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Co-optimisation of indoor environmental quality and energy consumption within urban office buildings

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ABSTRACT

This study aimed to develop a multi-component model that can be used to maximise indoor environmental quality inside mechanically ventilated office buildings, while minimising energy usage. The integrated model, which was developed and validated from fieldwork data, was employed to assess the potential improvement of indoor air quality and energy saving under different ventilation conditions in typical air-conditioned office buildings in the subtropical city of Brisbane, Australia. When operating the ventilation system under predicted optimal conditions of indoor environmental quality and energy conservation and using outdoor air filtration, average indoor particle number (PN) concentration decreased by as much as 77%, while indoor CO_2 concentration and energy consumption were not significantly different compared to the normal summer time operating conditions. Benefits of operating the system with this algorithm were most pronounced during the Brisbane's mild winter. In terms of indoor air quality, average indoor PN and CO_2 concentrations decreased by 48% and 24%, respectively, while potential energy savings due to free cooling went as high as 108% of the normal winter time operating conditions. The application of such a model to the operation of ventilation systems can help to significantly improve indoor air quality and energy conservation in air-conditioned office buildings.

1. Introduction

In most urban environments, vehicle emissions and new particle formation are the dominant source of outdoor particles [1–9]. Ambient air quality legislation regulates airborne particulate matter, in terms of particle mass concentration, expressed as $PM_{2.5}$ and PM_{10} (mass concentrations of particles smaller than 2.5 µm and 10 µm, respectively), and to date, these are also the most common parameters measured for research purposes. However, in terms of number the majority of particles emitted by vehicles and new particle formation belong to the ultrafine size range (UF < 0.1 µm) [10,11].

Epidemiological research has consistently shown an association between fine (<2.5 µm; $PM_{2.5}$) particle concentrations and increases in both respiratory and cardiovascular morbidity and mortality [12–16]. The health effects of UF particles are less well understood, though recent research indicates that they may be equally or more detrimental than those of $PM_{2.5}$ and PM_{10} [17–20].

Numerous studies have demonstrated that an increase in outdoor ventilation rate can improve occupant health and productivity [21–26], and reduce the energy consumption of the HVAC (Heating, Ventilation and Air Conditioning) system inside office buildings by taking advantage of free cooling during mild weather (i.e. when the outdoor temperature is equal to or lower than the desired indoor temperature) [27,28]. However, increasing the outdoor ventilation rate can also increase indoor particle levels, especially in buildings located in areas with high outdoor particle concentrations due to vehicle emissions [1,29–33] and particle formation (nucleation) events [34]. A particle formation or nucleation event is the result of gas-to-particle conversion, usually via photochemical reactions. Precursors are generally from local vehicle emissions and/or regional transport, and they significantly contribute to urban background ultrafine particle concentrations, as discussed in Quang et al. [34]. It has been suggested that the combination of economiser cycles (i.e. free cooling from outdoor air) and outdoor air filtration can simultaneously save building energy and improve

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indoor air quality within buildings [35–37], however, the authors did not quantify the ventilation rate required during hot, cold, or milder and cooler weather.

Numerous other studies of the indoor environment have sought to optimise indoor thermal comfort and energy consumption [e.g. [38–46]], but only a few have investigated impacts on indoor air quality, and those that did simply used CO_2 concentration as the sole indicator [47–58].

But indoor environmental quality is not solely determined by air quality; occupants of a building also require thermally comfortable conditions before a building can be said to be performing well. Thermal comfort studies have shown that a person's thermal sensation response to a given stimulus depends upon their state of thermal adaptation, which in turn depends on geographic location [e.g. [59]] and the time of year (i.e. seasons) [e.g. [60]]. A summer neutral (optimal) temperature has previously been quantified for indoor environments in Brisbane, Australia [61], however, the same is not true of the milder winter season.

In order to provide a robust tool for optimising the operation of building HVAC systems, the present study aimed to develop a multi-component model to simultaneously guide the optimisation of indoor environmental quality and the minimisation of energy consumption inside mechanically ventilated office buildings. More specifically, the objectives of the work were to: (i) develop indoor air quality models, including particle number (PN), a significant pollutant in all combustion and particle formation process, and CO_2, which affects workplace productivity and well-being; (ii) build an HVAC energy consumption model based on optimal indoor temperature and outdoor ventilation rates; (iii) quantify optimal temperature inside office buildings during winter to determine appropriate parameters for objective (ii); and (iv) apply a multi-component model to evaluate indoor air quality and energy usage under different ventilation scenarios during winter and summer, in urban office buildings located in area with high outdoor ultrafine PN concentrations.

2. Experimental methods

This study was conducted in subtropical Brisbane, the capital city of the State of Queensland in Australia, and is located at 27.4°S 153.1°E. Brisbane's weather is characterised by warm, humid summers, with an average temperature ranging from 21.3 to 30.3 °C during the warmer months; and by mild winter, with an average temperature ranging from 10 to 21.8 °C during the colder months [62,63].

2.1. Development of indoor air quality model

2.1.1. Indoor PN concentration model

For buildings located in areas with high outdoor PN concentrations, where particle concentrations are significantly higher than ambient levels, or outdoor particles are the main source of indoor particle concentration, a dynamic model of indoor particle number concentration was developed by Quang et al. [33]:

$$C_{\text{in}}^{t_i} = C_{\text{in}}^{t_{i-1}} e^{-\alpha_{t_i}\Delta t} + C_{\text{out}}^{t_i}\beta_{t_i}\Delta t \quad (\text{p cm}^{-3}) \tag{1}$$

where $C_{\text{in}}^{t_i}$: indoor PN concentration at time t_i (p cm^{-3}); $C_{in}^{t_{i-1}}$: indoor PN concentration at time t_{i-1} (p cm^{-3}); $C_{\text{out}}^{t_i}$: outdoor PN concentration at time t_i (p cm^{-3}); Δt: time step (h); α_{t_i}: total removal rate of the indoor PN concentrations at time t_i.

$$\alpha_{t_i} = \frac{3.6\times 10^3 k}{V}\left(Q_{\text{RA}}^{t_i}\text{FE}_{\text{AHS}} + Q_{\text{exc}}^{t_i} + Q_{\text{Exf}}^{t_i} + V\lambda_{t_i}\right) \quad (\text{h}^{-1}) \tag{2}$$

β_{t_i}: total penetration rate of outdoor particle indoor at time t_i

$$\beta_{t_i} = \frac{3.6\times 10^3}{V}\left[Q_{\text{OA}}^{t_i}(1-\text{FE}_{\text{OA}})(1-\text{FE}_{\text{AHS}}) + Q_{\text{Inf}}^{t_i}P_{\text{Inf}}^{t_i}\right] \quad (\text{h}^{-1}) \tag{3}$$

k: mixing factor (unitless) ($k = 1$ if perfect air mixing conditions are assumed); λ_{t_i}: particle deposition rate at time t_i (s^{-1}); $P_{\text{Inf}}^{t_i}$: penetration factor via the building envelope at time t_i (unitless); $Q_{\text{OA}}^{t_i}$: outdoor air flow rate at time t_i (m^3 s^{-1}); $Q_{\text{RA}}^{t_i}$: return air flow rate at time t_i (m^3 s^{-1}); $Q_{\text{exc}}^{t_i}$: general exhaust flow rate at time t_i (m^3 s^{-1}); $Q_{\text{Exf}}^{t_i}$: exfiltration flow rate at time t_i (m^3 s^{-1}); $Q_{\text{Inf}}^{t_i}$: infiltration flow rate at time t_i (m^3 s^{-1}); FE_{OA}: the overall efficiency of the outdoor air filter; FE_{AHS}: the overall efficiency of the air handing system filter.

2.1.2. Indoor CO_2 concentration model

A CO_2 mass-balance model was developed based on the balance of CO_2 generated inside a building, mainly by the building occupants, and also that brought from outside the building via ventilation and penetration through the building envelope. However, during the operation of a building's ventilation system, the inside air pressure usually remains positive and therefore, in this case, penetration can be considered negligible compared to the contribution from outdoor air brought in by ventilation. Hence, the model was formulated based on the following equations:

$$M_{p_{t_i}}^{\text{CO}_2} + M_{\text{vent}_{t_i}}^{\text{CO}_2} = 0 \tag{4}$$

where $M_{p_{t_i}}^{\text{CO}_2}$: CO_2 release by occupants inside the building at time t_i (mg s^{-1}).

$$M_{p_{t_i}}^{\text{CO}_2} = N_{p_{t_i}} \times G_{p_{t_i}}^{\text{CO}_2} \tag{5}$$

$N_{p_{t_i}}$: number of occupants inside the building at time t_i (person); $G_{p_{t_i}}^{\text{CO}_2}$: CO_2 release by an individual occupant at time t_i. $G_{p_{ti}}^{\text{CO}_2} = 0.00521$ l s^{-1} (or equals to 10.21 mg s^{-1}) for an average adult at a normal activity in the office, such as sitting, reading and writing [64]. $M_{\text{vent}_{t_i}}^{\text{CO}_2}$: CO_2 volume flow of the building ventilation system at time t_i (mg s^{-1}).

$$M_{\text{vent}_{t_i}}^{\text{CO}_2} = Q_{\text{OA}}^{t_i}\left(C_{\text{out}_{t_i}}^{\text{CO}_2} - C_{\text{in}_{t_i}}^{\text{CO}_2}\right) \tag{6}$$

$Q_{\text{OA}}^{t_i}$: outdoor air flow rate at time t_i (m^3 s^{-1}); $C_{\text{out}_{t_i}}^{\text{CO}_2}$: concentration of outdoor CO_2 at time t_i (mg m^{-3}); $C_{\text{in}_{t_i}}^{\text{CO}_2}$: concentration of indoor CO_2 at time t_i (mg m^{-3}).

From Eqs. (4)–(6), the final indoor CO_2 concentration model can be written as:

$$C_{\text{in}_{t_i}}^{\text{CO}_2} = \frac{N_{p_{t_i}} \times G_{p_{t_i}}^{\text{CO}_2}}{Q_{\text{OA}}^{t_i}} + C_{\text{out}_{t_i}}^{\text{CO}_2} \quad (\text{mg m}^{-3}) \tag{7}$$

or

$$C_{\text{in}_{t_i}}^{\text{CO}_2} = \frac{1}{1.8} \times \left(\frac{N_{p_{t_i}} \times G_{p_{t_i}}^{\text{CO}_2}}{Q_{\text{OA}}^{t_i}} + C_{\text{out}_{t_i}}^{\text{CO}_2}\right) \quad (\text{ppm}) \tag{8}$$

2.1.3. Quantification of optimal outdoor ventilation rates by integrating PN and CO_2 concentration models

It can be seen from Eqs. (1) and (8) that both indoor PN and CO_2 concentrations are dependent on outdoor air flow rates, Q_{OA}. If other parameters are assumed invariant during each time step, then Eqs. (1) and (8) can be written as:

$$C_{\text{in}_{t_i}}^{\text{PN}} = f(Q_{\text{OA}}^{t_i}) \quad \text{and} \quad C_{\text{in}_{t_i}}^{\text{CO}_2} = f(Q_{\text{OA}}^{t_i})$$

Since the units of indoor PN and CO_2 concentrations are different, to make their concentration values comparable, they were