Application Prospect of Energy Cyber-Physical Systems in Operation Optimizing of Wet Flue Gas Desulfurization

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Abstract. Limestone-gypsum WFGD is the most widely used to control SO\textsubscript{2} emission of coal-fired power plants in China. Although SO\textsubscript{2} and a variety of pollutants can be efficiently removed by WFGD. The WFGD has great potential in controlling SO\textsubscript{2} emissions and saving energy and reducing consumption due to the influence of operating conditions of coal-fired power plants after ultra-low emissions. In order to explore and analyse the feasibility of e-CPSs in operation optimizing of WFGD. The concept of e-CPSs is introduced systematically. Then the main building blocks of e-CPSs applied to WFGD are described in detail. The existing problems of WFGD are analysed. The operation optimizing method of WFGD based on e-CPSs is introduced. E-CPSs as a new more efficient and reliable intelligent control system. The prospect and benefit of its application in WFGD of coal-fired power plant are discussed in this paper.

Keywords: Wet flue gas desulfurization, SO\textsubscript{2}, Energy cyber-physical systems, Operation optimizing, Energy-saving and cost-reducing.

1. Introduction

The energy structure is dominated by coal because of the current resource situation of "rich coal, less gas and lack of oil" in China. Coal-fired power generation will still be the main source of electrical energy in the foreseeable future. Large amounts of gaseous pollutants were produced by coal combustion. So it has attracted wide publicity. The prevention and control of air pollution is of great concern to the Chinese government, and people have increasingly higher requirements for environmental quality. New technologies for controlling air pollutants have been developed rapidly [1-4].

In September 2014, ultra-low emission (ULE) of flue gas was first proposed in the field of coal power generation. By the end of 2019, about 890 million kW of coal-fired power plants had been retrofitted with ultra-low emissions of flue gas in China. SO\textsubscript{2} emission concentration was controlled below 35mg/m\textsuperscript{3} through flue gas desulfurization technology. Wet flue gas desulphurization (WFGD) based on the principle of limestone-gypsum [5], as the mainstream flue gas desulfurization technology, has a market share of more than 95% in the coal power industry (the following wet desulfurization equipment refer to limestone-gypsum wet flue gas desulfurization equipment).

In recent years, cyber-physical systems (CPS) has attracted more and more attention due to the breakthrough of "Internet Plus", Intelligent control and Big Data technology. However, the potential application of e-CPSs based on CPS in coal-fired power plants is rarely reported. As the extension end
of technology, it is rarely reported that WFGD is included into the e-CPSs for multi-dimensional research. This paper will first introduce the significance of the e-CPSs, and then introduce the research results of the possibility of using e-CPSs in the WFGD.

2. Development Status of e-CPSs
According to the definition of National Institute of Standards and Technology (NIST), CPS is an engineering interactive intelligent cyber system consisting of physical and computing components, which has the function of realizing technological progress in key fields and improving the quality of life [6]. Through the organic fusion and deep collaboration of 3C technology (Computation, Communication, Control), the physical entity was manipulated by cyber space based on CPS in a remote, reliable, real-time, secure and collaborative manner to realize the real-time perception, dynamic control and information service of large engineering system. The significance of CPS is to connect physical devices to the Internet, which enables physical devices to have five functions, including computing, communication, precise control, remote coordination and autonomy.

In 2018, Michael C. proposed the concept of e-CPSs. E-CPSs was the subsystem developed on the basis of the concept of CPS, which has the advantages of improving energy efficiency, reducing cost, flexible application and good security, etc., and the potential application value of e-CPSs was pointed out in effectively solving energy-related problems [7]. The potential application of e-CPSs in ULE coal-fired power generation was further elaborated by Zhao et, al [8].

Based on the above development status of e-CPSs, its potential application in WFGD, including e-CPSs architecture of WFGD and operation optimization method was further prospected.

3. e-CPSs Architecture for WFGD
Limestone-gypsum WFGD process was adopt by 95% of ULE coal-fired power plants, as shown in figure 1.

![Figure 1. Typical limestone-gypsum WFGD.](image)

At present, WFGD technologies based on limestone-gypsum principle include spray tower, compound tray, pH partition absorber and series absorber, etc. Among them, the technical core of compound tray desulfurization technology is to add sieve plate, tray, turbulence tube grid, poly gas ring and other key components to strengthen mass transfer on the basis of spray tower, so that the flue gas and desulfurization absorbent fully contact to improve desulfurization performance in the tower through strengthen the gas-liquid-solid three phase physical and chemical reaction, and the gas-liquid mass transfer effect. The dual circulation technology of pH value partition is characterized by installing slurry collection device between the spray layers in the absorber and connecting the circulating slurry box set independently outside the absorber through the pipeline, so as to realize the physical separation of the lower spraying first-level circulating slurry and the upper spraying second-level circulating slurry, and control the pH of the upper and lower circulating slurry separately. The pH value of the primary circulating slurry was 4.5~5.3, and that of the secondary circulating slurry was 5.8~6.2. Series absorber desulfurization technology is an extension and development of single-tower technology, and also a choice to achieve high desulfurization efficiency. Series absorber desulfurization technology is to increase the reaction time between flue gas and slurry by running two desulfurization towers in series on the flue gas channel at the same time.
SO₂ can be controlled by the new wet desulfurization process in ULE coal-fired power plants, and dust, SO₃ and other pollutants can be co-removed. However, due to changes in coal quality, working load and operating parameters, the WFGD still have great potential in effectively controlling SO₂ emissions and saving energy and reducing consumption. At the same time, due to the differences in technical route, design conditions and operation level, the technical economy of WFGD cannot be compared in multiple dimensions and a unified technical and economic benchmark can’t be formed. Therefore, from the perspective of operation optimization, the application of e-CPSs has great potential in solving the above problems.

Figure 2. The architecture of e-CPSs in WFGD [9].

The application prospect of e-CPSs in WFGD is shown in figure 2. The entire e-CPSs includes hardware subsystems, cyber systems, and specialists. They can all be connected to each other.

Hardware subsystems are an important part of the e-CPSs structure, because local embedded computing resources and standard protocol were provided on WFGD (such as flue gas, the absorber tower, oxidation wind, demister, gypsum slurry, gypsum dehydration, process water, desulfurization wastewater treatment) physical cyber connection. Improve performance, reliability, and security by interacting with software and algorithms in industrial control systems (ICSs). ICSs usually includes monitoring and data acquisition (SCADA) systems, distributed control systems (DCS), programmable logic controller (PLC), etc.

Table 1 lists the potential applications of the hardware subsystems of the e-CPSs in improving WFGD. DCS and SCADA can be used for sensors (main operating parameters such as SO₂, O₂, PM, droplet content, moisture content, temperature, pressure, flue gas flow, liquid level, pH, density, slurry supply, circulating pump current, etc.), monitors, actuators and instruments. PLCs can be applied to certain processes, such as power supply systems, WFGD additives, etc.

Table 1. The potential application of e-CPSs in WFGD [8].
Industrial Cloud and Machine Learning (ML) algorithm are the core to achieve the self-management of operation optimizing of WFGD. Massive data is stored on the industrial cloud to realize data sharing. Big data analysis technology and expert knowledge are linked through machine learning. The system can provide the foundation for the development and application of user terminals based on the next generation of artificial intelligence technologies (Big data and Human-computer interaction intelligence) new models, methods and standards, these technologies will become the user terminal equipment collector, processor and distribution related data sources. Not only in quantity, but also in speed, diversity and accuracy [10].

The data available to the e-CPSs-related ML algorithm for WFGD applications include the parameters in the main WFGD listed in table 2.

**Table 2.** The main operating parameters in WFGD.

| Project                        | Content                                                                                                                                 |
|-------------------------------|---------------------------------------------------------------------------------------------------------------------------------------|
| **Current coal-quality**      | Net calorific power, Nitrogen content, Ash content, Sulfur content, Volatiles 1) Steam flow, Pressure and Temperature, Coal consumption |
| **Host parameter**            | 2) Excess air coefficient at furnace outlet, Flow, Temperature, Pressure and Composition of flue gas 3) Flue gas temperature and pressure at the inlet/outlet of the air preheater |
| **Inlet/outlet**              | Flow, Temperature, pressure and composition of flue gas 1) Slurry circulation pump parameters: Model (flow rate, head, rated voltage, current, etc.), operating current, number of stations, power consumption, etc. 2) Slurry mixing pump parameters: Current, number of stations, power consumption |
| **Absorption system**         | 3) pH, liquid level height, density 4) Oxidation fan parameters: Power consumption, current of oxidation fan, number of running tables, valve opening, etc. |
| **Status parameter of WFGD**  | 5) Mist eliminator: Pressure, valve opening 1) limestone storage silo material level, current of Bucket elevator, current of vibrator feeder |
| **Slurry supply system**      | 2) ball grinding mill: current 3) Limestone slurry tank: Liquid level and density 4) Process water flow and valve opening |
| **Gypsum dehydration system** | 5) Limestone slurry pump: Current and number of operating stations 1) Gypsum slurry discharge pump: Current, number of running stations |

4) Operation parameters of gypsum slurry cyclone
Industrial software is the core of realizing industrial digitization and establishing information network. It is an intelligent system that links all system equipment and operating parameters together, and runs through different stages of activities throughout the life cycle [10]. In e-CPSs, the software is usually distributed across the entire computing apparatus, but as a whole which was acted for monitoring and control system of desulphurization.

In the era of rapid development of information cyber technology, information security is the core element and characteristic of e-CPSs, which must ensure the integrity and confidentiality of information in the application process. Because of the particularity of e-CPSs application scenario, security vulnerability will bring fatal harm to users. At the same time of developing the system, a comprehensive risk management framework should be established to ensure the safety of the system. The security goal of e-CPSs is to take a series of effective measures to reduce the risk of cyberattacks.

E-CPSs provides operators with new capabilities and possibilities to control the operation of WFGD through monitoring, contrast, data analysis, decision-making, operation and control mechanisms. An effective linkage ML and expert knowledge can more easily help people solve practical difficulties and problems. Therefore, the application of e-CPSs have a positive and effective effect of WFGD.

4. Wet Desulfurization Operation Optimization Method Based on e-CPSs

The coal sulfur is controlled separately, the unit participates in the depth peak regulation, the WFGD has the large margin after the transformation of ULE coal-fired power plants. The problem was caused by the extensive operation mode, such as the output reduction, increased energy consumption of WFGD, and so on. The main performance are as follows: (1) When operating at medium, low load or low sulfur content, the combined operation mode of slurry circulation pump and oxidation wind is unreasonable, leading to high power consumption of equipment and high system resistance. (2) The fluctuation of load and sulfur lead to the frequent start and stop of the slurry circulation pump, which affects the service life of the slurry circulation pump. (3) In the daily production process, the WFGD's overhaul and maintenance are not in place, which will lead to the performance degradation of the WFGD and the problems of excessive operation and higher power consumption of power-consuming equipment (slurry circulation pump, oxidation fan). (4) Unreasonable control of operating parameters of desulfurization system (such as liquid level and density) will also lead to high power consumption of slurry circulation pump and gypsum discharge pump.

In addition, the high material consumption of the WFGD is also a major problem. The main performance are as follows: (1) The consumption of limestone is caused by the poor quality of limestone. (2) The feedback of the slurry pH-slurry supply loop lags behind, causing the load and sulfur content fluctuation when the amount of slurry is higher than the design value. (3) The decrease of pulping system output results in substandard limestone sieving rate and high limestone consumption. (4) Unreasonable control of the pH value of slurry (such as series tower process I and II tower) causes CaCO$_3$ content in gypsum to be higher than the design value and increased limestone consumption. (5) Unreasonable control of the amount of flushing water of the mist eliminator, such as too high flushing frequency and high load single valve filling water, resulting in high amount of flushing water of the mist eliminator. (6) The desulfurization wastewater system can’t be put into normal operation, resulting in the deterioration of slurry quality, and thus affecting the safe operation of desulfurization.
Based on the above practical problems, the application potential of e-CPSs in the effective control of SO$_2$ emission and energy conservation and consumption reduction can be fully exploited. Under the framework of e-CPSs, in accordance with the principle of "one machine, one policy", the target is to reduce energy consumption (such as equipment power consumption, system resistance) and material consumption (absorbent, water) under the premise of standardized discharge of SO$_2$ concentration. Make full use of the industrial cloud data sharing function to obtain a large number of operation data of the same type of WFGD. Through big data analysis technology and optimization operation model, the optimal operation parameters are selected to obtain the optimal operation mode (such as number of circulating pumps, combination mode of circulating pumps, number of oxidation fans, slurry supply, slurry pH value, slurry density, etc.). Finally, the intelligent operation control of the WFGD is realized, the optimized operation of different power plants, different boilers and different WFGD is achieved, and the energy consumption and material consumption of the WFGD are reduced on the basis of standard discharge.

5. Conclusion
Since the implementation of ULE transformation in coal-fired power plants, WFGD have been widely used to control SO$_2$, providing technical methods for effective desulfurization and coordinated removal of various pollutants. However, with the emergence of various intelligent systems with hardware and software components for industrial control and Internet of Things, the potential for controlling SO$_2$ emissions and reducing energy consumption through possible application of e-CPSs is enormous. Therefore, this study introduces the concept of e-CPSs into the operation optimization of WFGD for the first time, and expounds the feasibility of this method to optimize the operation of WFGD. The main components, such as hardware components, WFGD, industrial software, industrial cloud and safety system, are summarized, and the application prospect of e-CPSs in operation optimizing of WFGD is preliminarily analyzed and demonstrated. Models for adopting this intelligent approach in real-world environments and power plants need further study.

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