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Summary of Research and Development of Intelligent Combustion Optimization System

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Abstract. This paper summarizes the purpose and significance of intelligent combustion optimization, and mainly introduces the theoretical research on intelligent combustion optimization algorithm and the development and application of intelligent combustion optimization system software. It makes a comprehensive assessment to the research results and technology development of intelligent combustion optimization, and gives an in-depth analysis of the current challenges and future development direction of intelligent combustion optimization technology. Finally, considering the latest research results and the current domestic thermal power development situation, it points out the urgency and necessity of the development of intelligent combustion optimization system.

1. Preface

In recent years, boilers often fail to achieve the best conditions of combustion due to the following reasons: 1) it has stringency of grid dispatching requirements and the variability and requirements for rapid response of the loads; 2) the greater changes of coal type in most coal-fired power plants were affected by the coal market, leading to the poorer of the coal quality[1]; 3) in the boiler operation and maintenance process, after the upgrading of the equipment, the thermal test cannot be carried out in time to adjust the operating conditions. Therefore, it is imperative to improve the economy, safety and environmental protection of the unit by optimizing its operation. With the gradual maturity and application of artificial intelligence and big data deep mining technology, intelligent combustion optimization technology has also been greatly developed, and has become an optimized operation mode for many power plants.

Intelligent combustion optimization technology is established under the basic conditions of the existing monitoring system, based on the original operation data. It uses advanced algorithms and artificial intelligence technology to model and optimize boiler combustion, and guides boiler operation to improve furnace efficiency and reduce the level of pollutant discharge. The technology is based on the existing equipment of the power plant and requires no additional modifications. Compared with other combustion optimization technologies, it has the advantages of effective emission reduction, low cost, safety and reliability[2].

At present, many universities, research institutes, control manufacturers and technology companies have launched intelligent combustion optimization systems with different characteristics to improve boiler combustion efficiency and reduce pollutant emission levels. This paper has made a comprehensive summary of the research and development of intelligent combustion optimization technology by studying a lot of literature, field research, product consultation and other methods.

2. Research Status of Intelligent Combustion Optimization Technology

2.1Research Status of Theoretical Algorithms

Establishing a model that accurately reflects the actual combustion situation is the basis for intelligent combustion optimization. The two most commonly used modeling methods are Artificial Neural Network (ANN) and Support Vector Machine (SVM). ANN uses mathematical methods and information processing techniques to abstract the human brain neural network and build a simplified model. The model acquires knowledge and stores it in a distributed manner by training sample data. ANN has the disadvantages of slow convergence and it is difficult to determine the number of hidden nodes[3]. SVM[4] is a learning model with supervised functions being commonly used in the field of machine learning. It is based on statistical learning theory and has the advantages of strong generalization ability and it can solve local minimum value problems. However, it has strict requirements on the sample, requiring a moderate sample size. If the sample is too large, it will train slowly and its modeling time will be extended[5]. And there is no uniform method for determining the normalization parameters and kernel functions.

The development and maturity of intelligent algorithms ANN and SVM technology bring combustion optimization technology into the field of intelligence, providing powerful technical support for establishing a combustion model with stable and reliable, generalization ability and accurate response to actual combustion conditions. Based on the intelligent optimization algorithm, the adjustable parameters are optimized to achieve the goal of improving boiler efficiency and reducing pollutant emissions.

There are many scholars and experts who are engaged in the theoretical research of boiler combustion model algorithms at home and abroad. Reinscmhdit et al[6] established a boiler combustion model on the basis of ANN and carried out simulation research; Irwin[7] built a nonlinear model of a 200MW oil-fired boiler based on ANN; Booth et al[8] established a combustion model of power station boilers under different loads with ANN; Gu et al[9] studied the online update algorithm of least squares support vector machine (LSSVM), and with which they established the combustion system model of power station boilers, and optimize the adjustable parameters by using genetic algorithm; Li et al[10] applied genetic algorithm and particle swarm optimization to optimize the important parameters in Support Vector Regression(SVR), which was applied in establishing NOx emission prediction model, laying an important foundation for optimal control of NOx emissions.

Some domestic universities have also carried out research by using artificial intelligence methods ANN and SVM to achieve combustion optimization control of boilers, and have achieved gratifying results in theoretical and production aspects. Hao Zhou et al[11,12] established a model to detect the carbon containing of boiler fly ash and NOx emission by using ANN technology. And they combined ANN with simulated annealing algorithm (SA) to optimize NOx emissions on the basis of a 600MW coal-fired boiler, which achieved good results; Li Guoqiang et al[13] proposed a parallel fast learning network (PLP-FLN), with which they successfully established a combustion fluidized bed boiler combustion system model. Gu Yanping et al[14,15] studied the least squares support vector machine (LSSVM) and proposed an improved algorithm, and the boiler combustion model was established on the basis of this, realizing the soft measurement of parameters such as the carbon content detection of fly ash, exhaust temperature and NOx emissions; Wang Yuelan et al[16] established carbon containing in fly ash prediction model of pulverized coal fired boiler on the basis of the adaptive neuro-fuzzy inference system (ANFIS). Under the circumstance of sufficient samples, it can achieve good prediction accuracy and generalization ability; Wang Qi et al[17] established circulating fluidized bed boiler (CFB) SO2 emission prediction model with high precision and generalization ability based on variable selection and support vector machine (SVM); NOx emission model was established by Niu Peifeng et al[18] through using the Gravitational Search Algorithm (GSA), the Drosophila Optimization Algorithm (FOA) and the Teaching and Learning Optimization Algorithm (TLBO) to optimize the kernel function parameters and normalized parameters in the SVM, which has high precision. Based on the online update of LSSVM, Lv You et al[19] established a NOx emission characteristic model, which can adapt to changes in boiler operating conditions and demonstrates high prediction accuracy.

2.2 Status of Development and Application of Intelligent Combustion Optimization System

Many intelligent optimization products have been put into use abroad. Such as: the combustion optimization system of Ultramax, Ohio, USA[2, 20, 21], the Pepesus Power Pefecter system and the NeuSIGHT system[2, 21, 22, 23] of Pegasus company. GE's KN3 combustion optimization system, Emerson's Smart Process[24,25] combustion optimization system, advanced combustion optimization (ACO) of large thermal power plants under the advanced process control module of STEAG, Germany. Among them, the NeuSIGHT system can reduce NOx emissions by 10% to 40% for boilers that have already installed low NOx burners, which reduces coal consumption by 0.5% to 5%. The KN3 system applies multi-objective optimization neural network technology to reduce NOx emission, which is reduced about 10%, resulting in that the furnace efficiency is increased by about 0.5%; the Smart Process system can reduce the heat consumption rate by 0.5% to 1.5% on average, and reduce NOx emissions by 15% to 35%; ACO is used on multiple units in Germany and India, achieving great result.

The year after 2000, some of China's power plants introduced a number of foreign intelligent combustion optimization systems. Because that it is difficult to adapt to the domestic variable load and coal quality conditions, the application effect is not as expected. At present, some research institutes and universities in China have developed a series of intelligent combustion optimization systems in accordance with the characteristics of coal quality and load change of power plants, and achieved good application results. For instance, Tsinghua University's OCP3 system[2,26], a system using neural network to establish combustion model, adjusted its weight neural network by transferring multi-objective optimization problem into single-objective optimization; BCOS-2000/2.0 system of Southeast University[20] applied neural network technology, and selected the initial sample from the historical operation data, to establish the initial combustion model. And it updated the model according to the running real-time data to improve the accuracy of the model. In addition, it performed nonlinear optimization on the basis of the model so as to find out the optimal air distribution and coal blending mode under different operating conditions to achieve optimal operation of the boiler combustion system; Based on the advanced concept and process optimization software of American FGS Company, Beijing Aipu Rui Company has developed a SOAP combustion optimization system combining with the operational characteristics of domestic power plants[27]; Zhejiang University and Xi'an Thermal Engineering Institute also compared and studied the global optimization algorithms, and proposed online optimized algorithm. By applying the combustion optimization process to the actual boiler, they developed a real-time control method guaranteeing low pollution and high transfection combustion efficiency of the online boiler.

3. Challenges in the Development of Intelligent Combustion Optimization Systems

3.1External Factors

3.1.1 Changes of Power Plant Coal Quality. The rising of coal prices has led to a sharp drop in profits in the coal-fired power industry. At the same time, it has led to the procurement constraints of fuel in power plants, resulting in the unstable source of coal, and some power plants even experienced coal-breaking phenomena[1]. The instability of the coal type made some power plants even completely deviate from the designed coal type, which is not conducive to the safe and efficient operation of the boiler equipment, bringing challenges to the operating personnel.

As for the intelligent combustion optimization system, the coal that enters the furnace too frequently will cause a large difference between the modeling and the actual combustion situation, making it difficult to make an optimal judgment, even if an adaptive intelligent combustion optimization system is unable to keep up with the coal quality that is changing too frequently.

3.1.2 Long Soot-blowing Time. In order to increase profitability and reduce fuel costs, many power plants have mixed high-ash, low-melting inferior coal, which increases the pollution degree of the boiler heating surface and also increases the risk of coking and slagging; The completion of low-nitrogen combustion technology has reduced the NOx emissions, lowered the temperature level in the furnace, and increased the reducing atmosphere in the furnace, and at the same time, caused combustion problems such as low temperature of main reheat steam, coking and high temperature corrosion.

In order to ensure good heat transfer effect and increase the temperature of main steam and reheat steam, it is necessary to frequently blow the boiler. At present, most power plants blow ash once per shift, about 2 hours each time, and the soot blowing time is about 6 hours per day. Some power plants even reached 8 hours per day.

At present, almost all final performance characteristics of parameters of intelligent combustion optimization systems are evaluated according to the calculated thermal efficiency or heat loss value in ASME PTC4.1 or GB10184. Both of these evaluation standards require that the boiler is operated under relatively stable operating conditions, and that soot blowing and sewage discharge are prohibited during the measurement process. In the actual soot blowing process, the combustion condition in the furnace is very complicated, and it is difficult to establish a stable and reliable combustion model for soot blowing. At present, the intelligent combustion optimization system put into operation is mostly unable to achieve the desired results in the soot blowing process.

3.1.3 Hardware Device Restrictions. In some power plants, due to the exiting dead zone of the on-site actuator, the actual opening degree of the site is greatly deviated from the command given, which leads to the impossibility to achieve precise control. Sometimes, the intelligent combustion optimization system calculates the optimization result, and transmits it to the field actuator, but the actuator is not in place and the optimization effect cannot be achieved.

In some older power plants, the overall automation level is relatively low, and many parameter controls that affect boiler combustion cannot be remotely regulated. When the combustion optimization system is modified, these control mechanisms need to be modified to achieve remote control, which will inevitably increase the cost of the intelligent combustion optimization system. Even some less-automated power plants will cost much higher retrofit fee than installing a combustion optimization system.

3.1.4 Measurement Problems. Real-time online monitoring equipment performance is not stable enough. The coal quality and the carbon-containing in fly ash are key points for boiler efficiency calculation. However, the measurement of such equipment in China is lagging behind thus it cannot be accurately measured in real time, which leads to inaccurate boiler efficiency in online calculation and becomes one of the obstacles[2] in optimal control of boiler operation.

At present, generally speaking, the oxygen measurement of power plants has problems of large measurement error and large fluctuations in short time, which seriously affects the accuracy of thermal efficiency calculation and the effect of closed-loop control[2]. As for the accurate and rapid measurement of NOx, although the technology and application are relatively mature, the expensive equipment price, the complicated operation and maintenance workload, as well as the expensive CO real-time online monitoring equipment render most power plants not install it; Besides, in terms of the study on on-line measurement of carbon in large slag, there are few studies on it; and the reliability and accuracy of furnace temperature measurement technology are not as expected. The lag of the development of real-time online monitoring equipment has become a difficult problem that restricts the large-scale application of combustion optimization control.

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3.2 Constraints of Intelligent Combustion Optimization Technology

3.2.1 Static Optimization. Static optimization often only considers the static model of the object, which may make the optimization of the target simpler, but its dynamic characteristics are neglected. The simple application of static model in dynamic changes leaves large optimization space when the load changes frequently. The typical example is the performance calculation of thermal power plant units. Software at home and abroad generally adopts the performance index calculation method which is based on ASME performance test standard or GB10184. However, this static algorithm does not consider the dynamic characteristics of the unit operation, and requires high standard of environment such as system isolation and load stability, etc., which is difficult to be satisfied. Most intelligent combustion optimization products are based on static optimization, and the optimization effect is better when the unit is running stably, while it performs not well when the unit load changes too frequently.

3.2.2 Local Optimization and Global Optimization. Global optimization must be locally optimized, but the combination of local optimizations is not necessarily global optimization. Boilers are large and complex equipment, and considering various factors, optimization problems will become extremely complicated. If the optimization range is too narrow, it will get unsatisfactory effect; if the optimization range is too large, the combustion stability may be affected. Considering the tight situation of coal market in recent years, combustion stability is often given priority. Intelligent combustion optimization systems need to fully consider the requirements of combustion stability, not just the problem of optimizing its simple performance.

3.2.3 Quantification of Energy Conservation Indicators Assessment Criteria. Generally speaking, the assessment of general energy-saving indicators is analyzed in the steady-state process. Under the current thermal power situation, the steady-state time period is rare to be seen during the actual operation, and the load changes rapidly, which leads to a phenomenon that the energy-saving effect of the combustion optimization system cannot be measured during the dynamic adjustment and variable load process, thus, it is difficult to determine its true energy-saving effect. How to realize real-time calculation and accumulate energy-saving emission reduction through background simulation and gain industry recognition is one of the key factors for the rapid introduction of intelligent combustion optimization technology to the market.

4. Future Development Trend of Intelligent Combustion Optimization Technology

4.1Continuous Improvement of Measurement Technology
Advances in measurement technology and the development of new measuring equipment are of great significance for the improvement of the operating level of thermal power units. For instance, breakthroughs in key technologies such as online measurement of carbon content and CO content of fly ash and real-time measurement of furnace temperature bring about considerable development of the intelligent combustion optimization system.

4.2Combination of Single Target Optimization with Multi-objective Optimization
When optimizing the operation with the optimization method, the optimization goal is fixed, but in the actual operation process, the optimization target changes with the running state of the unit. For example, in the optimization of boiler operation, when optimizing with optimization software, it is found that the adjustment of peroxygen is the best way to improve the operating efficiency of the boiler. The adjustment of oxygen quantity is especially effective for economic efficiency. The optimal oxygen amount is determined by ensuring that the sum of the heat loss of exhaust gas and the heat loss of incomplete combustion is minimized. Through field tests, it is found that the reduction of oxygen will increase the temperature that inside the furnace, and the coking phenomenon of the heated surface

will be significantly deteriorated, which will increase the operating cost of the soot blowing system and, more importantly, will greatly affect the operational safety of the boiler[28].

Under the current power situation that with rapid change of loads, more stricter of the grid responds to the load, and more and more deep peak shaving units, how to consider the operational safety of boilers and units into the optimization goal is an important issue.

4.3Further Research on Dynamic Optimization

Under the current situation, it retained a lot of optimization space when the load changes frequently. The current modeling research mostly focuses on steady-state modeling, and the efficiency calculation and evaluation methods are all carried out under steady-state conditions. Most of the intelligent combustion optimization products are based on static optimization, and the optimization effect is better when the unit is running stably. However, when the unit's load changes too frequently, it will not function as expected. In the face of variable coal quality and changes of loads, how to achieve intelligent combustion optimization in the dynamic adjustment process is an important direction for future research.

4.4Application of Data Mining Technology

With the development of information technology, thermal power generating units have accumulated a large amount of original operational data. Due to the huge amount of raw data, high latitude and strong coupling, it is difficult to discover and summarize the laws and knowledge contained in the data by traditional methods and means. How to use the advantages of the computer to find the knowledge and means to improve the operation from the operating data of the thermal power generating unit itself is of great practical significance and research value for improving the operating level and optimizing the combustion.

Making full use of data mining technology can effectively avoid model variability and optimization problems and computational difficulties in intelligent combustion optimization system, which is a new optimal control idea[28]. Data mining technology has made some progress in running applications and will be fully utilized in the future.

5. Conclusions

Boiler intelligent combustion optimization is a complex engineering, and related research work has been carried out in artificial intelligence modeling, algorithm optimization, data depth mining analysis, and control technology. From summarizing the research of intelligent combustion optimization technology and the research status of commercial software development, shows that the intelligent combustion optimization system can improve the economy, safety and environmental protection of thermal power plant operation and increase the automation and intelligence level of thermal power plants. It is important to standardize the operation of the operating personnel of the power plant to provide more operational convenience for production and management personnel.

At present, according to the characteristics of China's power market, it is imperative to study, develop and improve the software development of intelligent combustion optimization system that meets the actual operation of power station boilers in China. With the continuous deepening and promotion of operational optimization theory research and field practice, the intelligent combustion optimization system of thermal power plants will become the latest topic in the field of thermal power plants in the future.

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