This article is based on a paper presented at the 43rd AIVC - 11th TightVent & 9th Venticool Conference "Ventilation, IEQ and health in sustainable buildings" held on 4–5 October 2023 in Copenhagen, Denmark.
Full paper: https://www.aivc.org/resource/impact-increased-occupancy-particulate-matter-concentrations-mechanically-ventilated

Household Generated Particulate Matter in Mechanically Ventilated Homes




GERMAN HERNANDEZ
Mount Albert, Auckland, New Zealand
hhernandez@unitec.ac.nz

RAFAEL BORGE
Politécnica de Madrid, Spain

DAN BLANCHON
Auckland War Memorial, New Zealand

TERRI-ANN BERRY
Auckland University of Technology, New Zealand

This study examines the impact of high occupancy levels, due to COVID-19 stay-at-home orders, on IAQ in mechanically-ventilated residential buildings. Indoor $PM_{2.5}$ and PM_{10} concentrations increased in most houses (64% and 40% respectively), while outdoor levels decreased (34% and 31%), indicating internal sources were the main contributor to indoor concentrations.

Keywords: Indoor Air Quality, Mechanical Ventilation, Increased Occupancy, COVID-19 lockdown, Particulate Matter

Introduction

Indoor air pollution can be detrimental to human health (Cohen et al., 2005; Donaldson et al., 2001) and can lead to increased mortality rates (Hales et al., 2012). Numerous studies have shown that human exposure to indoor pollution is often more common than exposure to outdoor pollution (Logue et al., 2012; Weschler, 2006), especially where people spend most of their time indoors at home (Klepeis et al., 2001). The control of indoor air quality (IAQ) inside homes is therefore an important factor for the health and wellbeing of residents.

Inadequate ventilation can prevent escape of substances from within the home and lead to an accumulation of physical pollutants arising from internal sources (e.g., building materials, furnishings, personal care products, pesticides, and household cleaners). The term "Sick Building Syndrome" describes the relationship between the IAQ and its potential effects on occupants (Bernstein et al., 2008), such as headache, respiratory infection, and cognitive function (Taptiklis et al., 2017; Tookey et al., 2019). Positive pressure ventilation (PPV) systems use mechanical ventilation to extract and filter dry air from the roof space, creating a slight positive pressure to drive out stale air and maintain IAQ.

The recent Coronavirus disease (COVID-19) pandemic led to lockdown events which resulted in the general public spending the majority of their time at home. Numerous IAQ studies have investigated the effects of increased occupancy on IAQ, however these primarily focus on buildings which rely on natural ventilation. To improve understanding of the effects of occupancy on indoor pollutant concentrations, in particular where mechanical ventilation systems are installed, this study analysed IAQ parameters ($PM_{2.5}$, PM_{10}) in homes in Auckland, before and during COVID-19 lockdown. Due to the objective of mechanical ventilation being to improve thermal comfort, this study also included an evaluation of thermal comfort parameters (temperature, RH) in response to changes in occupancy.

Methodology

IAQ were monitored in six mechanically-ventilated Auckland homes with PPV systems, each having floor areas of 120 to 273 m² and three to four bedrooms, over a six-week period (three weeks before and three weeks during the COVID-19 lockdown). Three monitors were located indoors to measure $PM_{2.5}$, PM_{10}: in the master bedroom, another bedroom and the living area. Outdoor PM measurements were obtained from nearby council-owned air quality monitoring stations. Indoor and outdoor monitors were positioned 1.0 m and 1.5 m above floor level respectively (where possible). Low-cost sensors in this study were calibrated against two robust PM monitors (Aeroqual Dust Sentry Pro) before and after the monitoring period, with a one-week co-location period. $PM_{2.5}$ showed strong correlations (R2 values: 0.89–0.96) with the standard monitors.

Results and Discussion

Household Environment, Occupancy Rates and Activity

All six houses were single-storey open-plan of timber construction, with floor and roof insulation. All windows were single-glazed. All participants reported that their homes were typically only occupied outside of business hours (prior to lockdown) and were generally occupied full time during lockdown. Ventilation rates varied between 3 and 4 air exchanges per hour. Larger houses require additional fan units to guarantee this air exchange rate. The system uses a deep-pleat nano-fibre filter (F8), to remove all particles greater than 0.4 μm; tested to meet international (Eurovent and ASHRAE) standards. The PPV systems were controlled centrally, to adjust automatically according to the temperature differential measured between rooms and the roof-space.

Particulate Matter ($PM_{2.5}$, PM_{10})

The average PM concentrations (measured in the living area) across the three-week periods before and during lockdown are presented in **Table 1**. Three of the residential buildings (D, E and F) showed an increase in $PM_{2.5}$ of between 25% and 62%.

Table 1. *Average indoor concentrations of $PM_{2.5}$ and PM_{10}.*

Parameter	House	A	B	C	D	E	F
$PM_{2.5}$ (μg/m³)	pre-lockdown	0.55	0.73	20.62	4.20	4.96	4.37
	during lockdown	0.80	1.73	21.21	5.24	8.01	5.78
PM_{10} (μg/m³)	pre-lockdown	0.93	1.08	23.51	4.69	5.52	6.05
	during lockdown	0.58	0.36	21.50	6.13	9.00	7.71

This is consistent with findings by (Laltrello et al., 2022) and (Cowell et al., 2023). One house showed a substantial increase in $PM_{2.5}$ of around 136%, while two houses showed minimal change. The change in $PM_{2.5}$ levels for House A was close to the limit of the sensor accuracy. House C was identified as a rural/farming house, where the level of occupational activity outside the home was not affected by the lockdown. This house had the highest indoor concentration of $PM_{2.5}$ both pre and post lockdown.

Indoor PM_{10} concentrations increased following lockdown for three of the houses, between 27% and 63%, which is consistent with Laltrello et al. (2022) and Cowell et al. (2023). This may indicate the primary sources of PM_{10} were internal for these houses. Internal PM_{10} sources can include smoking, woodfire burning, unflued heaters and burning of candles. House F, for example, contained a fireplace. The other two houses where PM_{10} increased were geographically sheltered from the nearest roads, so internally generated PM_{10} is more likely to be the main component of indoor concentrations for these houses, and accordingly increase with occupancy. For the other three houses, the magnitude of change in PM_{10} was relatively minor (<1 μg/m³) for two of these, while the third house was the farmhouse mentioned previously, where day to day activities were not affected by the lockdown.

Average indoor $PM_{2.5}$ concentrations for two selected houses for the weeks immediately prior to and following COVID-19 lockdown are shown in **Figure 1**. These show that diurnal $PM_{2.5}$ peaks during lockdown were higher than those prior to lockdown. Background levels of $PM_{2.5}$ remained relatively low during the lockdown period as expected for people working from home, spending much of the day seated and limiting $PM_{2.5}$ emissions.

Average daily $PM_{2.5}$ and PM_{10} concentrations for each house were compared with the WHO Air Quality Guideline (AQG) limits (15 µg/m³ and 45 µg/m³ for $PM_{2.5}$ and PM_{10}, respectively). In general, the $PM_{2.5}$ limit was exceeded more frequently than the PM_{10} limit. Similar studies (Algarni et al., 2021; Cowell et al., 2023) have shown that WHO limits are typically exceeded with increased occupancy, but these mostly apply to homes which only have natural ventilation. Prior to lockdown, House C exceeded the $PM_{2.5}$ limit on 16 of the 21 days, while the only other exceedance was one day in House E. During lockdown, House C exceeded the $PM_{2.5}$ limit 11 days out of the 3-week period, House E exceeded on two days, while Houses B and D both exceeded one day. The PM_{10} limit was only exceeded twice, two different houses, each on a different day, both during lockdown. House C was identified as comprising residents who regularly smoked cigarettes indoors. Cigarette smoking has been shown to increase indoor concentrations of $PM_{2.5}$ up to 28 times that for non-smoking households (Algarni et al., 2021).

Indoor Vs Outdoor

Outdoor PM measurements were obtained from three local council-owned air quality monitoring stations located across central Auckland. Average PM concentrations were calculated for the three-week periods immediately prior to and following COVID-19 lockdown. Average $PM_{2.5}$ concentrations decreased by 34% (from 7.7 µg/m³ to 5.1 µg/m³), ranging between 30% and 37% for the three stations. PM_{10} decreased by 31% (from 17.3 µg/m³ to 11.9 µg/m³), ranging between 10% and 39%. Decreases in PM_{10} and $PM_{2.5}$ were expected due to reduced traffic volumes and restrictions on non-essential commerce and industry during lockdown (Laltrello et al., 2022). **Figure 2** compares indoor and outdoor $PM_{2.5}$ and PM_{10} levels for a selected house and AQ monitoring station, one week prior to and one week immediately after COVID-19 lockdown. Despite a gradual decrease in outdoor PM concentrations, indoor concentrations increased during the lockdown. Mechanical ventilation has been shown to substantially reduce indoor concentrations of outdoor-generated pollutants when compared with natural ventilation (Martins & Carrilho da Graça, 2018; Ren et al., 2017).

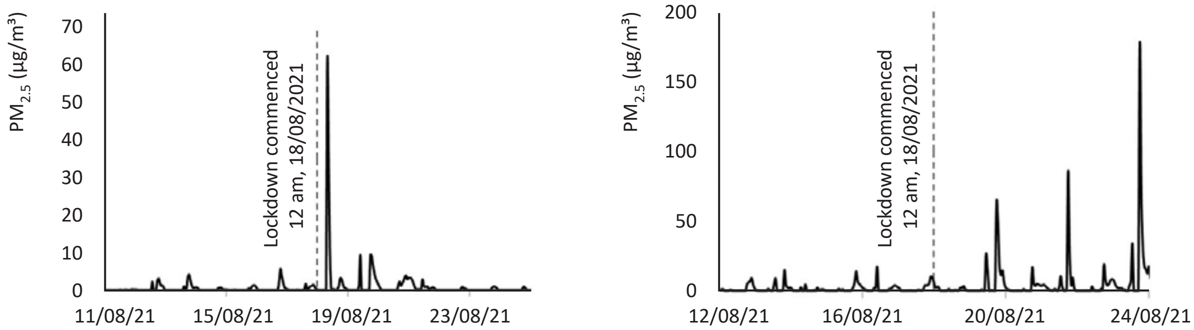

Figure 1. Indoor PM2.5 concentrations in House A (left) and House D (right), 1-week pre/post lockdown.

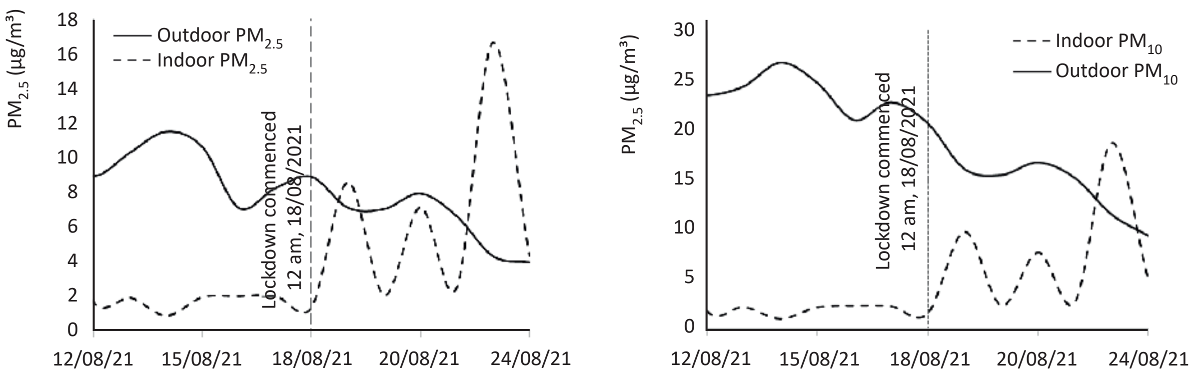

Figure 2. Indoor vs outdoor PM concentrations of $PM_{2.5}$ (left) and PM_{10} (right), 1-week pre/post lockdown (House D).

Conclusions

Outdoor concentrations of $PM_{2.5}$ generally decreased during lockdown (34%, on average compared with pre-lockdown levels). Despite this, indoor $PM_{2.5}$ concentrations were generally found to be between 25% and 62% higher during the lockdown period, suggesting internal sources. Furthermore, mechanical ventilation has been shown to substantially limit penetration of outdoor pollutants indoors, suggesting that internal concentrations are even more likely to have originated from internal sources. Diurnal peaks were also observed to be higher during lockdown, with highest peaks typically occurred during evenings.

Indoor PM_{10} concentrations generally increased during lockdown (40% average) compared with outdoor concentrations. Reduced traffic and industrial activity during lockdown may have been directly responsible for reduced outdoor PM concentrations. Increased indoor PM_{10} concentrations are therefore likely to be due to internal sources, mainly from combustion activities.

With the exception of one house (identified as a smoking household) average daily PM concentrations rarely exceeded WHO Air Quality Guideline limits for short term exposure. With mechanical ventilation, all homes were able to maintain indoor PM levels below the WHO guideline limits throughout the duration of the trial, despite the increased levels of occupancy.

Acknowledgements

HRV New Zealand, the households who participated in this study and Joanne Low for her generous assistance with this project.

References

Algarni, S., Khan, R. A., Khan, N. A., & Mubarak, N. M. (2021). Particulate matter concentration and health risk assessment for a residential building during COVID-19 pandemic in Abha, Saudi Arabia. *Environmental Science and Pollution Research*, *28*(46), 65822–65831. https://doi.org/10.1007/s11356-021-15534-6.

Bernstein, J. A., Alexis, N., Bacchus, H., Bernstein, I. L., Fritz, P., Horner, E., Li, N., Mason, S., Nel, A., & Oullette, J. (2008). The health effects of nonindustrial indoor air pollution. *Journal of Allergy and Clinical Immunology*, *121*(3), 585–591.

Cohen, A. J., Ross Anderson, H., Ostro, B., Pandey, K. D., Krzyzanowski, M., Künzli, N., Gutschmidt, K., Pope, A., Romieu, I., Samet, J. M., & Smith, K. (2005). The global burden of disease due to outdoor air pollution. *Journal of Toxicology and Environmental Health. Part A*, *68*(13–14), 1301–1307. https://doi.org/10.1080/15287390590936166.

Cowell, N., Chapman, L., Bloss, W., Srivastava, D., Bartington, S., & Singh, A. (2023). Particulate matter in a lockdown home: Evaluation, calibration, results and health risk from an IoT enabled low-cost sensor network for residential air quality monitoring. *Environmental Science: Atmospheres*, *3*(1), 65–84. https://doi.org/10.1039/D2EA00124A.

Donaldson, K., Stone, V., Seaton, A., & MacNee, W. (2001). Ambient Particle Inhalation and the Cardiovascular System: Potential Mechanisms. *Environmental Health Perspectives*, *109*, 5.

Hales, S., Blakely, T., & Woodward, A. (2012). Air pollution and mortality in New Zealand: Cohort study. *Journal of Epidemiology and Community Health*, *66*(5), 468–473. https://doi.org/10.1136/jech.2010.112490.

Klepeis, N. E., Nelson, W. C., Ott, W. R., Robinson, J. P., Tsang, A. M., Switzer, P., Behar, J. V., Hern, S. C., & Engelmann, W. H. (2001). The National Human Activity Pattern Survey (NHAPS): A resource for assessing exposure to environmental pollutants. *Journal of Exposure Science & Environmental Epidemiology*, *11*(3), 231–252. https://doi.org/10.1038/sj.jea.7500165.

Laltrello, S., Amiri, A., & Lee, S.-H. (2022). Indoor Particulate Matters Measured in Residential Homes in the Southeastern United States: Effects of Pandemic Lockdown and Holiday Cooking. *Aerosol and Air Quality Research*, *22*(5), 210302. https://doi.org/10.4209/aaqr.210302.

Logue, J. M., Price, P. N., Sherman, M. H., & Singer, B. C. (2012). A Method to Estimate the Chronic Health Impact of Air Pollutants in U.S. Residences. *Environmental Health Perspectives*, *120*(2), 216–222. https://doi.org/10.1289/ehp.1104035.

Martins, N. R., & Carrilho da Graça, G. (2018). Impact of PM2.5 in indoor urban environments: A review. *Sustainable Cities and Society*, *42*, 259–275. https://doi.org/10.1016/j.scs.2018.07.011.

Ren, J., Liu, J., Cao, X., & Hou, Y. (2017). Influencing factors and energy-saving control strategies for indoor fine particles in commercial office buildings in six Chinese cities. *Energy and Buildings*, *149*, 171–179. https://doi.org/10.1016/j.enbuild.2017.05.061.

Taptiklis, P., Phipps, P. R., & Plagmann, D. M. (2017). *Indoor Air Quality in New Zealand Homes and Schools—A literature review of healthy homes and schools with emphasis on the issues pertinent to New Zealand*. https://www.aivc.org/sites/default/files/Indoor%20Air%20Quality.pdf.

Tookey, L., Boulic, M., Phipps, R., & Wang, Y. (2019). *Air stuffiness index and cognitive performance in primary schools in New Zealand*. https://openaccess.wgtn.ac.nz/articles/conference_contribution/Air_Stuffiness_index_and_cognitive_performance_in_primary_schools_in_New_Zealand/20651283/1/files/36859050.pdf.

Weschler, C. J., & Shields, H. C. (2000). The influence of ventilation on reactions among indoor pollutants: Modeling and experimental observations. *Indoor Air*, *10*(2), 92–100. ■