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Reduction of exposure to nanoparticles by a local exhaust ventilation system during nanopowder mixing

Introduction

According to the report from the European Agency for Safety and Health at Work nanomaterials are one of the main and new hazards to the health of workers [*Kosk-Bienko, 2009*]. Exposure to nano-objects can occur through inhalation, ingestion and through the skin. Given that nanoparticles are able to penetrate the airway epithelial cells and may also be transported to the brain [*Kao et al., 2012*], the greatest risk is attributed to inhalation exposure.

Nanomaterials are usually used because of their high reactivity, hence they can have more side effects than composite materials with a particle size of micrometer. A small dimension of nano-objects makes their surface area large and their volume small. They are also characterised by greater capacity to adsorb other surface molecules [*Świdwińska-Gajewska et al., 2013*].

For this reason, there is a need at present to develop methods and measures to protect human health against the risk of airborne emission of engineered nano-objects, particularly in the processing of nanomaterials [*NIA, 2010*]. Rooms with nano-objects should have efficient technical solutions in place unabling such airborne agents to spread indoors. Furthermore, rooms should be equipped in a well-functioning local ventilation system to ensure air exchange, a necessary element for elimination or reduction of exposure to such agents.

The effectiveness of local exhaust ventilation (LEV) can be presented in terms of quality and quantity as the ability to stop and remove one or more pollutants that are released from a source inside the workspace. It can also be defined as the ability to limit possible distortions caused by draughts, movement of operating personnel or personnel passing nearby the emission source. In light of the fact that the parameters of the housing or the exhaust system are closely dependent on the emission parameters of nano-objects in a given room, examination of a local ventilation system under real conditions of use is of particular importance.

The primary focus of a number of studies is to assess adverse health effects of nano-objects on the worker in processing of nanomaterials [*Murashov et al., 2011; Yokel et al., 2011; Kuemple et al., 2012*]. Existing research on the protection against the health hazard potential in processing of nanomaterials involve the adaptation of ventilation solutions applied elsewhere to new and emerging risks associated with releasing nanomaterials into the environment.

The recent studies have sought to determine, among others, spatio-temporal distributions of physicochemical parameters of the airstream in the mining excavation [*Dziurzyński et al., 2012*]. It has been decided that the most effective method for determining air volume in the excavation is to define the velocity profile. Cross-sectional data from sensors could serve as the basis for qualitative and quantitative verification of multi-point measurements using anemometric stationary sensors. Data from parameter recordings could be furthermore used for calculations, making analyses, or could be viewed as input data for computer simulations to optimise modelling of air distribution.

Krach and others have developed a system [*Krach et al., 2006*] to study a distribution of the velocity field in the cross section of the excavation. A special design of the bearing system consisted of anemometric sensors which not only enabled measurements of local velocities and determination of the velocity profile, but it also allowed for determining the intensity of air volume flow based on appropriate mathematical models. A dozen methane concentration sensors, integrated with anemometers, were arranged on the grill to record distributions of air velocity and concentrations of methane in the section mining pits. The results of the measurements, made as part of the measuring experiments, proved significantly different from the results obtained by the mine ventilation services, who determine the air volume using stationary anemometers. Data recorded during the crossbars revealed lack of regularity in the distributions of air velocity in the mine workings.

Methods applied to make an anemometric measurement of airflow velocity served to evaluate performance properties of different local ventilation systems at various workstations in industry [*Bell, 2009*]. *Bemer et al.* [*2002*] used tracer methods for the assessment of process parameters of exhaust ventilation and evaluation of the pollution emission intensity from the source of their emission.

Makowski and *Orciuch* [*2011*] applied the anemometric and tracer methods to study local distributions of fluid velocity and tracer concentration in a tank reactor used in industry. *Cao et al.* [*2014*] examined the impact of various ventilation systems, including mixing and displacement ventilation, on air velocity distribution in buildings. According to the research findings, there are 5 main parameters responsible for shaping the indoor air: the rate of air, pollution removal efficiency, heat exchange, emission intensity and distribution of air velocity. *Prasauskas et al.* [*2013*] studied an influence of the distribution of air velocity on spreading airborne pollutants in the test chamber during the use of one- and two-way mixing ventilation. At present, due to the increasing production of nanomaterials in various fields of industry, research should address the problem of modelling air distribution in such a way so as to reduce the risk of the exposure to nano-objects.

The impact of air distribution on airborne pollutants near workstations in processing of nanomaterials is assessed, in particular, in connection with the processes of mass transport, heat and momentum, i.e. the molecular and turbulent diffusion, spreading of pollutants in the field of air velocity or electrostatic interaction.

Methods and experimental set-up

The parameters for the assessment of the distribution of ventilation air near the emission source are defined with *[EN 12599, 2012]*:

- an anemometric method to determine the volume airflow in the exhaust duct, air velocity on the face of working surface and air velocity distribution in surroundings of emission source,
- gas analyzer method allowing for the measurement of mass and number concentration and air exchange efficiency rate in surroundings of emission source.

Changes in the air velocity in the range from 0.10 to 20 m/s are determined with a set of thermo-anemometers (*Testo,* Germany). Fig. 1 shows the positioning of measuring probes of multipoint system.

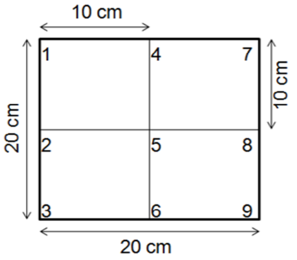

Fig. 1. View of the measurement module and placement of probes for measuring air velocity in surrounding emission sources

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The probe should be placed on the inner plane of the measuring points formed at the intersection of the following lines (Fig. 1):

- a series of at least three lines, evenly spaced between the lateral boundaries of the inner plane of the measurement, out of which two external lines are within (100 ± 5) mm from the lateral limits. The lines in the middle should be at a distance of up to 400 mm from the external lines and from each other;
- a series of at least three lines, evenly spaced between the horizontal limits of the inner plane of the measurement, out of which two external lines are within (100 ± 5) mm from the horizontal limits. The lines in the middle should be at a distance of up to 400 mm from external lines and from each other.

The measurements should be made with a probe located at each point of the measurement grid. Disturbances in the counter-sensor should be minimised and for each measuring point the turbulence intensity of air velocity *Tu,* [%] should be calculated. The intensity of turbulence is defined as the ratio of air velocity standard deviation S_r, [m/s] to the average air velocity at the measuring point $V_{av,n}$, [m/s]. It is determined by the following equation:

$$T_u = \frac{S_r}{V_{av,n}} \cdot 100 \tag{1}$$

where:

$V_{av,n}$ – the average air velocity in *n* at the measuring point, [m/s]

S_r – the air velocity standard deviation, [m/s]

A better and more balanced air distribution system results in a lower intensity of turbulence.

The gas analyzer method uses a spectrophotometer *Dust Trak* and condensation particle counter CPC. *Dust Trak* meter model 8520 (*TSI,* USA) enables measurement of the actual mass concentration of dust having a particle size from 0.1 µm to 10 µm in the range of 0.001 mg/m^3 to 100 mg/m^3. The condensation particle counter *CPC* model 3775 (*TSI*, USA) allows the counting of particles in the range of 4 nm to 3 mm, and measuring the number concentration of the particles to 10^7 particles/cm^3 at the measurement inaccuracies dependent on the concentration and measuring methods:

- ± 10% for concentrations up to $5 \cdot 10^4$ particles/cm^3 with a continuous correction due to coincidence,
- ± 20% for concentrations between $5 \cdot 10^4 \div 10^7$ particles/cm^3, a photometric method.

For a given position settings front face of ventilation air pollution concentration measurements performed with on C_{on} [particles/cm^3] and off C_{off} [particles/cm^3] ventilation systems. Calculate rate of air changes *E,* [%] as the quotient of the difference the average concentration of air pollution on and off ventilation using the formula:

$$E = \frac{C_{off} - C_{on}}{C_{off}} \cdot 100 \tag{2}$$

where:

C_{off} – the average concentration of air pollution without ventilation, [mg/m^3 or particles/cm^3]

C_{on} – the average concentration of air pollution with ventilation, [mg/m^3 or particles/cm^3]

Materials

The process of mixing was nanopowder of silicon oxide SiO_x APS 20 nm. In order to determine how changes in a ventilation system influence the parameters of air distribution in and around the workspace of emission sources of air pollutants used in processing of nanomaterials, four variants of ventilation were applied (Tab. 1):

- a ventilation system turned off,
- stationary local exhaust ventilation turned on – hood,
- mobile local ventilation turned on – nozzle,
- a partial housing turned on – chemical fume cupboard.

A diagram of the study was as follows. The first hour of the study was carried out with the emission sources of air pollutants switched off (as a benchmark). It was then followed by a three minute variant with the emission source of air pollutants enabled. And next, for another hour, yet another variant had the emission source switched off. Tests were repeated 6 times and were conducted according to the following diagram (Fig. 2).

Table 1. The values of the exhaust air flow Q and the statistics in various ventilation

Ventilation variant	Average air flow rate, m^3/h	Std. deviation, m^3/h
Hood	203.2	2.8
Nozzle	212.9	2.3
Fume cupboard	1381.9	15.4

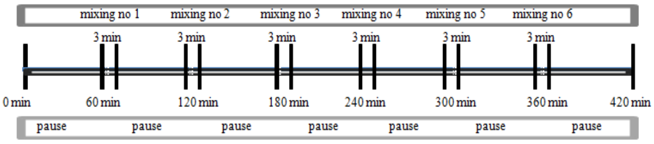

Fig. 2. Test procedure

Results and Discussion

The study on the distribution of air velocity around the object of research shows that directions of air flows tend to change both in horizontal and vertical planes proportionately to the distance from the emission source (Fig. 3).

Fig. 3. The air velocity distribution in the working emission source of air pollution

It has been found that when ventilation is turned off, air pollutants are lifted by air volume flow in the mixing process. The application of a partial housing and local exhaust ventilation caused differentiation of air velocity (an increase in the value and extension in the range of increased index values of intensity turbulence) near an emission source and a ventilation system (Fig. 4).

An interaction of a ventilation system with emission sources of air pollutants directed airflow straight from the source to the front surface of the exhaust duct. Increased velocity of air near the emission sources and the intensity of turbulence discharged from the emission workspace influenced the parameters associated with the intensity of

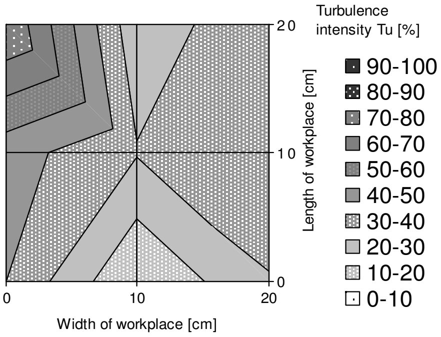

Figure 4 The turbulence intensity distribution in working emission source of air pollution

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air pollution (measurement parameter – concentration of nanoparticles) and efficiency of LEV (the measurement parameter – rate of air exchange). Larger values of air velocity and turbulence intensity in the workspace of emission source enabled a decrease in concentration of nanoparticles and an increase in the rate of air exchange (Fig. 5).

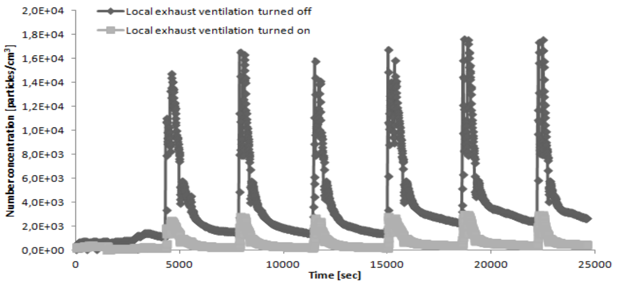

Fig. 5. Ventilation efficiency and number concentration changes in air pollution

An analysis of the study on the distribution of ventilation air in the proximity of emission sources in mixing of nanopowders, made it possible to compare ventilation systems in terms of their efficiency capture (Fig. 6, 7, 8).

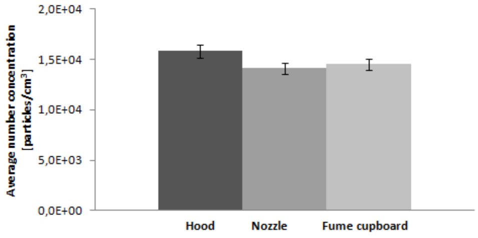

Fig. 6. A comparison of average number concentration of tested sources for mixing of nanopowders and turned off different kinds of ventilation

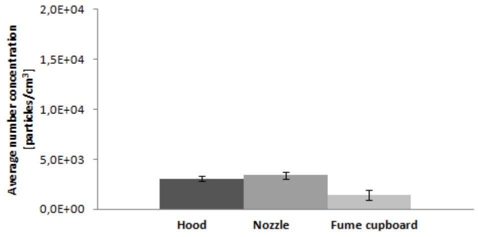

Fig. 7. A comparison of the number concentrations of the investigated sources for mixing nanopowders and turned on various types of ventilation

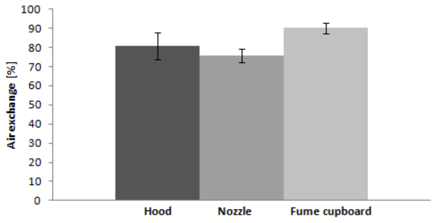

Fig. 8. A comparison of average air exchange rate during the processing of nanopowders mixing with local exhaust ventilation and the housing partial

Conclusions

An analysis of the results showed that an interaction with a local ventilation system has a significant influence on the parameters of air distribution in the workspace of emission sources of air pollutants in mixing of nanomaterials.

In those studies conducted under laboratory and real use conditions, anemometric measurements of air flow have an important role to play. The methods allow for illustrating and defining the role of individual parameters which are specific for spreading airborne pollutants from their emission source.

A study on the distribution of ventilation air around emission sources associated with mixing of nanomaterials can be used to compare the ventilation systems in terms of their efficiency capture. As compared to efficiency of local ventilation at the emission source, the highest efficiency in air exchange (over 90%) was reached by combining mixing of nanomaterials with a partial housing together with chemical fume cupboard.

The research methods presented in this article can be helpful in designing and verifying ventilation performance with a view to ensuring effective protection of workers against adverse health effects of air pollutants emitted from the sources of processing of nanomaterials.

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