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Impact of outdoor PM2.5 on natural ventilation usability in California's nondomestic buildings

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HIGHLIGHTS

- Impact of PM2.5 on the NV potential of office buildings in five Californian cities.
- Two approaches: statistical analysis and detailed simulation analysis.
- Elevated PM2.5 may occur in up to 50% of NV time.
- NV can increase indoor PM2.5 exposure up to fivefold.

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ABSTRACT

In California, the majority of office and other nondomestic buildings use mechanical cooling and ventilation even when an optimized natural ventilation (NV) system could meet cooling and fresh air requirements. Unfortunately, in most large California cities, the outdoor environment is contaminated with noise, fine particles, heat, toxic gases or, in most cases, a combination of all four. This contaminated environment has a detrimental impact on naturally ventilated buildings due to their lack of filtration and outdoor noise attenuation systems. This paper presents a study on the impact of airborne particle pollution on the potential for NV cooling of office buildings in California. The study uses a multi-year database of measured hourly weather data and PM2.5 data for the five largest metropolitan areas in California, representative of 90% of the state's population. The analysis is performed in two stages with increasing complexity. The first stage is a statistical analysis that identifies coincidence between high PM2.5 and outdoor air temperatures that are suitable for NV. In addition, this phase includes multivariable correlation to identify particular weather events or time periods that affect PM2.5 levels. The second level of analysis is more complex, using building thermal simulation (EnergyPlus) to perform a detailed assessment of NV potential in the five urban locations, calculating NV flow rates, resulting indoor exposure to PM2.5 and supplemental HVAC system energy consumption. The results show that using NV in moments when the outside weather is favorable can result in HVAC energy savings of 25–80%. However, limiting NV use to moments with outdoor particle levels below 12 $\mu g/m^3$ decreases this energy saving potential to 20–60%. In addition, in the majority of the cities analyzed in this study, the use of NV leads to an increase in indoor exposure to PM2.5 of outdoor origin of 400–500%.

1. Introduction

As a result of human activity, the level of airborne particulate matter (PM) has been steadily rising in and around the most densely populated areas of the world [1]. This increase has been higher in large cities of low and middle-income countries, mostly due to the rapid growth of motor transportation [2,3]. There is strong evidence of adverse health effects from exposure to airborne particles that are small enough to be inhaled (diameter below 10 μm [4,5]). Limiting airborne particle exposure has long been a priority of the World Health Organization (WHO), leading to continuously updated guidelines for maximum short term and annual mean exposures to airborne particles [6,7]. These guidelines set exposure limits in two overlapping particle size ranges: PM10 (particles with an aerodynamic diameter below 10 μm) and PM2.5 (below 2.5 μm). Coarse particles (PM10) are generated by a mix of natural and anthropogenic sources, such as windblown desert dust, sea salt and construction activities. Fine particles (PM2.5) are mostly generated by manmade combustion and are small enough to affect

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Nomenclature

A	area (m^2)
C	PM2.5 concentration ($\mu g/m^3$)
COP	coefficient of performance
E	electric power (W)
H	height difference between midpoint of opening and the neutral pressure level (m)
K	coefficient
N	number of yearly working hours
P	cumulative PM2.5 exposure (mg h m^{-3} $year^{-1}$)
T	temperature (K)
U	wind speed (m/s)
$\dot{V}$	air flow (m^3/s)
Y	number of hours in a year
e	yearly HVAC electricity load per unit area (kW h m^{-2} - $year^{-1}$)
g	gravity acceleration (m/s^2)
$\dot{m}$	air mass flow (kg/s)
p	pressure (Pa)

Greek symbols

Δ	variation
Φ	yearly potential
η	efficiency
φ	fraction of occurrences of criteria fulfillment for a given individual working hour
ψ	ratio between actual COP and that of an ideal Carnot engine

Subscript

D	discharge coefficient for stack-driven natural ventilation
$HVAC$	total HVAC electricity load
$cond$	heat pump condenser
$cool$	heat pump used for cooling
$evap$	heat pump evaporator
$filter$	mechanical ventilation system filter
$heat$	heat pump used for heating
i	individual working hour
$local$	local wind speed
max	maximum
nat	natural ventilation
$open$	opening area
$stack$	stackdriven natural ventilation
out	outside
$vent$	mechanical ventilation
w	opening effectiveness for winddriven natural ventilation
$wind$	winddriven natural ventilation
y	individual occurrence of a working hour
z	zone

the pulmonary alveoli, leading to a significant health risk. As a result, continued exposure to PM2.5 in amounts that are just above the natural background concentration of 3–5 $\mu g/m^3$ can cause adverse health effects [6,8]. The combination of a mostly anthropogenic origin and an increased exposure risk makes PM2.5 the preferred indicator for assessing health impacts from outdoor particles. Since any building requires outdoor air to remove internally generated pollutants, the impacts of outdoor pollution are also felt indoors.

In the majority of urban environments, outdoor air is a source of pollutants that have a detrimental impact on indoor air quality (IAQ). In addition to outdoor air pollution, buildings have internal pollution sources, indoor surfaces where the particles settle and particle re-suspension induced by occupant movement [9,10]. In buildings with no outside air particle filtration, the combination of these effects, may lead to a ratio between indoor and outdoor particle levels (I/O ratio) that is larger than one, subjecting users that expect to be in a controlled built environment to an IAQ that is lower than outside. Unfortunately, the energy costs of air filtering are high since this process requires mechanical ventilation, and the pressure loss in the high-efficiency filters that are used to remove PM2.5 is also high. This high pressure loss increases the mechanical ventilation fan energy consumption to levels which are comparable to indoor lighting, with power densities in the range of 5–15 W/m^2 [11]. Further, the average energy consumption of a mechanical cooling system has similar magnitude (or up to twice as much in hot and humid climates), compounding a heating, ventilation and air conditioning (HVAC)-related energy consumption of 50–60% of the total building energy consumption [12,13]. HVAC related electricity consumption creates a higher energy demand for the power stations. If the electrical production system uses coal or diesel, then the building ventilation filtration system will directly contribute to higher airborne particle and carbon dioxide emissions.

In response to the high energy consumption of traditional HVAC, the use and research of natural ventilation systems has seen an increase throughout the world, in both residential [14,15] and commercial buildings [16,17]. In the best contemporary design examples, NV can replace conventional cooling systems in the milder months of the year, reducing ventilation and cooling-related energy demand [18,19] as well as sick building syndrome [20]. NV cooling removes internal heat gains by direct exhaustion to the outside using ventilation air [21]. These low energy cooling and ventilation solutions can be integrated with traditional HVAC in hybrid systems that, depending on weather conditions, can alternate between HVAC and NV throughout the day. In these systems, when internal particle sources are low and the HVAC system has effective filtration, the main particle pollution source is the outdoor environment. In contrast, when the windows are opened to promote the large outdoor airflows that are required for ventilative cooling, indoor exposure to outdoor PM can be significant [18], with I/O ratios that are close to one. However, despite the existence of several recent studies on the energy-saving possibilities of NV [22,23], only one considered outdoor particles levels as a limiting factor of NV use [24], as the use of NV in moments of high outdoor particle concentration increases occupant particle exposure. To avoid this problem, a building connected to an outdoor PM2.5 sensor network must close the NV openings and revert to conventional HVAC during periods of high PM2.5. This requirement reduces the number of hours when NV can be used and requires HVAC energy consumption during these periods. It is likely that the magnitude of this impact will depend on the local weather circulation and particle source patterns, as particles suspended in the outdoor air are in an unstable state and their concentration can be changed by meteorological conditions, such as precipitation and wind sweeping [25,26]. Winds can also transport particles that are generated remotely [27] and contribute to the re-suspension of coarse particles (such as the Santa Ana winds, shown in Fig. 1 [28]).

Previous studies have shown that, for a well-designed building with low internal gains, user-controlled windows may be opened for outdoor temperatures as low as 10 °C [29]. Further, in climates without high summer daytime humidity levels, the typical maxi-