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Modeling the Effectiveness of Portable Air Cleaners with Open Windows

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ABSTRACT

Portable air cleaners have demonstrated their effectiveness in reducing indoor PM concentrations. Common rating systems assume the air cleaner is in a room having limited air exchange with ambient air and the rest of the building. In this analysis, we model conditions in which people operate air cleaners in rooms with some natural ventilation.

METHODS: A simplified mass balance model was developed for a 50 m^3 *room within a 350 m*^{3} *home, assuming well-mixed spaces, homogeneous infiltration, and applying the LBLX ventilation model. Natural ventilation was through a hung window in the room, open between 0 and 80 cm. The air cleaner was sized to minimum CADR rating. Ambient PM concentrations, temperature and wind speed, and the strength and location of indoor sources were varied. Effectiveness was defined as the reduction in indoor PM concentration compared to the same scenarios with the air cleaner off.*

RESULTS: The relative effectiveness depended only on the air exchange rate of the room, regardless of source strength and location, and ranged from almost 80% (the filtration efficiency) under recommended conditions (<1 ach), to less than 20% with maximum window opening (14 ach), under mild weather conditions (5℃ temperature difference, 2.5 m/s wind speed). Opening the window while operating the air cleaner was a more effective strategy to reduce indoor PM concentrations when the dominant PM source was located inside the room and ambient air concentrations were moderate. The reverse approach applied when ambient PM dominated.

CONCLUSIONS: Air cleaners can still reduce indoor pollutants when used in conjunction with natural ventilation under a wide range of conditions. This work may help inform user guidelines for air cleaners.

INTRODUCTION

Portable air cleaners offer a supplemental option to manage indoor air quality, in addition to source control and ventilation, and have demonstrated their effectiveness at reducing PM exposures indoors (EPA, 2018). To work as specified, it is assumed that they are operated in rooms with an air exchange below 1 hr^{-1} (ANSI-AHAM, 2013). It has been reported (Cai *et al.*, 2019), however, that sometimes people choose to operate them while also allowing natural ventilation through windows. This analysis examines the reduction in air cleaner effectiveness resulting from this approach, and the circumstances when it may minimize indoor PM exposure.

METHODS

The calculations were performed for a 50 m^3 room within a 350 m^3 home, assuming a closed door, but with no assumptions on room geometry or location for a single-hung window (width of 0.8 m). No other window openings were modeled in the house. An air cleaner placed in the room was sized at the minimum ANSI/AHAM recommendation for CADR (ANSI/AHAM, 2013), resulting in a flow rate of 318 m^3/hr, at 80% efficiency for all PM sizes.

The concentration of $PM_{2.5}$ in the room with air cleaner and in the rest of the house was modeled with a pair of 2-compartment mass-balance equations, solved under steady-state conditions that accounted for outdoor air exchange

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(natural ventilation and infiltration), deposition to surfaces, indoor emissions, filtration and interzonal air flow.

The air exchange through infiltration and the window was calculated using the LBLX model (Breen *et al.*, 2010), driven by temperature difference and wind speed, parameterized for a suburban home. Total air flows for the home were approximated through simplified superposition (ASHRAE, 2017). The interzonal air flow was calculated to balance air flow for the entire building, but with a minimum of 0.3 hr^{-1} to account for diffusion.

Calculations were performed under a variety of scenarios of window opening, ambient temperature and wind speed, outdoor concentrations, as well as indoor $PM_{2.5}$ sources, both in the room and in the rest of the house. The effectiveness of using the air cleaner was defined as the relative reduction of the indoor PM concentration while operating the air cleaner, compared to the same scenario with the air cleaner off.

RESULTS AND DISCUSSION

The effectiveness of the air cleaner declines with an open window under all scenarios, starting at a value near the cleaning efficiency (80%) and declining to 20% or lower at maximum realistic window opening (0.6-0.8 m), as shown in Figure 1, under mild weather conditions that encourage natural ventilation (5℃ temperature difference, 2.5 m/s wind speed). The effectiveness is not affected by the intensity of the indoor sources or the ambient air concentration, but does decrease with increasing natural ventilation, as the indoor-outdoor temperature difference or wind speed increases (Fig 1b). Due to the air exchange between the room and the rest of the house, there is also a modest concentration reduction benefit beyond the room.

Focusing only on effectiveness, however, misses the effect of window opening on the PM concentration in the room, whose reduction is the primary goal of both air cleaning and ventilation. In the absence of indoor sources, the lowest indoor concentration is always achieved with the window closed, following a pattern similar to that in Fig. 1a. As the relative contribution of PM from indoor sources and from ambient air changes, so does the optimal strategy to minimize PM in the room. For example, Figure 2a shows the effect of opening the window while a source is generating particles in the room at 100 μg/min. At higher ambient air concentrations, the concentration in the room is lowest with the window closed, but with increasingly cleaner ambient air, opening the window becomes first neutral, and then increasingly beneficial. As the strength of the in-room source decreases, so does, proportionally, the ambient air concentration at which window-opening becomes beneficial. The location and strength of the indoor sources also matter. With indoor sources located only outside the room, no realistic combination of ambient air concentration and source strengths produced scenarios where opening the window would result in lower concentrations in the room than keeping it closed (results not shown). Indoor sources both inside and outside the room, resulted in a diverse range of scenarios and of optimal strategies. Figure 2b shows one example with a relatively strong in-room source and relatively clean ambient air, where opening the window was optimal for any source intensity.

While the conditions for beneficial window opening could be calculated analytically, the complexity of the expression and the dynamic nature of ambient air make this approach of little practical value. Instead, some general observations can be made to inform combined air cleaner and window use under different scenarios:

1) Operating an air cleaner always reduces PM in the room, regardless of window status, even as the marginal effectiveness of the air cleaner decreases with an open window.

2) When using an air cleaner in a room without significant indoor PM sources, keeping the windows closed maintains the lowest possible concentration in the room, unless ambient air is truly pristine. This applies even if there are strong sources in the house outside of the room.

3) For a room with strong indoor sources, such as cooking, opening the window while operating the air cleaner generally leads to lower PM concentrations even when ambient air concentrations are relatively high.

4) With moderate indoor sources (candles, incense, vacuuming), the best approach is likely to vary significantly depending on ambient air quality

These observations reflect the limitations of the current analysis, including its simplification assumptions, lack of directional airflow, and limited scenarios, and should be interpreted primarily as proposals for further analysis, rather than operational guidance.

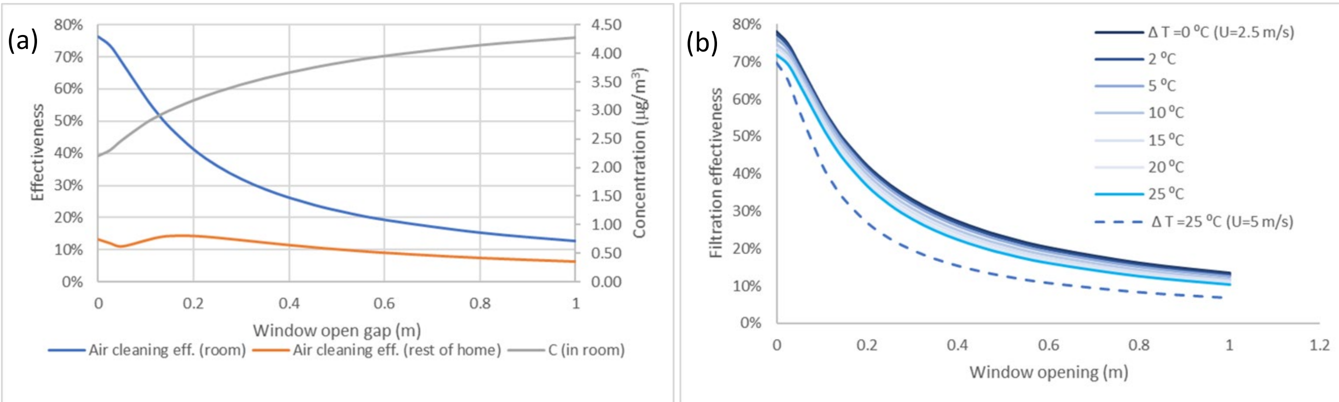

Figure 1 (a) Air cleaning effectiveness (in the room and the rest of the house) and concentration in the room with ambient air concentration C_o = 5 μg/m³ and in-room source of 10 μg/min (b) Air cleaning effectiveness as a function of indoor-outdoor temperature difference and wind speed.

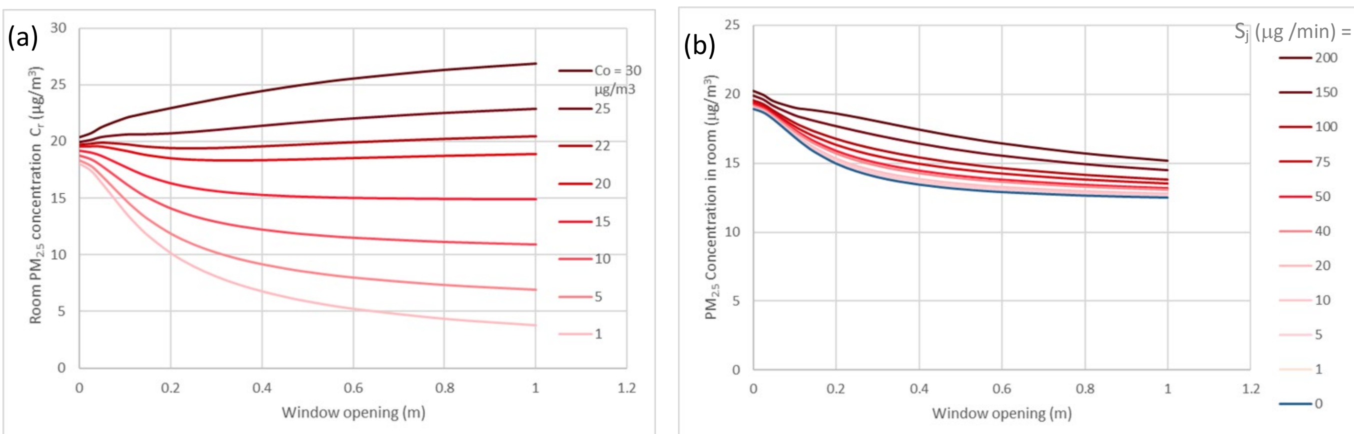

Figure 2 (a) Effect of window opening for different ambient air concentrations (C_o), with a source of PM in the room only (S_i), generating 100 μg /min. (b) Effect of window opening for different PM sources indoors but outside the room (S_j), along with a source in the room S_i = 100 μg /min; and ambient C_o = 12 μg/m³.

CONCLUSION

Operating an air cleaner reduces PM in a room even in conjunction with natural ventilation. The optimal window and air-cleaner use strategy to minimize PM concentration varies with scenarios, but some general strategies can be outlined. These results emphasize the need to consider air cleaning not in isolation but together with source control and ventilation to pursue optimal indoor air quality.

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