Impact of Ventilation Air Supply Type on Indoor/Outdoor PM: In-Situ Measurements.

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Abstract. Indoor comfort has been given significant attention to satisfy the occupants' needs, yet the Covid-19 pandemic accelerated awareness for creating also a healthy atmosphere. Besides infectious aerosols, Particulate Matter (PM) and Volatile Organic Compounds (VOCs) can induce health issues on the short and long term. Commercial ventilation systems are increasingly based on providing a good indoor comfort by monitoring CO_2, RH, and/or VOCs while targeting a low as possible energy consumption. Indoor PM is determined by various indoor and outdoor sources ranging from cooking and household activities to outdoor PM transported or infiltrating into the building. Consequently, the indoor PM level varies and potentially affects human health. This research contains in-situ measurements with Renson Senses quantifying indoor and outdoor PM in and near one single dwelling for examining the impact of commercial ventilation systems (Mechanical Extract Ventilation (MEV) and Mechanical Ventilation with Heat Recovery (MVHR)) on indoor PM1, 2.5, 4 and 10. The measurements encompassed four system configurations either without filter (natural or mechanical supply) or mechanical supply equipped with ISO Coarse >90% or ISO ePM1 50% filters to assess the filter efficiency in practice. The extraction flow rate was kept constant and identical to avoid the impact of different air exchange rates on indoor PM. Each configuration was active during two weeks resulting in a two months period (May-June, 2021) during which occupancy and indoor polluting activities were rare, allowing to assess the ventilation and filter impact on indoor PM. The analysis revealed that indoor PM levels are about half the outdoor PM levels without filtering on the air supply, when there was no occupation or activities. Using an ISO Coarse >90% filter showed no clear effect with a similar performance as an MEV system. Next to this, a MVHR system equipped with an ISO ePM1 50% filter significantly impacts the transport of outdoor PM to indoors, with an efficiency, expressed as the Indoor/Outdoor ratio, of about half the laboratory efficiency. Supposing that PM originates 50/50 from indoors and outdoors, the actual fine filter efficiency influencing indoor PM is about 15-25% of the measured lab efficiency.

Keywords. Indoor/Outdoor Particulate Matter, In-Situ Measurements, Mechanical Extract Ventilation, Mechanical Ventilation Heat Recovery, Filter Efficiencies.
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1. Introduction

The percentage of time that humans spend indoors at places like homes or offices is on average 87% [1]. Next to this, the Covid-19 pandemic demonstrated the importance of creating a healthy indoor climate by preventing the spread of diseases via infectious aerosols [2]. As a result, people are becoming aware of the quality of the air that we breathe in at each time of day, outdoors as well as indoors. Besides infectious aerosols, other pollutants like Volatile Organic Compounds (VOCs) and Particulate Matter (PM) are also present in the air and can impose severe health issues [3,4]. Recently constructed dwellings compared to older ones have an improved airtightness resulting in a reduced uncontrolled ventilation rate that depends on the cracks and crevices in the building envelope. Consequently, the concentration of pollutants generated indoors in modern dwellings can increase over time leading to a deteriorated indoor air quality. For this reason, a controlled ventilation system is applied to provide an adequate ventilation rate in the building to guarantee the indoor air quality [5]. An outcome of the AIVC project "Ventilation & Health" ranked PM in the indoor residential environment the highest priority concerning chronic health issues [3,4]. PM is classified based on particle diameter and typical PM fractions are PM1 (<1 µm), PM2.5 (<2.5 µm, fine), and PM10 (<10 µm, coarse). PM with a smaller particle diameter penetrates deeper into the human body imposing a higher health hazard. The indoor PM level is determined on the one hand by indoor activities like cooking, smoking, and walking; while on the other hand outdoor PM infiltrates the dwelling through leakages in the building envelope, via open windows, and the ventilation system [6]. The fraction of outdoor PM contributing to the indoor PM level is estimated to be up to 56% [3,4].

Over the years, outdoor PM levels have significantly improved in continents like Europe with a reduction of about 50% over 20 years, although PM peaks causing significant problems can still occur. Therefore, the Out2In study assessed with outdoor air the real-life performance of filters applied in a simple lab-constructed mechanical ventilation system and concluded that fine filters (class F7 or F9) improved the indoor air quality in contrast to the typically used coarse filters (class G3 or G4) [7,8]. This conclusion is supported by a simulation study that considered a Mechanical Ventilation with Heat Recovery (MVHR) system with filter types ranging from coarse to fine. That simulation study also encompassed a comparison between a Mechanical Extract Ventilation (MEV) system and a MVHR where the latter achieved a 50% reduction of indoor PM2.5 when compared to the former [9,10]. A field study examined in a classroom located near a highway the impact on indoor PM when a commercial MVHR is equipped once with and once without a F8 filter. The use of the filter reduced the indoor PM2.5 and PM10 by 30% and 34%, respectively, which are clearly lower than the theoretical filter values, despite no or limited indoor PM sources [11]. Similarly, the effect on outdoor PM2.5 transported to indoors when mechanical or mixed mode ventilation with eventual filtering is applied was examined in 37 offices in four countries. The field study concluded that indoor PM2.5 was generally lower than outdoor PM2.5 and the highest reduction was obtained when mechanical ventilation combined with a high efficiency filter was deployed [12]. Another field study analysed the influence of ventilation (natural versus unbalanced or balanced mechanical) on indoor PM in 15 homes selected from three sites and came to the same conclusions as the aforementioned work [13]. Next to this, also the variation of PM1, PM2.5, and PM10 was investigated in 40 inhabited houses in Germany. The main conclusion was an elevated indoor PM10 compared to outdoor PM10 due to indoor activities, whereas indoor PM10 significantly decreases or even reaches zero during the absence of activity [14].

The amount of transported outdoor PM to indoors due to the applied ventilation system has been extensively investigated over the years. Many studies focused on MVHR with filters, however, there is also a large share of houses equipped with MEV instead of MVHR, a system that was considered in the simulation study of Rojas [9,10]. In addition, the field studies encompassed a large variety of building functions ranging from residential housing to offices and classrooms, each exhibiting a specific occupancy profile and associated activities. Consequently, the indoor PM measurements were accompanied with periods of indoor generated PM, making it rather difficult to quantify the amount of transported outdoor PM via the ventilation system. Another aspect is the construction of both the building envelope and the ventilation system affecting the infiltration and transportation, respectively, of outdoor PM to indoors. For clarification, a study observed the PM transport from outdoors to indoors for two identically constructed houses each equipped with the exact same type of mechanical ventilation system. The amount of transported PM from outdoors to indoors differed up to 20% despite the fact that both houses should provide the same circumstances [15]. In this paper, the transport of outdoor PM to indoors between MVHR and MEV is assessed by means of in-situ measurements in several rooms of a dwelling. Both ventilation systems are present in the same dwelling providing identical test conditions for the following aspects: the exhaust framework, the set exhaust ventilation rate, and the house layout and interior. The outdoor PM concentration was the most variable parameter during the study. Moreover, the residence is typically unoccupied indicating the absence of indoor PM generating activities like cooking and smoking; while only a few people visited the house during the measurement campaign and therefore is the resuspension of indoor particles considered to be limited.

2. Research methodology

2.1 House and ventilation systems description

The in-situ measurements were conducted in the unoccupied Renson Concept Home that was completed in 2019 and is located in a low urban district of Waregem (Belgium). The building is an uninhabited furnished single-family detached house consisting of two bedrooms, a bathroom, a living room with open kitchen, and a technical room; the building layout is shown in Fig. 1. The residence has a total surface area of 184 m^2, a leakage rate of 2.20 $m^3/(h.m^2)$ at 50 Pa, and a Belgian energy performance score of E13 which corresponds with an A label. The house is equipped with two commercial ventilation systems: the smart Healthbox 3.0 and the Endura Delta [16,17]. The first system is MEV while the second is balanced MVHR that can be equipped with coarse or fine filters.

2.2 Measurement approach and schedule

Tab. 1 shows the timing schedule of the activated ventilation systems during the PM measurements. A total of four configurations were considered and each was in operation for two weeks at a fixed exhaust flow rate of 300 m^3/h. MEV was the first examined configuration where supply air is provided through trickle vents in the dry rooms, while mechanical extraction takes place in the wet rooms as well as in the bedrooms. The remaining configurations were MVHR where supply air in dry

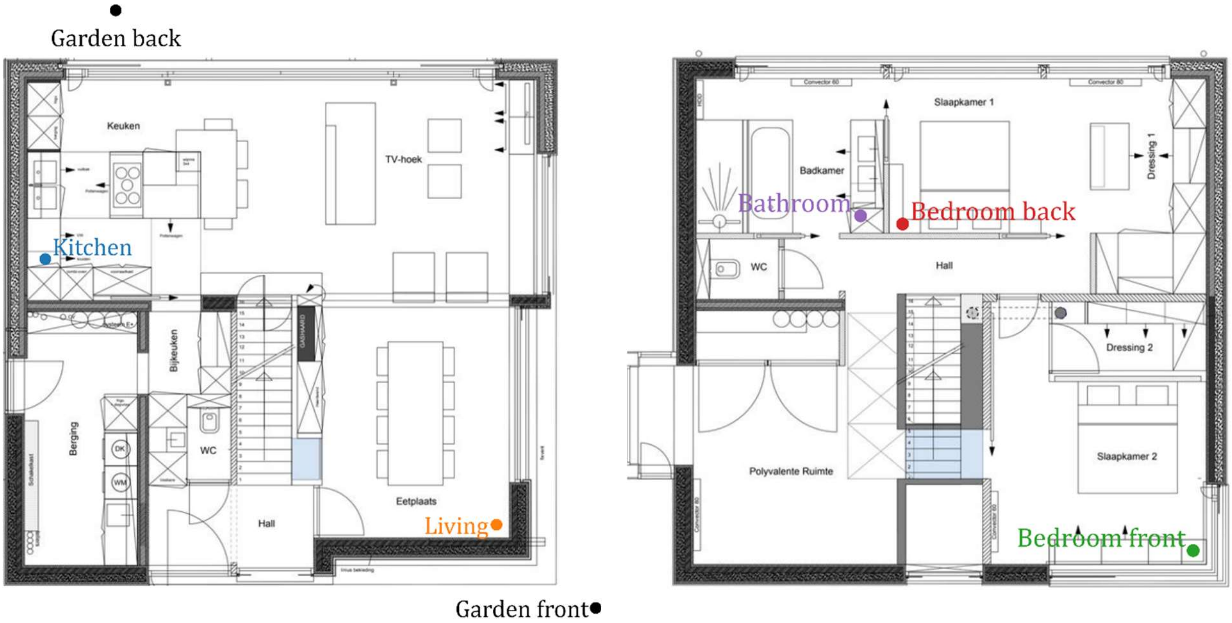

Fig. 1 – The building layout: left is ground floor, right is upper floor. The location of the PM measuring devices in and near the house are marked in colours.

rooms and return air in wet rooms are both mechanically driven. The difference between the three MVHR configurations was the utilized filter type, i.e.: no filter, a ISO Coarse >90% (≈ G4), and a ISO ePM1 50% (≈ F7) filter. This allowed to assess the impact of the filter on the amount of transported outdoor PM to indoors. The filters were brand new.

The PM levels were measured by means of Renson Senses at five indoor and two outdoor locations near the dwelling which are indicated in Fig. 1. The Sense at garden front was placed near the streetside whereas the one at garden back was positioned further away. In this manner, the impact of combustion particles caused by traffic can be examined as a function of the distance. Both outdoor devices were placed on the ground under a small roof to protect them from rain. The devices present indoors provide insight about the distribution of indoor PM throughout the building. These apparatus were at floor (living), night stand (bedrooms), or desk height (kitchen, bathroom). The use of identical devices allows a relative comparison of the results. The Sense is a connected autonomous device measuring parameters like PM, CO_2, humidity, temperature, VOC, and so on [18]. Concerning PM, the SPS30 optical PM sensor is integrated in the Renson Sense and measures PM1, PM2.5, PM4, and PM10 each minute [19]. From this data, the instantaneous Indoor/Outdoor ratio (IO ratio) of each considered room relative to the outdoor Senses was calculated and afterwards averaged to provide a general impression about the amount of transported outdoor PM into the building [1]. This was analysed for each of the ventilation systems listed in Tab. 1 and the aggregate data was used afterwards to compare the impact of the ventilation system and filter on the amount of transported outdoor PM to indoors.

Tab. 1: Considered ventilation systems, description, and measurement period.

Ventilation system (exhaust flow rate = 300 m^3/h)	Description	Measurement period (DD/MM/YYYY)
MEV	Natural supply in dry rooms, mechanical extraction in wet spaces as well as in bedrooms	28/04/2021 – 12/05/2021
MVHR without filter	Mechanical supply and extraction in dry and wet rooms, respectively	12/05/2021 – 26/05/2021
MWHR with ISO Coarse >90% filter (≈ G4)	Mechanical supply and extraction in dry and wet rooms, respectively	26/05/2021 – 09/06/2021
MVHR with ISO ePM1 50% filter (≈ F7)	Mechanical supply and extraction in dry and wet rooms, respectively	09/06/2021 – 23/06/2021

3. Results and discussion

3.1 Ventilation systems

Fig. 2 depicts the average IO ratio of the four PM fractions for each considered room relative to both outdoor locations (garden back and front) when MEV was the activated ventilation system. The average IO ratios in Fig. 2 lie in the range of about 40% up to 50% indicating that the indoor PM level is about half that of outdoors. Considering that there is no presence or indoor activities like cooking and smoking which can generate significant PM indoors, one concludes that about half of the outdoor PM transported into the building via the ventilation system (and also infiltration via leakages although this is small because of a good airtightness).This observation is in line with the literature where the fraction of outdoor PM contributing to the indoor PM level can be up to 56% according to the results of AIVC's "Ventilation & Health" project [3,4]. The average IO ratios related to the PM measurements at garden front are slightly lower than those referred to the garden back PM measurements. The small difference is due to the fact that the device at garden front was located near the street in contrast to the one at garden back. Consequently, the combustion particles emitted by traffic were more numerous present there, resulting in a larger denominator value for the IO ratio calculation, while the numerator representing the indoor PM level did not change. The average IO ratios of all considered rooms are quite similar except in case of bedroom front which are at least 5% higher. This room is located on the street side where the infiltration of combustion particles due to traffic through the trickle vents is more pronounced than in the other rooms, resulting in a slightly higher indoor PM level and therefore an increased IO ratio. The IO ratios of PM1 towards PM10 show a slight decrease which indicates that large diameter particles are less likely to be transported from outdoors into the building.

Tab. 2 gives an example of the measured PM mass concentrations at one sampling moment, similar observations would be drawn if another sampling moment was selected. Supposing that the PM sensor measures accurately the several PM fractions, the following results were found. A small difference is observed between the PM fractions when measured outdoors, whereas there is no difference among PM2.5 up to PM10 for indoors. Zhao et al [14] observed that the absence of indoor activities leads to almost no additional mass concentration for coarse particles (range 2.5 μm – 10 μm) in the indoor environment of dwellings with a good airtightness, which can explain the observation in Tab. 2. Next to this, the indoor PM concentrations in Tab. 2 are small compared to other studies like Zhao et al. [14] due to no human presence and therefore no activities in the house. Moreover, Tab. 2 demonstrates also that small particle sizes are dominant in both indoor and outdoor environments as expected from literature [7,9].

Tab. 2: Example of measured PM mass concentrations when the MEV system was activated.

Location	Concentrations of PM fractions [μg/m^3]			
	PM1	PM2.5	PM4	PM10
Garden back	7.27	7.73	7.77	7.80
Garden front	6.31	6.77	6.85	6.86
Kitchen	2.98	3.15	3.15	3.15
Living	2.37	2.51	2.52	2.53
Bedroom front	3.72	3.94	3.94	3.94
Bedroom back	3.48	3.55	3.55	3.55
Bathroom	2.71	2.76	2.76	2.76

Fig. 3 displays the average IO ratios when MVHR without a filter was deployed. All the IO ratios are similar, even that of bedroom front indicating that this air supply type realizes an evenly distributed transportation of outdoor PM into the entire building in contrast to the air supply type (trickle vents) of MEV. The central air intake by the MVHR system in contrast to the decentral air intake by the MEV system, could explain this difference. The average IO ratios based on the one hand by the outdoor PM measurements at garden front and those on the other hand at garden back, exhibit an analogous trend as in the case of MEV, therefore the same explanation is valid. The average IO ratios achieved with the MVHR without filter are about 10% higher than those of MEV, with the exception of bedroom front where it is rather unchanged. When considering no indoor PM generating activities like cooking and smoking, one concludes that MVHR without filter leads to slightly higher transport of outdoor PM into the building, as also found by Rojas [9]. Possible reasons are: a higher supply of outdoor PM when mechanically done, higher air turbulence and eventual resuspension due to mechanical instead of natural air supply, as well as the position of the measuring devices in the room may contribute also to the increased indoor PM levels.

Fig. 4 shows the average IO ratios when the MVHR was equipped with an ISO Coarse >90% (≈ G4, coarse) filter in the air supply path before the heat exchanger. This filter type is typically used in MVHR to protect the heat exchanger from fouling [10]. The average IO ratios except that of bedroom front drop about 5-6% when compared to those of MVHR without filter, thus less outdoor PM transports into the building because of the presence of the coarse filter. The average IO ratios are about 3-4% higher with respect to MEV, so MVHR equipped with a coarse filter does not outperform MEV, which agrees with the simulation study in literature [9]. The average IO ratios determined by the PM

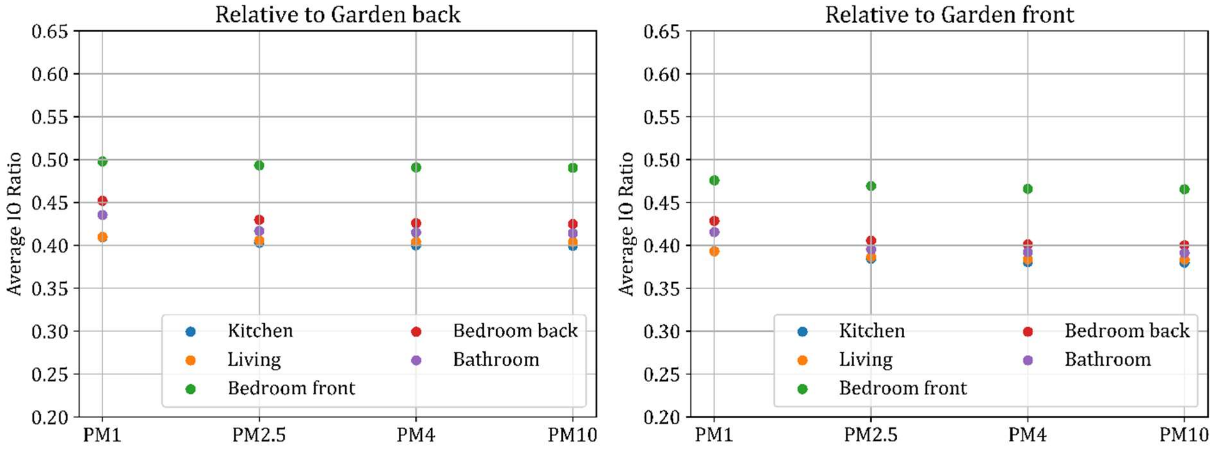

Fig. 2 – Average IO ratios of the PM fractions: PM1, PM2.5, PM4, and PM10 in the considered rooms of the building when MEV was activated (left: relative to garden back sensor; right: relative to garden front sensor).

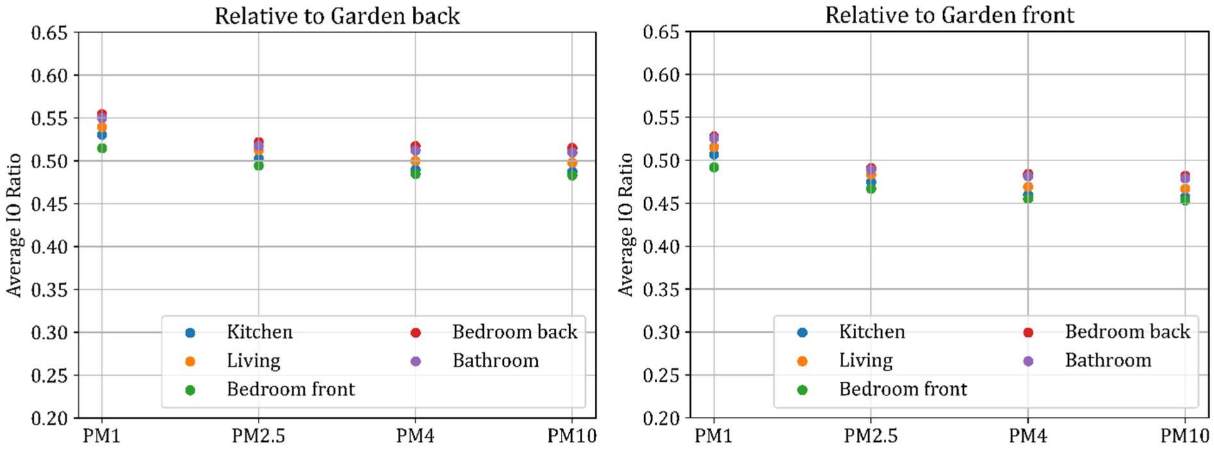

Fig. 3 – Average IO ratios of the PM fractions: PM1, PM2.5, PM4, and PM10 in the considered rooms of the building when MVHR without filter was activated (left: relative to garden back sensor; right: relative to garden front sensor).

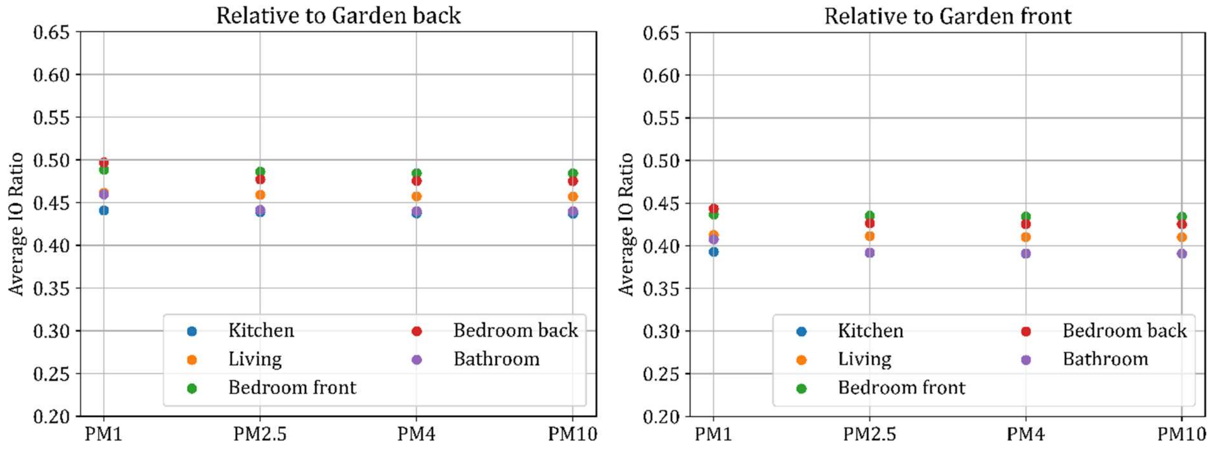

Fig. 4 – Average IO ratios of the PM fractions: PM1, PM2.5, PM4, and PM10 in the considered rooms of the building when MVHR with ISO Coarse > 90% (≈ G4) filter was activated (left: relative to garden back sensor; right: relative to garden front sensor).

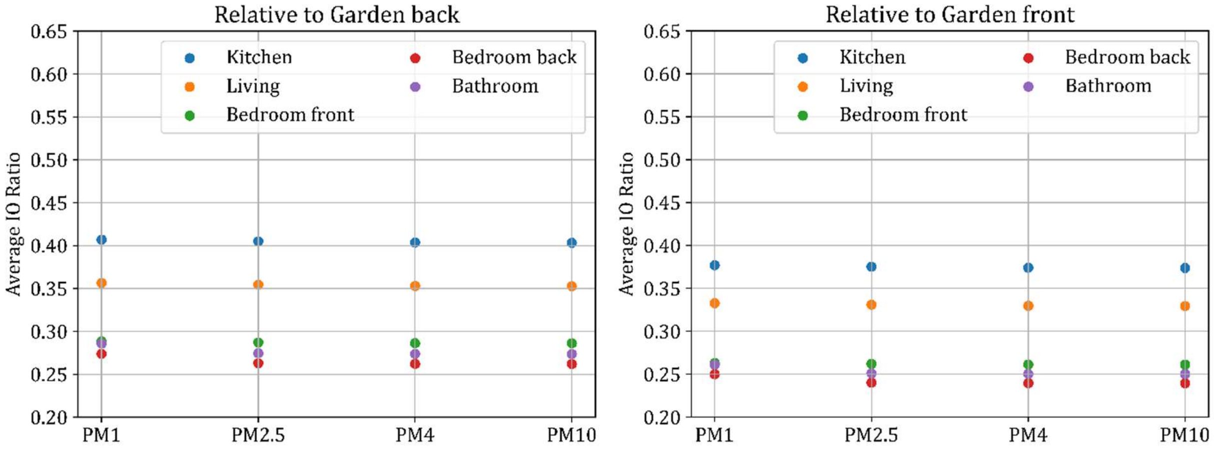

Fig. 5 – Average IO ratios of the PM fractions: PM1, PM2.5, PM4, and PM10 in the considered rooms of the building when MVHR with ISO ePM1 50% (≈ F7) filter was activated (left: relative to garden back sensor; right: relative to garden front sensor).

measurements of either garden front or back demonstrate comparable trends as in the cases of MVHR without filter and MEV, thus the same explanation applies again. A slightly wider spread of the average IO ratios is observed between the rooms which can be due to the weather conditions, temporary occupancy in the house, and so on. Yet, the values lie within the range of IO ratios in literature.

Fig. 5 presents the average IO ratios when the coarse filter was upgraded to an ISO ePM1 50% (≈ F7, fine) filter. The impact of this filter type on the average IO ratios is apparent for the rooms: bedroom front, bedroom back, and bathroom; while the effect is less pronounced for the living room and kitchen. This can be due to the location of the measuring devices in both the kitchen and living room, while temporary occupancies of the ground floor of the dwelling may contribute to a momentary elevated indoor PM level in those spaces. In general, more differences in IO ratio between the rooms are observed with higher filter efficiencies in case of a central MVHR system. Compared to MVHR without filter, the application of an ISO ePM1 50% filter reduces the average IO ratio from about 50% up to about 25-40%, thus the relative reduction in IO ratio is 20-50%. Similar results were obtained in the field study of the classroom (with minimal indoor PM sources) located near the highway where the MVHR was equipped once with and once without a F8 filter (≈ ISO ePM1 65%). The relative reduction in the IO ratio during teaching hours was 30% and 34% for PM2.5 and PM10, respectively. During non-teaching hours, the relative reduction in IO ratio was 42% for PM2.5 and 48% for PM10 [11]. Analogous to the conclusions made in literature, Figs. 4 and 5 point out that IO ratios improve from about 45% to 25-40% when applying a fine instead of coarse filter. Thus, the relative reduction in IO ratio is about 11-44%. The same finding is made when the average IO ratios of Fig. 5 are compared to those of Fig. 2 representing the MEV case. Also the simulation study by Rojas [9] pointed out that MVHR with F7 filter (≈ ISO ePM1 50%) achieves roughly a higher 50% reduction of exposure to outdoor PM2.5 relative to the case of MEV. Concerning the amount of transported outdoor PM to indoors, the results of Fig. 5 (neglecting kitchen) indicate a value up to about 30% when considering the absence of indoor PM generating activities like cooking or smoking. This value is in line with the in literature reported 67% reduction of indoor exposure to transported outdoor PM to indoors [10].

3.2 Room level filter efficiencies

The room level efficiency of the filters utilized in the MVHR are assessed at PM2.5 by calculating the percentual relative difference between the obtained IO ratios relative to those of MVHR without a filter, a method already reported in literature [11]. The measured IO ratios at PM2.5 for the considered MVHR configurations are given in Tab. 3, while the calculated room level filter efficiencies are listed in Tab. 4. According to the filter specifications, the PM2.5 filtration efficiency of the ISO Coarse >90% (≈ G4, coarse) filter is unspecified, whereas that of the ISO ePM1 50% filter (≈ F7, fine) ranges from 65-80% [20]. The room level filter efficiencies vary between the rooms due to small differences among the PM2.5 average IO ratios (see Tab. 3). The impact of the fine filter is clearly demonstrated, yet its room level filtration efficiency is lower than the specified in-lab values of 65-80%. On average, the room level filter efficiency is roughly about half, i.e., 30-50%, for outdoor-originated particles. Simulations performed by Rojas [9] showed a slightly improved reduction of the exposure to outdoor originated PM2.5 of about 55% when using a F7 filter. A similar observation is drawn from the classroom field study with limited indoor PM sources and a F8 filter on the air supply, where a 30% indoor PM2.5 reduction was observed compared to the filter efficiency of >80% [11,20]. The deviation between the room level and specified filter efficiency results from the change in testing of the filter performance. The room level filter efficiency was obtained for a practical scenario with natural outdoor particles, actual housing, ventilation system, and ductwork while the measuring devices were located at room level. The specified filter efficiency is evaluated in a laboratory environment with artificial PM where measuring probes are applied just before and after the filter to accurately quantify its performance [21]. Consequently, the observations suggest that the fine filter efficiency measured in-situ is roughly 30-50% of the specified lab value. Suppose that the indoor PM level consists of 50% indoor generated PM [3,4] and 50% transported outdoor PM, then the overall estimated fine filter efficiency on room level based on the indoor PM level is reduced once again by 50% resulting in an indoor PM fine filter efficiency of around 15-25% of the in-lab determined efficiency. A reduction of about 35% was estimated by Rojas [9] probably due to a lower supposed fraction of indoor generated PM.

Tab. 3: PM2.5 average IO ratios relative to the PM measurements at garden back for the considered MVHR configurations.

	PM2.5: average IO ratio relative to PM measurements at garden back		
Location	MVHR without filter	MVHR with ISO Coarse >90% filter	MVHR with ISO ePM1 50% filter
Bedroom front	0.49	0.48	0.29
Bedroom back	0.52	0.47	0.26
Living	0.51	0.46	0.35

Tab. 4: Room level filter efficiencies for PM2.5 of the MVHR systems equipped with either the ISO coarse >90% or ISO ePM1 50% filter.

	Room level filter efficiency [%] at PM2.5 (relative to MVHR without filter)	
Location	ISO Coarse >90%	ISO ePM1 50%
Bedroom front	2.04	40.82
Bedroom back	9.62	50.00
Living	9.80	31.37

4. Conclusions

For each indoor measurement location, no significant difference occurred between the indoor PM fractions at that location (≤1 µm up to ≤10 µm) which is probably due to the absence of indoor PM sources. The average IO ratios demonstrated that the indoor PM level in all rooms is clearly lower than outdoors, which is consistent with values reported in literature for unoccupied conditions. MVHR without a filter exhibited the worst IO ratio ranging between 50-55%. A slight reduction was obtained when equipping MVHR with an ISO Coarse >90% filter (≈ G4, coarse) where the IO ratio varied between 45-50%. Note that this MVHR configuration is commonly deployed and the single purpose of the filter is to protect the heat exchanger from fouling. A slightly better performance was achieved with MEV, although the position of the air inlet with respect to outdoor PM sources like traffic turned out to be important. The IO ratio was between 40-45% over all rooms, except for the room located near the street side where the value was about 50%. MVHR equipped with an ISO ePM1 50% filter (≈ F7, fine) realized the lowest IO ratio of about 27% on average. Compared to MVHR without filter, the fine filter achieved on average an indoor PM2.5 filtration efficiency on room level in the range of 30-50% which is approximately half of the in laboratory specified filter efficiency. Moreover, when indoor activities are present and assuming that a 50/50 contribution on the total indoor PM level exists between indoor generated PM and transported outdoor PM, then the actual filter efficiency on room level is further halved, leading to an achieved fine filter efficiency on room level of about 15-25% of the in laboratory determined efficiency. A continuation of this research could be the examination of the impact on the I/O PM ratio when the location of the indoor measuring devices is different compared with the locations adopted in this paper.

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Data Statement

The datasets generated during and/or analysed during the current study are/will be available upon reasonable request from the corresponding author.