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A perspective on the applications of energy-cyber-physical systems (e-CPSs) in ultra-low emission coal-fired power plants

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Abstract

To address the issue of air pollution in coal-fired power plants in China, the ultra-low emission (ULE) technology was proposed to control SO_2, NO_x and particulates, and ULE air pollution control devices have been quickly applied across the country. Although the ULE devices could work effectively for simultaneous removal of multi-pollutant, there is a great potential to efficiently control the emissions and to reduce the energy consumption by application of the energy-cyber-physical systems (e-CPSs). In order to explore the possibilities, the general conceptual overview of cyber-physical systems was first introduced, and then the feasible application in ultra-low emission coal-fired power plants were elaborated, along with an overview of major building blocks of such CPSs, including hardware components, devices for ultra-low emission air pollution control, industrial cloud, industrial software, and accompanying security systems. The perspective and benefits of application of e-CPSs in ultra-low emission coal-fired power plants were discussed, as a new modern approach for achieving more effective, efficient and reliable ULE air pollution control devices and the processes.

Keywords: Cyber-physical systems; Ultra-low emission control; e-CPS

1. Introduction

Coal was once living organisms and its formation took place over hundreds of millions of years. It is therefore referred to as a “fossil” fuel, which has been used as an alternative energy source to wood for cooking and heating since ancient times. However, it was still considered a minor resource until the industrial revolution. Since then, this fossil fuel has dominated the history of human energy utilization for more than 300 years. Over the past few decades, due to the more stringent environmental policies, the growth of global coal demand has slowed down, but it still

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increases with an average growth rate of 1.1% per annum [1]. According to the IEA's projection, the consumption of coal would still account for around one-quarter of global primary energy consumption by 2035 [2].

Generally, the coal plays a key role in electricity generation sector. Coal-fired power generation contributed to approximately 40% of electricity generation worldwide in 2012 [2, 3]. Although the combined share of power generation from carbon-free sources, such as renewables, hydro and nuclear, would increase from 32% in 2012 to 37% by 2035 (largely depending on policy-driven guidelines), the coal would still remain the largest primary energy source at the global level with only 4% annual decline [3]. Nonetheless, the coal-fired power generation in the United States will still be above 37% in the near future [4]. Since China is a coal-rich country and natural gas needs to be imported at a relatively high cost, coal-fired power plants instead of natural gas-fired power plants will continue to dominate the electricity generation in China. However, due to increasing concern about the environmental impacts of the coal utilization, the research towards clean coal technology has become increasingly important for coal-fired power plants, especially in China.

Due to the increased concern of the air quality, it has become an imperative to develop post-combustion air pollution mitigation technologies to reduce the emission of SO_2 [5-9], NO_x [10, 11], CO_2 [12-16], Hg^0 [17-22] etc. To address the air pollution environmental problem in coal-fired power plants in China, ultra-low emission (ULE) technology was proposed to control SO_2, NO_x and particulates with limits of 35 mg/Nm^3, 50 mg/Nm^3 and 10 mg/Nm^3, what are significantly lower limits than current emission standard limits of 100 mg/Nm^3, 100 mg/Nm^3 and 30 mg/Nm^3, respectively [23]. The ULE air pollution control devices have been quickly adopted in facilities in China during past five years.

Recently, technology advances and development in the fields of smart and intelligent interconnected control and monitoring systems attracted an increased general attention to cyber-physical systems (CPS) in many application areas. The application of CPSs in coal-fired power plants is particularly challenging and important as it provides new possibilities for better process monitoring and control. However, a little research on potentials of application of energy-cyber-physical systems (e-CPSs) in ultra-low emission coal-fired power plants has been conducted so far. In this paper, we shall first introduce a general overview of cyber-physical system concepts, and then we shall present the results of a research study on possibilities of using e-CPSs in ULE coal-fired power plants, encompassing the analysis of specific hardware components, ULE devices, industrial software, industrial networks, industrial cloud, intelligent services platform, and security systems.

2. General Overview of Cyber-Physical Systems

According to the National Institute of Standards and Technology (NIST), *cyber-physical systems* (CPS) are highly interconnected and integrated systems that provide new functionalities to improve the quality of life and to enable technological advances in critical areas, such as personalized health care, emergency response, traffic flow management, smart manufacturing, defense and homeland security, and energy supply and use, which are smart and intelligent systems that include engineered interacting networks of physical and computational components [24]. The definition of CPS is tightly related to some other widely adopted similar systems and concepts, such as Industrial Internet, Internet of Things (IoT), and Machine-to-Machine (M2M). There is a significant overlap between concepts of CPS and IoT and they are sometimes used interchangeably. CPSs are employed for distributed monitoring and control of physical environments through a network of sensors and actuators which collects data about environmental or process variables and provide means for closed-loop feedback control to cause changes in behaviour or state of the monitored environment. On the other hand, IoT is more focused to provide more general platform for easier networking of smart devices on the top of the existing Internet infrastructure, especially for devices with low power consumption and computational capabilities, such as battery powered sensors and similar devices[25]. CPS is more closely coupled with specific human engineered technical systems (such as plants, buildings etc.) and generally also more associated with Industry 4.0 paradigm, while IoT tends to provide similar features but with less focus on tightly coupling with a physical environment and it is more opened approach for device interoperability with external systems[25]. Both concepts are technically realized by using embedded computer systems with various resources and capabilities, depending of the intended use, where low cost, low power and real-time response are some of the most important factors for these system components. Therefore, we can say that the behaviour of CPS is a fully-integrated hybridization of computational (logical) and physical action blended into a single distributed computational system.

Dr Helen Gill presented the sub-definitions of *Cyber* (– computation, communication, and control that are discrete, logical, and switched), *Physical* (– natural and human-made systems governed by the laws of physics and operating in continuous time) and *Cyber-Physical Systems* (– systems in which the cyber and physical systems are tightly integrated at all scales and levels) [26].

Recently, Prof. Jinyue Yan proposed a concept of *Energy-cyber-physical systems* (e-CPSs), which further directs the potential application of CPSs to effectively address energy related issues [27]. The key benefits of the e-CPSs include enhanced energy efficiency and cost-effectiveness of resource management, operational agility and flexibility in dynamic environments, safety and resilience of interdependent critical infrastructures, and broadly defined human-centric services, such as comfort, privacy, health, and well-being [27].

Based on the above presented concept of e-CPSs, its potential application in ultra-low emission coal-fired power plants shall be further elaborated in this research, what will include major system components such as hardware, devices for ultra-low emission air pollution control, industrial cloud, industrial software, and security systems.

3. e-CPS Architecture for ULE in Coal-Fired Power Plants

The ultra-low emission air pollution control devices usually consist of selective catalytic reduction (SCR), electrostatic precipitators (ESP), wet flue gas desulfurization (WFGD), and wet electrostatic precipitator (WESP) as shown in the Fig. 2.

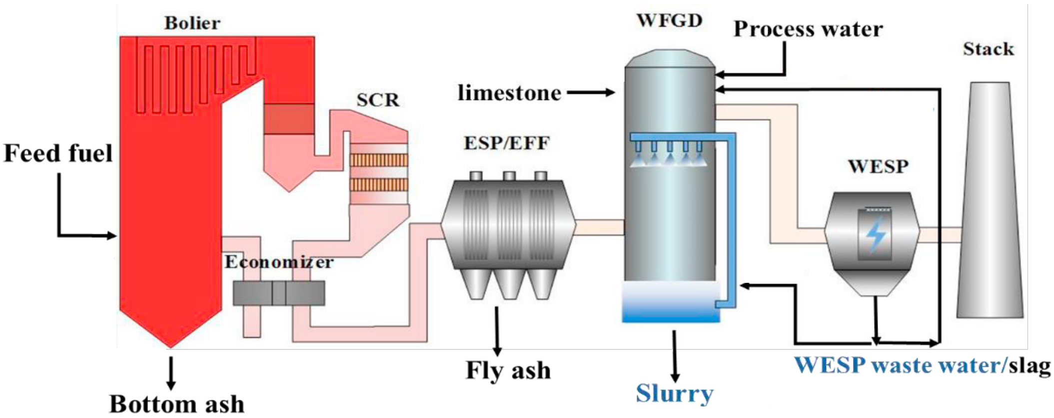

Fig. 1. The typical ultra-low emission air pollution control devices [23]

Although the air pollution control devices could work effectsively for simultaneous removal of multi-pollutant, there is a great potential to efficiently control the emissions and to reduce the energy consumption by the application of e-CPSs.

The perspective of application of the CPSs in ultra-low emission coal-fired power plants is illustrated in the Fig. 3. The overall CPS system consists of physical subsystems (hardware components), cyber system (software, cloud and security), and expert & staff members (human), which interact with each other.

Hardware components are important part of the e-CPS architecture because they provide both local embedded computational resource and physical network connection over standardized protocols for ultra-low emission air pollution control devices (e.g. SCR, ESP, WFGD and WESP), in order to improve their performance, reliability, and safety requirements through interaction with software and algorithms implemented in Industrial Control Systems (ICSs). ICSs typically include Supervisory Control and Data Acquisition (SCADA) systems, Distributed Control Systems (DCS), and other control system components, such as Programmable Logic Controllers (PLCs). ICSs are start and end points of a closed-loop data flow in a distributed intelligent control system, which processes data obtained from sensors, measurement instrumentation, and data acquisition systems via communication media in a real-time by means of digital signal and information processing algorithms, and provides services for automatic control of supervised system, and storage, analysis, post-processing and mining of acquired data.

The potential applications of hardware components within the concept of e-CPSs to improve ultra-low emission coal-fired power plants are listed in the Table 1. DCS and SCADA could be applied for sensors (for major pollutants such as NO_x, NH_3, SO_x and PM), monitors (for the air pollution control devices, such as SCR, ESP, WFGD and WESP), and actuators and meters (for controlling the air flow and additives). PLCs could be applied in some specific processes, such as NH_3 injection, ash removing device for SCR catalyst, power supply, and control for ESP and WESP, additives for WFGD and WESP.Cloud services for massive data storage and machine learning (ML) algorithms are the key elements to achieve self-improving knowledge base for ultra-low emission air pollution control. Machine learning approach provides a mechanism for connecting expert human knowledge with patterns recognized from the big data analysis by using supervised and unsupervised learning algorithms. Such system can provide a basis for development of new models, methods and standards for CSPs in ULE applications based on next generation AI technologies (big data intelligence and human-machine hybrid intelligence) on the devices that will be a major source, collector, processor and distributer of relevant data, not only in volume, but also in speed, variety and veracity [28]. The data that could be used by ML algorithms relevant to CSPs in ULE applications include NO_x concentration, NH_3 consumption, NH_3 leakage, SCR catalyst performance, PM concentration, electrode power supply, ESP performance, SO_x concentration, desulfurizer consumption, WFGD performance, water consumption, and WESP performance for the major ultra-low emission air pollution control devices, as listed in Table 2.Industrial software serves as a core for realization of industrial digital, networked, and intelligent system which links together all previously mentioned system parts and concepts and also different phases of the whole life-cycle activity, such as research, development, production, management, service, and disposal [28]. The software components are distributed throughout all levels of computational devices, ranging from low intensive smart sensor nodes and actuators, to more complex embedded real-time monitoring and controls systems, routers, PLCs, up to dedicated servers and cloud infrastructure for large-scale data collection, storage, and processing. In CSPs the software is typically distributed across the whole spectrum of computational devices, but as a whole it acts as an "environmental island" monitoring and control system, in a sense that the software is focused on particularly engineered technical system (such as plant), without a goal to provide maximum interoperability and connection with unrelated resources outside of the context of the monitored facility. The essential practical requirement for e-CPS is to create a system with state awareness, real-time analysis capabilities, scientifically based decisions upon expert and machine intelligence knowledge, and precise timely execution of the required actions.

Security is very important aspect and necessary feature of the CPS architecture that must ensure that the information used, processed, stored, and transferred by CPS has its integrity preserved and is kept confidential when needed. Data confidentiality, integrity, authentication, availability and freshness are only some of the key features that are often met in CPS applications[29]. Since the CPSs are naturally used in highly critical systems (such as power plants, industrial facilities etc.), the security breaches not only increase the severity of negative consequences, but also introduce additional types of vulnerabilities that are not encountered in other types of computer systems. Security has a comprehensive risk management framework, but in the simplest form the risk could be modeled as the product of expected threats, known system vulnerabilities, and resulting impacts, as shown by the following equation [30].

Risk = [Threat] x [Vulnerability] x [Impact]

Hence, the goal of security in CPS is to decrease the risk by minimizing the threats, dealing with system vulnerabilities, and acting upon possible negative impacts what will directly reduce the risk resulting from the successfully executed cyber attack.

The e-CPS provides human operators with new capabilities and possibilities for control of the ultra-low emission air pollution control devices and processes through sensing, observation, data analysis, decision-making, operation and control mechanisms. On the top of the system lays a machine intelligence learning and cognition, combined with human expert knowledge, what is the most important value-added element of e-CPS that can help to solve practical difficulties and problems more easily. Therefore, the application of e-CPSs could have a positive effect on the ultra-low emission coal-fired power plants with effective, efficient and reliable devices and processes.

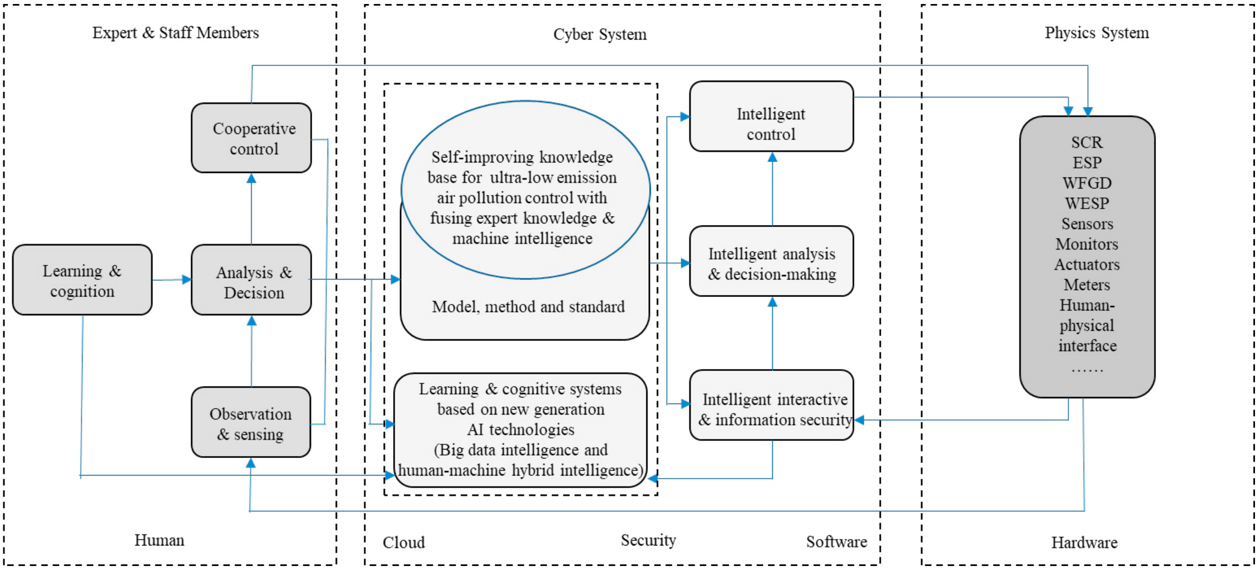

Fig. 2. The architecture of the cyber-physical systems (CPSs) in ultra-low emission coal-fired power plants [31]

Table 1. The potential application of the energy-cyber-physical systems (e-CPSs) in ultra-low emission coal-fired power plants

e-CPS	SCR	ESP	WFGD	WESP
Hardware	DCS and SCADA: Sensors for NO_x and NH_3, Actuators and meters for NH_3, Monitors for SCR catalyst. PLC: NH_3 injection, Ash removing for SCR catalyst.	DCS and SCADA: Sensors for PM. Monitors PLC: Power supply and control.	DCS and SCADA: Sensors for SO_x, Monitors PLC: Desulfurizer	DCS and SCADA: Sensors for PM. Monitors PLC: Power supply and control, water injection.
Cloud and Big Data	NO_x concentration, NH_3 consumption, NH_3 leakage, SCR catalyst performance.	PM concentration, electrode power supply, ESP performance.	SO_x concentration, Desulfurizer consumption, WFGD performance.	PM concentration, electrode power supply, Water consumption, WESP performance.
Industrial software	Software for 'environmental island' monitoring and control system			
Security systems	Protection of the information used, processed, stored and transferred in CPS from the cyber attack			
Effects of the applications	NO_x:> 50 mg/Nm^3 NH_3: no escape Catalyst: life-extending	PM: >30 mg/Nm^3 energy conservation	SO_2: >35 mg/Nm^3 Wastewater zero discharging	PM: >30 mg/Nm^3 energy and water conservations
	Effective, efficient and reliable ultra-low emission coal-fired power plants			

4. Conclusion

During past five years ULE air pollution control devices have been developed and quickly applied to control SO_2, NO_x and particulates at coal-fired power plants in China, what provided technical means for effective simultaneous removal of multi-pollutants. However, accompanied by the emergence of wide assortment of smart and intelligent systems with computational hardware and software components for industrial control and IoT, there is a great potential to efficiently control the emissions and reduce the energy consumption by the possible application of energy-cyber-physical systems (e-CPSs) in ULE air pollution control devices. Hence, the general overview of cyber-physical systems (CPSs) was first discussed in this research to justify why such approach could be beneficial for ULE power plants. Based on the concept of e-CPSs, the feasible application in ultra-low emission coal-fired power plants was elaborated with an overview of major building blocks, such as hardware components, devices for ultra-low emission air pollution control, industrial software, industrial cloud, and security systems. The perspective of using the CPSs in ultra-low emission coal-fired power plants was analysed and justified by illustrating how such systems can lead to effective, efficient and reliable ULE air pollution control devices and the processes, what is essential for the creation of the future ULE smart coal-fired power plants. Further research in this area is needed for such an approach could be adopted by adopting this intelligent approach in realistic environment and power plants.

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