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Research Methods and Progress in Estimating the Source Strength of Atmospheric Unorganized Emissions

HongLi Cui
College of Resource and Environment, Henan Polytechnic University, Jiaozuo 454003, China

ABSTRACT: With the rapid development of industrialization and urbanization, the situation of air pollution has become increasingly severe. Unorganized emissions of volatile organic compounds (VOCs) have become a key challenge in air pollution control. Accurate estimation of their emission source strength is crucial for formulating scientific and effective pollution control strategies and improving air quality. This paper systematically reviews the current mainstream methods for estimating the source strength of unorganized emissions in the atmosphere, analyzes the principles, advantages, disadvantages, and applicable scenarios of each method in detail, and elaborates on their application through practical cases. At the same time, it looks forward to future development trends, providing a strong reference for air pollution prevention and control work.

KEYWORDS: Atmospheric unorganized emissions; Source strength estimation; VOCs; Material balance

I. INTRODUCTION

In today's society, the acceleration of industrialization and urbanization has driven rapid economic development while also bringing a series of severe environmental problems, among which air pollution is particularly prominent. Volatile organic compounds (VOCs), as important precursors of air pollution, contribute to the formation of secondary organic aerosols and are major contributors to PM2.5[1]. They are widely present in the production processes of many industries, such as chemical, coating, and printing. Their unorganized emissions are characterized by dispersed emission points, inconspicuous emission processes, and no restrictions from fixed emission ducts. For example, in chemical enterprises, the leakage of materials during storage in tanks and transportation through pipelines, as well as the incomplete collection of exhaust gases in coating workshops, all fall into the category of unorganized emissions. These characteristics make the monitoring and control of unorganized emissions extremely challenging. Accurate estimation of their emission source strengths is a core task for precise air pollution control and public health protection, and it is of great significance for environmental management and sustainable development [2]. Most VOCs and their photochemical products are toxic and harmful substances that can directly affect human health [3].

Over the years, numerous researchers both domestically and internationally have conducted extensive studies on the estimation methods for unorganized emission source strengths, achieving fruitful results. This paper will provide a comprehensive review of these methods, conduct an in-depth analysis of their advantages and disadvantages, and offer prospects for future research directions, in the hope of providing scientific guidance for the practice of air pollution control.

2. METHODS FOR ESTIMATING THE SOURCE STRENGTH OF ATMOSPHERIC UNORGANIZED EMISSIONS

2.1 Material Balance Method

The material balance method is a classic estimation method based on the law of conservation of mass and is widely used in the field of estimating the source strength of unorganized emissions. Specifically, it states that the total mass of materials entering a system within a unit of time must equal the total mass of materials leaving the system, plus the mass of materials lost and accumulated [4]. When estimating the source strength of unorganized emissions, it is necessary to conduct an in-depth analysis of the production process and accurately sort out the input, output, and transformation relationships of materials in each link, thereby calculating the source strength of unorganized emissions.

Take the production of a certain product by a fine chemical enterprise as an example. The production process of this product involves the reaction of various raw materials. By keeping detailed records of the input quantities of each raw material and precisely analyzing the content of each element in the product and by-products, as well as the amount of recycled materials, a material balance equation can be established based on the law of conservation of mass. Through rigorous calculations, the unorganized emission volume of specific VOCs in the production process was successfully estimated, providing key data support for the company's subsequent pollution control efforts.

The advantages of the material balance method are quite evident. It can estimate the VOCs generation source strength for different processes and sections separately, with relatively precise results. At the same time, through the material balance process, the flow path of materials in the production process can be clearly presented, which facilitates companies in quickly locating potential unorganized emission sources and taking targeted prevention and control measures. However, the method also has certain limitations. On the one hand, it requires a high degree of understanding of the production process and the composition of raw and auxiliary materials, necessitating precise knowledge of various process parameters and detailed composition data of raw and auxiliary materials. In actual production, some companies may have incomplete or inaccurate production records, and the quality of raw and auxiliary materials may also fluctuate, all of which can affect the accuracy of the data. On the other hand, for some complex production processes involving multiple-step reactions and interactions among various materials, the calculation process of material balance can become extremely complicated. Not only does it require a large amount of data support, but it may also involve complex stoichiometric calculations, increasing the difficulty and workload of the estimation.

The material balance method is suitable for projects with clear production processes, well-defined raw and auxiliary material compositions, and detailed process parameters. In the environmental impact assessment reports of new or expanded projects where the process is highly similar to existing projects, the material balance method is often an important means of estimating VOCs. In practical applications, combining material balance diagrams for auxiliary calculations can make the calculation process more intuitive and clear, reducing the occurrence of errors.

2.2 Emission Factor Method Based on Raw and Auxiliary Materials

The emission factor method based on raw and auxiliary materials is a widely used estimation method in practical applications. Its basic principle is to estimate the amount of pollutants generated based on the usage of raw and auxiliary materials and the corresponding emission factors. An emission factor represents the amount of pollutants produced per unit of raw or auxiliary material used under specific technological, economic, and management conditions. The unorganized emission volume is determined based on the emission factors of relevant industries and projects [5].

During the environmental impact assessment (EIA) process of a furniture manufacturing enterprise, its production process is relatively fixed, with the main raw and auxiliary materials being various types of panels and paints. By consulting relevant literature, the VOCs emission factors corresponding to the unit area of panels and the unit mass of paint were obtained. Combining this with the planned usage of panels and paint by the enterprise, the source strength of VOCs generated in the production process was easily calculated, providing key data for the EIA work.

The advantage of this method is its simplicity and convenience. As long as the usage of raw and auxiliary materials and the corresponding emission factors can be obtained, the source strength of VOCs can be quickly calculated. In small enterprises or projects with relatively simple processes, where detailed production process data are lacking, the advantages of this method are particularly prominent. However, this method also has obvious shortcomings. Currently, VOCs emission factors have not yet covered all raw and auxiliary materials in various industries. For those raw and auxiliary materials without clear emission factors, this method cannot be used for calculation. Moreover, the selection of emission factors is influenced by various factors, such as differences in production processes, types of equipment, and levels of management. Under different conditions, emission factors may vary significantly. If the selected emission factor does not match the actual situation, it will lead to deviations in the estimation results.

This method is suitable for the estimation of VOCs in the EIA reports of construction projects where the specific parameters of processes and raw materials are not clear. In practical applications, it is essential to carefully select appropriate emission factors based on the specific industry characteristics and types of raw and auxiliary materials to improve the accuracy of the estimation.

2.3 Emission Factor Method Based on Product Output

The emission factor method based on product output is a method that estimates the amount of pollutants generated through the product output and the corresponding emission factor. Here, the emission factor refers to the amount of pollutants produced per unit of product under specific technological, economic, and management conditions [6].

A plastic products factory mainly produces plastic pipes. During the environmental impact assessment, due to the lack of detailed information on the production process and raw materials, but with relatively complete statistics on product output, the staff consulted relevant industry data to obtain the VOCs emission factor for producing a unit mass of plastic pipes. Combined with the company's annual output, they successfully estimated the amount of VOCs generated in the production process, providing an important basis for assessing the company's environmental impact.

Similar to the emission factor method based on raw and auxiliary materials, this method has the advantage of being easy to operate. As long as the product output and the corresponding emission factor are known, the source strength of VOCs can be quickly calculated. This method is widely used in industries with relatively single product types and stable production processes. However, it also faces similar challenges as the former method. The existing VOCs emission factors do not cover all products in various industries, and for products without emission factors, it is difficult to accurately calculate using this method. Moreover, the emission factors are also constrained by multiple factors such as production processes, equipment, and management, and there may be significant differences in actual emission factors among different companies.

This method is suitable for the estimation of VOCs in the EIA reports of construction projects where the specific parameters of processes and raw materials are unclear. In actual operations, it is necessary to reasonably select emission factors based on the specific industry and product type to ensure the reliability of the estimation results.

2.4 Analogy Method

The analogy method is a commonly used means for estimating pollutant source strength in environmental impact assessments. It involves using the design, data, or measured results from existing projects of the same type as the proposed project to conduct engineering analysis and determine the organized and unorganized emission volumes of the project [7]. The key to this method lies in selecting an appropriate analogy object, which should have a high degree of similarity to the target project in terms of production processes, equipment, and management levels.

In the EIA work of a newly constructed dyeing and printing factory, due to the lack of detailed production data, evaluators chose an existing dyeing and printing factory with similar geographical location, production processes, equipment, and environmental management level as the analogy object. By collecting the exhaust emission monitoring data from the analogy factory and combining it with the production scale and capacity of the new factory, the VOCs emission source strength of the new factory was reasonably estimated, providing an important reference for its environmental impact assessment.

The advantage of the analogy method is that it does not require complex calculations or a large amount of data. In the absence of detailed data, it can quickly provide a rough estimation result. It is especially applicable to new or complex processes where detailed production parameters are difficult to obtain. By analogy with similar projects, the pollution emission situation of the target project can be preliminarily understood. However, the accuracy of this method largely depends on the similarity between the analogy object and the object to be evaluated. If there are significant differences between the two, such as minor improvements in production processes or differences in equipment performance, it may lead to large deviations in the estimation results. Moreover, the analogy method usually only provides a relatively rough estimation value and cannot achieve high precision. Additionally, when selecting analogy data, attention should be paid to the timeliness of the data, with priority given to monitoring data from recent years to avoid the impact of process improvements or enhanced environmental standards on the accuracy of the estimation.

The analogy method is suitable for the estimation of exhaust pollutant source strength in new construction projects and is also applied in the estimation of noise pollution source strength and solid waste source strength. In practice, when the results of the emission factor method may be overestimated, the analogy method can serve as an effective alternative, providing more reliable basis for project EIA.

2.5 Measurement Method

The measurement method involves on-site determination of data related to the generation or emission of pollutants, thereby calculating the amount of pollutants generated or emitted per unit of time. It mainly includes automatic monitoring and manual monitoring.

A large thermal power plant, in order to accurately understand its atmospheric pollutant emissions, installed automatic monitoring equipment at the chimney outlet to continuously monitor the emission concentrations and volumes of pollutants such as sulfur dioxide, nitrogen oxides, and particulate matter. At the same time, it regularly used manual monitoring methods for comparison and calibration to ensure the accuracy of the monitoring data. The data obtained through the measurement method can truly and accurately reflect the plant's pollutant emissions, providing a reliable basis for environmental regulation by authorities and pollution control by the enterprise itself.

The greatest advantage of the measurement method is that it uses actual monitoring data for calculations, which can truly and intuitively reflect the emission situation of pollutants, with relatively accurate and reliable estimation results. In situations where the accuracy of emission data is extremely important, such as the regulation of key pollution sources and environmental protection acceptance, the measurement method is the preferred choice. However, the measurement method also has certain limitations. On the one hand, the monitoring cost is high, especially for the installation and maintenance of automatic monitoring equipment, which requires a significant investment of funds. On the other hand, this method has high professional requirements for technical personnel, who need to be specialized in monitoring operations and capable of scientifically analyzing the monitoring data. Additionally, during the monitoring period, it is necessary to synchronously record the operating conditions of the production equipment to ensure the validity and representativeness of the monitoring data.

The measurement method is suitable for existing pollution sources with effective continuous automatic monitoring data or manual sampling monitoring data, and it is also applicable for source strength estimation under abnormal emission conditions. In practical applications, the choice between automatic and manual monitoring should be based on the characteristics of the pollution source and the monitoring requirements to ensure the acquisition of accurate monitoring data.

2.6 Experimental Method

The experimental method is a calculation approach that involves conducting experiments under controlled conditions to determine the amount of pollutant emissions. It is usually carried out in a laboratory or simulated environment, where various conditions of the actual production process are replicated to study the emission of pollutants.

During the development of a new type of paint, to assess its VOCs emissions during use, researchers set up an experimental device in the laboratory to simulate a coating environment. By controlling factors such as temperature, humidity, and ventilation conditions to mimic the actual coating process, they monitored and analyzed the VOCs emissions from the paint. The experimental results provided important basis for optimizing the paint formula and evaluating its environmental performance.

The advantage of the experimental method is that experimental conditions can be precisely controlled, effectively reducing the interference of variables and thus enhancing the comparability of data. Under ideal or standardized experimental conditions, relatively accurate pollutant emission data can be obtained, which strongly supports in-depth research on the mechanisms of pollutant emissions. However, the experimental method also has some drawbacks. The costs of experimental equipment, materials, and human resources are high, and the requirements for the experimental environment and equipment are stringent. Moreover, experimental conditions often fail to fully replicate the complexities of actual production processes, such as fluctuations in operating conditions and equipment aging, which may lead to discrepancies between experimental results and real-world situations.

The experimental method is suitable for the environmental impact assessment of new technologies, processes, or products, especially when there is a lack of actual operational data. In practice, it is often used in combination with other methods (such as the measurement method and analogy method) to complement each other and provide a more comprehensive and accurate estimation of emissions.

2.7 Other Estimation Methods

2.7.1 Estimation Method Based on Emission Factors

The estimation method based on emission factors involves calculating pollutant emissions using predefined emission factors. An emission factor is the amount of pollutants generated per unit of activity level under specific conditions. The core of this method lies in the selection and determination of emission factors, which requires a comprehensive consideration of various factors such as the type of activity level, production processes, equipment types, and management levels. The U.S. Environmental Protection Agency's (EPA) AP-42 Emission Factor Manual provides extensive data support for emission estimation worldwide, covering a wide range of activity levels and production processes across numerous industries [8]. In some environmental impact assessments in China, emission factors from the AP-42 manual are referenced and adjusted to fit domestic production realities to enhance the accuracy of the estimations.

2.7.2 Estimation Method Based on Model Simulation

The estimation method based on model simulation involves using models to simulate the emission process of pollutants in order to estimate the emission volume. When selecting a model, it is necessary to consider factors such as the type of emission source, the type of pollutant, and the research purpose. The determination of model parameters is also crucial, requiring a comprehensive consideration of factors such as production processes, equipment types, management levels, and environmental conditions. The conventional ground concentration back-calculation method has certain limitations and does not take into account factors such as terrain. The concentration back-calculation method, which uses the on-site monitoring concentration contribution value of unorganized source emissions to perform concentration back-calculation, is more reliable and reasonable. Using the concentration back-calculation method in models can better simulate and estimate the source strength of pollutants[9]. By utilizing the CALPUFF model in combination with local meteorological data, topographical information, and pollution source distribution, the dispersion and transport of pollutants in the atmosphere can be simulated, thereby estimating the source strength of unorganized emissions and providing a scientific basis for urban air quality improvement plans. However, in China, the application of CALPUFF in the field of environmental impact assessment, such as data preprocessing, parameter selection, and standardized use of the model, has not been reported. There are only a few studies focusing on the comparison of results from different models [10].

2.7.3 Back-Calculation Method

The back-calculation method estimates the source strength of pollutants by using environmental monitoring data in conjunction with meteorological conditions and dispersion models. This method ingeniously leverages existing environmental monitoring data, avoiding the difficulties associated with direct measurement of source strength. In practice, atmospheric dispersion models are typically employed to perform reverse calculations to derive the source strength. However, the back-calculation method has high requirements for data quality, necessitating accurate meteorological data and appropriate dispersion models. Moreover, the calculation process is relatively complex, and the estimation results can be easily influenced by meteorological conditions and the assumptions of the dispersion model, introducing a certain degree of uncertainty.

When a city experienced abnormal air quality, the environmental protection department used data from surrounding monitoring stations, combined with real-time meteorological information provided by the meteorological department, and applied dispersion models such as AERMOD and the Gaussian dispersion model for back-calculation. In the back-calculation of source strength using the Gaussian dispersion model, concentration (C) is used as the independent variable, while the pollutant emission rate (Q) is the dependent variable [11]. This approach preliminarily identified potential unorganized emission sources and their source strengths, providing direction for subsequent pollution investigation and control efforts.

3.DEVELOPMENT TRENDS OF ESTIMATION METHODS FOR ATMOSPHERIC UNORGANIZED EMISSION SOURCE STRENGTH

3.1 Integrated Application of Multiple Methods

Single estimation methods often have limitations and cannot comprehensively and accurately reflect the true status of atmospheric unorganized emission source strength. In the future, the integrated application of multiple estimation methods will become the mainstream trend. For example, in the estimation of unorganized emission source strength in a large industrial park, the material balance method can be used first to make a preliminary estimation of the main production processes, then the emission factor method can be employed to supplement the calculations for some auxiliary production links, and finally, the estimation method based on exhaust gas collection efficiency and treatment efficiency can be used to calculate the organized emission part. By integrating the results of multiple methods, more accurate source strength data can be obtained. This integrated approach can fully leverage the advantages of each method, compensate for the shortcomings of a single method, and significantly improve the accuracy and reliability of the estimation results, providing stronger support for environmental management and pollution control in the park.

3.2 Integration of Model Simulation and Monitoring Data

Model simulation and monitoring data are important tools for estimating atmospheric unorganized emission source strength. Model simulation can comprehensively consider the impact of various factors on pollutant emissions, yielding systematic and comprehensive results. In contrast, monitoring data can truly reflect actual emission conditions and provide reliable validation and calibration for model simulation. In the future, there will be a stronger emphasis on the organic integration of model simulation and monitoring data.

With the continuous development of sensor technology and the Internet of Things (IoT), the acquisition of monitoring data will become more convenient, efficient, and have higher spatiotemporal resolution. These rich monitoring data, such as real-time pollutant concentration data from different regions and time periods, can provide more precise input parameters for model simulation. Researchers can adjust key information in the model, such as meteorological parameters and pollution source distribution, in a timely manner based on real-time monitoring data, allowing the model to better reflect actual conditions.

Real-time collection of VOCs concentration and meteorological condition data can be achieved. By inputting these data in real-time into models specifically designed for atmospheric pollution simulation, the models can more accurately simulate the diffusion pathways and concentration changes of pollutants. Comparing the simulation results with actual monitoring data can also reveal deficiencies in the model, allowing for the optimization of model parameters and algorithms, thereby continuously improving the simulation accuracy and making the source strength estimation results based on model simulation more reliable.

3.3 Refinement and Dynamism of Source Strength Estimation

As environmental management requirements continue to increase, higher precision and timeliness are demanded for the estimation of atmospheric unorganized emission source strength. Currently, VOC emission inventories are calculated on a provincial spatial scale and an annual temporal scale, which is not conducive for researchers to study VOC emission characteristics and formulate control strategies at smaller spatial scales [12]. In the future, source strength estimation will move towards refinement and dynamism.

In terms of refinement, more complex and precise estimation models will be established. These models will fully consider minor changes in the production process, such as fluctuations in equipment operating parameters and subtle differences in raw material compositions, as well as the impact of meteorological conditions and topography on pollutant emissions and dispersion. By more finely depicting the relationship between emission sources and environmental factors, high-precision estimation of atmospheric unorganized emission source strength can be achieved.

Regarding dynamism, with the help of IoT, big data, and artificial intelligence technologies, a wide-ranging and high-frequency monitoring network will be established. Real-time acquisition of information related to emission sources, such as the operating status of production equipment and real-time changes in pollutant emission concentrations, will be possible. By combining these real-time data with dynamically updated estimation models, dynamic monitoring and updating of source strength can be realized. In this way, once the conditions of an emission source change, the source strength estimation results can be adjusted in a timely manner, providing timely and accurate data support for environmental management decision-making. For example, in urban areas, grid-based monitoring technology can be used to divide the city into multiple small grids, with monitoring stations set up in each grid to continuously monitor atmospheric pollutant concentrations. At the same time, sensors installed on production equipment in enterprises can collect key data from the production process in real-time. These data can be transmitted in real-time to a big data platform, where dynamic estimation models driven by artificial intelligence algorithms can be used to continuously calculate and update the source strength of various unorganized emission sources within the city. When a sudden emission event occurs in a particular area, the system can quickly issue a warning and provide accurate source strength data for environmental protection departments to formulate emergency response plans.

4. CONCLUSIONS AND PROSPECTS

Accurately estimating the source strength of atmospheric unorganized emissions is a crucial part of air pollution control efforts and is of great significance for protecting the ecological environment and safeguarding public health. This paper has comprehensively reviewed and deeply analyzed the current mainstream methods for estimating atmospheric unorganized emission source strength, clarifying the principles, advantages and disadvantages, and applicable scenarios of each method.

It can be seen that each estimation method has its unique features and plays an important role in different application scenarios, but all have certain limitations. In the future, with the continuous progress of science and technology and the increasing demands of environmental management, the estimation methods for atmospheric unorganized emission source strength will continue to evolve towards the integrated application of multiple methods, deep integration of model simulation and monitoring data, coordinated development of source strength estimation and pollution control, and refinement and dynamism of source strength estimation.

To better achieve effective control of atmospheric unorganized emissions, researchers need to further strengthen research in related fields. On the one hand, continuous optimization of existing estimation methods is needed to improve their accuracy and reliability. On the other hand, exploration and development of new technological means and methods to meet the changing demands of environmental management are essential. At the same time, interdisciplinary cooperation should be enhanced, integrating knowledge from environmental science, mathematics, computer science, and other disciplines to improve the estimation methods and technical systems. Only in this way can we provide a more solid scientific basis for air pollution control and environmental management, helping to achieve continuous improvement of air environmental quality and sustainable development of human society.

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