

The influence of HVAC systems on secondary organic aerosol formation

Michael S. Waring¹, Jeffrey A. Siegel^{2,*}

¹Drexel University, Philadelphia, PA, USA

²University of Texas at Austin, Austin, TX, USA

*Corresponding email: jasiegel@mail.utexas.edu

SUMMARY

Chemical reactions between ozone and terpenoids can yield secondary organic aerosol (SOA), and the mass of SOA formed is influenced by the operation of the heating, ventilation, and air-conditioning (HVAC) system. This study models the influence of HVAC systems on SOA formation in typical residential and commercial buildings. A parametric analysis explores the role of ventilation and recirculation rates, filtration efficiency and loading, and the operation of heat exchangers. The most influential HVAC parameters are the flow rates, particle filtration, and indoor temperature for the residential and commercial models, as well as ozone removal on used filters for the commercial model.

KEYWORDS

Indoor chemistry, Particle formation, HVAC operation, Ozone, Terpenes

INTRODUCTION

Fine particles (< 2.5 μm in diameter) can penetrate deep into the alveolar regions of the lung. One source of indoor fine particles are secondary organic aerosol (SOA) that form due to chemical reactions between ozone and terpenes. Both reactants commonly occur indoors, and the reactions proceed at fast enough rates to compete with loss due to air exchange. The heating, ventilation, and air-conditioning (HVAC) system of a building can affect the mass of SOA formed by influencing the reactant and seed particle concentrations, as well as the indoor air temperature and relative humidity (RH). We explored the role of HVAC system design and operation and its effects with well-mixed models of a residential and a commercial building that predict the size-resolved mass of SOA formed in typical residential and commercial spaces with HVAC systems. In both models, we varied the HVAC parameters of (i) flow of ventilation and recirculation rates, (ii) the filtration efficiency for particles, (iii) the ozone removal due to particle loading on filters, and the indoor (iv) temperature and (v) relative humidity. A parametric analysis explored these HVAC system factors on SOA formation.

METHODS

The simulations use the same building geometries and are similar to the size-resolved particle model in Waring and Siegel (2008), with the addition of gaseous transport and emission and size-resolved SOA formation. For size-resolved parameters, a particle diameter (d_p) range of 0.01–10 μm was considered, and integration was numerical with 80 bins for d_p . The models assume steady-state and well-mixed conditions. These assumptions are not necessarily realistic over all conditions but are appropriate to compare the relative influence of HVAC systems on SOA formation. The steady-state indoor mass concentration of SOA, C_{SOA} ($\mu\text{g}/\text{m}^3$), is:

$$C_{SOA} = \left(k_{O_3,terp} C_{O_3} C_{terp} \int_{d_p} \frac{Y_{SOA}}{\beta_p + \lambda_i + \lambda_v + \lambda_r \eta_p} dd_p \right) (F_T F_{RH}) \quad (1)$$

where k_{terp,O_3} ($ppb^{-1} h^{-1}$) is the reaction rate constant of terpenes and ozone; C_{O_3} and C_{terp} (ppb or $\mu g/m^3$) are concentrations of terpenes and ozone, respectively; Y_{SOA} (μm^{-1}) is the size-resolved mass distribution yield of SOA (molecular weight of SOA assumed as 180 amu); β_p (h^{-1}) is the size-resolved deposition loss rate; η_p is the size-resolved removal efficiency to an HVAC filter; λ_i , λ_v , and λ_r (h^{-1}) are air exchange rates due to infiltration, ventilation, and recirculation, respectively; and F_T (-) and F_{RH} (-) are factors that adjust for changes in T and RH , respectively.

The varied HVAC parameters are in Table 1, with literature sources for the parameter values listed below. The residential flow cases considered duty (HVAC operation for one-sixth of the time) and continuous operation. The commercial flow cases considered continuous flow with 100% outdoor air (OA), 50% OA and 50% recirculated air (RA), and 10% OA and 90% RA. The PM Filtration cases used efficiency curves for new MERV <5, 6, 11, and 15 filters as well as an electrostatic precipitator (ESP). The O₃ Filtration cases considered a new and a used filter, assuming only the particle-laden filters removed any O₃ (the ESP generates rather than removes ozone). Indoor temperatures were modeled as 18.3, 23.9, and 29.4 °C (65, 75, and 85 °F) and relative humidity as 25, 50, and 75%, to account for a range of summer and winter conditions. The residential model had 162 unique scenarios and the commercial model had 243 unique scenarios. Base cases were defined for each model and are in bold in Table 1.

Table 1. Varied HVAC parameters in the models. The base cases are listed in bold.

| Parameter | Model | Case Title | Parameter Values |
|--|-------------|---|--|
| HVAC Flow ^a | Res. | Duty ; Continuous | $\lambda_i=0.75, \lambda_r=0.67; \lambda_i=0.75, \lambda_r=4 h^{-1}$ |
| | Comm. | 100% OA; 50% OA/50% RA; 10% OA/90% RA | $\lambda_i=0.25, \lambda_r=0, \lambda_v=4; \lambda_i=0.25, \lambda_r=2, \lambda_v=2;$ $\lambda_i=0.25, \lambda_r=3.6, \lambda_v=0.4 h^{-1}$ |
| PM Filtration ^b | Res., Comm. | MERV <5; 6 ; 11; 15; or ESP | η_p for MERV <5; 6 ; 11; 15; ESP |
| O ₃ Filtration ^c | Res., Comm. | New; Loaded | $\eta_{O_3} = 0$; 10% or $\eta_{O_3} = 0\%$; 41% |
| Temperature ^d | Res., Comm. | 18.3; 23.9 ; 29.4 °C | $F_T = 1.13, 0.98, 0.83$ |
| RH ^e | Res., Comm. | 25; 50 ; 75% | $F_{RH} = 1.02, 1.0, 0.98$ |

^aRiley et al. (2002), Waring and Siegel (2008); ^bWaring and Siegel (2008), Wallace et al. (2004); ^cZhao et al (2007); ^dLeungsakul et al. (2005), Sarwar and Corsi (2007); ^eLeungsakul et al. (2005)

The parameters $F_T, F_{RH}, \lambda_i, \lambda_v, \lambda_r,$ and η_p were directly varied due to the HVAC system. C_{O_3} and C_{terp} were calculated similarly to Eq. 1 and thus indirectly varied due to the HVAC system. C_{O_3} was calculated as due to indoor-to-outdoor transport with an outdoor concentration of 100 ppb, plus an indoor emission of 21.6 mg/h during any ESP operation (Viner et al., 1992). C_{terp} was calculated for each scenario as a floor mopping event with a pine-oil cleaner with emissions of 978 and 3,743 mg/h in the residential and commercial simulations, respectively, $k_{O_3,terp}$ as 0.05 $ppb^{-1} h^{-1}$, and Y_{SOA} as 0.197 (with geometric mean diameter of 0.37 μm and geometric standard deviation of 1.52) (derived from Singer et al. (2006) and Coleman et al. (2008) for the same pine-oil cleaner). β_p was as in Waring and Siegel (2008).

RESULTS AND DISCUSSION

SOA formation and other size-resolved parameters are log-normally distributed, so the median is used as a descriptive statistic. The median over 162 residential scenarios for C_{SOA} is $89.8 \mu\text{g}/\text{m}^3$ (range of $19.4\text{--}143 \mu\text{g}/\text{m}^3$) and over 243 commercial scenarios is $59.3 \mu\text{g}/\text{m}^3$ (range of $15.3\text{--}139 \mu\text{g}/\text{m}^3$). The base case C_{SOA} for the Residential Model is $120 \mu\text{g}/\text{m}^3$ and the Commercial Model is $83.1 \mu\text{g}/\text{m}^3$. Parametric influence was determined with the SOA Change Ratio (SCR), which is listed in Table 2. The SCR equals the adjusted SOA mass formed divided by the base case SOA mass formed, and the adjusted SOA mass formed is the result of holding all parameters in the base case constant except for the varied parameter. Thus, the SCR is a measure of how sensitive SOA formation is to a change of a given parameter, relative to the base case. Non-influential parameters have SCRs at or near unity. Cases with less SOA formation have an SCR less than unity, and cases with more SOA formation have an SCR greater than unity.

Table 2. SOA Change Ratios (see text) for the residential and commercial models.

| Parameter | Model | Base Case | Going To | SOA Change Ratio (SCR) | |
|---------------------------|-------------|---------------|---------------|------------------------|------------|
| | | | | Residential | Commercial |
| HVAC Flow | Res. | Duty | Continuous | 0.86 | |
| | Comm. | 10% OA/90% RA | 50% OA/50% RA | 0.51 | |
| | | | 100% OA | 0.71 | |
| PM Filtration | Res., Comm. | MERV 6 | MERV <5 | 1.01 | 1.04 |
| | | | MERV 11 | 0.80 | 0.44 |
| | | | MERV 15 | 0.62 | 0.22 |
| | | | ESP | 0.85 | 0.68 |
| O ₃ Filtration | Res., Comm. | Loaded | New | 1.00 | 1.37 |
| Temperature | Res., Comm. | 23.9 °C | 18.3 °C | 1.15 | 1.15 |
| | | | 29.4 °C | 0.84 | 0.84 |
| RH | Res., Comm. | 50% | 25% | 1.02 | 1.02 |
| | | | 75% | 0.98 | 0.98 |

The most influential HVAC parameters are in the Flow, PM Filtration, and Temperature cases for the residential and commercial models, as well as O₃ Filtration for the commercial model. In the residential model, going from the Duty to the Continuous case decreases the SOA formed since continuous air flow allows the HVAC filter to remove more of the SOA formed. Changing to different HVAC Flow cases in the commercial model has an even larger relative effect, since airflow is always continuous with an air exchange rate through the HVAC system of 4 h^{-1} . Pollutant concentrations of indoor origin, C_{terp} and C_{SOA} , decrease as the fraction of outdoor air increases, though C_{O_3} increases as more outdoor air is introduced. SOA concentrations generally increase with lower efficiency filters and decrease with higher efficiency filters. An increase in filter efficiency has a larger relative effect within the commercial than the residential model due to the continuous flow and larger volumetric flow rates through the HVAC filter. In the residential model, the O₃ Filtration had little effect on the SCR since there was an η_{O_3} of 10% and Duty air flow. However, the commercial model exhibited a large SCR since it had an η_{O_3} of 41% within a continuous flow case with 90% of its volumetric flow recirculated. The Temperature and RH cases affect the total mass of SOA formed with F_T and F_{RH} in Eq. 1, and their SCRs are equal to the change caused by the formation factors.

Figure 1 displays the median particle size-bin-resolved SOA formed in the (a) residential and (b) commercial models. Each bar summarizes the median of the geometric mean of all scenarios that used that particular PM Filtration and Flow case as inputs. Most of the resulting mass of SOA was with particles in the size range of 0.1–0.5 μm , with the rest in the range of 0.5–1 μm . This 0.1–0.5 μm range dominates SOA formation since it has the weakest filtration and deposition removal. In the residential model, the higher efficiency filters have a larger effect for the Continuous cases. In the commercial model, the effect of PM Filtration depends on the Flow case also, with higher filtration efficiency leading to more removal in cases with higher fractions of recirculated air. For the 100% OA case, more efficient filtration had no effect since all indoor air was continuously ventilated. The ESP led to higher SOA formation in this case due to its emission of ozone. The C_{SOA} for scenarios with the ESP change little for different Flow cases, since the removal by the ESP is challenged by the gain in SOA formation due to the increased influence of its ozone emission within recirculated air.

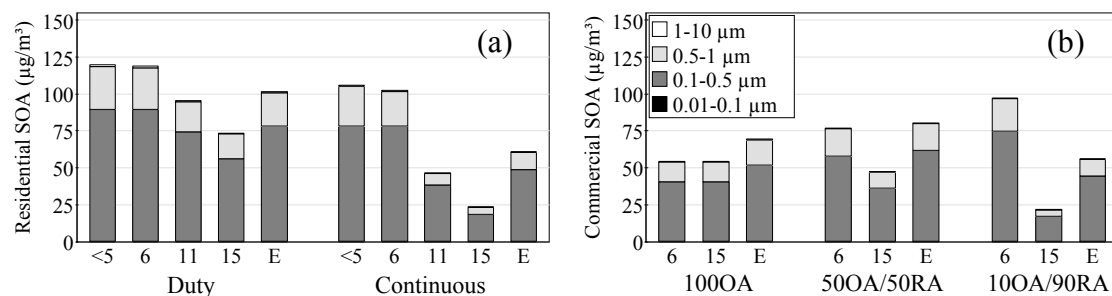


Figure 1. Median SOA concentrations for (a) residential and (b) commercial models.

CONCLUSIONS

The modeling study showed that the operation of an HVAC system can affect the concentrations of SOA indoors. Influential HVAC parameters are the flow rates, particle filtration, and indoor temperature for the residential and commercial models, and ozone removal by filtration in the commercial model. Higher efficiency filters had the largest effect in both models.

REFERENCES

- Coleman, B, et al. 2008. Secondary organic aerosol from ozone-initiated reactions with terpene-rich household products. *Atm. Env.* 42: 8234-8245.
- Leungsakul, S, et al. 2005. Kinetic mechanism for predicting secondary organic aerosol formation from the reaction of d-limonene with ozone. *Env. Sci. Technol.* 39: 9583-9594.
- Sarwar, G., Corsi, R.L., 2007. The effects of ozone/limonene reactions on indoor secondary organic aerosols. *Atm. Env.* 41, 959-973.
- Singer, B, et al. 2006. Cleaning products and air fresheners: emissions and resulting concentrations of glycol ethers and terpenoids. *Indoor Air* 16: 179-191.
- Viner, A., et al. 1992. Ozone generation in DC-energized electrostatic recipitators. *IEEE Trans. on Industry Applications* 28: 3, 504-512.
- Wallace, L, et al. 2004. Effect of central fans and in-duct filters on deposition rates of ultrafine and fine particles in an occupied townhouse. *Atm. Env.* 38: 405-413.
- Waring, M, Siegel, J. 2008. Particle loading rates for HVAC filters, heat exchangers, and ducts. *Indoor Air*, 18: 209–224.
- Zhao, P, et al. 2007. Ozone removal by HVAC filters. *Atm. Env.* 41, 3151-3160.