A Review of Sampling Representativeness and Sampling Systems for Gaseous Effluents from Nuclear Facilities

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Abstract

Gaseous effluents discharged from nuclear facilities often contain multiple radionuclides, and monitoring their emissions is of significant importance to environmental safety and public health. To accurately assess the emission source term and its environmental impact, sampling systems must possess good representativeness. This paper systematically reviews the latest research progress on sampling representativeness and sampling systems for nuclear facility gaseous effluents. First, relevant international and domestic standards and specifications are reviewed, clarifying the basic requirements and technical specifications for sampling representativeness. Second, research findings on sampling location representativeness within stacks are summarized from both experimental and numerical simulation perspectives, with focused discussion on particle deposition, flow field distribution, and their impacts on representativeness in mixed fields of aerosols and iodine. Then, the mechanisms by which system structural optimization measures, such as sampling lines and filter assemblies, enhance representativeness are summarized. Finally, commonly used representativeness evaluation methods are introduced, including experimental validation, CFD simulation analysis, and relative deviation evaluation methods. Comprehensive studies indicate that sampling representativeness is not only affected by emission source characteristics and flow conditions, but is also closely related to sampling system design. Future research should further focus on establishing precise representativeness evaluation methods under multi-component coupled fields and strengthening the improvement of standard systems to support the scientific and standardized nature of nuclear facility emission monitoring.

Full Text

Preamble

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A Review of Research Progress on Representativeness and Sampling Systems for Gaseous Effluents from Nuclear Facilities

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Abstract

Gaseous effluents discharged from nuclear facilities often contain various radionuclides, making discharge monitoring critical for environmental safety and public health. To accurately assess the source term and its environmental impact, sampling systems must exhibit good representativeness. This paper systematically reviews recent advances in research on sampling representativeness and sampling systems for gaseous effluents from nuclear facilities. First, relevant international and domestic standards are reviewed to clarify the fundamental requirements and technical criteria for sampling representativeness. Second, both experimental and numerical studies on the representativeness of sampling locations inside emission stacks are summarized, with a focus on the effects of aerosol and iodine mixtures, particle deposition, and flow field distribution on sampling representativeness. Third, structural optimization measures for sampling systems—such as sampling lines and filtration components—are discussed in terms of their mechanisms for improving representativeness. Finally, commonly used evaluation methods are introduced, including experimental validation, CFD simulation analysis, and relative deviation assessment. The overall findings suggest that sampling representativeness is influenced not only by source characteristics and flow conditions but also by the design of the sampling system. Future research should focus on establishing accurate evaluation methods under multi-component coupled fields and enhancing the standard system to support the scientific and standardized monitoring of nuclear facility emissions.

Keywords: Gaseous effluents; Sampling representativeness; Nuclear facilities; Sampling system; CFD simulation

With the rapid development of nuclear power worldwide, the safe operation and environmental monitoring of nuclear facilities have become increasingly important. During normal operation or accident conditions, nuclear facilities discharge certain amounts of radioactive gaseous effluents into the atmosphere. These effluents typically contain multiple radioactive substances, among which aerosols (such as cesium, strontium, xenon) and gaseous iodine (such as I_2, CH_3I) are particularly critical. They not only pose potential threats to the environment and public health but also serve as important bases for environmental impact assessment, source term reconstruction, and post-accident analysis of nuclear facilities. Therefore, accurate monitoring of the radioactive activity concentrations of these gaseous effluents is crucial for environmental protection and nuclear safety. Gaseous effluents generally include both gas and solid particle phases. Solid particles exist in the form of aerosols, which are typically small in size and possess strong deposition and diffusion capabilities, making them highly susceptible to airflow, temperature, humidity, and other factors during discharge. Gaseous iodine, as a chemically reactive gas, exists in multiple forms such as elemental iodine (I_2) and methyl iodine (CH_3I), exhibiting complex chemical behavior during discharge. Different iodine species undergo adsorption, transformation, or dissolution through different pathways, resulting in significantly different migration and deposition characteristics in mixed fields of aerosols and gases. During the discharge process of gaseous effluents, the distribution of aerosol particles and gases is usually non-uniform, which may be caused by factors such as the complexity of chimney structures, variations in airflow velocity, and interactions between airflow and solid particles. Specifically, factors like airflow vortices, temperature gradients, and aerosol particle deposition effects can lead to differences in the concentration distribution of aerosols and gases in the flow field, meaning that collected gas samples may not fully represent the overall chimney emissions. Consequently, how to select a representative sampling location under these complex flow conditions has become an important research topic in gaseous effluent monitoring.

In monitoring gaseous effluents from nuclear facilities, the selection of sampling location is a key factor ensuring the representativeness and accuracy of monitoring data. Since gaseous effluents are often unevenly distributed in chimneys or exhaust ducts, traditional multi-point isokinetic sampling methods, while capable of reducing the impact of uneven airflow distribution to some extent, have certain limitations in practical applications. Particularly when monitoring solid particles like aerosols, they are often affected by particle losses within the duct, thereby reducing monitoring accuracy [1]. McFarland et al. [2] found that multi-point isokinetic sampling decreases aerosol penetration rates, leading to increased measurement errors. Therefore, international standards and research have gradually advocated for single-point sampling methods in recent years. Single-point sampling can reduce losses and errors associated with multi-point sampling through rational selection of the sampling point location. Whether single-point sampling can truly reflect the overall emission profile depends critically on whether the sampling location is situated in a region where the flow field is well-mixed and the concentrations of various radioactive substances are uniformly distributed.

In recent years, with the rapid development of Computational Fluid Dynamics (CFD) technology, numerical simulation has become an important tool for evaluating flow field uniformity in chimneys and determining appropriate sampling locations. Researchers have proposed sampling location optimization methods based on flow field uniformity criteria, using CFD simulations and experimental validation to identify ideal single-point sampling locations. Through CFD models, researchers can accurately predict fluid velocity, swirl angle, gas concentration, and aerosol particle concentration within chimneys, providing theoretical bases for sampling point placement. Meanwhile, experimental validation methods provide indispensable support for this field. Combining simulation and experimental data can effectively verify the representativeness of sampling locations and ensure the accuracy of monitoring results.

Currently, multiple international standards have been established to regulate the representativeness of gaseous emission sampling from nuclear facilities. For example, the U.S. national standard ANSI/HPS N13.1-1969 "Guide to Sampling Airborne Radioactive Materials in Nuclear Facilities" [3] and the international standard ISO 2889:1975 [4] both provide criteria for sampling point selection, covering parameters such as gas and aerosol concentration distribution, airflow velocity, and swirl angle. While these standards provide theoretical support for evaluating sampling representativeness, their applicability to different types of nuclear facilities, particularly for new reactor types (such as molten salt reactors, gas-cooled reactors), still presents significant practical challenges, and unified solutions have yet to be developed. Subsequently, the ANSI/HPS N13.1 standard underwent two revisions in 1999 and 2011, released as ANSI/HPS N13.1-1999 [5] and ANSI/HPS N13.1-2011 [6], with the latter version focusing primarily on editorial improvements without changes to core content. Based on this series of U.S. standards, the International Organization for Standardization later updated the ISO 2889 standard, culminating in the latest version, ISO 2889-2023 [7].

This paper aims to review research progress on the representativeness of gaseous effluent sampling from nuclear facilities, focusing on analyzing current main research methods and technologies, particularly the combined application of CFD simulation and experimental validation, and evaluating their applicability and challenges in actual nuclear facilities. By reviewing domestic and international research findings, this paper summarizes the advantages and disadvantages of existing technologies and proposes future research directions, aiming to provide theoretical support and technical references for the monitoring and source term assessment of gaseous effluents from nuclear facilities.

1 Standards and Regulations for Sampling Representativeness of Gaseous Effluents from Nuclear Facilities

In environmental monitoring of nuclear facilities, ensuring the representativeness of gaseous effluent sampling is of great significance for accurately assessing the discharge and dispersion of radioactive substances. Based on considerations for ensuring monitoring data quality, a series of standards and guidelines concerning sampling location placement and sampling methods have been issued internationally and domestically to regulate sampling practices and enhance result reliability. Regarding the arrangement of sampling cross-sections, while there are differences among various standards, they generally emphasize avoiding areas with significant upstream and downstream disturbances to allow airflow to achieve a high degree of uniform mixing within the measurement cross-section, thereby ensuring good representativeness in the sampling process. The following are specific requirements for sampling cross-section locations in some standards.

1.1 International Standards and Regulations

ANSI/HPS N13.1-2011 [6]: Issued jointly by the American National Standards Institute (ANSI) and the Health Physics Society (HPS), this standard primarily addresses sampling methods for radioactive aerosols and gaseous iodine in the environment. It specifies performance requirements for sampling equipment, criteria for sampling location selection, and data processing methods to ensure the representativeness and accuracy of sampling results. According to ANSI/HPS N13.1-2011, sampling probes should preferably be installed in the duct area between the fan and chimney outlet, avoiding proximity to the chimney exit to minimize the influence of external flow fields on velocity distribution. When determining sampling probe locations, comprehensive consideration should also be given to radiation protection needs for operators, cooling treatment of high-temperature exhaust gas, and aerosol particle deposition in sampling lines. The standard requires that to ensure representativeness of chimney sampling, pollutants must be fully and uniformly mixed at the sampling cross-section. This uniformity can be measured across four dimensions: average gas flow swirl angle, airflow velocity distribution characteristics, tracer gas concentration uniformity, and tracer aerosol concentration consistency. The relevant technical indicator requirements are as follows: the average swirl angle at the sampling cross-section should not exceed 20°, the coefficient of variation (COV) of airflow velocity should be controlled within 20%, the COV of tracer gas concentration should also be less than 20% with deviation between any measurement point concentration and the cross-section average not exceeding 30%, and the COV of tracer aerosol should similarly be below 20%.

ISO 2889-2023 [7]: Published by the International Organization for Standardization (ISO), this standard specifies general requirements for sampling gaseous effluents from nuclear facilities. It emphasizes that sampling points should be selected where concentration distribution is uniform in the airflow field and sets clear requirements for sampling equipment design and performance to ensure data reliability. ISO 2889-2023 stipulates that chimney sampling points should be installed between the fan and chimney outlet, avoiding positions near the exit to reduce wind effects on airflow velocity fields at the sampling location. The optimal sampling nozzle should be located in a region where airflow is fully mixed and representative, typically at a distance of 5–10 hydraulic diameters downstream or no less than 3 hydraulic diameters upstream, sometimes requiring extended placement distances based on specific operating conditions. Airflow velocity and pollutant concentration distribution at the sampling cross-section must meet the following requirements: (1) the average swirl angle of the cross-section should be less than 20°, typically evaluated based on the maximum swirl angle; (2) the COV in the central region of the cross-section should be controlled within 20%; (3) the deviation between the maximum concentration of tracer gas and its cross-sectional average should not exceed 30%, with the COV within the central 2/3 area of the cross-section not exceeding 20%; (4) the COV of tracer aerosol in this region should also be controlled below 20% to ensure good spatial representativeness of measurement results.

IAEA Safety Series No. 115 [8]: Published by the International Atomic Energy Agency (IAEA), this safety series report provides guidance principles for sampling gaseous and liquid effluents from nuclear facilities. It elaborates on sampling point arrangement, sampling equipment selection, and quality assurance measures to help countries establish effective environmental monitoring systems. First, sampling points should be far from flow field disturbance sources such as fans, valves, and pipe elbows to avoid the impact of non-uniform airflow. Second, they should be selected in regions where the flow field is fully mixed, typically in the middle section of the flow channel, away from inlets and outlets. Meanwhile, sampling points should avoid local high-concentration areas and ensure location stability, preventing impacts on sampling due to equipment vibration or maintenance. The convenience of sampling equipment installation, operation, and maintenance must also be considered to ensure the reliability of the sampling system.

The U.S. Environmental Protection Agency (EPA) specifies in "40 CFR PART 60 Appendix A Method 1" [9] that the distance of sampling locations from chimney inlet and outlet should be no less than 8 times and 2 times the chimney diameter, respectively.

According to the regulations in "Measurement of Velocity and Volume Flow Rate of Gas Streams in Ducts from Power Plant Chimneys" (ISO 10780-1994) [10], the sampling duct section should be straight with a length of at least 7 hydraulic diameters, and the sampling location should be 5 hydraulic diameters from the gas-borne inlet; if the sampling location is near the atmospheric end of the chimney outlet, the distance should also be no less than 5 hydraulic diameters.

1.2 Domestic Standards and Practices

According to the requirements of "General Rules for Sampling Airborne Radioactive Materials" (HJ/T 22-1998) [11], sampling points should be installed in regions of emission pipelines or chimneys where airflow is fully mixed and uniformly distributed to ensure sample representativeness. For chimney emissions, the optimal sampling point is typically located in the top region where airflow mixing is most complete. However, excessively high sampling points or overly long sampling pipelines may cause other problems. Therefore, sampling points are usually selected downstream of locations where airflow direction changes significantly or pipe diameter changes abruptly, maintaining a distance of no less than 5 pipe diameters from such change points.

According to the requirements of "Regulations for Environmental Radiation Protection of Nuclear Power Plants" (GB 6249-2025) [12], nuclear power plant operators must compile emission monitoring outlines and monitor gaseous and liquid radioactive effluents accordingly. To ensure sampling data representativeness, emission monitoring system design should adopt reasonable engineering measures to minimize losses during sampling.

The "General Rules for Monitoring Effluents at Nuclear Facilities" (GB11217-1989) [13] also requires that "nuclear facility operators shall monitor the types and concentrations of radionuclides in the surrounding environment and the total amount of radionuclides in facility effluents." Effluents from nuclear power plants are divided into airborne and liquid categories, with airborne effluents being discharged into the environment through chimneys after purification. To achieve effective monitoring, nuclear facilities typically deploy airborne effluent sampling systems on chimneys or pipelines. Since radioactive substances exhibit non-uniform distribution in flow fields and deposition along pathways, the representativeness of samples directly affects the accuracy of monitoring data.

In the "Technical Specifications for Radioactive Monitoring of Effluents from Nuclear Power Plants (Trial Implementation)" (NNSA [2020] No. 44) §3.3.5 [14], it is mentioned that gaseous effluents should be sampled at constant velocity to minimize deposition in sampling pipeline elbows and losses during transport. The design of chimney sampling locations, sampling nozzles, sampling pipelines, and sampling materials should comply with relevant technical requirements, and sample collection efficiency must be strictly calibrated. For airborne effluent sampling, the pipeline deposition rates for aerosol and iodine sampling should be demonstrated and used to correct collection efficiency.

NB/T 20374-2016 "Sampling of Airborne Radioactive Materials from Nuclear Power Plant Chimneys" [15] requires that sampling of airborne effluents from nuclear power plant chimneys must meet several key conditions. First, in terms of sampling location selection, airflow within the chimney should be fully mixed and uniformly distributed, with sampling ports installed in the top region of chimneys or emission pipelines while avoiding areas with significant local flow field disturbances to ensure sample representativeness. Second, sampling pipeline length, number of elbows, and pipe diameter changes should be reasonably designed to minimize aerosol deposition in pipelines and losses during transport. Third, sampling devices should be equipped with standardized sampling nozzles and materials, and the collection efficiency for different types of radionuclides such as aerosols and iodine should be demonstrated and corrected as necessary to ensure accurate and reliable sampling data. NB/T 20374 also proposes specific requirements for airflow velocity, sampling time, and pipeline cleanliness to ensure the repeatability of continuous monitoring and comparability of data.

In the design of gaseous effluent sampling systems for nuclear power plants in China, primary reference is made to international standards such as ISO 2889 and ANSI N13.1. While similar to these international standards in overall objectives, China’ s approach includes specific provisions tailored to engineering practices in domestic nuclear power plants regarding sampling port arrangement details, pipeline design constraints, and nuclide correction methods, providing clear technical foundations for the design and operation of chimney airborne effluent sampling systems in domestic nuclear power plants. Combined with domestic realities, a design and implementation path with Chinese characteristics has been formed. Depending on reactor type, design timing, and operational requirements, various plants show significant differences in sampling location arrangement, whether penetration coefficient analysis is conducted, and airflow uniformity demonstration, reflecting the diversified application of standards in engineering practice. The design status of sampling systems for nuclear island chimneys in some domestic nuclear power plants is shown in Table 1 , including key indicators such as implementation standards, sampling methods, airflow uniformity demonstration, and particle penetration calculations [16].

2 Research Progress on Sampling Location Representativeness

Gaseous effluents discharged from nuclear facilities typically contain multiple radioactive components such as aerosols, iodine, and tritium. The spatial distribution of these components in exhaust systems is jointly influenced by multiple factors including airflow structure, particle size characteristics, temperature and humidity conditions, and system geometry. Therefore, whether the sampling location is situated in a region where pollutants are fully mixed directly determines whether sampling results can truly reflect the actual composition and concentration characteristics of the emission source. In recent years, with increasing safety regulatory requirements and demands for improved monitoring accuracy in nuclear facilities, research on sampling location representativeness has gradually shifted from empirical judgment to theoretical simulation and experimental validation.

2.1 Application of CFD Simulation in Mixing Uniformity Analysis

In recent years, CFD methods have been increasingly applied in mixing uniformity studies of gaseous effluent sampling systems for nuclear facilities, becoming an important technical tool for analyzing sampling representativeness. This method can effectively compensate for limitations in field tests such as space constraints, limited measurement points, and operational complexity, providing theoretical bases and auxiliary verification for rational sampling location selection. Wang Xie et al. [17] used CFD to model and analyze the flow field in a nuclear facility exhaust system based on sampling location criteria from the new ISO 2889 standard, pointing out that existing sampling point selection had insufficient representativeness and recommending that sampling ports be installed in straight pipe sections approximately 20 m downstream of elbows to obtain more representative samples. The study demonstrated that CFD can not only output parameters such as velocity, temperature, and concentration to predict mixing uniformity regions but also compensate for the difficulty and large errors in actual aerosol concentration measurements, making it particularly suitable for evaluating sampling representativeness under different operating conditions.

Regarding model construction, as shown in Figure 1 [Figure 1: see original paper], Yang Chuan et al. [18] introduced the Discrete Phase Model (DPM) and Discrete Random Walk (DRW) model to establish a gas-solid multiphase turbulence coupling simulation system for a chimney. Using the k- model to solve the continuous phase and DPM to simulate aerosol particle transport, they analyzed in detail the variation patterns of velocity distribution, swirl angle, and concentration coefficient of variation with cross-section height in exhaust ducts. Results showed that mixing degrees of airflow and tracer components at some cross-sections met standard requirements, verifying the feasibility of rapid screening of representative sampling locations based on CFD.

Ding Shihai et al. [19] also conducted mixing uniformity simulations of chimney flow fields for a nuclear facility using CFD technology. Results showed that airflow velocity could meet ISO 2889 requirements, but tracer gas and aerosol concentration distributions could not meet standards, as shown in Table 2 , indicating that CFD simulation alone may be insufficient to accurately describe complex aerosol behavior. Therefore, the study emphasized that CFD results must be fully compared with field tests before being used to guide engineering practice, while also proposing that mixing devices could be introduced to improve on-site mixing conditions to meet standard requirements.

In engineering practice, Wang Tong et al. [20] analyzed the mixing uniformity of the gas sampling flow field in the Qinshan Nuclear Power Plant chimney. The schematic diagram of the Qinshan chimney and grid division is shown in Figure 2 [Figure 2: see original paper]. They systematically evaluated the mixing conditions at different elevations before and after chimney sampling system renovation through CFD simulation, comparing and analyzing indicators such as swirl angle, gas velocity, and tracer gas and aerosol distribution. They found that the sampling cross-section at 50 m after renovation was significantly superior in mixing uniformity to the original 71.6 m elevation, better meeting standards such as ISO 2889 and ANSI/HPS N13.1, further confirming the application value of CFD in on-site renovation scheme design and verification.

Overall, CFD simulation has demonstrated significant potential in flow field modeling and representativeness analysis of nuclear facility exhaust systems, with advantages in high-resolution parameter output, multi-condition adaptability, and visualization capabilities, particularly suitable for preliminary scheme evaluation and optimization [21,22]. However, attention should also be paid to its limitations in aerosol simulation accuracy and boundary condition settings, and it should be combined with experimental validation methods to form complementary approaches that enhance the credibility of analysis conclusions.

2.2 Experimental Research Methods and Validation Techniques

To verify whether gaseous effluent sampling systems meet representativeness requirements under actual operating conditions, experimental research, as an important method complementary to computational simulation, has been widely conducted in nuclear facilities at home and abroad. This method constructs scaled physical models or relies on operational facilities to measure flow field parameters and pollutant distribution characteristics under controlled conditions, evaluating sampling location representativeness according to relevant international standards and providing direct support for system design and optimization.

In scaled model experiments, to ensure that experimental results can be reasonably extrapolated to prototype systems, similarity in geometry, dynamics, and boundary conditions must be fully considered. First, geometric similarity requires that scaled models strictly maintain the ratio of chimney diameter and height, with sampling port positions corresponding one-to-one with the prototype system, while internal pipelines, support structures, and flow channel designs must also be scaled at the same ratio to avoid impacts on overall results from local flow field anomalies. For local protrusions, bends, splitters, and other geometric features, potential local disturbances and flow field non-uniformity caused during the scaling process should be analyzed and corrected through appropriate design or verification experiments to ensure that model geometry is representative of overall flow behavior. Second, dynamic similarity requires that key dimensionless parameters such as Reynolds number, Stokes number, and Reynolds stress ratio be matched as closely as possible to maintain consistency in turbulence structure, vortex distribution, and aerosol particle motion and deposition characteristics between the model and prototype [23]. When designing experiments, scaling effects of fluid inertial forces, viscous forces, and particle inertial effects should be considered, and potential deviations in local deposition patterns and sampling efficiency should be evaluated using correction methods or empirical formulas reported in literature. Third, boundary condition similarity requires that inlet velocity distribution, velocity profiles, turbulence characteristics, and fluctuation amplitudes be as consistent as possible with the prototype, while aerosol particle size distribution, concentration, and particle injection methods must also match actual operating conditions [24]. Additionally, factors such as temperature, pressure, humidity, wall roughness, and inlet disturbances can also potentially affect local flow fields and particle motion and should be considered in model design and experimental analysis. By strictly controlling similarity in geometry, dynamics, and boundary conditions, scaled model experiments can achieve reasonable extrapolation of results to prototype systems while ensuring operability and repeatability, providing references for subsequent numerical simulation, design optimization, and engineering applications.

Dong Xinfang et al. [25] constructed a 1:5 scaled chimney model for the “Hualong I” third-generation pressurized water reactor nuclear power unit based on the ANSI/HPS N13.1-1999 standard, as shown in Figure 3 [Figure 3: see original paper]. Using a single-point sampler design and combining it with the actual unit chimney, they conducted multiple verification tests covering key parameters such as gas velocity distribution, swirl angle, tracer gas concentration, and tracer aerosol concentration. Under three different elevation cross-sections and two design ventilation conditions, the obtained COV of airflow velocity, extreme values of swirl angle, and COV of pollutant concentration distribution all met standard limit requirements. Further verification tests conducted in the actual chimneys of Units 1 and 2 at Fuqing Nuclear Power Plant yielded results consistent with model tests, confirming that the system possesses good representativeness and can effectively monitor chimney emissions using single-point sampling.

Liu Hongtao et al. [26] focused on the rationality of sampling point selection and arrangement for airborne radioactive material sampling systems. Following the technical route of the ANSI/HPS N13.1 standard, they conducted experimental research on a scaled model of a nuclear power plant chimney, using equipment such as Pitot tubes, hot-wire anemometers, SF_6 tracer gas, and aerosol generators to systematically verify swirl angle, flow velocity, and pollutant distribution conditions. Test results shown in Table 3 confirmed that their designed sampling scheme exhibited good representativeness under scaled model conditions and could effectively evaluate sampling performance under real operating conditions, providing important basis for subsequent design of actual emission monitoring systems for nuclear power plants.

In summary, experimental research, as a powerful complement to CFD simulation, possesses advantages in visualization, quantification, and standard-compliant verification, making it an indispensable important method in current representativeness analysis of gaseous effluent sampling systems. In actual engineering, scaled models are often constructed for preliminary verification, combined with on-site measurements to ensure system performance meets relevant standard requirements. With continuous advancement in tracer technology and measurement equipment, the precision and applicability of experimental methods will be further enhanced, providing more reliable data support for radioactive monitoring of nuclear facilities.

2.3 Current Status of Combined CFD and Experimental Validation Research

In research on sampling system representativeness for nuclear facility gaseous effluents, relying solely on CFD simulation or experimental validation methods has limitations. In recent years, with continuous development in sampling technology and measurement methods, an increasing number of studies have combined CFD simulation with experimental validation, achieving comprehensive understanding of airflow organization and pollutant distribution through complementary advantages and enhancing the scientificity and reliability of sampling system layout.

CFD simulation possesses powerful visualization and parameter controllability capabilities in analyzing flow field structures and pollutant migration behaviors, enabling systematic prediction of boundary conditions and internal variables that are difficult to measure in practice. However, numerical models still have uncertainties in describing complex physical processes such as aerosol transport, turbulent diffusion, and wall deposition. Particularly in exhaust systems with wide particle size distributions and drastic flow field changes, simulation results are prone to deviations due to model settings or grid division. Therefore, validating and correcting CFD results based on field or scaled experiments has become an important means to improve simulation reliability.

Taking the research by Wang Xie et al. [17] on a nuclear facility exhaust system as an example, although they preliminarily determined reasonable sampling locations through CFD analysis, their conclusions still required validation through subsequent experiments. The research by Ding Shihai et al. [19] further pointed out that even when simulations indicate uniform velocity at a cross-section, pollutant (especially aerosol) concentrations may still not meet standard requirements, thus recommending that simulation conclusions be verified through experimental means. In actual engineering, such as in the development of the "Hualong I" chimney sampling system, the team conducted scaled model experiments and field validation tests after completing CFD simulations, comparing and analyzing velocity fields and tracer distributions to verify the accuracy of simulation conclusions and provide decision-making basis for final sampling location determination.

Additionally, some studies have explored introducing feedback mechanisms in the iterative optimization of simulation and testing, where preliminary experimental data is used to correct model boundary conditions to improve CFD calculation accuracy, and high-precision simulation results are then used to guide second-round experimental design, gradually converging to the optimal sampling scheme. This "model-test coupled design" strategy has been applied in multiple sampling system renovation projects at nuclear power plants with good results.

Overall, the combination of CFD and experimental validation has become the mainstream technical route for sampling representativeness research. In the future, with the development of high-precision aerosol transport models, multi-scale coupling algorithms, and intelligent experimental data acquisition systems, the integration of the two approaches will be further deepened. Key research priorities and challenges remain in how to efficiently establish correspondence between simulation and experiment, construct unified evaluation index systems, and achieve optimization of representative sampling schemes under uncertainty control.

2.4 International Practices and Experience

In addition to increasingly strengthened research and engineering verification on gaseous effluent sampling representativeness in China, systematic work has also been conducted internationally. The Pacific Northwest National Laboratory (PNNL) in the United States has long been dedicated to chimney sampling representativeness assessment and system optimization research in support of projects for the U.S. Nuclear Regulatory Commission (NRC) and Department of Energy (DOE). PNNL has conducted systematic research on gaseous effluent sampling representativeness, covering various technical paths including field test verification, scaled model experiments, and numerical simulation analysis. These studies have not only enhanced understanding of chimney flow field characteristics and the rationality of sampling probe placement but also provided solid engineering foundations for sampling system design optimization. Regarding the basic principles and applicable conditions of single-point aerosol sampling, Rodgers et al. [27] early proposed the fundamental theory for using single-point sampling technology in actual flow fields and analyzed its limitations. Subsequently, Anand et al. [28] further conducted systematic research on the relationship between gas mixing degree and single-point sampling representativeness in straight pipes through combined experiments and numerical simulations, clearly indicating that representative single-point sampling can be achieved when pipe flow meets specific Reynolds number and turbulence characteristic conditions. In terms of field verification of chimney sampling systems, Ballinger et al. [29] conducted field tests on sampling point placement at PNNL's high-level waste building under return flow conditions, verifying whether probe positions met standards such as ANSI/HPS N13.1 under complex flow backgrounds, providing key references for actual engineering placement. In scaled model experimental research, Recknagle et al. [30] used scaled models combined with wind tunnel experiments to evaluate gas mixing performance at sampling locations in wastewater treatment facility chimneys, clarifying the impact of different probe arrangements on sampling representativeness and providing references for future model experimental designs. In research on standard compliance assessment of multi-probe positions, Glissmeyer et al. [31] used simulation and statistical analysis methods to quantitatively evaluate whether multiple specific chimney arrangement schemes (such as LB-C2, LB-S2, LV-S1) complied with ANSI/HPS N13.1-1999, demonstrating how to systematically determine the normativity of probe placement. Such research has direct guiding significance for probe location selection in actual engineering. Regarding evaluation work on sampling probe placement for 3410 building exhaust systems, Yu et al. [32] and Glissmeyer et al. [33] respectively evaluated the performance of original and revised sampling probe arrangements. These studies revealed the impact of structural modifications on airflow mixing and sampling consistency, emphasizing the necessity of re-conducting representativeness verification after design adjustments. In summary, PNNL has formed a complete verification methodology system in sampling representativeness research through close integration of theory, experiment, and engineering application. These achievements have important reference value in international standard formulation and revision, sampling system upgrading, and new facility design. Table 4 lists the main research and demonstration methods conducted by PNNL and other international institutions for chimney sampling representativeness, demonstrating their engineering practical experience in sampling system design and verification at different stages [16].

These efforts have provided important technical support for the formulation of standards and engineering applications of emission monitoring systems for U.S. nuclear facilities, particularly in the optimal design of sampling systems under complex flow fields, which is of extremely high engineering value. Through the research results of PNNL and other institutions, we can see their comprehensive methods for verifying chimney sampling representativeness in nuclear facilities, including scaled model experiments, field tests, and theoretical simulations. The combination of these methods not only improves the accuracy and reliability of experimental results but also provides valuable experience and inspiration for the design and verification of gaseous effluent sampling systems for nuclear facilities in China. Through summarization of international practices, it is evident that differences in airflow distribution and emission pathways among different facilities make the applicability of each sampling method vary, emphasizing the necessity of customized design according to facility characteristics. Meanwhile, the introduction of theoretical simulations has further enhanced the scientificity and rationality of sampling system design, providing valuable references for the design and optimization of sampling systems for new reactor types in China, especially in airflow uniformity analysis and sampling point placement. These international experiences provide profound inspiration and support for technological progress and standardization construction in related fields in China.

2.5 Limitations and Improvements of CFD Methods in Sampling Representativeness Research

In research on aerosol sampling representativeness in nuclear facility chimneys, CFD simulation, as an important numerical analysis tool, can provide spatial distribution information of flow fields and particle transport. However, in practice, CFD results often show certain differences from experimental data, primarily due to limitations in turbulence and particle models. First, commonly used RNG k- or standard k- turbulence models have difficulty accurately capturing local vortex structures and turbulent kinetic energy dissipation characteristics when dealing with complex swirling flows and high Reynolds number turbulence, thereby affecting predictions of velocity field uniformity at sampling cross-sections. Second, the discrete phase model typically treats aerosols as non-interacting ideal particles, ignoring processes such as particle agglomeration, charging effects, and wall resuspension, leading to deviations in concentration field distribution from actual conditions. Additionally, simplified settings of inlet boundary conditions often cannot fully reproduce turbulence intensity and particle size distribution at emission outlets, and such errors are further amplified at downstream sampling cross-sections. Finally, in numerical calculation processes, grid division precision, near-wall treatment methods, and convergence criteria significantly affect results. Without systematic grid independence verification, errors may be non-negligible.

To address these limitations, recent studies have proposed various improvement strategies. In turbulence modeling, introducing Large Eddy Simulation (LES) or hybrid RANS-LES methods can better resolve transient vortex structures and swirling characteristics, improving prediction accuracy of local velocity fields. In particle phase modeling, using turbulence-particle two-way coupling models and considering physical processes such as particle agglomeration and deposition when conditions permit can more realistically reproduce aerosol migration behaviors. In boundary condition settings, using experimental measurement data and scaled model results as driving inputs can effectively improve simulation authenticity and reliability. Finally, calibration and validation of CFD simulation results are also crucial. Comparison with scaled experiment or field measurement data can be used to reversely correct model parameters and clarify the applicable scope of simulation results, thereby enhancing the application value of CFD in sampling representativeness research. Overall, current international and domestic standards have clear representativeness indicator requirements for sampling locations and system performance, but practical application and verification under complex conditions still have deficiencies. These issues have prompted researchers to explore representativeness evaluation methods based on numerical simulation and experimental verification in subsequent work.

3 Research on Transmission Efficiency of Sampling Systems for Aerosols and Iodine

The sampling system in nuclear facility emission monitoring serves as a critical bridge connecting the source term and measurement results. As the most important radionuclide forms, the migration efficiency of aerosols and iodine in sampling pipelines directly affects the accuracy and representativeness of sampling data. Due to differences in their physical and chemical properties, their transmission efficiency in sampling paths is influenced by various factors including flow state, path structure, pipe material, gas temperature and humidity, and nuclide forms. ANSI/HPS N13.1-2011 explicitly requires that the transmission efficiency of the entire transport system for particles with aerodynamic diameter of 10 m should not be lower than 50%. However, in actual engineering, due to complex pipeline structures and varying flow conditions, aerosols and iodine are prone to deposition and adsorption losses during transport, affecting the representativeness and accuracy of final monitoring data. In recent years, multiple nuclear power projects in China have conducted systematic research on pollutant transmission efficiency in sampling systems, achieving important results.

3.1 Research on Transmission Efficiency of Aerosols and Iodine

Aerosol particle transmission efficiency in sampling systems is significantly affected by aerodynamic behavior, with gravity settling and inertial impaction losses more likely to occur especially under conditions of approximately 10 m particle size. Wu Pingtao et al. [34] evaluated the sampling system for Units 1 and 2 of Fuqing Nuclear Power Plant, measuring the transmission efficiency of 10 m aerosols in the original system at only 33.5% and 23.5%. Based on deposition mechanism analysis, the research team proposed improvement plans, optimizing pipeline routing, shortening horizontal sections, and reducing the number of elbows. After verification using Deposition 2001a simulation, efficiency was improved to 59%, significantly enhancing system performance.

Zhang Yong et al. [35] identified long-distance horizontal pipelines as the main bottleneck for aerosol transmission efficiency in the sampling system structure of Qinshan Nuclear Power Plant. By moving sampling and monitoring equipment from remote locations to the calibration room at the chimney base, canceling 85.4 m of horizontal pipeline while retaining 70.6 m of vertical pipeline, particle losses were effectively controlled. Correction factors for transmission errors were controlled within 1.65 and 1.1 under accident and normal conditions respectively, demonstrating that structural optimization is of great significance for improving transmission efficiency.

Shen Fu et al. [36] measured the unit length penetration rates of different pipeline types for aerosols through standardized test platforms in Tianwan, Taishan, and CAP1400 nuclear power projects, finding that transmission efficiency of horizontal sections was far lower than that of vertical sections, with 90° elbows being particularly significant. The schematic diagram of the experimental setup is shown in Figure 4 [Figure 4: see original paper], mainly consisting of an aerosol generator, dispersion chamber, test components, and sampler. Significant aerosol concentration underestimation was observed under both 60 L/min and 100 L/min flow rates, indicating that pipeline structure should be prioritized in sampling system design.

Compared with aerosols, iodine has more complex physical and chemical forms (such as elemental iodine and methyl iodine) and is more susceptible to influences such as pipe wall adsorption and reaction transformation in sampling systems. After improving the sampling system of Fuqing Nuclear Power Plant, Wu Pingtao et al. [34] conducted bench tests for iodine, measuring transmission efficiencies of 84.00% and 84.97% for elemental iodine and methyl iodine respectively, both higher than those for aerosols, indicating that iodine could maintain good representativeness in the optimized system. Research by Zhang Yong' s team [35] at Qinshan Nuclear Power Plant also confirmed similar trends, with adsorption losses of iodine significantly reduced and transmission efficiency improved after system renovation, ensuring accurate monitoring response for iodine when combined with system evaluation under accident and normal conditions.

3.2 Transport Behavior and Engineering Optimization in Aerosol-Iodine Mixed Fields

In actual emission scenarios from nuclear facilities, aerosols and iodine often coexist, and their synergistic transport behavior is more complex than single components, yet systematic research remains lacking. Although relevant experiments are limited, existing engineering projects have gradually introduced the concept of "mixed fields" in test design. For example, in the study by Wu Pingtao et al. [34], synchronous measurement of aerosols and iodine was conducted to compare their transmission efficiencies under the same conditions, finding that iodine penetration rates were higher than those of aerosols under the same conditions, indicating that its deposition mechanism in pipelines is milder. Additionally, Tang Yuqin et al. [1] analyzed response differences between multi-point and single-point sampling nozzles under mixed field conditions at Sanmen Nuclear Power Plant, finding that multi-point sampling nozzles, due to their complex structure, easily create turbulence and deposition dead zones, particularly disadvantageous for large-particle aerosol transport and indirectly affecting iodine monitoring accuracy. Therefore, they recommended adopting a sheathed single-point sampling scheme and improving overall transmission stability and consistency through structural optimization and flow velocity control.

To address insufficient transmission efficiency of sampling systems in existing nuclear facilities, multiple engineering practices have provided representative optimization pathways. These include layout optimization (shortening horizontal sections, reducing elbow numbers), position adjustment (installing monitoring units nearby), structural substitution (single-point sheathed sampling), and parameter control (flow velocity, pipe diameter, etc.), all proven to effectively improve pollutant penetration rates. Based on operational experience at Qinshan Nuclear Power Plant, Zheng Guowen et al. [37] established a systematic test method to evaluate relationships between pipeline length, layout angle, and pollutant losses, providing quantitative basis for renovation of old plants and design of new plants. The quantitative experimental research by Shen Fu et al. [36] further emphasized the importance of conducting transmission efficiency simulation and test verification during the initial design phase, proposing that performance evaluation mechanisms should be established synchronously throughout the entire lifecycle of nuclear facilities to construct standardized design and assessment processes.

In summary, the transmission efficiency of aerosols and iodine is not only an important indicator for sampling system design and evaluation but also directly affects the accuracy and traceability of radioactive emission monitoring. Through systematic optimization design combined with experimental verification, the adaptability of nuclear facility sampling systems to complex emission environments can be effectively improved, ensuring long-term operational representativeness and compliance.

4 Future Research Directions and Recommendations

Although preliminary progress has been made in research on sampling system representativeness for gaseous effluents from nuclear facilities in China, the overall stage remains a transition from engineering experience-based approaches to theory-guided approaches. Current research mostly focuses on individual engineering case analyses, and systematic, forward-looking methodological systems and technical platforms are still lacking. Combining domestic and international development trends and existing key issues, future research should focus on the deep integration of CFD simulation and experimental validation, construction of adaptation standards for new reactor types, introduction of system modular design concepts, and real-time monitoring and intelligent compensation of sample transmission efficiency, gradually establishing a scientific, operable, and engineering-adaptable technical system.

First, research on the coupling of CFD simulation and experimental validation should be strengthened. CFD technology has been widely used in predicting transmission efficiency of sampling systems due to its efficiency in complex flow simulation. However, since aerosol and iodine transport processes are significantly affected by factors such as particle size distribution, aerosol adhesion, and flow velocity instability, single numerical simulation results cannot fully reflect actual system transmission losses. Therefore, strengthening coupling and verification between CFD models and experimental results is a key direction for improving research credibility. On one hand, representative test platforms should be built in laboratories or on-site to obtain deposition data in typical structures (such as elbows, horizontal sections, sampling nozzles) through transport experiments using real-particle-size aerosols and different iodine forms. On the other hand, CFD simulation boundary conditions and particle motion models need to be continuously corrected based on experimental results to improve their predictive capability for transmission efficiency. Furthermore, future exploration could introduce artificial intelligence algorithms to achieve efficient model training based on experimental databases, thereby improving computational efficiency and accuracy under complex conditions.

Second, corresponding standard supplementary documents or technical guidelines should be developed to address differences in emission characteristics of new reactor types. Currently, the design and operation of gaseous effluent sampling systems for nuclear facilities in China mainly refer to international standards such as the ANSI N13.1 series and ISO 2889, which have been widely applied and proven applicable in traditional reactor types. However, with the operation of new reactor types such as AP1000, CAP1400, and Hualong I, their emission pathways, chimney structures, and flow field characteristics differ significantly from traditional reactor types, resulting in limited adaptability of existing standards in aspects such as sampling point placement, particle size range coverage, and evaluation of multi-point sampling and velocity uniformity. Therefore, it is recommended that, based on continuing the technical framework of existing standard systems, supplementary standard documents or technical guidelines be formulated in combination with emission characteristics and monitoring needs of new reactor types, detailing recommended values for key technical parameters, layout schemes, and assessment methods. Such supplementary documents can not only strengthen the applicability of standards to new reactor types but also help enhance the scientificity, standardization, and data comparability of sampling system design. Meanwhile, attention should be paid to drawing on international advanced experience and combining domestic engineering application practices to promote the formation of a sampling system technical guideline system that both aligns with international standards and reflects Chinese characteristics, providing more solid technical support for environmental monitoring capabilities of new-generation nuclear power technologies.

Additionally, to improve system operational flexibility and maintainability, modular and replaceable design of sampling systems should be promoted. Traditional nuclear facility sampling systems mostly adopt customized on-site designs with fixed structures and poor flexibility. Once systems exhibit insufficient performance or large losses, effective replacement or upgrading is often difficult without interrupting operation. To adapt to the practical needs of long operation cycles, complex maintenance environments, and high monitoring accuracy requirements of nuclear facilities, modular and replaceable design concepts for sampling systems should be actively promoted in the future. By integrating sampling heads, sampling tubes, flow control devices, and analysis interfaces into standard modules to form system components with unified structures and compatible interfaces, rapid on-site deployment, online maintenance, and flexible replacement can be achieved. Meanwhile, digital modeling methods should be introduced in the design phase to conduct three-dimensional simulation and interference analysis of system layout, improving space utilization efficiency and operational safety. Furthermore, modular design also provides a good hardware foundation for subsequent intelligent transformation and upgrading of systems, enabling the entire sampling system to better adapt to long-term operation and technological iteration needs.

Finally, there is an urgent need to develop intelligent monitoring systems with real-time monitoring and compensation capabilities. Currently, most nuclear facilities still use static correction factors in transmission efficiency assessment, making it difficult to dynamically reflect representativeness changes in systems during long-term operation due to deposition, clogging, or flow velocity fluctuations. Under the premise that aerosols and iodine are highly sensitive to deposition environments, there is an urgent need in the future to develop intelligent monitoring systems with real-time monitoring capabilities and automatic compensation functions. High-precision flow velocity sensors, particle size analyzers, or small radioactive detectors can be deployed at key nodes of sampling pipelines to obtain real-time system operation status and pollutant transport parameters. Combined with existing CFD simulation data and historical monitoring experience, data-driven transmission efficiency assessment models can be constructed to achieve online calculation and dynamic correction of representativeness factors. Ultimately, real-time transmission efficiency correction results can be integrated into environmental dose assessment and automatic emission reporting systems to achieve closed-loop control of the data chain, significantly improving the reliability and scientificity of monitoring data and providing solid technical support for environmental safety management of nuclear facilities.

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Note: Figure translations are in progress. See original paper for figures.