A MATHEMATICAL EXPLORATION OF BUSHFIRE SMOKE ($PM_{2.5}$) INFILTRATION INTO AN AIR CONDITIONED BUILDING

John Innis[1], Fay Johnston[2], Fabienne Reisen[3], Chris Roulston[3], Grant Williamson[2], Amanda Wheeler[3]

[1] EPA Tasmania, Hobart, Australia

[2] University of Tasmania, Hobart, Australia

[3]CSIRO, Aspendale, Australia

Abstract

Understanding the contribution that ambient air pollution has on indoor air quality is important for studies assessing personal exposure, how to reduce infiltration by improving building design, and for public health purposes. This is particularly relevant during widespread pollution events, such as the 2019-20 bushfires in eastern Australia. Work by a number of groups has shown that passive infiltration is highly dependent on the building age and design. The circumstances appear more complex for buildings with active heating and ventilation air control (HVAC) systems. In these cases, the rate of air exchange and, potentially, particle filtration via the air intake, ducting and other parts of the HVAC may significantly influence indoor air quality.
In late 2019 an air monitoring campaign was conducted at Port Macquarie, NSW, during a long-duration bushfire smoke event. CSIRO's low-cost 'SMOG' sensors were deployed inside and outside a public library. A description of this work has been published by Wheeler et al, 2021, who found that there were reductions in $PM_{2.5}$ inside the building compared to outside.

For the current work, this extensive dataset has been re-analysed in an exploratory study attempting to mathematically simulate HVAC operation, such as the mixing of ambient and 'return' air, to predict inside $PM_{2.5}$ levels based on the outside $PM_{2.5}$ dataset. The HVAC was in operation during normal business hours, when access to the library was frequent. Not surprisingly, the mathematical model predicted (and successfuly modelled) greater infiltation during HVAC and building operation. Hence the duration and time-of-day of the external smoke occurrence, relative to HVAC operation, significantly influenced the infiltration of outdoor pollutants indoors. We note this is a preliminary model, and that a more focussed study would be needed to investigate this effect further.

Keywords: Smoke; Indoor air quality; HVAC systems; $PM_{2.5}$; Infiltration

1 Introduction

Infiltration of ambient air pollution into occupied buildings is one of the greatest determinants of population exposure levels for people in Australia and New Zealand due to the large number of hours per day spent inside. The issue is of increasing importance as public health messaging often suggests 'sheltering in place' or spending time in air conditioned buildings (such as shopping centres or libraries) during large–scale, long–duration pollution events such as from bushfire smoke. In many instances however the heating, ventilation and air–conditioning plant (HVAC) of buildings of these types have little or no specific capability to filter smoke particles or otherwise scrub the supplied air.

Recently Wheeler et al. (2021) carried out a measurement program with low–cost sensors at a public library in Port Macquarie, NSW, during an extended bushfire smoke interval. Sensors were deployed outside and inside the library for a number of months. Based on a comparison of day–averaged $PM_{2.5}$ levels from inside and outside sensors, Wheeler et al. (2021) reported for one such sensor pairing (which we will further investigate here) the campaign median outdoor $PM_{2.5}$ was near 31 μg m^{-3}, but the indoor median $PM_{2.5}$ was lower at 20 μg m^{-3}.

A re–evaluation of two months of the Port Macquarie data is undertaken here, using the original 5–minute time–resolution of the data. The daily hours of operation of the HVAC and the time of day of the onset of bushfire smoke will be explored: If outside smoke levels are high when the HVAC is not operating infiltration would be expected to be reduced, compared to when the HVAC is mechanically bringing in outside air. We will investigate this hypothesis in this work.

1.1 HVAC systems

Typical 'non–critical' building air–conditioning systems are designed to provide approximately 10 to 20% outside air[1]. This outside air is then mixed with return air from the air–conditioned space. The combined air is filtered using dry filter media, and then either heated or cooled, depending on ambient temperature, and delivered back into the building. The reuse of the return air greatly reduces the heating and cooling demands on the HVAC system.
This means in the early stages of a smoke event there will be a 'dilution' advantage inside the building, as approximately only 10% to 20% of the building supply air will be smoke–tainted in the early stages of the event. However, as time goes by, if ambient smoke levels do not fall, and if the HVAC is in continuous operation, the inside smoke concentrations would move towards an equilibrium with the outside concentrations.
Following Australian Standard AS/NZS-1668.2, a typical HVAC design for a public building or shopping centre would deliver between 7.5–10 litres/sec of air–flow per person (of which 10 to 20% is outside air), depending upon the level of air filtration, based on a known specified occupancy, or a flow of 1.0 litre/m^2 if the occupancy rate is not known.
All commercial (non-critical) air conditioning systems will include air filtration in the mixed (outside air and return air) plenum. In retail buildings these are very unlikely to be HEPA filters (High–Efficiency Particle Absorbers), which is what would be needed to remove smoke particles. Conversely hospitals, high-performance computer labs, and similar infrastructure most likely would use HEPA filtering. In general, HEPA filters cannot be easily fitted to an existing, non–critical, air–conditioning system, as the existing supply–air static pressure is too low to overcome the high resistance of the HEPA Filters. Hence a critical air conditioning system has the added expense not only of the HEPA filters but also the bigger systems and greater energy needs for these to operate. Electrostatic precipitators are also of moderate effectiveness in removing smoke, but again these come with an increased operating–energy need.
Commercial premises, such as shopping centres, and most public buildings, are unlikely to have suitable air-conditioning/ventilation systems to be able to filter significant levels of fine particles and hence cannot provide clean air during long-duration smoke events.

2 Measurements at Port Macquarie, Oct–Nov 2019

Wheeler et al (2021) give a full account of the measurement campaign, where pairs of the CSIROs SMOG sensors were located in several places inside the Port Macquarie library, as well as directly outside. For the purposes of the current study we will consider one outside (ambient air) sensor and one sensor from the internal media room[2]. We select the data from the 1st of October to the 28th of November 2019. Smoke levels were very high in mid November in 'Black Summer'. Figure 1 shows the time–series of 5–minute outside and inside $PM_{2.5}$ selected for this study.

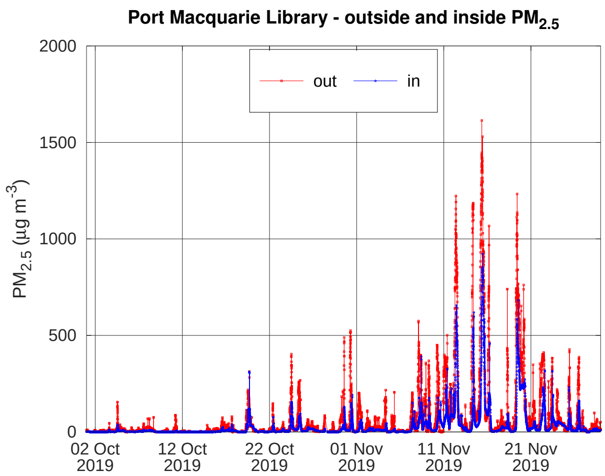

Figure 1: Time–series of 5–minute $PM_{2.5}$ measured by the SMOG units at Port Macquarie, 1st October – 28th November 2019. Red symbols: Outside; Blue symbols: Inside.

In Figure 2 we plot the 'composite day', or average diurnal pattern of outside smoke (as $PM_{2.5}$) for the study interval. There is a marked pattern with the highest smoke occurring near 8 am. The HVAC system at the library operated on 6 days of the week. In Wheeler et al. (2021) the HVAC operating hours were given as from 8

[1]The authors acknowledge discussions with Ventilation Plumber and Facility Manager Chris Morrison for information used in this section.
[2]Outside: SMOG unit 28. Inside: SMOG unit 47.

am to 7 pm with a 10% to fresh air intake during operation. We revise these here to 08:00 to 19:30 Monday–Friday; 08:00 to 12:30 on Saturday; and no operation on Sunday. This revision in based on the recorded library opening hours (which are half an hour after and half an hour before the HVAC start and stop times) and inspection of the dataset. The only revision to this is we believe the HVAC may have been operated on a weekday schedule on Saturday the 19th of October, as noted in the appendix.

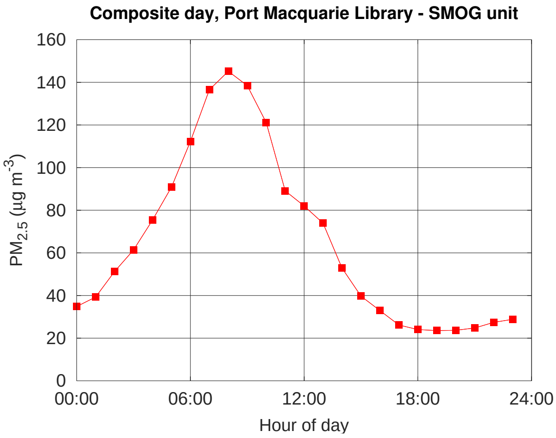

Figure 2: 'Composite day' (average diurnal variation) in ambient $PM_{2.5}$ measured by the SMOG unit at Port Macquarie, 1st October – 28th November 2019.

3 Modelling the $PM_{2.5}$ infiltration

The mathematical model for infiltration of ambient smoke into the library media room incorporated the following: It was assumed that the outside and inside SMOG units were effectively equivalent in response to $PM_{2.5}$, and hence were not adjusted relative to each other. We take the outside air time-series and passed these through a model that calculates (or predicts) the inside $PM_{2.5}$ time–series. We tested the appropriateness of the model by comparing the model output with the measured inside air time–series.
The mix of fresh air into the system was assumed to be 10% (as given in Wheeler et al., 2009). When the HVAC was not operating, a smaller rate of infiltration was present representing a passive process. This also was adopted in an equivalent but opposite sense as the rate of passive exfiltration of inside air. A value of 0.4% was adopted (see below). As the volume of the media room was not known, the relevant parameter used was the number of air–exchanges per hour in the room. Typically in a non–critical system the HVAC flow is set to ensure 3 to 5 air–exchanges per hour in the conditioned volume[3]. In this work we found that a value near 8 air–exchanges per hour was required to match the model output with the measured time–series of inside $PM_{2.5}$. We speculate that this may be a function of flow–rate set for the larger library volume, resulting in a greater rate of exchange for the smaller volume of the media room, but this is just speculation.

[3]Note: the air exchanged still only has a 10% fresh air mix

3.1 Mathematical model

The model is a chronological calculation of the predicted inside $PM_{2.5}$ as follows. The first (5–minute) data–point in the model is seeded by the measured inside $PM_{2.5}$ for the first data point in the time series. (This is the only use of the measured inside $PM_{2.5}$ for the calculation.) The second data point is calculated based on the current outside air $PM_{2.5}$ value (5–minute measurement) with an infiltration rate that depends on whether the HVAC is currently operating. If it is not operating, the passive infiltration rate is used to calculate the contribution of the current outside $PM_{2.5}$ that has come in to the room. If the HVAC is operating the 10% mix of air and the current outside $PM_{2.5}$ is used to calculate the $PM_{2.5}$ concentration in the infiltrated fraction. The rate of 8 air–exchanges per hour is expressed as a 5–minute value (i.e. 0.67 air–exchanges per 5–minutes) to determine the fraction, *F*, of 'new air' that has entered the room in this time–step. This is combined with (1-*F*) of the previous predicted inside $PM_{2.5}$ to derive the current $PM_{2.5}$. A duty–cycle term is also incorporated to represent that the HVAC may not operate continuously, but cycles to keep the temperature within specified limits. This duty-cycle was set to 80%. (i.e. the HVAC operates on average for 4 minutes in 5.) There is also a small 'loss' factor of about 4% which was found to be needed and likely reflects an absorption of smoke particles in the HVAC ducts and perhaps the room surfaces. The process continues chronologically through the data–set.
All parameter values were set via a trial–and–error iterative procedure. As the various aspects of the processes operate on different time–scales or at different times of the day it was relatively easy to refine the parameter values – for example the passive infiltration rate can be investigated for times of the day when the HVAC is not operating.

4 Results

Figure 3 shows one week of the ambient $PM_{2.5}$, inside $PM_{2.5}$, and model–predicted inside $PM_{2.5}$. This is the interval with the peak ambient smoke during the campaign. Ambient $PM_{2.5}$ is shown in red, measured inside $PM_{2.5}$ in blue, and the model–predicted $PM_{2.5}$ in green. The model tracks the inside measured $PM_{2.5}$ remarkably well considering the simple assumptions used. Another example week of data and model predictions is shown in Figure 4, for the 19th to the 25th of November 2019, which is the week immediately following that shown in Figure 3. Again the agreement between the measured inside $PM_{2.5}$ and model–predicted $PM_{2.5}$ is considered to be very good.

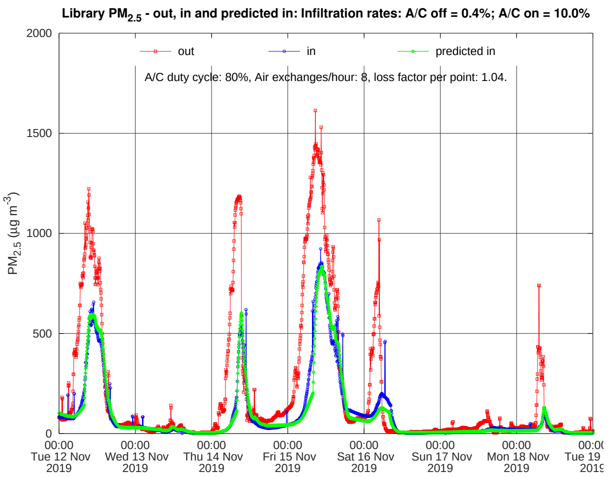

Figure 3: Example of measured ambient and inside $PM_{2.5}$, and model–predicted $PM_{2.5}$, 12th–18th November 2019. Red symbols: Ambient $PM_{2.5}$; Blue symbols: Measured inside $PM_{2.5}$; Green symbols: Model–predicted $PM_{2.5}$.

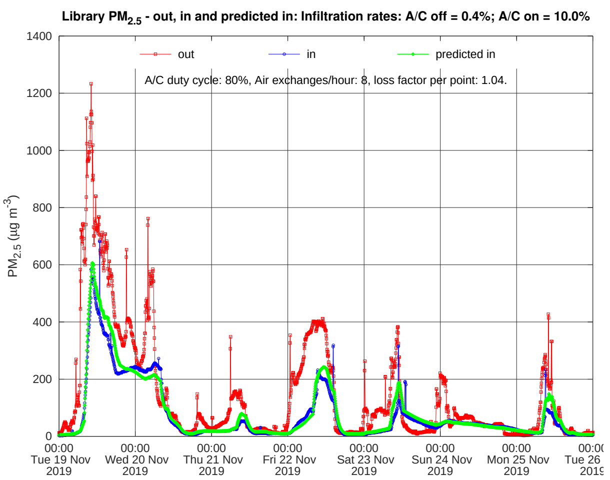

Figure 4: Example of measured ambient and inside $PM_{2.5}$, and model–predicted $PM_{2.5}$, 19th–25th November 2019. Red symbols: Ambient $PM_{2.5}$; Blue symbols: Measured inside $PM_{2.5}$; Green symbols: Model–predicted $PM_{2.5}$.

Figure 5 shows a scatter plot of measured inside $PM_{2.5}$ (horizontal axis) and model–predicted $PM_{2.5}$ (vertical axis) for the 2–month study interval. A 1:1 line is also shown. The general agreement is reasonable but deviations from the 1:1 line are systematic, and arise from small time–delays between the variations in each quantity. The values of the parameters used in the model were chosen to minimise the size of these deviations. It is noted that the model does not take account of effects such as the ambient temperature, which may influence the HVAC operating parameters, or wind speed, which may influence the passive infiltration/exfiltration rates. Library occupancy, which is not known, may also affect aspects of the HVAS operation. Given these non–modelled effects, the performance of the model in predicting the inside $PM_{2.5}$ – based on the ambient $PM_{2.5}$; a value of the inside $PM_{2.5}$ levels 5–minutes earlier; and the modelled air–transfer - is considered satisfactory for characterising the important features of the processes.

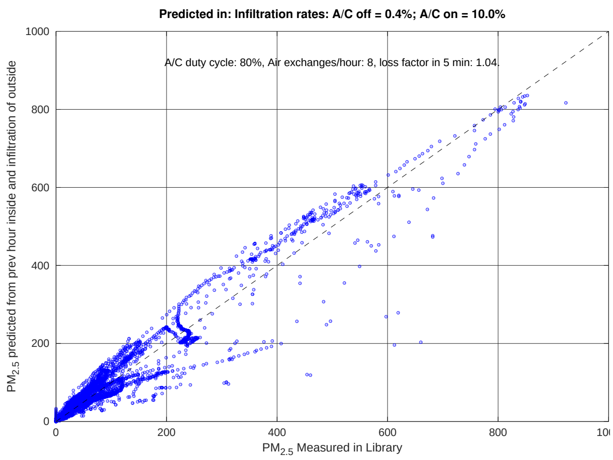

Figure 5: Scatter plot of inside measured $PM_{2.5}$ (horizontal axis) and model–predicted $PM_{2.5}$ (vertical axis). A 1:1 line relationship is shown by the dashed line.

5 Discussion

5.1 General Comments

The relatively basic numerical model employed here attempts to capture the main processes of mixing outside air in the operation of a HVAC system and the implications for smoke infiltration. As noted, the model omits a number of processes that may be important (such as ambient air temperature), but based on the good agreement between the model–predicted inside $PM_{2.5}$ and the measured inside $PM_{2.5}$ it is argued the model as is reflects the main contributory factors.

From this exercise, the importance of the time of occurrence of peak ambient smoke relative to the times of operation of the HVAC will be critical for the level of infiltration that will result. As noted, the result of Wheeler et al. (2021), based on campaign median values of ambient and inside $PM_{2.5}$, found the inside $PM_{2.5}$ was approximately two–thirds of the ambient $PM_{2.5}$. For the 1st October to 28 November 2019 interval considered here, the mean ambient $PM_{2.5}$ was 65 μg m^{-3}; the mean measured inside $PM_{2.5}$ was 30 μg m^{-3}. The mean model–predicted $PM_{2.5}$ was slightly higher at 33 μg m^{-3}. This is also reflected in the greater number of data points above the 1:1 line in Figure 5.The work reported here argues that as the HVAC did not operate for 24 hours each day, the time–of–day of occurrence of smoke needs to be considered.

5.2 Active control of ventilation to reduce infiltration

An obvious extension study using the model is to consider the advantages of active control of the HVAC system to prevent high smoke levels from being brought into the indoor air. Clearly indoor air quality has other dimensions than smoke levels, but for a first investigation the following criteria were applied to the Port Macquarie ambient air $PM_{2.5}$ and HVAC model.

The normal HVAC hours of operation were retained. However the fresh air mixing rate of 10% was set to be variable. For ambient $PM_{2.5}$ below 10 μg m^{-3} it remained at 10%. For ambient $PM_{2.5}$ between 10 μg m^{-3} and 25 μg m^{-3} it was set to 2.5%. For ambient $PM_{2.5}$ between 25 μg m^{-3} and 50 μg m^{-3} it was set to 1%. Above 50 μg m^{-3} the fresh air rate was set to zero. Additionally, when the inside $PM_{2.5}$ was greater than 10 μg m^{-3}, and the outside $PM_{2.5}$ was less than 5 μg m^{-3}, the fresh air rate was set to 30% to flush the inside at a more rapid rate. This 'flush' was programmed to occur even if outside the normal HVAC hours of operation.

Figure 6 shows an example week of ambient $PM_{2.5}$ (red), measured inside $PM_{2.5}$ (blue), and the 'actively–controlled' inside $PM_{2.5}$ (green). For much of the interval the ambient smoke levels were high in the morning, prior to the HVAC operation, so the passive infiltration rate dominates. Several examples of the advantage of the active–control can be seen however. The first is near the middle of the 8th of November 2019, where the HVAC has been 'turned off' in the active control model. Active–control $PM_{2.5}$ levels remained below 100 μg m^{-3} while actual inside levels reached to near 150 μg m^{-3}. Secondly, on the afternoon of the 10th of November 2019 (a Sunday) the fresh–air flush turned on when ambient $PM_{2.5}$ levels fell, and rapidly reduced the modelled $PM_{2.5}$, while actual inside levels fell only slowly. Lastly, the active–control model turned off the HVAC on the afternoon on Monday the 11th of November, again keeping the modelled inside $PM_{2.5}$ below the actual measured $PM_{2.5}$.

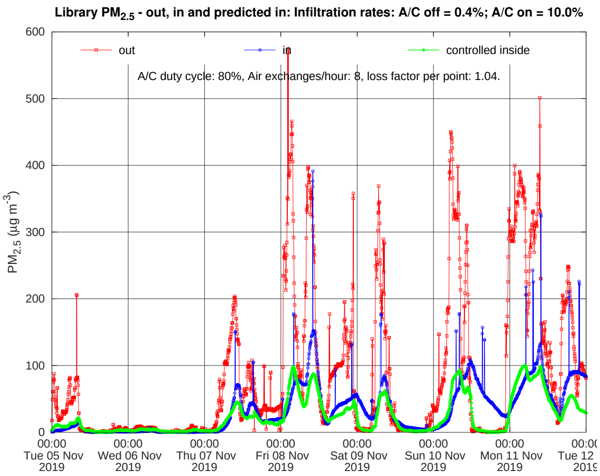

Figure 6: Measured ambient $PM_{2.5}$, inside $PM_{2.5}$, and 'actively–controlled' inside $PM_{2.5}$, 5th–11th November 2019. Red symbols: Ambient $PM_{2.5}$; Blue symbols: Measured inside $PM_{2.5}$; Green symbols: actively–controlled indoor $PM_{2.5}$.

For completeness, it is restated that during the 1st October to 28th November 2019 interval, the mean ambient $PM_{2.5}$ was 65 μg m^{-3}. The mean measured inside $PM_{2.5}$ was 30 μg m^{-3}, but the mean 'actively–controlled' modelled $PM_{2.5}$ was significantly lower at 19 μg m^{-3}. As discussed, indoor air quality in not solely concerned with infiltration of ambient pollution levels, but this work suggests there may be merit in considering active control of HVAC systems in long–duration smoke events.

5.3 Modelling the $PM_{2.5}$ infiltration for continuous HVAC operation

Lastly, we use the model to estimate the effect of running the library HVAC system continuously during the study interval, as in for 24 hours each day. Figure 7 shows the results for the 7th to 10th of November 2019, where we plot the ambient $PM_{2.5}$, measured inside $PM_{2.5}$, and 'actively–controlled' $PM_{2.5}$, as well as the modelled 'HVAC always on' $PM_{2.5}$. Note again that the ambient levels are highest during the day, when the HVAC is normally operating. Two features will be noted from this Figure. On the 8th of November the first smoke onset is soon after midnight. The ‘always on’ modelled $PM_{2.5}$ (cyan symbols) increases to reach over 200 μg m^{-3}, which is higher than the measured inside $PM_{2.5}$. Conversely in the early hours of the 9th of November the ‘always on’ $PM_{2.5}$ levels fall as clean outside air is brought in, whereas in reality only passive infiltration was happening.

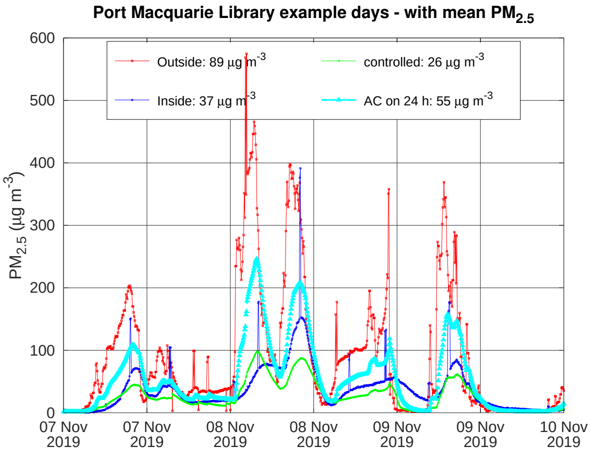

Figure 7: Example time series showing the ambient $PM_{2.5}$ (red), the measured inside $PM_{2.5}$ (blue), the ‘actively–controlled’ modelled inside $PM_{2.5}$ (green), and the modelled ‘HVAC always on’ $PM_{2.5}$ (cyan).

Table 1 summarises the campaign mean $PM_{2.5}$ for the various quantities used here for ease of reference. Over the 1st October to 28th November 2019 interval, the mean modelled ‘HVAC always’ on $PM_{2.5}$ was 40 μg m^{-3}. This is higher than the measured inside $PM_{2.5}$ mean of 30 μg m^{-3}, and approximately twice the ‘active–control’ modelled mean $PM_{2.5}$ of 19 μg m^{-3}.

$PM_{2.5}$ quantity	mean (μg m^{-3})
Ambient air	65
Measured inside	30
HVAC model–predicted inside	33
Actively–controlled HVAC	19
‘HVAC always on’ model	40

Table 1: Mean $PM_{2.5}$ for the various study quantities for the campaign interval of 1st October to 28th November 2019

6 Closing comments

A simple mathematical model was created of the HVAC air–exchange and passive infiltration of ambient smoke and applied to a data set from Port Macquarie during part of the Black Summer bushfire interval. The model was able to reproduce the main features of the measured inside $PM_{2.5}$ using the outside $PM_{2.5}$ time-series and a small number of parameters representing the HVAC operation. It seems clear that the resultant infiltration of smoke over a long–duration pollution event will depend on the relative timing of the smoke onset and the HVAC hours of operation, assuming that the HVAC is not operated continuously. The model did not include the possible influence of ambient temperature on HVAC operation or performance, nor did it include for example the effect of wind speed on passive infiltration rates. It appears that these and other process may be secondary to HVAC–driven infiltration rates.
The model was also run in a ‘active–control’ mode as a thought–experiment to see if inside $PM_{2.5}$ could be reduced from the actual recorded levels, by judicious use of the HVAC with reference to the contemporaneous ambient and inside $PM_{2.5}$ levels. The active–control included reducing the fresh air fraction used in the HVAC air during high ambient smoke intervals, and flushing with a higher fresh air fraction when inside levels were high but clean air was present outside. The active–control resulted in lower modelled inside $PM_{2.5}$, as would be expected. In the real–world other parameters also need to be included in assessing indoor air quality, such as CO_2 and oxygen levels, not solely $PM_{2.5}$, but there still may be some room for improving indoor air quality by actively monitoring and controlling HVAC systems during long–duration pollution events.

Acknowledgements

We thank Chris Morrison, Ventilation Plumber and Facility Manager, for extensive discussions on HVAC systems, and peak–bagging around Mawson in winter 1993.

Reference

Wheeler, A.J., Allen, R.W, Lawrence, K., Roulston, C.T., Powell, J., Williamson, G.J., Jones, P.J., Resisen, F., Morgan, G.G., Johnston, F.H., 2021. *Int. J. Environ. Res. Public Health*, **18**, 4085, doi 10.3390/ijerph18084085

A Appendix – Saturday 19th October 2019

It was mentioned in the main body of the paper that the hours of operation of the Port Macquare Library HVAC on Saturday, 19th October 2019 appeared not to follow the usual 12:30 close down. Figures 8 and 9 below respectively show model results for the week including Saturday the 19th of October, modelled with the HVAC turning off at 12:30 as would normally be expected for a Saturday, and for the case if the HVAC was turned off at 19:30 as on a weekday. The far better agreement for the second case leads us to suspect that the HVAC was in operation until 19:30 on this day. An internet search was conducted but no record of any public event in the Port Macquarie Library was found for this date. We note the co–incidental occurrence of several 'spikes' in both outside (ambient) and measured inside $PM_{2.5}$ near 19:30, but we do not know what is the significance of these.

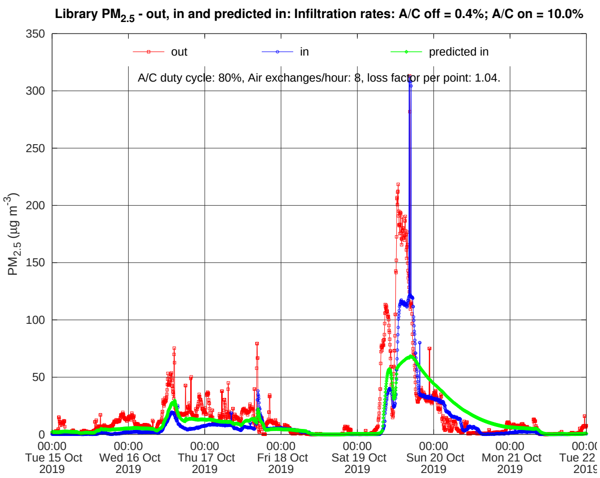

Figure 8: Measured ambient and inside $PM_{2.5}$, and model–predicted $PM_{2.5}$, 15th–22nd October 2019, with the HVAC turning off at 12:30 on Saturday 19th October 2019. Red symbols: Ambient $PM_{2.5}$; Blue symbols: Measured inside $PM_{2.5}$; Green symbols: Model–predicted $PM_{2.5}$.

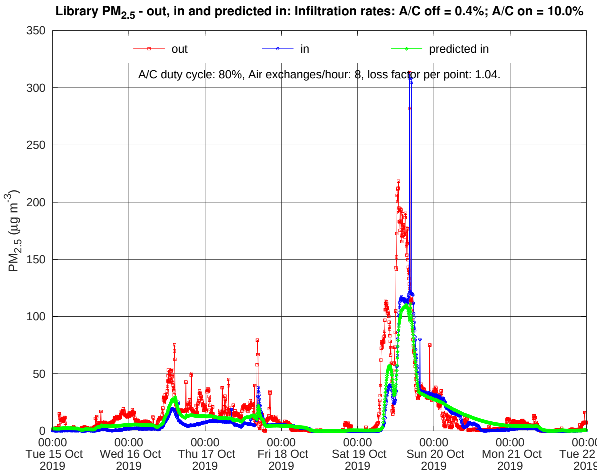

Figure 9: Measured ambient and inside $PM_{2.5}$, and model–predicted $PM_{2.5}$, 15th–22nd October 2019, now with the HVAC turning off at 19:30 on Saturday 19th October 2019. Red symbols: Ambient $PM_{2.5}$; Blue symbols: Measured inside $PM_{2.5}$; Green symbols: Model–predicted $PM_{2.5}$.