Experimental Study on Aerosol Particle Loss Characteristics in Horizontal Sampling Ducts

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Abstract

The gaseous effluent monitoring system for nuclear facilities requires continuous sampling and measurement of radioactive materials. Aerosols undergo deposition within sampling pipes due to effects such as Brownian diffusion, gravity, and turbulence. This paper conducts experiments on the penetration efficiency of micron-sized aerosols in horizontal sampling pipes, and performs comparative validation against existing empirical formulas and published data from domestic and international sources. Considering the combined effects of effective roughness, turbulent diffusion, and gravitational settling, a modified deposition velocity prediction formula applicable to both the diffusion regime and the diffusion-impaction regime is proposed, with predicted values showing good agreement with experimental results. Experimental results demonstrate that: since roughness alters the near-wall flow field and frictional resistance along the pipe, different roughness values exert a significant influence on deposition rates; changes in roughness at the micron scale may also vary turbulent deposition rates by an order of magnitude. For aerosols in the diffusion regime within horizontal pipes, their settling is jointly controlled by gravitational and Brownian diffusion mechanisms, exhibiting relatively low settling velocities. For aerosols in the diffusion-impaction regime, the penetration rate is jointly affected by gravity, turbulent eddies, and residence time within the pipe, and there exists an optimal sampling flow velocity at which the penetration rate reaches its maximum value.

Full Text

Experimental Study on Aerosol Particle Loss in Horizontal Sampling Pipes of Nuclear Facilities

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Abstract

The gaseous effluent monitoring system in nuclear facilities requires continuous sampling and measurement of radioactive materials. Aerosol particles undergo deposition within sampling pipelines due to Brownian diffusion, gravity, and turbulent effects. This study investigates the penetration efficiency of micron-sized aerosols in horizontal sampling pipes through experimental methods, with results compared against existing empirical formulas and published data from domestic and international sources. Considering the combined effects of effective roughness, turbulent diffusion, and gravitational settling, a modified deposition velocity prediction formula applicable to both the diffusion and diffusion-impaction regimes is proposed, showing good agreement with experimental results. Experimental findings demonstrate that surface roughness significantly affects deposition rates by altering the near-wall flow field and frictional resistance along the pipe, with micron-scale variations in roughness potentially changing turbulent deposition rates by an order of magnitude. For aerosols in the diffusion regime within horizontal pipes, settling is jointly controlled by gravity and Brownian diffusion mechanisms, resulting in relatively low deposition velocities. For aerosols in the diffusion-impaction regime, penetration efficiency is influenced by the combined effects of gravity, turbulent eddies, and residence time within the pipe, leading to an optimal sampling flow velocity that maximizes penetration efficiency.

Keywords: Gaseous effluent; Sampling system; Deposition; Aerosols; Penetration efficiency **Chinese Library Classification:** TL7

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Introduction

Before gaseous effluents from nuclear facilities are discharged into the atmosphere, dedicated gas sampling systems must be employed to continuously sample and measure radioactive nuclides contained within them [1]. Wall deposition refers to the process where aerosol particles deposit onto pipe walls under the influence of gravity, turbulence, and Brownian forces. If wall deposition in sampling systems is incorrectly estimated, the sampling results lose their representativeness.

Friedlander [2] first experimentally investigated particle settling patterns in turbulent flow, discovering that deposition velocity correlates with pipe flow velocity and particle size. Chamberlain [3] experimentally found that in the diffusion regime, increased particle size leads to reduced deposition. Liu [4] and Sehmel [5] conducted studies on particle settling in the diffusion-impaction regime, with Liu' s [4] method being widely used for validating deposition models and empirical formulas due to its reliability and reproducibility. Reeks [6] and Wells [7] found that in the inertial regime, deposition velocity decreases with increasing relaxation time. Sippola [8] investigated material effects on deposition. These experiments revealed that aerosol settling mechanisms can be categorized into three regimes based on dimensionless relaxation time [9]. Currently, predicting aerosol deposition in pipes relies primarily on empirically fitted relationships.

Due to the difficulty in accurately measuring roughness and the common assumption that it is smaller than the boundary layer thickness, most early formulas assumed perfectly smooth pipe walls. Wood' s [10] empirical model for smooth conditions is frequently used for comparative validation due to its broad applicability and accuracy. Additionally, Muyshondt [11] proposed empirical formulas incorporating Reynolds number as a parameter to account for hydrodynamic effects on deposition. Domestically, Lu Zhengyong [12] summarized empirical formulas for straight-pipe penetration efficiency based on American standards for aerosol sampling monitoring in nuclear facility effluents.

Grass [13] studied roughness effects on turbulence characteristics through visualization experiments, proposing classification into hydraulically smooth, transitional, and fully rough regimes based on roughness, suggesting different mechanisms of roughness influence on aerosol deposition in each regime. El-Shobokshy [14] conducted experiments with different dimensionless roughness values, demonstrating that even when roughness is smaller than the boundary layer thickness, minor changes significantly affect deposition rates. Wells and Chamberlain [3] compared aerosol deposition rates on smooth copper pipes versus rough surfaces with 100 m average roughness for particles in the diffusion and diffusion-inertial regimes, finding deposition on rough surfaces was 2-3 orders of magnitude higher than on smooth surfaces. Lai [15] investigated deposition velocities of monodisperse particles (0.7-7.1 m) on smooth and rib-roughened surfaces using neutron activation, showing deposition rates on columnar-roughened surfaces were up to seven times higher than on smooth surfaces.

Fan and Ahmadi [16] addressed roughness effects on aerosol deposition, deriving dimensionless deposition velocity formulas for square ducts using perturbation methods. They proposed the concept of effective roughness, hypothesizing that roughness displaces the origin of the velocity profile. Due to the irregular and complex nature of wall roughness, deriving universal laws for velocity boundary layer displacement is theoretically challenging, so they assumed the velocity profile displacement distance is a fixed proportion of average roughness.

Numerical simulations have also been employed to study roughness effects.

Guha [17] used Lagrangian particle tracking and Eulerian models assuming a fixed proportionality between virtual origin displacement and roughness. Zahtila [18] found through direct numerical simulation that in the inertial regime, roughness enhances particle rebound from walls, returning aerosols to the flow field and reducing deposition velocity. Zhao Bin [19] identified relationships between velocity profile displacement distances and roughness in different roughness regimes, proposing an improved Eulerian model for predicting deposition rates.

While empirical equations are often proposed as the best means for predicting particle deposition, their applicability and accuracy remain limited by experimental and assumed conditions, requiring selection and modification based on specific circumstances. Existing penetration efficiency calculation models and software for nuclear facility sampling pipes often assume perfectly smooth walls, neglecting actual roughness effects. For example, both the ISO 2889-2023 standard [20] and domestic software developed by the China Institute for Radiation Protection [12] fail to adequately consider this factor.

To address the specific effects of roughness, aerosol particle size, flow velocity, and pipe diameter on particle deposition, this study conducts penetration efficiency experiments in horizontal straight pipes using different roughness materials, pipe diameters, average flow velocities, and aerosol particle sizes. The experimental apparatus and procedures are described, and a modified penetration efficiency model for nuclear facility sampling systems incorporating roughness is proposed. Experimental results are compared with historical empirical models and the modified model, with key factors influencing penetration efficiency analyzed in depth.

1.1 Experimental Apparatus and Equipment

This experiment focuses on investigating the effects of roughness, flow velocity, particle size, and pipe diameter to accurately evaluate aerosol penetration efficiency in horizontal sampling pipes. [Figure 1: see original paper] shows a schematic diagram of the experimental apparatus, which mainly comprises an airflow regulation device, aerosol injection system, sampling pipeline, and measurement system. The airflow regulation device adjusts fan speed via a frequency converter to obtain the required flow rate, with a flow meter providing real-time display. The core of the aerosol injection system is an aerosol generator and mixing chamber. The generator utilizes a solid particle fluidization principle, using high-pressure nitrogen to entrain SiO_2 particles, which are then blown into the mixing chamber for blending with the airflow.

After uniform mixing in the chamber, aerosol particles are sampled through the test pipe while continuously monitoring the concentration distribution at the pipe inlet until reaching a stable state as shown in Figure 2: see original paper. The stability criterion requires the relative standard deviation of concentration distributions from three consecutive samples to be less than 5%. To maintain constant aerosol concentration, the mixing chamber includes a bypass line to divert excess aerosol.

The measurement system employs sampling devices at the pipe inlet and outlet, monitoring aerosol concentration with a TSI 3321 Aerodynamic Particle Sizer (APS). [Figure 2: see original paper] shows the monitoring schematic. For larger pipe diameters, five measurement points are sampled at the outlet; for smaller diameters, only the center point is measured. Both inlet and outlet concentrations undergo three independent experimental measurements, with relative standard deviations strictly controlled within 5%. The average of the three measurements is then used to calculate the penetration coefficient. Continuous sampling is employed with each sample lasting 20 seconds, and average particle concentrations are obtained by selecting appropriate size channels. Additionally, a pitot tube anemometer measures air velocity at the pipe center, while a Ribo U9 surface roughness meter measures roughness of different pipe materials. Detailed experimental conditions and parameters are listed in .

1.2 Aerosol Penetration Model

In aerosol dynamics research, dimensionless relaxation time (τ^+) is a key parameter characterizing the relative importance of particle inertia versus fluid turbulence. This parameter reflects particle inertia magnitude and relates to particle size, density, and flow velocity, connecting aerosol deposition behavior with fluid dynamic characteristics. Existing empirical models typically predict dimensionless deposition rates based on τ^+ to study particle deposition in pipes. Equation (1) gives the expression for dimensionless relaxation time of spherical particles, where ν_a is air kinematic viscosity ($\mathrm{m^2/s}$), μ is air dynamic viscosity ($\mathrm{Pa \cdot s}$), C_c is the Cunningham slip correction factor accounting for slip when aerosol particle size approaches the gas mean free path, and λ is molecular mean free path (m).

Without considering gravity, the deposition velocity (V_d) caused by Brownian diffusion and turbulent inertia is defined by Equation (3) [8], directed radially from the pipe center toward the wall, where J is particle flux per unit time per unit area and $\bar{C}$ is average particle concentration in the pipe. The dimensionless deposition velocity (V_d^+) is the ratio of V_d to friction velocity (u^*), with u^* calculated using Equation (5), where f is the friction factor obtained from the Colebrook-White iterative formula (Equation (4) [21]) and Re is Reynolds number.

In horizontal pipes, gravity also causes wall deposition in addition to Brownian diffusion and turbulent inertia. Gravitational settling velocity (V_g) is the terminal velocity achieved under balance of gravity, buoyancy, and drag forces, expressed by Equation (7) when particle Reynolds number (Re_p) is less than 1.

Since gravitational settling, turbulent inertia, and Brownian diffusion occur simultaneously in horizontal pipes, the effective deposition velocity is the vector sum of V_g and V_d. For nuclear facilities, the primary concern is aerosol penetration efficiency in sampling systems; for instance, ISO 2889-2023 [20] requires >50% penetration for 10 m particles. Penetration directly relates to sampling representativeness and monitoring accuracy. Therefore, a quantitative relationship between deposition velocity and penetration efficiency must be derived [8], with detailed calculations shown in Equations (9)-(12), where P is pipe hydraulic perimeter (m) and A is pipe cross-sectional area (m^2).

[Figure 3: see original paper] illustrates the physical model of particle deposition in a horizontal circular pipe section.

2.1 Empirical Models

Current empirical models for dimensionless turbulent deposition velocity are based on core assumptions: (1) aerosol concentration is low enough to neglect particle-particle interactions; (2) fully developed turbulent flow; (3) negligible influence of aerosols on air turbulence structure; (4) ideal deposition environment where particles do not rebound or re-entrain upon wall contact; (5) neglect of thermophoresis and electrophoresis. The following introduces the most commonly used models for comparison: Wood' s model for smooth conditions, Ahmadi' s model considering roughness, and the modified model proposed in this study.

Wood [10] developed a calculation formula for V_d^+ (Equation (13)) for particle deposition on smooth walls based on experimental data and theoretical derivation, where Sc is Schmidt number and D_B is Brownian diffusion coefficient.

Fan and Ahmadi [16] proposed that roughness causes separation of free shear flow from the wall, displacing the virtual origin of the assumed velocity profile. They introduced the concept of effective roughness and proposed a dimensionless deposition velocity formula (Equation (15)), where h is effective roughness (m), σ_k is roughness standard deviation (m), e is velocity profile origin displacement distance (m), and h^+ is dimensionless effective roughness. Fan and Ahmadi assumed the ratio of velocity profile displacement distance e to average roughness is a constant 0.55.

Regarding the specific influence of roughness on particle deposition, different roughness levels produce different free shear flow separation patterns. This study introduces effective roughness and uses Equation (19) to calculate dimensionless velocity profile virtual origin displacement for different roughness values [19]. Combining historical experimental data with current results, Fan and Ahmadi' s model is modified (Equation (20).

2.2 Experimental Results

First, the modified model is compared with Ahmadi' s and Wood' s models against historical experimental data [4][5][7][8] to evaluate their accuracy in predicting aerosol deposition. In early historical experiments, wall roughness was not recorded as a measurement parameter, making actual roughness values unknown. [Figure 5: see original paper] compares predicted dimensionless deposition rates from the three formulas with historical data. The modified model shows good agreement, with most historical data falling within the predicted roughness range of 0-10 m. Results also indicate that micron-scale roughness variations can significantly impact dimensionless deposition velocity, potentially changing it by an order of magnitude.

[Figure 6: see original paper] and related figures present experimental penetration efficiency results for different pipe materials, comparing them with predictions from multiple empirical models including Wood [10], Ahmadi [16], Papavergos [9], Muyshondt [11], and Lu Zhengyong [12]. The modified model better predicts aerosol penetration efficiency under different roughness conditions, showing high agreement with experimental results with deviations generally controlled within 10%.

Experimental results demonstrate that roughness, turbulent diffusion, and gravitational settling collectively influence aerosol deposition behavior. For 10 m aerosols at constant pipe length, penetration efficiency exhibits a parabolic trend with increasing flow velocity. In horizontal pipes, aerosol deposition velocity comprises gravitational and turbulent components. Increased flow velocity reduces residence time but enhances dimensionless turbulent deposition velocity due to stronger inertial forces. At low velocities, gravitational settling dominates and penetration increases with velocity. At high velocities, turbulent inertia effects strengthen and penetration decreases with velocity. Different roughness levels also affect deposition rates: at low velocities where gravity dominates, roughness has minimal impact, while at high velocities, roughness significantly affects near-wall turbulence structure and frictional resistance, thereby substantially influencing penetration efficiency.

[Figure 7: see original paper] shows penetration efficiency results for carbon steel pipes (D=50 mm, L=5 m), while [Figure 8: see original paper] presents dimensionless relaxation time variations for 2 m, 5 m, and 10 m aerosols under different flow velocities. Different τ^+ values correspond to different dominant deposition mechanisms: $\tau^+ < 1$ represents the diffusion regime dominated by Brownian diffusion; $1 < \tau^+ < 10$ represents the diffusion-impaction regime influenced by turbulent eddies and inertial forces; and $\tau^+ > 10$ represents the inertial regime dominated by particle inertia.

[Figure 9: see original paper] compares penetration efficiency results for 2 m, 5 m, and 10 m aerosols in stainless steel pipes with diameters of 50 mm and 110 mm. Larger pipe diameters yield higher penetration efficiency because particles must travel longer distances to reach the wall. For 2 m and 5 m aerosols, penetration efficiency increases with flow velocity regardless of pipe diameter. As shown in [Figure 8: see original paper], these aerosols primarily reside in the diffusion regime, with modified model calculations yielding dimensionless deposition velocities in the low range of 10^{-5} to 10^{-3}, accurately reflecting Brownian-motion-dominated settling. The 10 m aerosol transitions through diffusion, diffusion-impaction, and inertial regimes, with deposition velocity increasing with flow velocity, resulting in the observed parabolic penetration trend.

This study developed a calculation model for aerosol penetration efficiency in horizontal pipes considering pipe factors (diameter, length, wall roughness) and aerosol factors (particle size and density). The model shows good agreement with both current and historical experimental data, providing a reference for radioactive aerosol penetration efficiency. Key conclusions from the factor analysis are:

1. Pipe inner surface roughness significantly affects aerosol deposition rates by altering the near-wall flow field and frictional resistance. Micron-scale roughness variations can cause turbulent deposition rates to fluctuate by up to an order of magnitude, as demonstrated in [Figure 5: see original paper] and [Figure 6: see original paper].
2. For aerosols in the diffusion-impaction regime in horizontal pipes, penetration efficiency is influenced by gravity, turbulent eddies, and residence time, resulting in an optimal sampling flow velocity that maximizes penetration efficiency.
3. Small particles in the diffusion regime follow the flow better and are less affected by turbulent inertia. Their deposition is primarily controlled by gravity and Brownian diffusion mechanisms, resulting in lower deposition velocities.

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