graph,

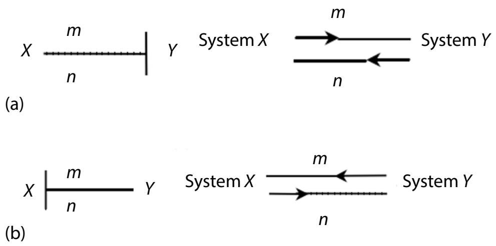

Figure 1. The meaning of causality; (a) the input is a potential variable, and (b) the input is a stream variable

rather than relying on the accurate mathematical model calculation of the system, the fault diagnosis method based on bond graph belongs to qualitative fault diagnosis, which has better rapidity and flexibility. As shown in fig. 1(a), it shows that for the Y object, the potential variable *m* is the input and the cause and the flow variable *n* is the output and the result. In fig. 1(b), for the Y object, the flow variable *n* is the input, which is the cause and the potential variable *m* is the output, which is the result.

According to the actual enthalpy drop (*i.e.*, working capacity) of high, medium and low pressure steam in the steam turbine, the effective output total energy (*i.e.*, effective output power) of the waste heat boiler per unit time can be accurately calculated. However, for partial load calculation, the wind speed and coal feed rate in the combustion chamber have changed, the material concentration distribution has changed, and the corresponding heat transfer coefficient has also changed. Therefore, the calculation under partial load is the key point of this paper. For example, when watching the fire, it is found that a certain water wall tube sprays steam, so it can be considered that the water wall tube has failed to leak. If the pipe section before the sewage valve is touched by hand (when the sewage is not discharged) feels hot and hot, it is concluded that the sewage valve is not locked or defective. Only one potential variable (or flow variable) is defined as the input, while the flow variable (or potential variable) is the output. Input is the cause, output is the result, and this causal relationship is indicated by a causal cross (short line perpendicular to the key) at the end of the key [17]. On the one hand, the uncertainty of the rule itself is mainly caused by the uncertainty of the diagnostic object itself or the uncertainty of the understanding and description of the diagnostic object, on the other hand, it is the uncertainty caused by premise. With the increase of afterburning amount, the proportion of steam turbine capacity increases. According to the exhaust temperature of the gas turbine, the best afterburning quantity can be determined to maximize the efficiency of the unit, and the available coal or other cheap fuels can be afterburned.

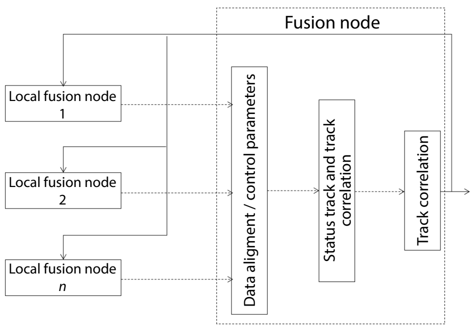

Figure 2. Multi-level fusion structure model

Multi-level fusion structure in the multi-level structure, each local node can be a centralized, distributed or hybrid fusion center at the same time or separately [18]. They will receive and process data from multiple sensors or tracks from multiple trackers, and the fusion nodes of the system will correlate and synthesize the track data transmitted by local nodes again, that is to say, the target detection report will go through more than two levels of position fusion processing, so it is called a multi-level system. The multi-level fusion structure model is shown in fig. 2.

Material particles are divided into *N* grades according to their particle size. Under the condition of static operation, the mass balance of the *i*-grade particles with the diameter, d_i, should satisfy [19]:

$$m_{\rm fc}(d_i) - m_{\rm fa}(d_i) - m_{\rm d}(d_i) + m_{\rm shift}(d_i) = 0 \tag{6}$$

where $m_{\text{fe}}(d_i)$ [kgm^{-2}s^{-1}] is the material inflow rate of the first i grade particle, $m_{\text{fa}}(d_i)$ [kgm^{-2}s^{-1}] – the fly ash flow rate of the first grade i particles, $m_{\text{fd}}(d_i)$ [kgm^{-2}s^{-1}] – the slag discharge material flow rate of the first i grade particles, and $m_{\text{shift}}(d_i)$ [kgm^{-2}s^{-1}] – the change rate of the net mass of the i-grade particles caused by abrasion.

The $C_{dfc}(d_i)$ is used to represent the grading separation efficiency of the separator for the i-grade particles, which can be written:

$$m_{\text{fa}}(d_i) = [(1 - C_{\text{efc}}(d_i)]m_{\text{elu}}(d_i) \tag{7}$$

where $m_{\text{elu}}(d_i)$ [kgm^{-2}s^{-1}] is the material flow rate of the first q grade particles at the furnace outlet. Assuming that the material particles are uniformly mixed in the bed, the slag discharge flow rate of the i-block particles can be expressed by the i-block components $Bed(d_i)$ in the main bed:

$$m_{\text{d}}(d_i) = [1 - C_{\text{drain}}(d_i)]m_{\text{drain}}Bed(d_i) \tag{8}$$

where $C_{\text{drain}}(d_i)$ is the weight coefficient of slag discharge after considering selective slag discharge, which is determined by experiment, m_{drain} [kgm^{-2}s^{-1}] – the total slag discharge flow rate.

The key problem of information fusion research is to put forward some theories and methods to process multi-source information with similar or different characteristics and modes, so as to obtain fusion information with relevant and integrated characteristics. Firstly, the probability statistics of track correlation results and the results of target state estimation and attribute recognition are carried out, and then a set of scientific, reasonable, complete and testable performance indicators are extracted [20, 21]. In summer, when the air temperature is high and the unit output rate is insufficient, the pressurized fan can be used to replenish fresh air to the waste heat boiler. In this way, more fuel can be burned in the waste heat boiler to increase the output of the whole device. When dealing with variable load, the heat storage capacity of metal pipe wall is considered to make up for the inconsistency between the heat absorbed by working medium side and the heat released by flue gas side. There are a large number of highly correlated process variables in the control system of industrial boilers, which play a vital role in the reliability and safety of boilers in normal operation. Therefore, the design performance of waste heat boiler must match the performance of gas turbine and steam turbine to ensure the performance of the whole combined cycle unit. However, a series of complex physical and chemical reaction processes, such as volatile release, coke combustion and crushing accompanying combustion, of coal in the combustion chamber are simply attributed to the final ash formation. Thus, a fault tree is formed, and the most boundary parameter of this tree is the cause of the fault or the value that conflicts with the fault.

Result analysis and discussion

The characteristic of knowledge randomness is that the previous results are known, but the posteriori results are unknown. It describes an either-or phenomenon. When the waste heat boiler uses forced blower to supply air to make the steam turbine system run independently, the inlet air temperature of the boiler is very low, and it needs to burn more fuel, so the thermal efficiency is much lower than that of the combined cycle, and with the decrease of load. Therefore, there is an error between the boiler performance data obtained by design calculation and the measured data. If the real-time pollution of boiler tube wall surface can be considered in the theoretical model of boiler design and calculation [22], the theoretical value can be closer to the measured value. In addition, when some faults occur, the mean and variance of process variables do not change, but the correlation between process variables changes. That is, the flow rate and particle size distribution of coal entering the furnace are replaced by the actual ash forming flow rate and particle size distribution of the coal [23]. However, system failures may be caused by the failures of one or more devices, and sometimes the failures of various devices are related. Efficiency only reflects the balance of total heat, but does not accurately reflect how much work capacity the steam produced has.

During the test, the parameters such as gas turbine exhaust flow, gas turbine exhaust temperature, gas turbine exhaust moisture content, condensate temperature, high pressure main steam pressure, cold reheat temperature, hot reheat pressure and low pressure steam pressure all deviate from the design values, so they need to be corrected according to relevant correction curves. The total energy output by effective energy is the part of the total enthalpy of steam that can actually do work in the steam turbine, rather than the total enthalpy. The effective work capacity of each pressure steam of the waste heat boiler is shown in tab. 1.

Table 1. Effective working capacity of steam under different pressures in waste heat boiler

Projects	Numerical
High pressure main steam	18634
Reheat steam	146805
Low pressure steam	8914
Overall working capacity of waste heat boiler	156270
Design work capacity of waste heat boiler	132499

According to the test results, the measured thermal efficiency of the waste heat boiler in the combined cycle is 89.24%, which is 4.62% higher than the design value of 84.62%. See tab. 2 for comparison of the influence of waste heat boiler on the overall performance analysis of combined cycle.

Table 2. Influence of waste heat boiler performance on overall performance of combined cycle

Projects	Guaranteed value	Test result	Better than guaranteed value [%]	Conclusion
Total heat consumption rate of combined cycle [kJkWh^{-1}]	8.241	8607.61	0.36	Achieve
Efficiency of waste heat boiler [%]	84.62	89.24	2.5	Achieve
Overall working capacity of waste heat boiler [kW]	153708	149952	0.054	Achieve
Gas turbine and steam turbine performance	–	–	–1.27	Miss

As the overall performance of combined cycle mainly depends on gas turbine, steam turbine and waste heat boiler, it can be seen from the previous data that if the whole combined cycle is evaluated by the thermal efficiency of waste heat boiler, it can be concluded that the performance of gas turbine and steam turbine cannot reach the design value, with a difference of 4.62%, and may face huge commercial fines.

An actual operating device is actually a complex system. Because people's cognitive ability is limited, some information or knowledge cannot be known accurately or cannot be known. Under the supercharging condition, the combustion intensity and heat transfer coefficient in the boiler are obviously increased, so the volume of supercharged boiler is much smaller than that of normal pressure boiler, and its metal consumption and plant investment are greatly reduced. Ash deposition loss leads to the decrease of heat transfer coefficient and heat transfer quantity, which leads to the decrease of boiler efficiency and the increase of coal consumption. The fault diagnosis analysis based on bond graph is a qualitative analysis, which can get the fault cause of the system without a lot of derivation and calculation. Moreover, because the bond graph model contains the structural information of the system, this qualitative fault diagnosis method has better completeness and flexibility. It is a participant in gas-solid reactions such as combustion and desulfurization and it determines the axial and radial heat exchange. The concentration of material passing through the suspension section determines the heat transfer to the heating surface; The steam flow rate and work capacity of each pressure are different from the design value, the high pressure steam flow rate and low pressure steam flow rate are lower than the design value, and the reheat steam flow rate exceeds the design value. At this time, the problem involved is the closeness between two fuzzy subsets, not the membership degree of elements to sets.

Figure 3 shows the particle size distribution of fly ash, slag discharge and furnace outlet materials when the load is 99%, in which the point is the analysis result of sampling after actual operation, and the line is the model calculation result. Figure 4 shows the change of solid material concentration carried by flue gas at furnace outlet under different loads. It can be seen that the calculated results of the model are close to the experimental values.

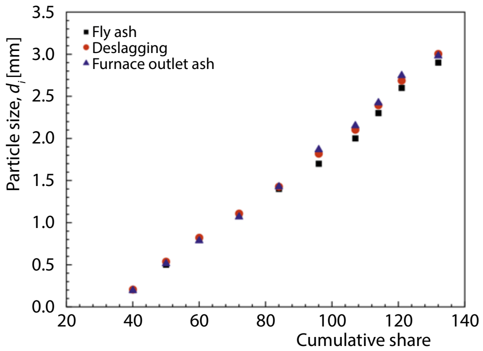

Figure 3. Comparison of particle size distribution calculation and model prediction results

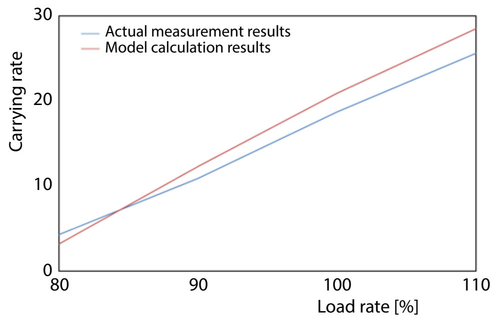

Figure 4. Comparison of furnace outlet concentration and model prediction results

Under the condition of partial load, the material flow rate and particle size distribution at the outlet of the furnace can be calculated, so if the average free settling velocity of particles can be known, the material concentration at the outlet of the combustion chamber can be obtained. Fortunately, according to the calculation results of material balance and field observation, it is found that the particle size distribution of materials at the outlet of combustion chamber is in a very narrow range under different loads, which can be assumed to be single particle size.

The MATLAB/SIMULINK environment is used for simulation. When the speed of steam turbine drops suddenly in 10 seconds, the response curve of discharge pressure of feed water pump is shown in fig. 5. It can be seen from fig. 5 that the discharge pressure of the feed water pump tends to decrease with the decrease of the speed of the steam turbine. This fully shows that the discharge pressure of feed water pump is related to the speed of steam turbine, that is, the decrease of the speed of steam turbine can lead to the fault of low discharge pressure of feed water pump, which is consistent with the fault diagnosis conclusion obtained in this paper. The fault diagnosis method based on bond graph proposed in this paper is feasible and effective.

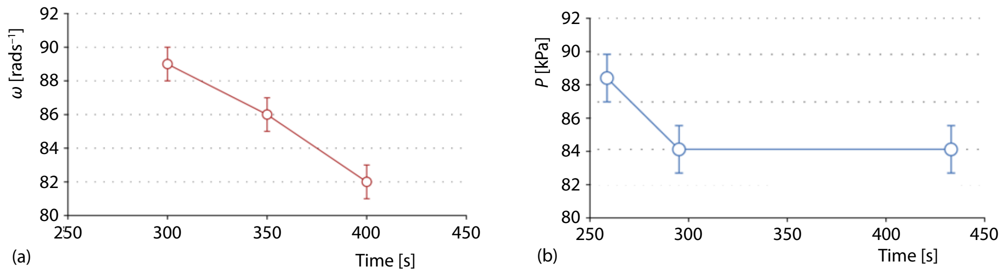

Figure 5. Response curve of pump discharge pressure under steam turbine speed disturbance; (a) turbine speed disturbance and (b) discharge pressure response of pump

For waste heat boiler combined cycle with afterburning, it can improve the thermodynamic parameters of main steam and increase the power of the unit. When the natural soot loss at the current moment is equal to the soot blowing loss per unit time, it is the best soot blowing cycle of the heating surface. For a considerable part of coal, due to the insufficient strength of ash particles, it is easy to wear and produce a large number of fine ash particles which cannot be captured by the separator. When the loss of this part reaches the same order of magnitude as the amount of fly ash normally separated by the separator, it is necessary to consider the influence of the self-wear of coal ash particles on the material balance of the circulating fluidized bed. In this way, the occurrence probability of each hypothesis under the *comprehensive* evidence can be calculated separately, and the hypothesis with the highest occurrence probability is considered as the main cause of the event. Soot blowing on high temperature superheater or reheater will also affect steam temperature and desuperheating water flow. The soot blowing of air preheater and economizer has great influence on exhaust gas temperature, which can effectively improve boiler efficiency and reduce flue resistance. From the point of view of improving the utilization rate of energy and saving energy, the combined cycle of waste heat boiler without afterburning should be the mainstream direction of development.

Conclusions

The internal structure of industrial boiler control system is complex and there is strong coupling among process parameters, so it is difficult to describe it with accurate mathematical model. In this paper, a method of thermal performance fault diagnosis and health management for multi-source data fusion equipment based on fog computing model is proposed. Using the theory of multi-source data fusion analysis, the qualitative values of the parameters of the fog computing model are marked, and the causes of the failure of the failure variables are obtained. Complete the fault subspace identification, and comprehensively evaluate the equipment status according to multi-attribute decision. In the design of waste heat boiler, more high-grade steam should be produced as much as possible, so as to improve the overall output power of waste heat boiler and further improve the thermal efficiency of combined cycle units. There are only a plurality of rule modules that meet the needs of sample clustering, and there are control modules that control the network output. Therefore, it can deal with complex systems well and meet the requirements of boiler real-time diagnosis.

The application of multi-source information fusion technology in fault diagnosis of operating equipment in thermal power plants is still in its infancy, and the effectiveness and adaptability of the new method need further study before it can be put into practice. In this paper, the state recognition is mainly carried out for the running state data, and a variety of detection methods should be adopted for comprehensive diagnosis in actual diagnosis.

Acknowledgment

This work was financially supported in part by the Key Research and Development Program of Shaanxi, China under Grant 2019ZDLGY01-01-01.

References

[1] He, B., *et al*., Leakage Diagnosis of Gas-Steam Combined Cycle Waste Heat Boiler Based on Principal Component Analysis, *Guangdong Electric Power*, *30* (2017), 6, pp. 1-5
[2] Zhao, Y., *et al.*, Summary of Wind Turbine Condition Monitoring and Fault Diagnosis Technology, *Thermal Power Generation*, *45* (2016), 10, pp. 1-5
[3] Jin, X., *et al*., Summary of Research on Fault Diagnosis and Prediction Technology of Wind Turbines, *Chinese Journal of Scientific Instrument*, *38* (2017), 5, pp. 1041-1053
[4] Chen, C., *et al*., Fault Diagnosis of SCR Flue Gas Denitrification System in a Power plant, *China Electric Power*, 5 (2016), pp. 63-66
[5] Shi, Z., Signal Detection and Fault Diagnosis of Driving Drum of Large Belt Conveyor, *Mining Machinery*, (2016), 4, pp. 27-30
[6] Huang, B., *et al*., Fault Diagnosis of Thermal Equipment Based on Similarity Modelling and Fuzzy Probability Directed Graph, *Thermal Power Generation*, *47* (2018), 377, pp. 108-113
[7] Shi, Z., *et al*., Fault Diagnosis Method of Public Bicycle System Based on Naive Bayes Classifier, *China Mechanical Engineering*, *30* (2019), 8, pp. 983-987
[8] Pan, H., Zhang, Y., Fault Diagnosis of Ammunition Supply System Based on Texture Features of SST Time-Frequency Graph, *Journal of Vibration and Shock*, *39* (2020), 6, pp. 132-137
[9] Baldi, S.M., *et al*., Real-Time Monitoring Energy Efficiency and Performance Degradation of Condensing Boilers, *Energy Conversion and Management*, *136* (2017), Mar., pp. 329-339
[10] Fouad, M. A., Early Failure of Waste Heat Boiler and Redesign to Overcome Premature Failure, *Journal of Failure Analysis & Prevention*, *17* (2017), 3, pp. 395-399
[11] He, J., *et al.*, Typical Fault Diagnosis of SCR Flue Gas Denitrification System Operation in Coal-Fired Power Plants, *China Electric Power*, *8* (2016), pp. 148-153
[12] Li, W., *et al*., Thermal Parameter Sensor Fault Diagnosis Based on Dynamic Data Mining, Vibration, *Testing and Diagnosis*, *36* (2016), 4, pp. 694-699
[13] Lei, Y., *et al*., Opportunities and Challenges of Mechanical Intelligent Fault Diagnosis under Big Data, *Chinese Journal of Mechanical Engineering*, *54* (2018), 5, pp. 94-104
[14] Wang, L., *et al*., Fault Diagnosis Method of Asynchronous Motor Using Deep Learning, *Journal of Xi'an Jiaotong University*, *51* (2017), 10, pp. 128-134
[15] Tu, Y., *et al*., Research on Optimal Fault Diagnosis Algorithm Based on Dimensionality Reduction Observer, *Chinese Space Science and Technology, 37* (2017), 223, pp. 44-49
[16] Imasato, K., *et al*., Exceptional Thermoelectric Performance in Mg3Sb0.6Bi1.4 for Low-Grade Waste Heat Recovery, *Energy & Environmental Ence*, *12* (2019), 3, pp. 965-971
[17] Zhao, Y., *et al*., Analysis of Thermoelectric Generation Characteristics of Flue Gas Waste Heat from Natural Gas Boiler, *Energy Conversion and Management*, *148* (2017), 9, pp. 820-829
[18] Wang, D., *et al.*, Calculation and Analysis on Recovery of the Waste Heat of the Flue Gas in Gas Boiler in Cold Region, *Journal of Jilin Institute of Civil Engineering and Architectur*e, *35* (2018), 2, pp. 48-52
[19] Duan, A., *et al*., Heat Exchanger Simulation and Recovery Device Design of Waste Heat Boiler of Gas Turbine Generator Set on Ocean Platform, *Journal of Intelligent and Fuzzy Systems*, *38* (2020), 2, pp. 1257-1263
[20] Liu, X., Cause Analysis of Damages of Coalescer of Waste Heat Boiler in Petroleum Refinery and Countermeasures, *Petroleum Refinery Engineering*, *48* (2018), 6, pp. 49-52
[21] Zhu, Q. B., Li, Z., Application of Heat Pipe Boiler in Waste Heat Recovery from the System of Acid Making with Gas in a Copper Smelter, *Energy Saving in Non-Ferrous Metallurgy*, *35* (2019), 3, pp. 24-28
[22] Zhang, C. L., *et al*., Intelligent Fault Diagnosis Method of Power Transformer Based on Deep Learning, *Journal of Electronic Measurement and Instrument*, *1* (2020), pp. 81-89
[23] Wang, *et al*., Power Dispatch Fault Diagnosis Based on Warning Signal Text Mining, *Electric Power Automation Equipment*, *39* (2019), 4, pp. 126-132

Paper submitted: June 21, 2020
Paper revised: August 28, 2020
Paper accepted: September 23, 2020