Journal of Hazardous Materials 280 (2014) 226–234

Contents lists available at ScienceDirect

Journal of Hazardous Materials

journal homepage: www.elsevier.com/locate/jhazmat

Development of a self-cleaning dispersion and exposure chamber: Application to the monitoring of simulated accidents involving the generation of airborne nanoparticles

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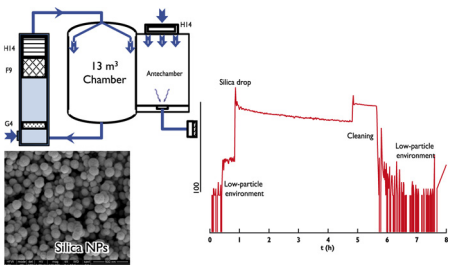
HIGHLIGHTS

- Design of an airtight and self-cleaning chamber for dispersing hazardous matter.
- Dispersion testing in both low-particle and background-filled environments.
- Accidental release of nanosized silica analyzed in terms of source strength.
- Released nanoparticles reached a peak in the most penetrating size range.
- Stronger matter release in low-particle environments than in particle-filled media.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 29 April 2014
Received in revised form 4 July 2014
Accepted 24 July 2014
Available online 4 August 2014

Keywords:
Exposure chamber
Nanosafety
Nanoparticle emission
Source strength

ABSTRACT

The release of hazardous nanoparticulate matter in accidental situations was simulated in a specially designed 13-m^3 stainless steel airtight chamber, which allowed the dispersion analysis of airborne matter in a practically particle-free environment (less than 2 #/cm^3) and in presence of background atmospheric aerosols. A fast recovering of the initial situation was achieved by means of a tandem HEPA-filtered air and deionized water system. Both unintended spilling of silica-based nanoparticulate powders and continuous emission of 100-nm SiO_2 nanoparticles were used as aerosol generation events. The emission of airborne nanoparticles was analyzed in terms of particle number concentrations (PNC), size distributions and source strengths. The emission of nanoparticulate aerosols reached peak PNC for particles in the range from 5 nm to 1 μm with source strengths about 10^8 #/h in a background-filled environment and 10^{10} #/h in a practically particle-free atmosphere. No agglomeration was noticed for the released nanoparticles, suggesting that PNC was low enough to prevent coagulation and that particle diameters were over 80 nm. Results indicate that emitted matter was within the range of the most penetrating particle sizes and with source strengths similar to accidental scenarios.

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http://dx.doi.org/10.1016/j.jhazmat.2014.07.053
0304-3894/

1. Introduction

The health [1–3] and environmental [4–6] consequences related to the exposure to airborne nanosized matter have stirred a considerable scientific and technological interest. This has exceeded the basic research in the laboratory [7] or industrial processes and consumer products [8] reaching to the regulatory bodies to develop decision-making environmental policies on the basis of the particle number concentration (PNC) [9,10]. The distribution of the atmospheric nanoparticles could be considered uncertain and only a few studies have reported the modeling the environmental concentration of nanoparticles [11]. Since the impact of engineered nanoparticles in health could be considerably larger [12] even at smaller concentrations than naturally occurring nanoparticles, a growing interest in safer and environment-friendly nanotechnologies has been developed [13,14]. A large share of this concern was linked to the nanotechnology industry, where some accidental scenarios involving nanomaterials have been recently reported in which emerged the need of adequate risk management schemes [15].

Several facilities have been designed to study and validate indoor settings dealing with the release of nanosized matter. Seipenbusch et al. [16] performed a detailed theoretical and experimental analysis of the time-based evolution of Pt nanoparticle aerosols generated on line by an evaporation/condensation procedure in an aluminum chamber with a volume of 2 m^3 with a filter-equipped air inlet to prevent the pressure drop. They monitored both the evolution of particle number concentrations and size distributions for several hours to determine the agglomeration kinetics in high-concentrated aerosols (about 10^6 #/cm^3) and to reveal the fate of nanoparticles in workplaces. This study was further developed [17] in a similar chamber enclosure to predict the agglomeration behavior of both Au nanoparticles produced using spark discharge and DEHS generated by atomization, showing that coagulation is found concentrations over 10^5 #/cm^3 for particles up to 1 μm. Nørgaard et al. [18] studied the release of volatile organic compounds (VOCs) and particles during the use of commercial nanofilm spray coatings in a closed stainless steel chamber with cylindrical shape and a testing volume of 0.66 m^3. Their results showed the increase in number concentration up to 10^8 #/cm^3 for sizes from 6 to 600 nm during the application of those products in conditions similar as reported in households. Furthermore, Frijns et al. [19] presented an indoor 72-m^3 chamber to simulate occupational exposure conditions and processes that involve the emission of nanosized matter. This system allowed a negative pressure system and controllable flows in the internal volume of the system using HEPA-filtered inlets, while monitoring temperature and humidity in the chamber. A similar 32-m^3 chamber with continuous air exchange had been proposed to test the indoor sources of fine and ultrafine particles produced during daily life activities [20]. All reported exposure chambers were designed to keep a constant air renewal system that removed airborne matter, depleting nanoparticle concentration during tests that could hinder part of the aerosol dynamics in the case of low concentrations or in still air conditions. In fact, the indoor wind velocities at industrial locations rarely exceed 0.3 m/s [21], which can be practically considered as stationary and where the released nanosized matter could be breathable for long periods. Moreover, Su & Vincent [22] reported on the use of aerosol samplers in calm air to collect micrometric glass particles in a stainless steel chamber with an analysis volume of 1 m^3.

Up to date, handling nanoparticle emissions in simulated working environments required complicated and time-consuming protocols. This was especially remarkable for removing the deposited nanomaterials in the internal surfaces, which were rarely specified. There is a need to challenge adequate testing compartments for the emission of nanoparticle aerosols with potential impact in human health and the environment. Such environments would be crucial to understand the behavior of indoor nanosized matter at different concentrations and size ranges in large-scale conditions similar to real life scenarios. To this end, we have developed a 13-m^3 dispersion room specially designed to simulate indoor environments and exposure conditions to carry out hazard measurements avoiding the costs and difficulties of real life scenarios. The chamber consisted in a sealed space for the analysis of the temporal and spatial evolution of the emission of nanoparticulate matter. This test environment was designed to eliminate the deposited matter after dispersion tests using a high-pressure stream of deionized water that was sprayed along the inner walls from the center point using a rotating nozzle. Using this self-cleaning test chamber, we have simulated the emission of hazardous aerosol matter. Since the risk assessment of the emission of nanoparticles usually takes into account either a spontaneous [23] or a continuous release [24,25], both situations have been considered as potential sources of nanoparticles. The drop of dry silica nanoparticulate powder in the center of the chamber was used for testing a spontaneous emission of nanomaterials upon a handling accident. The continuous release of nanosized matter was simulated by the injection of silica nanoparticles for prolonged periods, in order to simulate the emission from damaged pipes. The evolution of indoor PNC, particle sizes and source strengths was simultaneously analyzed under still air conditions, simulating the natural convection mixing of real indoor scenarios.

2. Experimental

2.1. Design and construction of the chamber

The setup consisted of four functional zones: dispersion area, air purification system, water cleaning unit and detection and control devices. The main chamber (Fig. 1(a)) consisted in a cylindrical (2.5 m wide and 3.5 m height) stainless steel container with a total volume of 13 m^3. The cylindrical shape avoided stagnant areas common to clean rooms with parallel walls, while allowing easy access to internal areas. The indoor atmosphere was sampled through 18 ports located at three different levels along the external surface, which permitted the connection of measuring and control equipment through airtight clamps. Four inspection windows granted a quick and easy visual check of the interior. The air supply unit (Termoven, Madrid, Spain) consisted in an insulated box of galvanized steel with mounted fan and filters (Fig. 1(b)). The air stream was purified by sequentially passing through a G4, F9 and H14 HEPA filters (according to standard EN 779:2011, G4 efficiency > 90% for synthetic dust, F9 efficiency > 95% for 400-nm DEHS particles, H14 efficiency > 99.995% for the most penetrating particle sizes). The purified air stream was driven through the main chamber from the upper part using an air deflector to direct the purified airflow towards walls. Finally, shut-off dampers for the isolation of the internal volume during tests were located in both inlet and outlet 0.4-m diameter pipes at the top and bottom of the chamber. The cleaning of the internal surfaces was performed using a deionized water spray system that consisted in an Elix-10 (Millipore, Billerica, MA) water treatment device, which was further sprayed throughout the inner volume of the chamber by means of a rotating spray nozzle located at the top (see supplementary data file for details). This washing procedure removed both the airborne matter and the deposited particles onto walls and inner surfaces. A subsequent high-flow dry air stream eliminated the excess humidity out of the dispersion volume, which at the end provided a clean and practically particle-free atmosphere. At the end, the cleaning procedure allowed a fast recovering of the background conditions in terms