Study and Application on Evaluation Methods of Air Pollution Control Technologies

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Abstract. At present, a complete evaluation system of air pollution control technologies (APCTs) in China has not been established. Evaluation system of China is relatively simple, and the understandings of evaluation rules are various. It has not yet formed a systematic, scientific, comprehensive and approved by authoritative departments of standard evaluation method for APCTs. Based on the comparative study of foreign environmental technology evaluation system, the method of air pollution control technology evaluation (APCTE) was put forward. Furthermore, the coal-fired boiler ultra-low emission technology was used as an example of application, and its applicability and environmental effects were tested and analyzed.

1. Introduction
In recent years, the overall deterioration trend of air quality in China is obvious and extreme air pollution incidents have occurred frequently, which is particularly significant in the Beijing-Tianjin-Hebei, Pearl River Delta, Yangtze River Delta and other urban economic belts. At present, atmospheric pollutants mainly include particulate matter (PM), sulfur dioxide (SO₂), nitrogen oxides (NOx) and volatile organic compounds (VOCs). Technology emission reduction has always been the focus of attention, but the choices of different industry control technologies perplex technology users[1]. Therefore, scientific and reasonable evaluation of the performance of air pollution control technologies (APCTs) is essential for the efficient and economical prevention and control of atmospheric pollution.

Air pollution control technology evaluation (APCTE) is an application branch of technology evaluation. Technology evaluation refers to the process of comprehensive and systematic analysis of technology, and making reasonable choices of atmospheric pollutant control technology. Developed countries and regions have conducted comprehensive and systematic research on APCTE, forming the best available control technology (BACT)[2], the Environmental Technology Verification (ETV)[3], and the best available technology (BAT)[4] and other complete evaluation systems. However, the basic information and data which these evaluation methods were based on are complex and difficult to be popularized and applied in China. The domestic study of APCTE was mainly focused on the desulfurization and denitrification of thermal power plants[5-8]. The evaluation results of different literatures were quite different. At present, China's APCTE system is relatively simple, and there are different understandings of the evaluation rules. A systematic, scientific, comprehensive and standard evaluation method for APCTs approved by authoritative departments has not yet been formed.
This study summarized the environmental technology evaluation system of developed countries, summarized and analyzed the commonly used technical evaluation methods, and took the ultra-low emission technology of coal-fired industrial boilers as an example to carry out the technology evaluation, aimed at providing technical guidance for the evaluation and selection of APCTs.

2. The development of technology evaluation

2.1. Technology evaluation in developed countries

Environmental technology evaluation has shown a trend of systematization, institutionalization and regularization in developed countries such as Europe and the United States. A relatively complete evaluation procedure and evaluation method of Environmental technology evaluation have been formed, and the status and role of Environmental technology evaluation in the decision-making process have been determined in the form of regulations[9].

2.1.1. Canada. Canada began to carry out environmental technology evaluation in since 1997 and was led by the Canadian Federal Ministry of the Environment and Industry, and the main implementation was carried out by the Canadian Environmental Technology Promotion Centre, which was a social organization and has certified 39 technologies or products until now. References Environmental technology verification system (ETV) implemented in Canada [10-14] can quantitatively analyze the true level of new and improved environmental technologies, thereby improving the credibility and market competitiveness of the technology and ensuring the effectiveness and speed of reliable environmental protection technology entering the market. So that users, developers, regulators and others can make informed choices about purchasing, applying and managing innovative technologies. Furthermore, ensure the effectiveness and reliability of environmental performance through independent test data and information support, establish the reputation of technology suppliers and the confidence of buyers.

2.1.2. The United States. In 1993, the United States regulated the performance evaluation activities of government departments in the form of legislation, requiring all federal agencies, including government-funded scientific institutions and scientific and technological activities, to use performance evaluation techniques and inform the public about their performance respectively. The US science and technology evaluation has been institutionalized and regularized, and the establishment of scientific and technological evaluation organizations was relatively sound. The evaluation agencies of government and society, federal and local region coexisted. The level of science and technology evaluation institutions in the United States was divided into three categories: congress and federal government science and technology evaluation institutions, state government science and technology evaluation institutions, and science and technology evaluation institutions of large universities and research institutes[15-19]. In practical work, the evaluation of science and technology in various fields and types was widely carried out, but there were few evaluation activities directly hosted by federal or state agencies in the United States. Generally, the government entrusted a large number of high-level and relatively stable social consulting and evaluation institutions, including enterprises and non-profit organizations, to undertake specific evaluation activities. The separation of the investor and the appraiser ensured the fairness and impartiality of the appraisal activities.

2.1.3. The Unite Kingdom. The evaluation of science and technology has been taken as an indispensable part of the macro-management of science and technology including the formulation and implementation of science and technology plans in UK. The evaluation of science and technology was mainly conducted to evaluate the effect of science and technology plans or projects, especially national plans, important schools and institutions and key projects related to national economy and people's livelihood. In terms of evaluation institutions, they can be generally divided into three categories: science and technology evaluation institutions set up by the government, research
institutions and science and technology intermediary institutions (professional science and technology evaluation companies). In the 1980s, the technology evaluation in UK gradually socialized. A batch of independent science and technology intermediary institutions emerged. Science and technology intermediary institutions were divided into two categories: public welfare and profitability institutions, among which profit-making institutions were the main body. Intermediary evaluation institutions employed experts in this field to form an evaluation team by way of contract entrustment to make evaluation on the projects. The entrusting parties were generally government agencies, institutes, colleges and universities, etc. They decided whether to grant funds to the applicants according to the evaluation results of the evaluating companies.

2.1.4. Japan. The science and technology evaluation in Japan can be traced back to the science and technology review council system in the 1940s, that deliberated major strategic and decision-making issues in science and technology. Subsequently, the technology evaluation system and support system were gradually established until the basic law on science and technology promulgated by the Japanese government in 1995, which clarified the status of science and technology evaluation. In August 1997, the Japanese cabinet approved the implementation of the guidelines for the outline of national research and development implementation measures, and in November 2001, the revised evaluation guidelines were approved. In order to highlight the importance of evaluation, one of the five "special investigation committees" set up by the Japanese government at the beginning of the comprehensive science and technology conference was "special investigation committee for evaluation", whose responsibility was to implement effective allocation of R&D resources of the Japanese government, formulate evaluation criteria for science and technology, and carry out evaluation on important R&D activities. The establishment and improvement of evaluation system of science and technology activities in Japan and the rational use of the evaluation results have played an important role in promoting the allocation of scientific research resources, the formulation of scientific and technological policies, the reform of scientific research institutions and the reform of personnel system in Japan.

2.2. Technology evaluation in China
The law of the People's Republic of China on scientific and technological progress was the first basic law on science and technology in China and has promoted the all-round development of science and technology in China. In order to improve and perfect the evaluation system of science and technology, the ministry of science and technology issued the decision on improving the evaluation work of science and technology and the evaluation method of science and technology, and put forward clear requirements on the evaluation methods and evaluation activities. These two documents mainly solved the government management, science and technology projects, or funded research project, research institutions and personnel evaluation. The issue of these two documents marked the transformation that the organization and implementation of science and technology evaluation activities conducted by government departments was changed to commissioned by governments and carried out by third party institutions. The evaluation activity of science and technology in our country has entered into the phase of comprehensive evaluation, and evaluation methods increasingly diversified. Since then, the socialization and marketization of science and technology evaluation activities in China have been accelerated, and various evaluation models and methods have been continuously developed and improved, which was an important milestone in the development of science and technology evaluation in China.

3. The technology evaluation system in China
In China, "science and technology" is referred to as "scientific research" and "research and development". Similarly, in terms of the evaluation system of science and technology, "technology evaluation" is regarded as an organic part of the evaluation system of science and technology, without emphasizing that technology evaluation is an independent system and unique connotation. The
purpose and outcomes of science and technology evaluation are mainly used to science and technology management and the development and application of scientific and technological achievements. In China, the classification of scientific and technological evaluation activities is usually based on the evaluation objects and considering the evaluation stage. The science and technology evaluation activities are divided into research and development (R&D) evaluation and science and technology achievements evaluation.

3.1. Research and development evaluation (R&D)
Research and development evaluation activities are divided into four categories according to evaluation objects, including science and technology plans, science and technology projects, research and development institutions and personnel evaluation. In terms of time stage, it includes national or local science and technology development plans and policy plans within a certain period, as well as evaluation of all stages from project initiation and mid-term to acceptance of science and technology projects, as well as late-stage performance evaluation of plans and projects when necessary. Among them, science and technology projects refer to the research and development activities carried out by researchers from universities, research institutions and enterprises aiming at specific scientific and technological issues in accordance with national or local science and technology plans, and plans funded by central or local finance. Science and technology projects can be divided into strategic and free exploratory basic research projects, application research projects, science and technology industrialization projects, social welfare research projects, science and technology condition construction and support service projects.

3.2. Scientific and technological achievements evaluation
The evaluation of science and technology achievements can be regarded as the evaluation of the results of research and development activities, or the performance evaluation before the science and technology achievements into application and market. The main evaluation objects of science and technology achievements include basic research achievements, applied technical achievements and soft science research achievements.

4. Research on evaluation method of air pollution control technology
Based on the characteristics and needs of technology evaluation, there are five categories of evaluation method that can be used for APCTE, including peer review method, multi-index comprehensive evaluation method, comparative method, economic analysis, forecast method.

4.1. Peer review method
Peer review method is an evaluation method that takes experts’ experience and knowledge as the main evaluation basis to evaluate the objects. The experts generally have extensive experience in that field of evaluated technologies and can make decisions based on their experience. The application scope of Peer review method is extensive and it has been the most basic evaluation method among evaluation methods. The peer review method can be adopted according to actual needs for expert consultation and can be applied in evaluation scheme formulation, organizational work, evaluation methods, etc.

4.2. Multi-index comprehensive evaluation method
Multi-index comprehensive evaluation method is a kind of evaluation method that, after determining the evaluation objectives, build the evaluation index system, calculate or give the index weight according to the evaluation requirements and technological characteristics, and then calculate the evaluation outcomes through the comprehensive evaluation method or formula. It is a relatively mature evaluation method and is widely used. Common multi-index comprehensive evaluation methods include analytic hierarchy process, fuzzy comprehensive evaluation method, grey system comprehensive evaluation method and attribute hierarchical model method.
4.3. **Comparative research method**

Comparative research (one of the typical methods is case retrospective analysis method) is one of the basic methods of science and technology evaluation. It is a process of comparing and analyzing the evaluated objects to clarify the internal and external factors of various phenomena. It is generally used in the performance and impact evaluation of scientific plans, projects and achievements. Its evaluation purpose is similar to the comprehensive analysis and research of air pollution control technology.

4.4. **Economic analysis**

Economic analysis can be used for the operating and investment expenses evaluation of APCT. Generally, the economic factor needs to be considered in the technology scheme comparison and selection. It is difficult to promote technologies with high technology costs in the market, and even if the governance effect is better, the technology demanders will be deterred by such high costs.

4.5. **Scenario analysis method**

Scenario analysis application of informative technology is the key to the performance data and application status data, master enough to support the trend for the future of information, such as: the forecast of economic development, industry development forecast, industrial emissions reduction targets, etc. It is necessary to gather excellent experts in various fields such as industry, technology, economy, management, and social development to make reasonable predictions on the future application of technology. Only in this way we can get more reliable analysis results. Scenario analysis method has high costs and high-quality requirements for evaluation data. Therefore, it is mainly used in macro decision analysis and generally used in screening technologies. Scenario analysis method is more suitable for the comprehensive screening and evaluation of multiple technologies with multiple indicators.

4.6. **Comparison of evaluation methods and applicability**

Evaluation methods have applicable field and relative limitation. Therefore, in the specific work of APCTE, it is necessary to consider the cooperation and application of various evaluation methods according to the requirements and objectives, so as to improve the accuracy and credibility of the evaluation, reduce the cost and optimize the evaluation process on the premise of ensuring the quality of the evaluation. Table 1. is the comparison table of five common evaluation methods.

| Method                        | Advantage                                                                 | Disadvantage                                                                 | Cost       | Range of application                                                                                                                                 |
|-------------------------------|--------------------------------------------------------------------------|-----------------------------------------------------------------------------|------------|--------------------------------------------------------------------------------------------------------------------------------------------------|
| Peer review method            | Wide application scenarios, easy to organize and implement, short evaluation cycle. | Highly subjective and influenced by the expertise level of experts.          | Low        | As the core method of expert evaluation and peer selection evaluation, it plays an auxiliary role in other evaluation models of air pollution prevention and control technology. |
| Multi-index comprehensive evaluation method | Suitable for complex problems, practical; Combining qualitative and quantitative indexes, the evaluation structure is reasonable and the subjective influence of experts is low. The evaluation method was determined and the conclusion is highly repeatable. | There are many kinds of evaluation methods, and the physical meaning of evaluation index is sometimes unclear. The construction of evaluation method and the calculation work of evaluation process are large; Vulnerable to data. | Lower      | Peer evaluation (expert meeting), comprehensive evaluation model, peer screening evaluation model, multi-index comprehensive screening evaluation model. |
| Method                          | Implementation                                                                 | Workload of Data Collection | Uncertainty | Application |
|--------------------------------|--------------------------------------------------------------------------------|------------------------------|-------------|-------------|
| Comparative research method    | The implementation method is simple and easy.                                  | The workload of data collection is large and the uncertainty is high.   |             | It can be applied to all kinds of evaluation process and provide ideas for technical evaluation. |
| Economic analysis method       | The economy of technology or comprehensive benefits can be judged quantitatively. | The data demand is many, the evaluation model is complex, the environmental benefit, the social benefit is difficult to quantify. | High        | It is mainly used for multi-index comprehensive screening evaluation model and single technology comprehensive evaluation model. |
| Scenario prediction method     | Multi-index comprehensive screening evaluation model, and mainly used for macro technical decision-making. The prospect of technical solutions can be judged. | The comprehensive quality of experts and the degree of data collection are required, and the workload of the evaluation process is large. | High        | Multi-index comprehensive screening evaluation model, and mainly used for macro technical decision-making. |

5. The application of air pollution control technology

In order to better improve the applicability and accuracy of air pollution control evaluation methods, in this study, the peer review method was applied to evaluate the ultra-low emission technology (SNCR + bag + limestone gypsum wet method + wet electricity) of flue gas applied in a 3×75t/h circulating fluidized bed boiler of an enterprise in Shandong province. The pollutants emission level index was verified by field testing and data analysis.

5.1. Evaluation content

To evaluate the emission reduction effect of ultra-low emission technology of flue gas adopted by the enterprise on PM, NOx, SO2, mercury and their compounds, and whether it can meet the special emission limit requirements of air pollutants in “Emission standard of air pollutants for boiler GB13271-2014”. The total sampling time was 14 days, divided into 2 cycles, and each cycle lasted 7 days. During the sampling and testing, the components of coal powder and limestone were kept stable. Five load tests were conducted every day, and one set of valid data was collected for each load, then 70 sets of valid data was obtained. The testing flue gas parameters included flue gas temperature, pressure, flow rate, oxygen content, moisture content, etc. Combined with the field test conditions of ultra-low emission technology for coal-fired industrial boilers, two sampling sections were selected. The sampling section 1 was located in front of the dedusting device and the sampling section 2 was located on the exhaust chimney behind the wet electric dedusting device. The sampling section location met the requirements of “Technical specification for emission monitoring of stationary source HJ/T 397-2007” fixed source exhaust gas monitoring”. The sampling section diagram is shown in Figure 1.
During the sampling period, the system ran smoothly without any failure affecting the normal operation of the process. Through the analysis of spot testing data, it can be seen that the particles and SO\textsubscript{2} removal efficiency of the plant’s operation technology (SNCR+ cloth bag + limestone gypsum wet method + wet electricity) was more than 99%, and the pollutant emission concentration was lower than the standard limit, which indicated that the ultra-low emission technology had a great removal effect on four kinds of pollutants. The test results are shown in Table 2.

### Table 2. Test data of ultra-low emission pollutants from coal-fired industrial boilers

| No. | Pollutant               | Inlet concentration (mg/m\textsuperscript{3}) | Exit concentration (mg/m\textsuperscript{3}) | Standard limit (mg/m\textsuperscript{3}) |
|-----|------------------------|-----------------------------------------------|---------------------------------------------|-----------------------------------------|
| 1   | PM                     | 7721                                          | 3.8                                         | 30                                      |
| 2   | SO\textsubscript{2}     | 253                                           | 1                                           | 200                                     |
| 3   | NO\textsubscript{x}     | 84                                            | 50                                          | 200                                     |
| 4   | Mercury and its compounds | 0.022                                        | 0.002                                      | 0.05                                    |

5.2. Evaluation method

Peer review is an evaluation method based on the subjective judgment of evaluation experts. It has the most extensive application scope and is the most basic evaluation method among many evaluation methods. The peer review method in this study was applied to single technology evaluation and multiple technology evaluation models.

5.2.1. Single evaluation. The single evaluation was the evaluation of the first level single index, which was calculated according to the following formula.

\[
P_i = \frac{X_i}{X_{i0}} \times 100 \tag{1}
\]

- \(P_i\) —— The relative scoring rate of a single item, expressed as a percentage (%);
- \(X_i\) —— The actual score of each item;
- \(X_{i0}\) —— Single standard points.

5.2.2. Comprehensive evaluation. The comprehensive evaluation was calculated according to the following formula.

\[
P = \sum \frac{X_i}{X_{0i}} \times 100 \tag{2}
\]

- \(P\) —— Combined relative scoring rate in percentage (%);
- \(X_{0i}\) —— Total standard score (100).

The comprehensive evaluation results were divided into four grades: "key recommendation", "recommendation", "alternative" and "unsuccessful". When the relative score of a single item...
cannot meet the requirements of grade setting, the comprehensive evaluation should be reduced to one level.

| Evaluation result | Combined relative scoring rate | Individual relative scoring rate |
|-------------------|--------------------------------|---------------------------------|
| Key               | ≥90%                           | ≥70%                            |
| Recommendation    | 75%≤P<90%                      | ≥60%                            |
| Alternative       | 60%≤P<75%                      | —                               |
| Unsuccessful      | 60%<                           | —                               |

5.3. Evaluation results
Based on the peer review method, the single relative scoring rate was used to evaluate. The combined relative scoring rate of the ultra-low emission technology of coal-fired industrial boilers was 92%, and the evaluation result was “recommendation”.

6. CONCLUSIONS
The development experience of environmental technology evaluation system in developed countries has been analyzed and the commonly used technology evaluation methods have also been summarized and compared in this study. In China, the commonly used technology evaluation methods include peer review method, multi-index comprehensive evaluation method, comparative research method, economic analysis method and scenario prediction method. We took the ultra-low emission technology of coal-fired industrial boilers as an example to conduct technology evaluation based on peer review method. The evaluation result was “recommendation”.

The evaluation method system complements the lack of environmental technology evaluation in the field of APCTs in China and improves the efficiency of market transformation and popularization of practical new technologies. Since the time of science and technology evaluation in China is not long, the system of science and technology evaluation is still in the process of continuous improvement and perfection. Therefore, we should actively carry out air pollution prevention and control technology evaluation practice, promote scientific and technological achievements with industrial needs, and mobilize social resources to promote the transformation of scientific and technological achievements.

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