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Spatial and temporal variations of particulate matter concentrations in multifamily apartment buildings

Tadas Prasauskas [a], Dainius Martuzevicius [a,*], Edvinas Krugly [a], Darius Ciuzas [a], Inga Stasiulaitiene [a], Ruta Sidaraviciute [a], Violeta Kauneliene [a], Lina Seduikyte [b], Andrius Jurelionis [b], Ulla Haverinen-Shaughnessy [c]

[a] Department of Environmental Technology, Kaunas University of Technology, Radvilenu pl. 19, LT50254 Kaunas, Lithuania
[b] Department of Building Energy Systems, Kaunas University of Technology, Radvilenu pl. 19, LT50254 Kaunas, Lithuania
[c] Department of Environmental Health, National Institute for Health and Welfare, Neulaniementie 4, Kuopio FI-70701, Finland

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A B S T R A C T

We report a comprehensive assessment of PM concentrations and its variations in multifamily apartment buildings. Fifty apartments in ten multifamily buildings were investigated during heating seasons of 2011 and 2012 in Kaunas city, Lithuania. PM concentration and size distribution measurements were performed using the optical particle counters indoors and outdoors. Usually mean 24-h indoor PM concentrations were lower (median 7.8 μg/m^3 for $PM_{2.5}$) than outdoor concentrations (median 16.9 μg/m^3 for $PM_{2.5}$) of corresponding location, and I/O ratios of $PM_{2.5}$ were lower (0.70) than that of PM_{10} (0.98). Night time levels, representing background indoor exposure to PM, were equal to 5.0 ($PM_{2.5}$) and 6.7 μg/m^3 (PM_{10}), respectively. Particle deposition rates were determined by regression fitting of the measured $PM_{2.5}$ concentration decay curves, with the median equal to 0.32 h^{-1}. The data have been discussed aiming to characterize indoor PM sources and select the most representative indicator(s) for an assessment of the effects of energy saving refurbishment on indoor air quality. We found that a combination of several indicators allowed an adequate characterization of indoor PM sources and can be used in the subsequent assessment.

1. Introduction

The living environment is very important for overall human well-being. Indoor air quality (IAQ) is one of the most important factors influencing indoor microclimate. At the same time, airborne particulate matter (PM) is considered to be one of the key pollutants due to its complexity and adverse health effects. PM, especially its fine fraction, referred to as $PM_{2.5}$ (particles with aerodynamic diameter lower than 2.5 μm) has been associated with various adverse health effects [1–6]. A report from WHO [7] stated that on a global scale, 4–8% of premature deaths are related to the exposure to PM in the ambient and indoor environment. Franck et al. [8] has revealed significant associations between indoor particle concentrations and the risks for respiratory diseases in young children, and indicated that short-term measurements can help to assess the health risks of indoor particles.

The indoor environment has multiple sources of PM. Among those, outdoor pollution is identified as a key factor influencing indoor air particle concentrations due to its continuous impact [9–12]. Major outdoor particle pathways into the indoor environment are through open windows and infiltration or penetration through cracks and fissures of a building envelope [13]. The main urban outdoor PM sources during heating season are fuel combustion, transport exhaust, and atmospheric reactions [14–16]. Multiple sources such as cooking, smoking, candle, and incense burning as well as cleaning activities have been found to be significant PM emitters indoors [17–27]. Type of stove or oven, the time of the year and the floor area in the dwelling affect the concentrations of fine particles indoors as well [28].

During the past decade a number of studies have been conducted involving indoor and outdoor measurements at single-family homes [10,22,24–27,29–35] and multifamily residential buildings [36–40]. The most recent studies have focused on continuous measurements of indoor and outdoor ultrafine particle concentrations (UFP), including analyses of temporal and spatial variability [27,41,42].

* Corresponding author. Tel.: +370 61325111; fax: +370 37 300 152.
E-mail address: daimart@ktu.lt (D. Martuzevicius).

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Increasing requirements for the building energy efficiency (EE) raise new challenges for IAQ management. The countries within the European Union have assumed commitments to build low energy consumption buildings from 2016 to 2020 [43]. This usually means improving EE and air tightness of the building envelope. In the future, EE of existing buildings must also be improved. The main goal of the building refurbishment process is energy saving and improvement of building systems, but the improvement of occupants' wellbeing should also be considered as one of the most important refurbishment goals. From this perspective, IAQ research in low energy/refurbished buildings is of high importance. The modification of building systems, including structures (e.g. insulation of external walls) and heating, ventilation, and air conditioning (HVAC) systems, and new building materials, may have a significant influence on IAQ and subsequently, PM levels.

Selected multifamily apartment buildings were located in the Kaunas city area. It is the second-largest city in Lithuania (pop. 311 100; total area 157 km^2). About 66% of the Lithuanian population lives in multifamily houses built before 1993. Some 5000 multifamily buildings (majority has been built during the period of the Soviet Union) are located in the Kaunas city, of which 26% were built before 1960, 65% between 1960 and 1990, and the remaining 9% after 1990. The average age of the buildings is about 40 years. These buildings are known for their leaky envelope, low thermal insulation, and unbalanced both heating and natural ventilation systems. The combination of these parameters results in a wide variety of IAQ issues.

We report a comprehensive assessment of PM concentrations and its variations in Lithuanian multifamily apartment buildings, researched in a framework of INSULAtE (Improving energy efficiency of housing stock: impacts on indoor environmental quality and public health in Europe) project. The results presented in this paper reflect a pre-refurbishment measurement phase. A specific aim was to select comparative parameters and indicators for demonstration of the effects of refurbishment on IAQ.

2. Methods

2.1. Measurement design

Ten multifamily buildings (five apartments per building) were included in the measurement campaign during two heating seasons of years 2011 and 2012 (Dec 2011–Apr 2012 and Oct–Dec 2012). The winter time was chosen because of presumably lower impact of outdoor air entering through open windows, more stable thermal conditions indoors [44], and longer time spent at home by residents. Measurements were performed during working days (Monday–Friday). All buildings were located in urban areas, affected by traffic pollution from streets. The apartments were selected with the aim to represent different conditions within the building, such as facing south and north directions; upper and lower floor; situated in the middle and corners of the building. General characteristics often case study buildings are presented in Table 1.

2.2. Measurement methods

PM concentration and size distribution measurements were performed using optical particle counters (OPCs, Handheld 3016 IAQ, Lighthouse Inc, USA). These units are capable of classifying aerosol particles into six channels by optical diameter: >0.3, >0.5, >1.0, >2.5, >5.0 and >10.0 μm at the flow rate of 2.83 l/min. Direct-reading instruments allowed the estimation of highly time-resolved fluctuations (1 min averaging) of pollutant concentrations, corresponding to daily activities of inhabitants or other pollution sources. Sampling duration in each apartment was at least 24 h (full day measurement). PM mass concentrations were calculated based on particle density of 1.5 g/cm^3. The density of ambient particles mostly falls within 1.2–1.8 g/cm^3 [45,46]. Particle density is an important parameter affecting the calculation of particle mass from number measurements with OPCs [47]. In this perspective, the absolute mass concentration values presented in this manuscript may be biased compared to gravimetric measurements. The OPCs are also known for varying responses to different density, refractive index and shape of particle [48]. They are also not capable of detecting nano-sized particles (<0.3 μm). On the other hand, they are compact and lightweight devices providing highly time-resolved particle size distributions and are extensively utilized in indoor and ambient air quality measurement studies [35,49–52].

In each apartment, measurements were conducted indoors and outdoors. One OPC was set indoors, mostly in the living room, positioned in the area with no primary activities. The indoor sampling height was chosen according to the human breathing zone as seated, i.e. 1.2–1.5 m above ground. Another OPC was set outdoors in the apartment's balcony or hung outside of the window. The OPCs were enclosed in insulated boxes (specially adapted cooler boxes) with the aim to protect them from environmental stress as well as to protect the inhabitants from the pump noise.

In parallel to the PM measurements, the ambient temperature and relative humidity (DT-172 logger, Shenzhen Everbest Machinery Industry Co., Ltd, China) and concentrations of CO_2 and CO (HD21AB IAQ Monitor, Delta OHM S.r.L., Italy) were recorded. The effectiveness of natural ventilation was determined by anemometer (417, Testo AG, Germany) by on-spot measuring of air flow velocity through the air vents. The vents are usually sized as 0.14 × 0.18 m, sometimes having a mechanical blower installed, which operates on a short-term basis. Vents in the kitchen are often connected to the stove exhaust hood. The occupants were asked to fill diaries for the assessment of daily indoor and outdoor activity patterns.

Table 1
General characteristics of ten case study buildings.

Building no.	Year of construction	Type of ventilation	Type of construction	No. of floors	No. of apartments	Total floor area, m^2	Average floor area per apart., m^2
B1	1965	Natural[a]	Panel Ferro concrete	5	100	5270	49.5
B2	1957	Natural[a]	Brick	3	25	2384	66.7
B3	1979	Natural[a]	Brick	13	60	4946	61.8
B4	1975	Natural[a]	Brick	12	48	3726	62.1
B5	1992	Natural[a]	Brick	5	60	3331	47.2
B6	1982	Natural[a]	Brick	5	51	3277	54.6
B7	1992	Natural[a]	Brick	5	30	2056	58.3
B8	1981	Natural[a]	Brick	12	60	3445	51.7
B9	1960	Natural[a]	Monolithic Ferro concrete	3	30	2531	59.3
B10	1958	Natural[a]	Monolithic Ferro concrete	3	18	1344	57.5

[a] Most of the apartments had a mechanical exhaust hood above the kitchen stove.