air exchange at 50 Pa differential

Use of low-cost PM-sensors to determine the infiltration of outdoor particles into indoor environments

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Abstract. Whether due to traffic, industry or private households – particulate matter enters our air every day and pollutes the air we breathe. When the term air pollution is used, hardly anyone ever thinks of the air inside their own home. However, many urban residences are located in the immediate vicinity of busy roads with high concentrations of particulate matter. Consequently, the outside concentration of fine dust has considerable influence on the indoor concentration. Given the fact that many people spend more than 90 % of their lifetime indoors, it is important to measure and understand particle transport from the outside to the inside in order to assess the effects of exposure to outdoor particles on human health. A two-room apartment near a main road in Leverkusen, North Rhine-Westphalia, Germany was used in the investigation in this research project. Particulate matter concentrations for PM2.5 and PM10 were measured simultaneously inside and outside of the building. Results are size-specific deposition rates, indoor/outdoor ratios and infiltration factors, which provide information on the relationship between internal and external concentrations and the associated health consequences. The particulate matter concentration was measured using low-cost PM-sensors, which were developed and calibrated within the scope of this research project.

n50

Nomenclature

			pressure (h ⁻¹)
a	infiltration air change rate (h ⁻¹)	Р	penetration coefficient (dimensionless)
a_k	intercept (dimensionless)	0	volumetric airflow rate (m ³ h ⁻¹)
b	slope (dimensionless)	\widetilde{Q}_d	volumetric airflow due to deposition
C_{end}	indoor PM mass concentration at the	-	$(m^3 h^{-1})$
	end of the deposition process ($\mu g m^{-3}$)	R^2	coefficient of determination (%)
C_i	indoor PM concentration ($\mu g m^{-3}$)	S	standard deviation of regression
$C_{i,m}(t)$	indoor PM mass concentration at time t,		$(\mu g m^{-3})$
	$C_i(t) (\mu \mathrm{g} \mathrm{m}^{-3})$	SDS _{PM.meas}	measured particle mass concentration of
C_o	outdoor PM concentration (µg m ⁻³)		the uncalibrated SDS ($\mu g m^{-3}$)
C_s	indoor PM mass concentration at the	SDS1 _{PM10.calib}	particle mass concentration (PM10) of
	beginning (start) of the deposition		the calibrated SDS1 ($\mu g m^{-3}$)
	process (µg m ⁻³)	SDS1 _{PM2.5,calib}	particle mass concentration (PM2.5) of
feff.comp	Correction factor for the system and		the calibrated SDS1 ($\mu g m^{-3}$)
	component-dependent infiltration to be	SDS2 _{PM10,calib}	particle mass concentration (PM10) of
	taken into account when dimensioning		the calibrated SDS2 ($\mu g m^{-3}$)
	the ventilation components	SDS2 _{PM2.5,calib}	particle mass concentration (PM2.5) of
	(dimensionless)		the calibrated SDS2 ($\mu g m^{-3}$)
$f_{eff,loc}$	Correction factor for the effective	SS_{Error}	sum of the deviation squares for the
	infiltration air content as a function of		model-specific errors (µg m ⁻³) ²
	the building location (dimensionless)	SSRegression	sum of the deviation squares estimated
F_{in}	infiltration factor (dimensionless)		in the regression model $(\mu g m^{-3})^2$
I/O profile	average indoor/outdoor ratio profile	SS_{Total}	sum of the observed deviation squares
	(dimensionless)		of all cases ($\mu g m^{-3}$) ²
I/O ratio	indoor/outdoor ratio (dimensionless)	V_{eff}	effective volume of the test room (m ³)
k	deposition rate (h ⁻¹)	x_i	random PM concentration of the
k_i	number of independent variables		uncalibrated SDS, SDS _{PM,meas} (µg m ⁻³)
	(dimensionless)	\overline{x}	arithmetic mean of the measured PM
n	sample size (dimensionless)		concentration of the uncalibrated SDS
ni	pressure exponent (dimensionless)		$(\mu g m^{-3})$

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y_i	random PM concentration of the Model		
	5030 SHARP (µg m ⁻³)		
\overline{y}	arithmetic mean of the measured PM		
	concentration of the Model 5030		
	SHARP, $(\mu g m^{-3})$		
ŷ	estimated PM concentration for the		
	calibrated SDS, SDS _{PM,calib} (µg m ⁻³)		
∆p	rated differential pressure (Pa)		
λ	time constant (h ⁻¹)		
$(dC_{i,m}(t)/dt)$	rate of change of indoor PM mass		
	concentration, $(dC_i(t)/dt)$ (µg m ⁻³ min ⁻¹)		
$(dC_i(t)/dt)_{dep}$	indoor PM deposition rate		
	$(\mu g m^{-3} min^{-1})$		
$(dC_i(t)/dt)_{exf}$	PM exfiltration rate (μ g m ⁻³ min ⁻¹)		
$(dC_i(t)/dt)_{inf}$	PM infiltration rate ($\mu g m^{-3} min^{-1}$)		
$(dC_i(t)/dt)_{gen}$	indoor PM generation rate, E		
	$(\mu g m^{-3} min^{-1})$		
$(dC_i(t)/dt)_{res}$	indoor PM resuspension rate, R		
	$(\mu g m^{-3} min^{-1})$		

1 Introduction

At present, air pollution is a major problem in many regions of the world. Recent studies by the Max Planck Institute (MPI) concluded that 3.3 million people worldwide die prematurely each year as a result of air pollution. According to the MPI, this figure could double by the year 2050 if emissions continue to rise at the same rate [1]. This continuous increase in air pollution has been known for quite some time and is increasingly being perceived by the general public as a threat to health and the environment. The European Directive 2008/50/EG, which was transposed into national law by the 39th Federal Immission Control Ordinance (39th BImSchV), defines limit values for outdoor air pollutants in Germany. State agencies check these limit values by means of individual measuring stations. Indoor air quality, on the other hand, is not legally anchored anywhere in Germany and is not monitored, even though we spend 90 % of our life indoors and breathe in the air there. Nevertheless, particular importance is attached to air pollution by particulate matter, as many studies have shown the relationship between increased particulate matter concentration and morbidity/mortality [2, 3]. Airborne respirable particles are referred to as fine dust. The particle size of the particulate matter (PM) is described by a curve that is based on the separation curve of the human respiratory tract and has an aerodynamic diameter of 10 or 2.5 µm and a value of 50 % (PM10 and PM2.5) [4]. In reality indoor air is often more heavily polluted than the outdoor air. There are many reasons for poor indoor air quality. For example, furnishings such as furniture and carpets may contribute to a higher load, as well as, electronic devices such as printers or computers. In addition, there are continuous stresses from the metabolic processes of the inhabitants and their activities, caused by cooking, vacuuming, burning candles or the use of household products. Moreover, fine dust particles can enter the interior through ventilation or infiltration and contribute to increasing the particle concentration in the interior the same as like internal particle sources. The higher the air exchange, the higher the probability that fine dust particles from the outside air enter the interior. When the particles enter the building, they are not only deposited but are also influenced by various chemical and physical processes. This in turn influences their composition, distribution pattern or concentration [5]. There are three widely used parameters that provide information on the relationship between the internal and external concentration of particles. For closed and unused spaces, the penetration factor P can be determined, which is defined as the proportion of the particle fraction with a specific diameter, which in turn enters the interior with the incoming outside air [6]. It is a dimensionless number and can have values between 0 and 1. To determine it, the so-called deposition rate k and the air exchange rate amust first be determined. Both parameters can be determined using a natural decay test. In addition to the penetration factor, there is the indoor/outdoor ratio (I/O ratio), which, as the name suggests, represents the ratio of internal concentration to external concentration. This factor gives a first impression of the relationship between indoor and outdoor concentration in the respective building. However, various studies show that the I/O ratio varies greatly and is therefore not very meaningful [7]. Last but not least, the infiltration factor F_{in} should be mentioned, which represents the equilibrium state of surrounding particles. This refers to those particles that enter the interior from the outside and remain suspended. Mixing with particles from indoor sources is not assumed [7]. Measuring instruments must be used to determine these factors as well as for the aforementioned limit value monitoring. State of the art measuring methods differ considerably from each other, and range from gravimetry to spectroscopy and inertia principles. Recently more and more inexpensive optical aerosol spectrometers as well as photometers have been appearing on the market. The great advantage of optical metrology over all other methods is the considerably lower support and maintenance effort, which leads to very high data availability in continuous operation. One of the most popular low-cost PM-sensors at present is the Nova PM SDS 011 V1.3, which was used in this study. It was calibrated in this study and used to measure indoor/outdoor ratios, infiltration factors and deposition rates. The aim is to demonstrate that particle transport into the building can be visualized with little effort and lowcost equipment. In addition, the series of measurements carried out in this study will allow a better understanding of the transport processes and particle behavior in the room.

2 Methodology

2.1. Equipment and experimental setup

All experiments were carried out between November 2017 and August 2018. A two-room apartment near a main street in Leverkusen, North Rhine-Westphalia (NRW), was used for the investigations in this research project. The characteristic parameters of the apartment can be found in Table 1. The selected non-smoking

apartment is located on the first floor of an apartment building and measures 52.28 m². The bedroom was chosen as the test room because it is lockable and borders on the main road. The room has an 1.60 m x 1.30 m window and a room door to the hallway of the apartment. The apartment was usually used by two people. The bedroom was equipped with a bed and a wardrobe. Furthermore, the room had smooth surfaces on floors, ceilings and walls. The entire building was conditioned with natural ventilation and had no air conditioning or ventilation systems. The main objective of this study was the quantification of the actual particle concentration in the room as well as the determination of indoor/outdoor deposition rates and infiltration factors. ratios. Accordingly, in order to reduce the influencing parameters, the measurements were carried out while no occupants or other particle sources were in the room (excluding the I/O ratios). The PM10/2.5 indoor and outdoor concentrations were monitored simultaneously.

Table 1. Characteristics of the apartment.

Room name	Volume (m³)	Floor area (m²)	Floor level	Site description
Bedroom	38.53	15.29	1	Laminate floor, walls/ceiling primed and painted
Living room	39.37	15.62	1	Laminate floor, walls/ceiling primed and painted
Bath- room	10.94	4.34	1	Tile floor, walls/ceiling primed and painted
Kitchen	37.50	14.88	1	Laminate floor and some tile walls, most walls/ceiling primed and painted
Hallway	5.43	2.15	1	Laminate floor, walls/ceiling primed and painted

Two Nova PM sensors SDS 011 V1.3, which can detect the PM10 and PM2.5 fractions, were used to measure the particle mass concentrations. This sensor is referred to in the following as SDS and is only one component of the measuring device used (senseBox). The schematic structure of the measuring device and its positioning in the building is shown in Fig. 1. The senseBox is a weather station which originated from a Citizen Science project. The SDS installed in it is controlled via a microcontroller (Arduino Uno) and supplied with power via a mains plug. The measurement data can be recorded by the microcontroller in real time via WLAN. This low-cost PM-sensor SDS detects PM based on the optical scattered light principle and falls under the category of photometers. As a measure of particle concentration, the SDS uses all the light scattered

in a particle cloud. To determine the mass concentrations, the SDS assumes an unknown particle size distribution, which may lead to uncertainties. The SDS measures the particle mass concentration in the range from 0.0 to 999.9 μ g m⁻³ and has a maximum relative error of \pm 15 % and \pm 10 μ g m⁻³ at 25 °C and 50 % relative humidity.



Fig. 1. Schematic design of the building model and the measuring device

2.2 Calibration method

The SDS is not a measuring device for the direct determination of the mass concentration, but converts scattered light pulses via an algorithm into a mass. A separate calibration to determine individual calibration functions was performed for both sensors used (SDS1 & SDS2). A series of calibration measurements were performed for the SDS1 at Turiner Straße in Cologne using a Model 5030 SHARP (Synchronized Hybrid Ambient Real-time Particulate Monitor) from Thermo Fisher Scientific. The Model 5030 SHARP is an official measuring instrument of the State Agency of Nature, Environment and Consumer Protection North Rhine-

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Westphalia (LANUV) and was provided for calibration. It combines light-scattering nephelometry with beta attenuation technology and measures particle fractions PM10 and PM2.5. A separate regression analysis was performed for both SDSs to determine and apply a calibration function. In order to preserve the so-called regression function, the regression coefficient b was determined, which represents the slope of the compensation function [8]:

$$b = \frac{\frac{\sum_{i=1}^{n} (x_i - \bar{x})(y_i - \bar{y})}{(n-1)}}{\frac{\sum_{i=1}^{n} (x_i - \bar{x})^2}{(n-1)}} = \frac{Covariance_{y,x}}{Variance_x}$$
(1)

This results from the ratio of the covariance of the xand y-values to the variance of the x-values. Variance is a measure of dispersion that indicates the distribution of values around the mean value. Often it is simply called the square of the standard deviation. If the sum of the squared deviations of all values from the arithmetic mean is divided by the number of values, the variance is obtained. Covariance, on the other hand, is an interrelationship measure for two variables that are subject to the same probability distribution. If the covariance = 0, there is no relationship. If the covariance is > 0, there is a positive correlation and if it is < 0, there is a negative correlation. In addition to the regression coefficient *b*, the regression constant a_k must be determined, which describes the ordinate segment as follows:

$$a_k = \overline{y} - b\,\overline{x} \tag{2}$$

When both parameters have been determined, a regression equation can be formed from them and their corresponding x-values according to the following scheme, with which the y-values can be estimated and the SDS calibrated:

$$\hat{y} = a_k + b x_i \tag{3}$$

For the PM calibration, the PM concentrations measured by the SDS serve as x-values and the PM values measured by the Model 5030 SHARP serve as y-values. In order to make a statement about how accurate a regression function is, the determination coefficient R^2 is determined [8]:

$$R^{2} = \frac{\sum_{i=1}^{n} (y_{i} - \bar{y})^{2} - \sum_{i=1}^{n} (y_{i} - \hat{y})^{2}}{\sum_{i=1}^{n} (y_{i} - \bar{y})^{2}} = \frac{SS_{Total} - SS_{Error}}{SS_{Total}} = \frac{SS_{Regression}}{SS_{Total}}$$
(4)

This indicates how many fewer errors are made in predicting the y-values, taking into account the x-values. In other words, the coefficient of determination is a measure of the deviations of the predictions of a regression model, i.e., a measure of the model fitting. R^2 can only assume values between 1 and 0, where 1 stands for a perfect model adaptation and the value 0 means that no prediction of the target variable is possible via the regression equation. In addition to the determination coefficient R^2 , the standard error S of the individual regressions can be determined, which indicates the

average deviation of the data points from the regression line [8]:

$$S = \sqrt{\frac{SS_{Error}}{n - k_i - l}}$$
(5)

After the SDS1 was calibrated, it could be used as a reference device to calibrate the SDS2. For this purpose, comparative measurements were carried out in the described test room of the two-room apartment. A further regression analysis was carried out on the basis of these measured values.

2.3 Indoor particle model

The particle concentration in the interior is influenced by both particle sources and sinks, which can be illustrated by the mass balance from equation (6) [9]:

$$\left(\frac{dC_{i,m}(t)}{dt}\right)_{i} = \sum_{j=l} \left(\frac{dC_{i,m}(t)}{dt}\right)_{i,j}$$
(6)

During the experiments to determine k and F_{in} , there were no persons or other particle sources in the interior. For this reason, an identical particle density is assumed between the interior and exterior areas. The sum of the particle sources and sinks is composed of infiltration, exfiltration, deposition, resuspension and generation and is listed in equation (7) [10]:

$$\left(\frac{dC_{i}(t)}{dt}\right)_{i} = \begin{bmatrix} \left(\frac{dC_{i}(t)}{dt}\right)_{inf} + \left(\frac{dC_{i}(t)}{dt}\right)_{exf} + \left(\frac{dC_{i}(t)}{dt}\right)_{dep} \\ + \left(\frac{dC_{i}(t)}{dt}\right)_{res} + \left(\frac{dC_{i}(t)}{dt}\right)_{gen} \end{bmatrix}_{i}$$
(7)

For the sake of clarity, the indoor particle mass concentration $C_{i,m}(t)$ is subsequently declared as $C_i(t)$. Each individual term on the right side of equation (7) can be further transformed into the following form:

$$\left(V_{eff}\frac{dC_{i}(t)}{dt}\right)_{i} = \left[PQC_{o} - QC_{i}(t) - Q_{d}C_{i}(t) + R(t) + E(t)\right]_{i} (8)$$

 V_{eff} corresponds to the effective room volume in m³. Infiltration is described by the term PQC_o and can be described as a particle source. $QC_i(t)$, on the other hand, stands for the exfiltration of particles out of space and has a negative sign as a particle sink. The deposition also corresponds to a particle sink and is described by $Q_dC_i(t)$. Consequently, R(t) represents the particle suspension and E(t) the particle generation in the interior. If equation (8) is further transformed, equation (9) results:

$$\left(\frac{dC_i(t)}{dt}\right)_i + \left[\left(\frac{Q+Q_d}{V_{eff}}\right)C_i(t)\right]_i = \left(\frac{R(t)+E(t)+PQC_o}{V_{eff}}\right)_i \tag{9}$$

Assuming t = 0 and $C_i(t) = C_s$ results in the following equation:

$$C_{i} = \left[C_{s} - \frac{R + E + PQC_{o}}{(Q + Q_{d})}\right]e^{-((Q + Q_{d})/V_{eff})t} + \frac{R + E + PQC_{o}}{(Q + Q_{d})}$$
(10)

Since, as mentioned above, there were no persons in the test room during the series of measurements, it can be assumed that no particles were swirled up or even generated. Therefore the terms R(t) and E(t) can be neglected. The result is equation (11):

$$C_{i} = \left[C_{s} - \frac{PQC_{o}}{(Q + Q_{d})}\right] e^{-((Q + Q_{d})/V_{eff})t} + \frac{PQC_{o}}{(Q + Q_{d})}$$
(11)

$$\lambda = a + k = \frac{Q + Q_d}{V_{eff}} \tag{12}$$

The time constant λ is the sum of the air exchange rate a and the deposition rate k in h⁻¹ (Eq. (12)). In the case of limited growth, λ is referred to as the growth constant and in the case of limited decrease as the decrease constant. This constant thus determines how fast the function $C_i(t)$ strives against the limit value C_{end} . The higher this constant, the steeper the curve and the faster the limit value is reached. The decrease factor is $e^{-\lambda}$, which describes the percentage decrease of the residual concentration ($C_s - C_{end}$) per time unit. Substituting the steady-state final concentration C_{end} and combining equations (11) and (12) results in Eq. (13):

$$C_{i} = (C_{s} - C_{end})e^{-(a+k)t} + C_{end}$$
(13)

Fig. 2 shows an exemplary settling profile of the indoor concentration for PM10.



Fig. 2. Exemplary indoor PM10 profile during the natural decay test

The drawn C_{end} line represents the concentration at which the descent process apparently ends and a stationary state occurs. The average particle concentration value that is obtained in the period between reaching the stationary state and the end of the experiment is the C_{end} value. In the experiments carried out, the average time until this value was reached was 2.5 to 3 hours. The initial concentration during the decay test is called C_s . The time constant λ can be determined by drawing an exponential trend line. The deposition rate k is then obtained by subtracting the air exchange rate a from the time constant λ or can be converted into the following equation by substitution:

$$k = \left(\frac{l}{t}\right) \ln \left(\frac{C_i - C_{end}}{C_s - C_{end}}\right) - a \tag{14}$$

The air exchange rate a required for this can be determined both metrologically and mathematically in

various ways. The tracer gas method or the blower-door test is usually used to determine the air exchange by measurement. To determine the deposition rate, it is best to do this at the same time as determining the time constant. CO_2 or sulphur hexafluoride are often used the tracer gas. The air exchange rate can be approximately determined according to equation (15) as follows [11]:

$$a = f_{eff,comp} n_{50} \left(\frac{f_{eff,loc} \Delta p}{50}\right)^{nl}$$
(15)

The computational approach was chosen for the experiments. The variable n_{50} is the air change at 50 Pa differential pressure. Depending on the type of ventilation, building envelope and usage unit, an air exchange of category A, B or C can be assumed according to DIN 1946-6. The correction factor for the system and component-dependent infiltration $f_{eff,comp}$ to be taken into account when dimensioning the ventilation components can also be taken from DIN 1946-6. The correction factor is selected according to the ventilation system and type of apartment and varies between 0.15 and 0.8. In addition, a rated differential pressure Δp is required to determine the infiltration air exchange. The effective infiltration air content can be corrected by the factor $f_{eff,loc}$ depending on the building location. By default, this correction factor is set to 1 and is therefore neglected. Furthermore, a pressure exponent is required that is specified in DIN 1946-6 with ni = 2/3.

In addition to the deposition rate, the ratio of internal concentration to external concentration (I/O ratio) and the infiltration factor F_{in} can be determined to establish a relationship between internal and external concentration. In case there are no particle generators in the room, the I/O ratio also corresponds to the infiltration factor:

$$I/O ratio = \frac{C_i}{C_o} = F_{in}$$
(16)

3 Results and discussion

The study results are divided into four sections and are considered separately. The results of the regression analysis are given in section 3.1. Section 3.2 presents the indoor/outdoor ratios, section 3.3 the infiltration factors and section 3.4 the results for the deposition rates.

3.1. Calibration function

When performing the regression analysis (see 2.2.), the following parameters result from Table 2, from which individual calibration functions for PM10 and PM2.5 can be formed. The calibration curves for the SDS1 can be taken from Fig. 3. For the SDS2, the functions were determined according to the same principle. The regression line that results from the regression function (Model 5030 SHARP vs. SDS1) has an average deviation of 2.18 μ g m⁻³ from the data points for PM2.5 and 2.33 μ g m⁻³ for PM10. This information is not very meaningful as there is no clear basis for comparison. However, to find out how well the regression line describes the distribution of data points, the determination coefficient *R*² is used,

which is 71.09 % for PM2.5 and 79.37 % for PM10. Furthermore, a low degree of dispersion is recognizable, which is expressed by the small variances.

	SDS1 (SDS2)	SDS1 (SDS2)
	PM10	PM2.5
Covariance	16.15 (27.23)	7.83 (2.36)
Variance	12.47 (32.22)	5.21 (2.76)
Correlation	0.89 (0.90)	0.84 (0.97)
a _k	7.89 (9.48)	5.51 (8.11)
Ь	1.29 (0.80)	1.50 (0.85)
R^2	0.79 (0.81)	0.71 (0.94)
S	2.33 (2.27)	2.18 (0.33)

Table 2. Characteristics of the regression analysis

In addition, both regression functions have a covariance > 0, which is why a positive correlation between the PM measured value of SDS1 and the resulting PM value can be assumed after calibration. In other words, if the uncalibrated SDS1 measures a high PM2.5 mass concentration, the regression equation results in a higher PM2.5 particle mass concentration.



Fig. 3. Model 5030 SHARP and SDS correlation

The following calibration functions are the results for the SDS1 and SDS2:

$$SDS1_{PM10,calib} = 7.89 + 1.29 SDS1_{PM10,meas}$$
(17)

$$SDS1_{PM2.5, calib} = 5.51 + 1.50 SDS1_{PM2.5, meas}$$
 (18)

$$SDS2_{PM10,calib} = 9.48 + 0.80 SDS2_{PM10,meas}$$
 (19)

$$SDS2_{PM2.5,calib} = 8.11 + 0.85 SDS2_{PM2.5,meas}$$
 (20)

 $SDS_{PM,meas}$ represents the measured particle mass concentration of the uncalibrated SDS. The two SDSs were corrected with the calibration functions shown before the indoor/outdoor ratios, infiltration factors and deposition rates were determined.

3.2 Indoor/Outdoor ratio

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The I/O ratio establishes a direct relationship between internal and external particle concentrations. The most commonly used measurement method, which was also used in this experiment, is the installation of two particulate matter monitors - one inside and one outside the test building. Two SDSs were used to monitor the particle mass concentration. The SDS1, which was positioned inside the bedroom was approx. 1.60 m above the floor. It was attached to the inner wall, which borders the unheated hallway of the building. The SDS2, placed outside, hung about 4.5 m above the ground and was attached to the street side. This is a heavily trafficked twolane road. The linear distance from the internal to the external sampling point was approximately 5 m. Measurements were taken every minute for each day in December 2017 and May 2018. In principle, two people used the apartment for normal purposes (ventilation, cooking, cleaning, etc.). During the measurements, the bedroom remained largely unused during the day and was used for sleeping in the evening/night. Only after work do the occupants use the bedroom again to hung their jackets in the wardrobe. The bedroom door and windows were closed at bedtime. The daily occupation and activity scheme of the studied apartment can be summarized as follows:

- Bedtime: from 22:00 to 9:00,
- Ventilation: from 9:00 to 9:15 (tilt ventilation),
- Working time: from 10:00 to 18:00 (Person 1),
- Working time: from 10:00 to 15:00 (Person 2),
- Cooking time: between 15:30 and 16:00,
- · Cleaning time: one day per month.

The measurement results of the individual days were sorted and averaged by daily hours in ascending order so that an average daily indoor/outdoor ratio profile (*I/O profile*) was created for a selected month. The average daily *I/O profile* for December 2017 is shown in Fig. 4. The black solid line shows the ratio of 1.00, where both concentrations, inside and outside, are equal. Looking at PM2.5, *I/O ratios* in the range from 0.55 to 0.92 can be identified and are thus below 1.00 on average at any time of day. Accordingly, the concentration of PM2.5 in the outdoor air was always higher than in the indoor air. Furthermore, a clear trend in *I/O ratio* for PM2.5

averages 0.87 and decreases continuously until 9:00, when it reaches its 0.55 minimum.



Fig. 4. Average I/O profile of December 2017

The ratio then rises to 0.88 by 15:00 and drops again in the following three hours, reaching its maximum of 0.92 at 20:00. Once the maximum is reached, the I/O ratio drops again slightly and oscillates to 0.87. The I/O ratio is then reduced to 0.88 by 20:00. The same behaviour is apparent for PM10, with the difference that its I/O ratios are mostly lower than PM2.5. Only from 19:00 to 0:00 does the ratio of PM10 significantly exceed that of PM2.5 and, with the exception of 19:00, exceed the value of 1.00. The reason for the described course from 0:00 to 15:00 lies for the most part in the usage behaviour. The sleep phase of the building users lies between 0:00 and 9:00. As a result, the particle mass concentration in the interior decreases continuously due to deposition processes. Furthermore, sleep reduces the effects of resuspension through reduced exercise. Subsequently, the ratios increase again due to increased user activities. However, there is no clear reason why the I/O ratios for PM10 exceeded 1.00 in the evening hours. It could be because coarser particles are swirled up on the bed before going to bed. In summary, it can be concluded from the daily profile for December that on average there is a lower PM concentration inside than outside and not, as is often claimed, vice versa. To confirm this statement, a further series of measurements was carried out for May 2018, which is shown graphically in Fig. 5.



Fig. 5. Average I/O profile of May 2018

Here, the same process can be seen too, with the difference that significantly higher *I/O ratios* were measured for both fine dust fractions. However, comparatively lower outdoor particle mass concentrations were measured in May than in December. Due to the fact that ventilation is more frequent and longer in summer,

the higher *I/O ratios* make sense. In addition, it is noticeable that in all cases (except for 11:00) the internal and external ratio of PM10 is greater than that of PM2.5. A plausible explanation for this cannot be found. However, the results from May show that the indoor concentration may well be higher than the outdoor concentration.

3.3 Infiltration factor

By measuring the infiltration factor F_{in} , conclusions can be drawn about the tightness of the building and the influence of particle infiltration inside the building can be investigated. To determine F_{in} , the indoor concentration in the closed bedroom was first measured over a period of 10 days (2018-06-20 to 2018-06-29). The external concentration was measured at the same time. There were no persons or other particle generators in the bedroom during the measurement period. Furthermore, the measurement was carried out outside of the heating period, and the heating was also switched off. This should prevent particles from being swirled up due to convection currents. In order to ensure that resuspension and deposition effects did not influence the measurement, the measured values from 2018-06-22 to 2018-06-27 were used to determine F_{in} . The infiltration factors are shown in Fig. 6.



Fig. 6. Infiltration factor for PM10 and PM2.5

For PM10, F_{in} ranges between 0.48 and 0.67 and gives an average total infiltration factor of 0.58. The infiltration factors for PM2.5 are higher than for PM10 on all measured days. On average, an infiltration factor of 0.69 can be determined for this fine dust fraction. The reason for this is probably the difference in size, as the PM2.5 particles have a smaller aerodynamic diameter than the PM10 particles and can therefore more easily enter the building through cracks or leaks. The infiltration factor can therefore vary greatly on different days. One of the main reasons for these fluctuations is the air exchange rate, which depends on the temperature difference between the indoor and outdoor air and the wind pressure on the building envelope in naturally ventilated buildings. The raw measurement data reveal that the closer the external and internal concentrations are to each other, the greater the infiltration factor. In contrast, the further away the external concentration is from the internal

concentration, the smaller the infiltration factor becomes. Here a weakness of the infiltration factor becomes apparent, namely the dependence on external concentration. This can erroneously give the impression that a building is very leaky at low outdoor concentrations, although this does not correspond to reality.

3.4 Deposition rate

According to DIN 1946 [11], an infiltration air exchange of 0.215 h⁻¹ results for the apartment. Taking this number into account, deposition rates in the range of 0.18 to 6.55 h⁻¹ could be determined for PM2.5. This shows a clear dispersion of the measurement results. The higher the initial concentration, the higher the time constant λ was. In principle, a particle fraction should always have the same deposition rate. However, the PM2.5 and PM10 concentrations behaved differently depending on the measurement series. On the one hand, this can be related to the air exchange rate, which was approximately determined to be 0.215 h⁻¹. However, this value can vary greatly due to the individual tightness of the various buildings and influence the deposition rates.



Fig. 7. Deposition rate for PM10 and PM2.5

For particles with an aerodynamic diameter of 10 µm, the deposition rates are usually between 7 and 10 h^{-1} [12]. On average, the deposition rates from this study were well below this range. The reason for these deviations could be the measuring principle and its unknown algorithm for determining the mass concentration. The SDS only has one comparator threshold for the classification of scattered light intensities in PM fractions. The PM2.5 fraction is limited downwards by a rapidly decreasing intensity of scattered light with finite sensitivity of the Transimpedance Amplifier (TIA). However, only the nonlinear saturation effect of the gain is a limitation for PM10. Particle spectra above 5 µm can sometimes be measured incorrectly. Although the calibration partly compensates for this effect, the measured particles then have a different sink behaviour, as this study shows. In summary, the determination of the deposition rates makes it clear that particle deposition represents an important particle sink in buildings. Also, in most cases a persistent state could be determined after about three hours. The term "steady state" refers to the point in time at which there is apparently no more decrease in concentration.

4 Conclusion

A two-room apartment was used for the investigations in this research project. Low-cost PM-sensors were used and successfully calibrated using a simple method. Furthermore, the particle transport into the building could be visualized and quantified by infiltration factors and indoor/outdoor ratios. The experiments showed that PM2.5 particles can penetrate the building more easily than PM10 particles and stay longer in the ambient air (deposition rate). Nevertheless, outdoor climate, user activity and sensor location have a significant influence on the results.

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