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Particulate matter in residential buildings in New Zealand: Part I. Variability of particle transport into unoccupied spaces with mechanical ventilation

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HIGHLIGHTS

- 20% variation in PM transportation into two similar unoccupied houses.
- Mean I/O ratios (all PM sizes) were < 1; 38% higher in the Control bedroom.
- The relationship between external/internal [PM] was not linear as previously noted.
- Calculated F_{inf} values showed considerable variation over time.

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ABSTRACT

Air pollution measured as particulate matter (PM) has been shown to be detrimental to human health and can lead to increased mortality rates. There are four main indoor sources of episodic PM emissions: smoking, cooking, cleaning and resuspension. This study has eliminated all human activity and provides data on the variability of the contribution from external sources via mechanical ventilation. The transportation of PM from an external to internal environment by mechanical ventilation is investigated in the same room in two, similar timber-framed houses, constructed identically apart from details affecting their airtightness.

There was significant variation in the transportation of PM from an external to internal environment in two similar houses ([PM] Control > [PM] Test ($\rho = 0.001$)) despite both houses operating the same mechanical ventilation system. Mean internal PM_{10} concentrations = 2.4 $\mu g\,m^{-3}$ (Control) and 1.3 $\mu g\,m^{-3}$ (Test) with corresponding mean external PM_{10} concentrations of 5.4 $\mu g\,m^{-3}$ and 5.2 $\mu g\,m^{-3}$ respectively. Particle removal efficiency between the two houses varied by approximately 20%. These findings indicate that there is considerable variation in filtration efficiencies even when the same mechanical ventilation system is in use in similar homes in the same location.

The infiltration factor (F_{inf}) was calculated and demonstrated considerable variability both between houses (Control-Test PM_{10} 0.40–0.23) and over time (Control PM_{10} 0.40–0.18) which indicates that relationship between external and internal concentrations of PM is not linear and should therefore be used with caution. This questions simplifying F_{inf} into one factor as there are likely to be multiple contributing factors. For example, the effect of air flow on particle adsorption to internal surfaces, natural variations in filter efficiency and variations in particle loss.

Over the duration of this study, PM concentrations decreased in both bedrooms by 52% (Control) and 37% (Test), which may be due to a number of factors including changes in internal environmental conditions, filter age and the cumulative effect of the use of mechanical ventilation over time reducing the transportation of PM into the houses.

1. Introduction

Air pollution measured as particulate matter (PM) has been shown to be detrimental to human health (Cohen et al., 2005; Donaldson et al., 2001; Pope et al., 1995) and may lead to increased mortality rates (Dockery et al., 1993; Hales et al., 2010). PM may include material in both liquid and solid phases suspended in the air. Chemically, these particles may be highly diverse and this is dependent on their source.

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World Health Organisation (WHO) recommends a long-term guideline limit of 20 μg m^{-3} PM_{10} (annual mean) to provide a minimum level of protection against long-term health risk (World Health Organization, 2005). PM_{10} was originally adopted for this guideline as small particles (≤10 μm) were thought to be most damaging. However, increased risk of health issues from those particles smaller than 2.5 μm (including 1 μm sized particles) has been identified, likely due to their ability to be deposited deeper within the respiratory system (Ostro et al., 2015). Despite these findings, in New Zealand, PM_{10} is still the most commonly monitored particle size to provide an indicator of general air quality conditions. The NZ National Environmental Standards (NES) for Air Quality is based on external air, however in the absence of standards for internal air, the WHO guideline limit for PM_{10} (with a daily limit for PM_{10} of 50 μg m^{-3}) may be applied (Ministry for the Environment, 2004). The National Ambient Air Quality Guideline for $PM_{2.5}$ (to protect human health) is 25 μg m^{-3} (Ministry for the Environment, 2002) and is also based on outdoor air. This study will consider 10 μm, 2.5 μm and 1 μm particle sizes.

In Auckland's subtropical climate, natural ventilation is feasible for the vast majority of the year, however an increasing trend towards building air tightness to reduce energy costs (McNeil et al., 2012) has encouraged the use of mechanical ventilation to maintain or improve indoor air quality. Bringing outdoor air via natural or mechanical ventilation into an indoor environment can decrease important indoor emitted pollutants. However, the introduction of poor quality outdoor air can increase the concentration of certain pollutants (for example, particulate matter) which are not attenuated via natural ventilation (Ben-David & Waring, 2016). The majority of mechanical ventilation systems employ PM filters in the supply airstream which can reduce indoor particulate matter concentrations (ASHRAE, 2013). Factors other than ventilation rate and efficiency can affect indoor particulate matter concentrations, including internally generated sources, outdoor concentrations and ambient meteorological conditions.

To be able to assess, control and mitigate the effects of exposure to airborne PM, there needs to be a fundamental understanding of both source emissions and human intake factors (Licina et al., 2017). Within these two categories of interest, there are a number of factors which may need investigation as demonstrated in Fig. 1. Langer et al. (2016), found that season and occupancy had the greatest effect on their measured indoor air quality (IAQ) variables, which included particulate matter.

In this study, pollutant attributes were constant (as the houses were located next to each other), human factors were removed and building factors such as room size were standardised to establish the effect of air flow on particle size and concentration. In New Zealand, a study has found that timber-framed houses are the most common choice for new houses (data from 2002 to 2012) and that timber-framing currently has the potential for developing advanced residential construction (Buckett, 2014). New Zealand has a unique environment which is rarely affected by air pollution generated from any other land mass and generally has good air quality (mean annual PM_{10} Auckland (Henderson) = 13 μg m^{-3}) (LAWA, 2016).

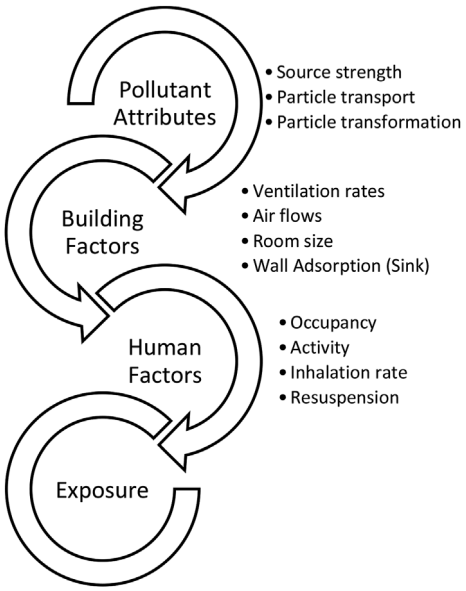

Fig. 1. Factors affecting exposure to airborne PM.

The houses used in this study were constructed at Unitec Institute of Technology as part of a course of study and provide an opportunity to undertake full-scale testing on real buildings which are unoccupied and co-located on campus. Factors such as indoor/outdoor (I/O) PM ratios, infiltration factors (F_{inf}) and the contribution from internal sources (C_s) have been calculated for comparison with other IAQ research for which duplicate buildings have not been available.

This applied research aims to examine the variation in the transportation of PM from an external to internal environment under mechanical ventilation in two similar houses (1); To establish the effect of mechanical ventilation on particulate matter and its size distribution within timber-framed houses typical for Auckland's climate (2); To investigate infiltration factor (F_{inf}) and its variability within similar homes (3) and to examine any cumulative effects of mechanical ventilation on internal concentrations of PM over time (4).

This research will be succeeded by further studies which investigate the effect of mechanical ventilation, airtightness and simulated occupancy.

2. Materials and methods

2.1. Study area

Auckland is located on an isthmus in the north of New Zealand, between the Manukau and Waitemata harbours and has a population of around 1.5 million. Auckland is surrounded by approximately 3100 km of coastline, with the Tasman Sea to the west and the Pacific Ocean to the east. Auckland has a humid, subtropical climate with warm, humid summers and mild, damp winters. The average daily temperature is 23 °C in summer and 14 °C in winter. The mean annual rainfall is 1240 mm and the mean annual wind speed is approximately 3.9 m s^{-1} (NIWA, 2014).

Due to Auckland's isolated position in the South Pacific, air arriving at the coastline is relatively pure and unpolluted (Auckland Council, 2017). However, numerous natural and anthropogenic inputs, mainly from mainland and coastal areas, can deteriorate air quality. According to Auckland Council, the primary sources of PM_{10} in Auckland are domestic (e.g. wood fires during winter), industry (e.g. metal finishing, mining, construction) and transport (e.g. domestic and public). These sources contribute 72%, 7% and 21% respectively to PM_{10} concentrations during winter. PM_{10} levels are nearly four times higher in winter than in summer (Auckland Council, 2015). As the largest city in NZ, Auckland has some areas that occasionally exceed the annual average PM_{10} guideline (20 μg m^{-3}) (exceeding 50% of the years between 2006 and 2013), recording PM_{10} levels between 21 and 30 μg m^{-3}, (Statistics New Zealand, 2015).

2.2. Testing schedule

This study comprised five testing phases. The first three investigated PM transfer into both houses with the mechanical ventilation system in operation, while the last two phases concentrated on the variation in PM generated within the house environment under simulated occupancy with and without mechanical ventilation. Further explanation about the testing phases is shown in Table 1.

This paper is concerned with Phases 1, 2 and 3, while Phases 4 and 5

Table 1
Five testing phases.

Phase	External	Test House	Control House	MVHR* On	MVHR* Off	Simulated Occupancy
1	✓		✓	✓		
2	✓	✓		✓		
3		✓	✓	✓		
4		✓	✓		✓	✓
5		✓	✓	✓		✓

Key: √ indicates both where measurements were taken e.g External (located next to but outside of the study houses), or within the Control or Test houses AND the internal conditions where *MVHR – mechanical ventilation and heat recovery.

will be covered in a future paper, (Part II, Wallis et al., 2019b).

2.3. Data acquisition

Weather data was collected using a Vaisala WXT530 weather station and an OTA OSK15180T tipping rain gauge, mounted 10 m above ground level. The WXT530 provided wind data, air temperature and relative humidity (RH) with the following accuracy: Wind range: 0–60 m/s, accuracy $< \pm 3\%$ at 10 m/s; RH: 0–100% RH, accuracy $< \pm 3\%$ RH at 90% RH; Temperature: −52 to +60 °C, accuracy $< \pm 0.3$ °C at 20 °C.

Within each bedroom, Lascar EL-USB-2 Humidity & Temperature data loggers were set up to sample the internal air temperature at hourly intervals. These units have a range of 0–100% RH and −35 - +80 °C temperature. The sensors were located identically in both houses, suspended from the ceiling to 1.5 m above floor level. Calibration against a mercury thermometer indicated an accuracy of ± 0.5 °C.

Two Dust Profilers (Aeroqual, New Zealand) were used to measure concentrations of PM_{10}, $PM_{2.5}$, PM_1, and TSP (Total Suspended Particulates) in the two bedrooms, situated at a height of 1.1 m to represent the head level of a seated occupant as recommended by standard ISO 7726:1998(E) (International Organization for Standardization, 1998). The sensor ranges are: PM_1 200 μg m^{-3}; $PM_{2.5}$ 2000 μg m^{-3}; PM_{10} 5000 μg m^{-3}; TSP 5000 μg m^{-3}, with accuracy of $< \pm 5$ μg m^{-3} + 15% of reading. The minimum detection is 0.3 μm. The profiler comprises an optical particle counter that converts counts to a mass fraction via a proprietary algorithm stored in the system firmware. Analysis was carried out at 20-min intervals for the first three testing phases increasing to hourly measurements for the last two phases. The laser particle counters were calibrated by the spectrometer manufacturer (Met-One) and previously the particulate monitors were checked at the Chullora Reference Air Quality Station, Sydney, Australia (Reid, 2016). The Aeroqual dust profiler has been used worldwide for regulatory PM monitoring and research by various agencies and institutions.

Initially, profilers were co-located to establish the repeatability of the determination of atmospheric PM. The process of comparing analysis between profilers within the same environment was repeated monthly (or after every move to a new location) to ensure repeatability. Adjustment factors based on these comparisons were applied to minimize the differences between individual instruments throughout the whole monitoring period. (R^2 range 0.988–0.989) The mean absolute difference between profiler readings was 0.26 ± 0.30 μg m^{-3} which lies within the manufacturer's specifications of ± 1 μg m^{-3}.

2.4. Experimental houses

Three-bedroom timber-framed houses (Control and Test) were constructed with identical floorplans on Unitec's Mount Albert campus. Both were undecorated and without floor coverings or wall finishes and are designed as transportable in their complete form to any site in the Auckland region. The house dimensions were 16 m by 7.5 m with a standard room height of 2.4 m. Within each house, the same test room was used (bedroom 2, floor area 11 m^2) which contained one north-west facing window, receiving direct sunlight from midday onwards (Fig. 2).

The Control house was constructed in 2010. As part of a wider investigation into the impact of increasing airtightness on the internal thermal hygroscopic and particulate environment, the Test house was constructed two years later. In this house, the wall underlay was replaced with 7 mm thick plywood sheet treated to H3.2 CCA (Copper Chrome Arsenate – a wood preservative) in accordance with AS/NZ 1604.3 (Standards New Zealand, 2012) to meet AS/NZS 2269.0 (Standards New Zealand, 2012b), with vertical sheet joints sealed with flashing tape. The plywood sheet combines the functions of seismic resistance bracing and provides a rigid air barrier (RAB). In addition, the Test house contained a vapour check membrane (VCM) (Intello, Pro Clima, NZ) located behind the internal surfaces of the external walls and ceiling. Although the VCM was not incorporated solely to reduce airtightness (but also for moisture control), the natural ventilation rates were reduced by the inclusion of the VCM and the RAB.

2.4.1. Mechanical ventilation

Both buildings were installed with mechanical ventilation heat

Fig. 2. House plan for Control and Test bedrooms (test room shaded).

recovery (MVHR) systems (MoistureMASTER™ HX heat recovery home ventilation system, MoistureMASTER™, NZ) just previous to testing (November 2016). The MVHR system has a fan that draws outside air in through a grille in the external façade and filters the air. The filtered air then passes over an "Air to Air Heat Exchanger" and is supplied to the Lounge, Kitchen, Dining room and three bedrooms. A separate fan extracts air from the living areas (lounge/Kitchen/Dining). This extract air pre-warms the incoming outside air by passing through the heat exchanger before being discharged to the outside via a separate grille in the external façade. Each bedroom room was positively pressurised with excess air spilling out into the hall way through the undercut doors, for final extraction in the kitchen. Very low volume flows are required and each fan can run at one of three fixed speeds. The supply fan was set at its lowest speed and the extract at its highest. According to manufacturer, the MVHR is best suited to airtight homes (MoistureMASTER, 2019). The accuracy of the equipment is 3% of mean volume +3.3 $m^3 h^{-1}$ at 22 °C. A Testo 420 vol flow hood was used to quantify the individual airflows. The low volumes recorded put the measurement at the minimum limit of the testing equipment of 40 $m^3 h^{-1}$.

Air flow volumes and air change rates were measured in Bedroom 2 of both houses. In the Control house, the air flow was 48 $m^3 h^{-1}$ with 1.75 air changes h^{-1}. The Test house measured 65 $m^3 h^{-1}$, with 2.4 air changes h^{-1}. Both MVHR systems were set to the same fan speed however variations could be due to the frictional differences in ducts or because air flow volumes were measured at the bottom limit of the equipment accuracy.

According to ASHRAE standards, the minimum mechanical rate for residential dwellings requires 9 $m^3 h^{-1}$ per occupant plus an additional 1.1 $m^3 h^{-1}$ per m^2 of occupied floor space (ASHRAE, 2013). Based on a floor area of 11 m^2 and an occupancy of 2 persons (which equals half the average number of people for a 3-bedroom house as the test rooms were half the size of the average living room size for a five-room house in New Zealand (Khajehzadeh and Vale, 2016). This standard requires a minimum ventilation rate of 30 $m^3 h^{-1}$.

The MoistureMASTER™ MVHR contains air filters (European Specification, EU4) which are efficient for coarse particles > 10 μm and are "guaranteed to remove approximately 96% of all pollen and about 30% of all particles at 3 μm" (2019). In Europe, fine filters are the minimum class for guaranteeing acceptable IAQ (Andersson, 2011). The mechanical air change rates were far in excess of natural infiltration rates (0.4 air changes. h^{-1} (Control) and 0.09 air changes. h^{-1} (Test)) measured previously using blower door tests carried out to European standard EN 13829:2000 (European Committee for Standardization, 2000).

3. Results and discussions

3.1. Background testing of PM on campus

Prior to this study, atmospheric PM concentrations were determined over Winter 2016 (Hernandez et al., 2017). During this timeframe, mean values of PM_{10}, $PM_{2.5}$, PM_1, = 6.0 μg m^{-3}, 5.2 μg m^{-3} and 3.8 μg m^{-3} respectively. These values were consistently lower than the New Zealand National Limit (and the WHO guideline limit) for PM_{10} of 50 μg m^{-3} (24 h mean). The average temperature and relative humidity over this winter period was 12.1 °C and 74.5%.

Further analysis was carried out over Spring and Summer periods (Nov to March 2016). Table 2 shows external PM concentrations and meteorological conditions for the background study. Although the mean PM concentrations were consistent across the three seasons (within ± 1 μg m^{-3} for all particle sizes); the maximum Winter concentration was more than two times greater than those measured in Spring and approximately five times greater than Summer maxima. This finding was expected due to the contribution from solid-fuel burning over Winter.

Table 2
External air quality (measured as PM) and ambient meteorological conditions on campus.

Season		PM_{10} (μg m^{-3})	$PM_{2.5}$ (μg m^{-3})	PM_1 (μg m^{-3})	Temp (°C)	RH (%)
Winter	Mean	6.0	5.2	3.8	12.1	74.5
	Min	0.5	0.3	0.2	3.7	40.4
	Max	74.7	73.2	63.0	19.6	92.7
Spring	Mean	5.4	4.5	3.0	16.2	69.8
	Min	0.7	0.6	0.4	10.5	39.1
	Max	30.7	28.8	25.9	22.4	90.9
Summer	Mean	5.2	4.3	2.8	18.1	67.3
	Min	0.3	0.3	0.2	10.4	37.1
	Max	15.2	13.7	10.8	24.9	91.3

Table 3
External and internal PM concentrations (Phase 1 & 2).

Phase		External			Internal		
		PM_{10} (μg m^{-3})	$PM_{2.5}$ (μg m^{-3})	PM_1 (μg m^{-3})	PM_{10} (μg m^{-3})	$PM_{2.5}$ (μg m^{-3})	PM_1 (μg m^{-3})
1 (Control)	Mean	5.4	4.5	3.0	2.4	2.3	1.9
	Min	0.7	0.6	0.4	0.3	0.3	0.3
	Max	30.7	28.8	25.9	10.7	9.0	8.4
2 (Test)	Mean	5.2	4.3	2.8	1.3	1.3	1.1
	Min	0.3	0.3	0.2	0.2	0.2	0.2
	Max	15.2	13.7	10.8	3.7	3.7	3.3

3.2. Comparison of internal/external PM concentrations

Phases 1 and 2 compared external PM levels with internal PM levels for the Control and Test bedrooms respectively (Table 3). In the Control bedroom during Phase 1 mean PM concentrations of 2.4 μg m^{-3} (PM_{10}), 2.3 μg m^{-3} ($PM_{2.5}$) and 1.9 μg m^{-3} (PM_1) were measured and in the external environment PM concentrations were 5.4 μg m^{-3} (PM_{10}), 4.5 μg m^{-3} ($PM_{2.5}$) and 3.0 μg m^{-3} (PM_1). Test (Phase 2) measured mean concentrations of 1.3 μg m^{-3} (PM_{10}), 1.3 μg m^{-3} ($PM_{2.5}$) and 1.1 μg m^{-3} (PM_1) and 5.2 μg m^{-3} (PM_{10}), 4.3 μg m^{-3} ($PM_{2.5}$) and 2.8 μg m^{-3} (PM_1) for the internal and external environments respectively. Comparisons of internal concentrations in both bedrooms showed that [PM] Control > [PM] Test ($\rho = 0.001$), despite both houses operating the same mechanical ventilation system.

Reductions in PM concentration from external levels were 56% (PM_{10}), 49% ($PM_{2.5}$) and 37% (PM_1) for the Control and 75% (PM_{10}), 70% ($PM_{2.5}$) and 61% (PM_1). These reductions are greater for all PM sizes than the manufacturer's specification (EU4 filter) of 30% (at PM_3). By comparison with the particle removal efficiency based on ASHRAE's minimum efficiency reporting value (MERV), the filters performance would most closely align with MERV6 (35–50% average removal of particle size 3–10 μm). According to ASHRAE (2013), MERV 6 or higher is minimum requirement for the removal particulate matter smaller than PM_{10}.The actual MERV grade for the filters used could not be provided by the manufacturer so this is an approximate guide only. Chen et al. (2016) measured indoor and outdoor particles during a severe pollution event (haze, Singapore, 2013) using filters of MERV grade 7 which removed up to 80% particles (sizes 3.7 μm and 6.0 μm–independent tests) and < 30% removal efficiency for PM_1) which is greater than removal efficiencies measured in this study. A lower removal efficiency range of 2–21% for $PM_{2.5}$ was measured for filter grades MERV6 and MERV7 by Azimi et al. (2014).

During this study, factors such as internal and external sources and building characteristics were kept constant between the houses however, the particle removal efficiency between the two houses was variable by approximately 20%. These findings suggest that there is considerable variation in PM removal even when the same mechanical

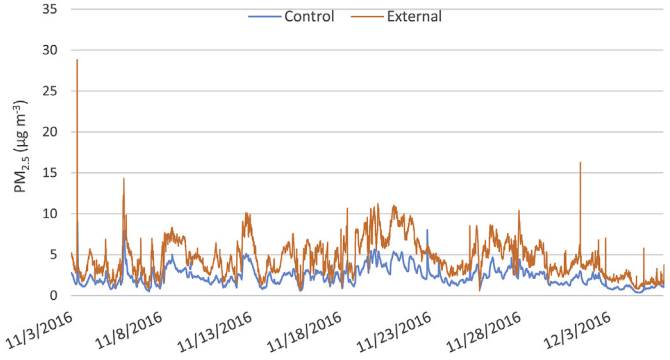

Fig. 3. Graph of PM over time in the Control house vs external (Phase 1).

ventilation system is in use in similar homes in the same location. Morawska et al. (2009), measured 58% removal of outdoor particles via HVAC system, duct and indoor surfaces which is similar to findings in the Control house. On upgrading their HVAC system (including moving inlet location), Morawska et al. (2009) increased removal efficiency to 82% however as measurements were taken at different times (pre and post-modification), this increase could also be due to variability as demonstrated by this study.

There was a very strong positive correlation between external and internal PM for all particle sizes (Spearman's rank coefficients ranged between 90 and 95%), which would be expected given the lack of internal sources. Spearman's rank was found to increase as particle size decreased for both phases, which may be explained by decreased filter efficiency for the smaller particles. This finding concurs with a study by Chen et al. (2016), which found that indoor particle concentrations in the range 0.3–2.5 µm, most closely tracked corresponding patterns of outdoor particle concentrations. .

Figs. 3 and 4 show internal and external $PM_{2.5}$ values over the study period for both phases, which Show that fluctuations were less for internal PM than external PM (an observation also noted by Morawska et al., 2009), and that fluctuations in internal PM were less still for the Test house than the Control house. Direct comparison of internal PM fluctuations (for concurrent testing of Control and Test, Phase 3) will be discussed in Section 3.3. Analysis of the results confirmed this statistical variance (Control = 1.3 and Test = 0.4). Also, for each phase and PM size, the median value was slightly lower than the mean which suggests the data has a positive skew (much of the data is lower in concentration than the mean).

The observed internal concentrations lie within the range of $PM_{2.5}$ concentrations observed by Mandin et al. (2017) in a comprehensive study of office buildings across Europe. During the summer, $PM_{2.5}$ concentrations ranged from 2.7 to 17.0 µg m^{-3} and in the winter from 3.4 to 32.0 µg m^{-3}. A study of 567 occupied dwellings in France found internal $PM_{2.5}$ ranges of 16–26 µm in non-smoking homes, this higher range is most likely due to the contribution from internal sources

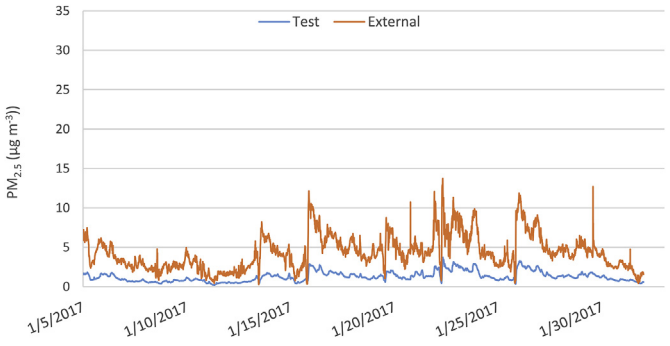

Fig. 4. Graph of PM over time in the Test house vs external (Phase 2).

(Langer et al., 2016). Although the mean external PM concentrations were relatively similar between the measurement phases 1 and 2, Control PM_{10} = 5.4 µg m^{-3} (Phase 1); Test PM_{10} = 5.2 µg m^{-3} (Phase 2), the range of values was variable although due mainly to a few outliers (Control PM_{10} range = 30.0; Test PM_{10} range = 14.8 µg m^{-3}). In fact, ambient (external) PM concentrations were statistically significantly higher in Control (Phase 1) than Test (Phase 2) ($\rho = 0.001$), which may partially explain why the internal concentrations were higher in the Control bedroom.

At this time of year (Spring/Summer), the main contributors to PM_{10} pollution are sea salt and motor vehicle emissions, given the absence of solid fuel burning for home heating (Davy et al., 2011). In particular, sea salt particles lie closer to the 10 µm size range and can therefore result in lower particle counts for a set concentration. It is worth noting that the study site on campus was located approximately 2 km from the Waitamata harbour. External contribution of coarser particles to PM_{10} is generally higher than for internal environment in part due to the contribution from internally sourced very fine particles.

In terms of the internal climate, the temperature in the Test bedroom was slightly higher than in the Control bedroom with mean values of 20.9 °C (Control, Phase 1) and 23.8 °C (Test, Phase 2) (statistically significant, $\rho = 0.001$). By contrast the RH was lower in the Test bedroom (53%) than the Control (58%) (statistically significant, $\rho = 0.001$). This finding was expected as testing Phases 1 & 2 were carried out during Spring/Summer (November–December) and mid-Summer (January–February) respectively and not concurrently (concurrent testing occurred in Phase 3).

3.2.1. Diurnal PM profiles

Although external PM concentrations were considerably higher than internal concentrations, the diurnal profiles show very similar trends (Figs. 3 and 4) but with significant smoothing of external peaks and troughs. Generally, PM_{10} maxima were observed from 09:00–12:00 and minima between 12:00–16:00 (externally and internally) during both phases. Morawska et al. (2009), found similar morning timescales for PM concentration maxima (07:00–09:00) but not for minima (01:00–04:00). Within urban areas, Sajani et al. (2015) stated that traffic contributes a major source of fine and ultrafine particles, however in Auckland (as previously mentioned), sea salt spray is a major natural source of PM_{10} during the summer months (Davy et al., 2011). This may explain the later minima which is less related to traffic flow (or solid fuel burning) than variations in sea salt spray. There were no distinguishable differences between weekday and weekend PM levels, inside or outside the houses.

Spearman's rank analysis was used to assess the influence of temperature and RH on PM_{10} concentrations, both inside and outside the houses. This analysis found there was generally a weak positive correlation between PM_{10} and temperature and a weak negative correlation between PM_{10} and RH, which is consistent with findings from previous studies (Hernandez et al., 2017).

3.2.2. PM size ratios

During Phases 1 and 2, external $PM_{2.5}/PM_{10}$ ratios ranged from 0.83 to 0.84 while $PM_1/PM_{2.5}$ ratios ranged from 0.64 to 0.66, indicating the relative contribution of coarse particles in the external environment. Meanwhile, internal ratios were somewhat higher (0.98–0.99 $PM_{2.5}/PM_{10}$, 0.83–0.86 $PM_1/PM_{2.5}$), suggesting the majority of indoor PM_{10} is fine particulates ($\leq PM_{2.5}$) for both bedrooms. This is likely due to the action of MVHR filters which are more efficient at removing larger particles especially when the filters are new and relatively clean.

A study considering indoor-outdoor relationships at homes, preschools and schools in Stockholm, Sweden found that $PM_{2.5}$ concentrations in indoor environments were mainly due to indoor sources (Wichmann et al., 2010). In this study, mean PM concentrations ranged from 18.2 to 49.0 µg m^{-3} and with $PM_{2.5}/PM_{10}$ ratios ranging from 0.93 to 0.99 during times of non-occupancy and $PM_1/PM_{2.5}$ ratios

≥0.90 so the majority of $PM_{2.5}$ was ≤1 μm. Research by Meng et al. (2007) identified that composition and source contributions of ambient $PM_{2.5}$ are substantially modified by outdoor to indoor transport. According to Meng et al. (2007), infiltration depends on:

- Air exchange rate
- Particle size distribution
- Thermodynamic properties of PM species
- House characteristics

In consideration of these factors; the PM sources are the same (mainly external) and therefore should show similar particle size distribution; the thermodynamic properties of PM should be fairly constant between the two bedrooms (same sources); and the houses were constructed identically (except for the VCM in the Test house). It would therefore be expected that infiltration would be very similar between the houses however our results show that PM concentrations in the Test bedroom were significantly lower than the Control. This could be due to:

- Natural variations observed in dynamic systems (but the impact of this external variability needs more research in unoccupied houses)
- The difference in temperature and/or humidity gradients (external/internal) between the two bedrooms or differences in internal climates. The small difference in air flow volumes generated by the mechanical ventilation (1.75 air changes h^{-1} Control and 2.4 air changes h^{-1} Test) (however difference was measured at the bottom limit of the testing equipment accuracy). Also the air flow volumes were slightly higher in the Test bedroom which may have been expected to produce higher internal PM concentrations (as dominant PM source was external).
- The assisted wet deposition of particles internally, however relative humidity was 4.7% higher (based on mean) in the Control bedroom which would result in lower not higher concentrations.
- The effect of increased air flow rate on particle removal (via adsorption to internal surfaces) within the bedroom due to additional exchange between air and surfaces …

3.2.3. Indoor/outdoor (I/O) PM ratios

Mean I/O ratios for PM_{10}, $PM_{2.5}$ and PM_1 were 0.68, 0.52 and 0.46 respectively in Phase 1 (Control) which indicate a dominance of outdoor sources. Lower I/O ratios were observed in Phase 2 (Test) at 0.42, 0.31 and 0.26 respectively. Chen et al. (2016) also found that there is a tendency for I/O ratio to increase with increasing particle size although for the approximate size range 0.01–0.65 μm. These values are lower than ratios measured under natural ventilation, for example, Cyrys et al. (2004) identified a median I/O ratio for $PM_{2.5}$ of 0.63 within an unoccupied test room in Europe and a range of 0.63–0.83 (with increasing levels of ventilation). Lower I/O values are likely to be due to the action of the MVHR filters however it was not expected that the I/O ratio ranges for the Test bedroom would be considerably lower than Control I/O ratios. Control I/O ratios were within the range identified by Sajani et al. (2015) of 0.40–0.70 measured in residential homes in Bologna, Italy. In naturally ventilated buildings, the contribution of outdoor PM on indoor PM levels is mainly governed by building air exchange rate, the penetration efficiency of particles through building cracks or window frames and the degree of deposition on indoor surfaces (Loupa et al., 2006). Whereas factors affecting I/O ratios in mechanically ventilated buildings identified by Chen et al. (2016) were particle size, air exchange rate and filter efficiency.

The following sections will assess variations in calculated infiltration factors and the contribution from internal sources.

3.2.4. Infiltration factor (F_{inf})

F_{inf} was determined using the expression derived by Chen and Zhao (2011):

Table 4
Calculation of F_{inf} for each PM mass size (using graphical methods), where C_s = intercept.

Phase	PM Size	C_{in} (mean) (μg m^{-3})	F_{inf}	C_s (μg m^{-3})
1 (Control)	PM_{10}	2.36	0.40	0.20
	$PM_{2.5}$	2.31	0.46	0.23
	PM_1	1.91	0.56	0.25
2 (Test)	PM_{10}	1.29	0.23	0.11
	$PM_{2.5}$	1.27	0.26	0.14
	PM_1	1.09	0.35	0.13

$$C_{in} = F_{inf}.C_{out} + C_s \quad (1)$$

Where C = concentration and C_s = the internal particle concentration which is contributed to by internal sources. For Phases 1 and 2, C_s was derived graphically by plotting inlet against outlet PM concentrations and taking the intercept value. F_{inf} was then calculated using the expression above.

Table 4 shows the F_{inf} calculated is lower for the Test house than the Control house (by approximately 50% (for PM_{10}). As the similar mechanical ventilation rates in both spaces were expected to dominate the infiltration factor and external PM levels were similar, this large difference was not expected. Variations in meteorological conditions between Phases 1 and 2 may affect infiltration rate. External mean temperature and relative humidity for Phases 1 and 2 respectively were 16.2 and 69.8% and 18.1 and 67.3% (Table 2). Temperature differentials (internal-external) for Phases 1 and 2 were 4.9 °C and 5.7 °C and relative humidity differentials were −12% and −14.3% for Phases 1 and 2 respectively. The mean external wind speeds for Phases 1 and 2 were 4.7 m/s ± 2.6 m/s and 4.9 m/s ± 2.9 m/s. The maximum gust speeds were 14.1 m/s and 19.2 m/s respectively. Unfortunately wind direction data was not available which is an omission in this study. The simplified relationship to describe F_{inf} does not account for these variations. In addition, Gao et al. (2016) noted that analysing indoor air pollutants using a linear relationship (Eq (1)) with one unknown, did not account for variables such as the natural permeability from outdoors or the entry and exit of indoor environments. In this study, the bedrooms were under positive pressure by the mechanical ventilation system so natural permeability is highly unlikely as is transferral from elsewhere inside the building. The exit of PM from the bedroom via natural ventilation (e.g. door gaps) or PM sinks within the room need more investigation. This will be discussed in greater detail in section 3.3. F_{inf} values are inversely proportional to particle size, which is due to the prevention of coarser particles entering the building due to MVHR filters.

C_s were consistently low for each phase (< 0.3 μg m^{-3}), although the Test bedroom had lower concentrations of particles sourced internally (by approximately 50%). A difference of this size was not expected, however, this may not be significant as the mean absolute difference between particulate monitors (when co-located) was 0.26 ± 0.30 μg m^{-3} and external PM concentrations were significantly different (as described in section 3.2).

3.3. Direct measurement of control vs test (phase 3)

3.3.1. PM concentrations

Phase 3 compared indoor air quality between the two bedrooms (with mechanical ventilation) over the same timeframe (Fig. 5). Air flow rates from mechanical ventilation were 48 $m^3 h^{-1}$ (Control) and 65 $m^3 h^{-1}$ (Test). The only other structural variation between the houses was the inclusion of the VCM and RAB in the Test house. Table 5 summarises the PM data for both Control and Test houses.

Greater concentrations of PM_{10}, $PM_{2.5}$ and PM_1 were observed in the Control bedroom (1.1 μg m^{-3}, 1.1 μg m^{-3} and 1.0 μg m^{-3}

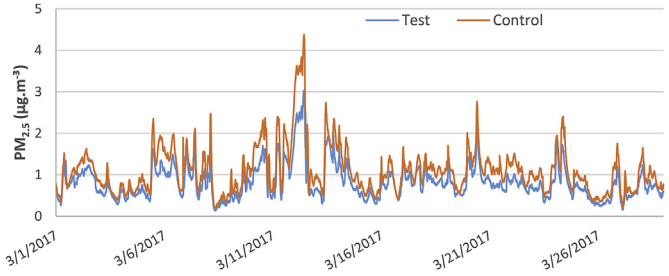

Fig. 5. Graph of $PM_{2.5}$ over time for both Test and Control houses (Phase 3).

Table 5
Comparison between Test and Control PM concentrations (Phase 3).

	Test			Control		
	PM_{10} (µg m^{-3})	$PM_{2.5}$ (µg m^{-3})	PM_1 (µg m^{-3})	PM_{10} (µg m^{-3})	$PM_{2.5}$ (µg m^{-3})	PM_1 (µg m^{-3})
Mean	0.8	0.8	0.7	1.1	1.1	1.0
Min	0.1	0.1	0.1	0.2	0.2	0.2
Max	3.1	3.0	2.7	4.4	4.4	4.0

respectively) than the Test (0.8 µg m^{-3}, 0.8 µg m^{-3} and 0.7 µg m^{-3} respectively). The mean difference between Control and Test was close to the mean absolute difference measured between co-located particulate monitors (0.26 ± 0.30 µg m^{-3}) which suggests further testing may be required. However, there was also a noticeable difference between PM concentration minima and maxima for all sizes with [Control] > [Test]. The lower concentrations measured in the Test bedroom may be due to:

1. Increased filter efficiency at higher air flow rates
2. Increased exit of PM from bedroom 2 to the rest of the building (or the external environment) caused by positive pressure from MVHR.
3. Increased PM adsorption to walls, floor and ceiling within the bedroom caused by increased air flow rate.

The temperature difference between the two bedrooms remained minimal throughout the phase, however RH was higher in the Control (62.2%) than the Test (59.1%) (although this difference was measured at the limits of sensor accuracy).

From Phase 1–3, PM concentrations decreased in both bedrooms by 52% (Control) and 37% (Test), which may due a number of factors including:

- The increase in relative humidity (Control +4.4%; Test +6.1%) which can provide a pathway for wet deposition (and overall loss) of PM.
- A significant change in external PM (which was not measured in Phase 3) but previous external air testing over the course of one year has shown that this is unlikely.
- The increase in filter age between Phase 1 (filters new), Phase 2 (filter age 3 months) and Phase 3 (filter age 5 months).
- The cumulative effect of the use of mechanical ventilation over time which has introduced less PM into the bedrooms due to filtration. It is surprising that this did not show quicker effects.

3.3.2. PM size ratios

During Phase 3, the internal $PM_{2.5}/PM_{10}$ ratios were very similar to those in Phases 1 and 2 (0.98 and 0.99 for the Control and Test bedrooms respectively). The internal $PM_1/PM_{2.5}$ ratios during Phase 3 were slightly higher than in Phases 1 and 2 (0.88 and 0.89 for Control and Test respectively). This confirms the previous finding that the majority of internal PM is comprised of fine particulates ($\leq PM_{2.5}$). Over the duration of the study, there has been a slight increase of $PM_1/PM_{2.5}$ ratios in both bedrooms (0.83–0.88 Control; 0.86–0.89 Test), although $PM_{2.5}/PM_{10}$ have remained consistent. This may be due to the cumulative effect of the use of mechanical ventilation over time which has removed more of the larger particles or a factor of filter age.

Table 6
Comparison of infiltration rates during Phases 1 - 3.

Phase	F_{inf} (based on PM_{10})	F_{inf} (based on $PM_{2.5}$)	F_{inf} (based on PM_1)
1 (Control)	0.40	0.46	0.56
3 (Control)	0.18	0.20	0.26
2 (Test)	0.23	0.26	0.35
3 (Test)	0.15	0.15	0.21

3.3.3. Infiltration factors

Infiltration factors were estimated using the previously calculated Cs values and using a mean external diurnal profile measured at 5-min intervals taken from November 2016 for C_{out} values (ambient external PM was not measured in Phase 3 due to financial limitations). Table 6 shows F_{inf} ranges for PM_{10}, $PM_{2.5}$ and PM_1 for both bedrooms.

The infiltration rates for each house for each particle size for Phase 3 were considerably lower than those of Phases 1 and 2 (Table 6), by 45% (Control) and 65% (Test). Again this was unexpected as it was thought that the similar mechanical ventilation rates would standardise the F_{inf} results. There may be a number of reasons for this difference, first of all, our assumption that there were very few internal PM sources may have been incorrect and contribution was significant. This is unlikely as the internal PM concentrations were very low and also C_s was calculated for both bedrooms during Phases 1 and 2 (< 0.3 µg m^{-3} – refer Table 4). External air quality may have decreased considerably during this time resulting in mean PM_{10} concentrations < 3 µg m^{-3}, although unlikely given previous results for Phases 1 and 2 (mean PM_{10} = 5.4 and 5.2 µg m^{-3} respectively) and background studies from the winter period (mean PM_{10} = 6.0 µg m^{-3}) (Hernandez et al., 2017). This questions the value of equation (1) (for mechanically ventilated buildings) which simplifies F_{inf} into one factor but for which there are likely to be multiple contributing factors. The relationship between external and internal PM concentrations in this scenario is not linear as previously suggested. For example, the effect of increased air flow on particle adsorption to internal surfaces (which may have explained the difference in F_{inf} between phases 1 and 2), variations in filter efficiency (both between Control and Test and also over time) and variations in particle loss (via exit from bedrooms or adsorption to surfaces).

It is interesting to note that there was far less variation in F_{inf} for different PM sizes in Phase 3. For the Control house (Phase 1), F_{inf} increased by 0.16 from PM_{10} to PM_1. However, using the lower F_{inf} values for Phase 3, F_{inf} increased by only 0.05 from PM_{10} to PM_1. The change in F_{inf} rates has reduced the preferential selection of smaller particle sizes which supports the effects of variations in filter efficiency (over time) and variations in particle loss within the bedrooms which may be affected by changes in internal climate. It has not been possible to determine which of the possible factors had the greatest influence or if other factors are involved and further work is required.

4. Conclusions

There was significant variation in the transportation of PM from an external to internal environment in two similar houses ([PM] Control > [PM] Test (ρ = 0.001)) despite both houses operating the same mechanical ventilation system located adjacent to each other with the same orientation and solar exposure. Mean internal PM_{10} concentrations = 2.4 µg m^{-3} (Control) and 1.3 µg m^{-3} (Test) with corresponding mean external PM_{10} concentrations of 5.4 µg m^{-3} and 5.2 µg m^{-3} respectively. Particle removal efficiency between the two

houses varied by approximately 20%. These findings indicate that there is considerable variation in filtration efficiencies even when the same mechanical ventilation system is in use in similar homes in the same location. Although external PM concentrations were statistically significantly higher in Control (Phase 1) than Test (Phase 2) ($\rho = 0.001$), this only partially explains why the internal concentrations were higher in the Control bedroom.

There was a very strong positive correlation between external and internal PM for all particle sizes (Spearman's rank coefficients ranged between 90 and 95%), which would be expected given the lack of internal sources. PM concentration fluctuations were less for internal PM than external PM and fluctuations in internal PM were less still for the Test house than the Control house.

During Phases 1 and 2, internal PM ratios were 0.98–0.99 $PM_{2.5}/PM_{10}$ and 0.83–0.86 $PM_1/PM_{2.5}$, suggesting the majority of indoor PM_{10} is fine particulates ($\leq PM_{2.5}$) for both bedrooms. This is due to the action of MVHR filters which are more efficient at removing larger particles. Variations in infiltration rates under the same mechanical ventilation system may be due to factors including variations in air flow volumes and internal particle deposition rates.

Mean I/O ratios for PM_{10}, $PM_{2.5}$ and PM_1 were less than one (indicating a dominance of outdoor sources) and higher in the Control bedroom that the Test bedroom. These values were lower than ratios measured under natural ventilation (due to presence of air filters) and there was a tendency for I/O ratio to increase with increasing particle size. Factors which affect I/O ratios in mechanically ventilated buildings previously identified include particle size, air exchange rate and filter efficiency. However, air flow rates may also have an effect on the deposition of PM onto indoor surfaces in mechanically ventilated houses.

The infiltration factor (F_{inf}) was calculated and demonstrated considerable variability both between houses (Control-Test PM_{10} 0.40–0.23) and over time (Control PM_{10} 0.40–0.18) which indicates that relationship between external and internal concentrations of PM is not linear as previously proposed and should therefore be used with caution. This challenges simplifying F_{inf} into one factor as there are likely to be multiple contributing factors. For example, the effect of air flow rates on particle adsorption to internal surfaces, variations in filter efficiency and variations in particle loss.

Direct comparison of internal PM concentrations in the two houses over the same time-frame showed that Control > Test and that there was a noticeable difference in minimum and maximum values for all sizes with [Control] > [Test]. The temperature difference between the two bedrooms remained minimal throughout the phase, however RH was higher in the Control (62.2%) than the Test (59.1%). The lower concentrations measured in the Test bedroom may be due to factors such as variations in filter efficiency and particle removal processes.

Over the duration of this study, PM concentrations decreased in both bedrooms by 52% (Control) and 37% (Test), which may be due to a number of factors including changes in internal environmental conditions, filter age and the cumulative effect of the active extract function of the MVHR system over time reducing the transportation of PM into the houses. In addition, there has been a slight increase of $PM_1/PM_{2.5}$ ratios in both bedrooms (0.83–0.88 Control; 0.86–0.89 Test). This may be due to the aforementioned cumulative effect removing more of the larger particles and/or a factor of filter age.

Whilst this study was site specific, it found considerable baseline variability occurring in real houses over time without the complication contributed by occupancy. This work questions the variability caused by occupant activity alone and also the variation in F_{inf} values under consistent mechanical ventilation rates reinforces the necessity to further examine this relationship. Establishing whether this variation might have been a factor in previous research warrants investigation by repeating the process under controlled occupancy conditions.

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Appendix A. Supplementary data

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The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

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