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Measured influence of supply airflow rate and supply air temperature on air mixing time in a room with overhead mixed system

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Abstract. Air mixing and movement are often driven by the design and operating conditions of the heating, ventilation, and air conditioning (HVAC) system, and are influenced by occupants and thermal gradients at windows and walls. Air mixing affects the indoor-generated pollutants dispersion and thus influences the effectiveness of ventilation and within-room air cleaning systems, including upper-room germicidal ultraviolet disinfection (GUV). In rooms with a ceiling exhaust and/or upper-room GUV, upward airflow from occupants can enable faster pollutant removal compared to well-mixed conditions. We used pulsed ethanol as a tracer and measured concentration at 2 s time resolution using fast-response metal oxide sensors at three levels: near the floor at 0.1–0.4 m, mid-height at 1.1–1.4 m, and at 2.4 m, 0.3 m from the 2.74 m ceiling. Forty experiments were conducted under the following conditions: HVAC off; supply air at ~380 (low) or ~1200 m^3 h^{-1} (high) at neutral, cooling, or heating temperatures with 20% or 100% outdoor air; and added mixing fans. Air mixing times were determined from the start of ethanol release until the relative standard deviation of the concentrations fell below 20%, indicating an approximately well-mixed condition. We found that the air mixing time was longest with the HVAC off (15.1–15.4 min), followed by conditions with a low total supply airflow rate at all temperatures (6.6–11.4 min under heating; 5.6–10.1 min under neutral/cooling), and was fastest under high airflow at neutral/cooling temperatures (2.9–5.6 min) or when mixing fans were added (1.9–4.8 min). The outdoor airflow rate (20% or 100%) did not significantly affect spatial heterogeneity or air mixing time. Long air mixing times resulted in high spatial variability of absolute integrated concentrations and relative exposures. Under slow mixing conditions (HVAC off or low airflow rate) and with releases associated with heaters simulating occupants, several upper or mid-level sensors peaked after the release, and mixing into the upper room and occupied space was slow. Under fast mixing conditions (high airflow rate with neutral/cooling settings or added fan), air reached and mixed in the upper room more quickly and spread faster in the occupied zone.

Keywords. Ventilation effectiveness; Air distribution; Airborne transmission; Infectious aerosol; Germicidal ultraviolet irradiation

1 Introduction

Indoor air cannot be perfectly mixed to achieve uniform physical and chemical properties, and it requires time to reach even approximate uniformity in conditions [1,2]. It is often assumed that the room is well-mixed when estimating the effectiveness of in-room air cleaning systems or applying a uniform inactivation rate under different room conditions and airflow patterns in models. In reality, air mixing does not occur instantaneously or reach a fully well-mixed state. The assumption that a room is well-mixed may be acceptable when mixing is rapid or unimportant for practical purposes; however, mixing becomes significantly important in various practical applications and modeling.

Air mixing and movement are often driven by the design and operating conditions of the heating, ventilation, and air conditioning (HVAC) system, and are influenced by occupants and thermal gradients at windows and walls. Air mixing affects the indoor-generated pollutants dispersion and thus influences the effectiveness of ventilation and within-room air cleaning systems, including upper-room germicidal ultraviolet disinfection (GUV). In rooms with a ceiling exhaust and/or upper-room GUV, upward airflow from occupants can enable faster pollutant removal compared to well-mixed conditions. Yet, experimental research on air mixing for evaluating the effectiveness of in-room air cleaning systems remains limited, and most existing studies [1–4] were not conducted in full-scale rooms under typical occupant densities and HVAC configurations.

Our previous study [5,6] developed and demonstrated a novel tracer method to measure within-room air movement and mixing under real-world conditions in operating buildings, with the potential to be applied in occupied spaces. Using the method, this study reports air mixing time under different supply airflow rates and supply air temperatures in a room with an overhead mixed system.

2 Method

2.1 Climatic chamber configuration and HVAC

The experiment was held in Cell 3A of the FLEXLAB facility at Lawrence Berkeley National Laboratory with dimensions of 6.10 m (east-west) × 9.34 m (north-south) × 2.74 m (height), and a volume of 158 m^3. The room was configured as a meeting room, with four or six heated cylinders (130 W each) and two researchers placed around a central table to simulate thermal plumes (Fig.1). On the south-facing window, metal blinds were installed to limit radiant heat gain within the room.

The room was equipped with an overhead air supply at the center of the room and return registers located in the northeast. Supply air was delivered through two ceiling-mounted mixing diffusers. Return air was extracted through a dedicated duct that conveyed air directly from the room back to the air handling unit (AHU).

Fig. 1. Room configuration and sensor deployment at the upper, middle, and lower levels of the room. The photograph was taken from the northwest corner of the room, facing the east wall and south window. Blue stars indicate the three release locations at seated height (1.1 m), and purple stars indicate the two release locations at standing height (1.4 m). The photograph shows four heated cylinders and one researcher; however, some test conditions included two additional cylinders at the north and south ends of the table, and all conditions involved two researchers.

2.2 Tracer release and measurements

We used pulsed vaporized ethanol as a tracer and measured concentration at 2 s time resolution using fast-response metal oxide sensors [5]. Ethanol vapor was generated by pumping air (15 liters per minute, for 20–60 s) through a tube into a bottle containing liquid ethanol, then directing the saturated ethanol vapor from the top of the bottle through a second tube, releasing 0.6–1.7 g. In some experiments, approximately 1–2 g of tracer was manually released using a spray bottle. Release locations and heights varied: with 19 releases at standing height in the southwest corner; 8 at sitting height between the two heated cylinders on the west side of the table; 4 at standing height on the north side of the room in front of the table; 12 and 11 inside the heated cylinder at the south and north head of the table (sitting height) (Fig.1).

At the start of each experiment, the HVAC system was set to achieve the target supply airflow and temperature or turned off for HVAC-off conditions. Mixing fans were initially operated to establish a uniform baseline concentration for cross-calibration. The fans were then turned off (or kept on for mixing-fan cases), after which the tracer was released, and the conditions were maintained for 10–15 min to observe air mixing. At the end of the experiment, the mixing fans were turned on again to produce a well-mixed, high-concentration state for two-point sensor cross-calibration.

Metal oxide sensors were interfaced with a Raspberry Pi Pico microcontroller for the digitization of analog signals associated with resistance changes induced by chemical reactions, while Raspberry Pi was used for data transmission. Sensor outputs were linearly normalized using baseline and span values obtained under two well-mixed conditions. Twenty-seven sensors were located at three vertical levels: sixteen at 0.3 m from the 2.74 m; nine at mid-height (1.1–1.4 m), and five near the floor (0.1–0.4 m) (Fig.1).

Table 1. Experimental conditions.

Icon	Condition	Supply air flow rate (m^3 h^{-1})	SAT, SAT – RAT (°C)	OA (%)
	HVAC off	NA	NA	NA
	Low heat	390	31–34, 7.3–9.5	20
	Low Neutral	380–460	20–23, -5.4– -0.3	20
	Low cool	390	17–19, -6.7– -5.3	20
	High heat	1250–1260	30, 4.5	20
	High neutral	1250–1280	23–28, -1.7–0.1	20
	High cool	1290	19–22, -4.6– 3.0	20
	Mixing fan on	NA	NA	NA
	Low heat	330	31–34, 7.9–8.8	100
	High neutral	1040–1130	14–20, -4.5– -2.6	100

SAT: Supply Air Temperature, RAT: Return Air Temperature, OA: Outdoor Air

2.3 Experimental conditions

Forty experiments were conducted under the following conditions: HVAC off; the combinations of supply air flow at ~380 (low) or ~1200 m^3 h^{-1} (high); supply air temperature at neutral, cooling, or heating temperatures; 20% or 100% outdoor air; and added mixing fans (Table 1).

2.4 Data analysis

Air mixing times were determined from the start of ethanol release until the relative standard deviation (RSD) of the concentrations fell below 20%, which was taken to represent an approximately well-mixed condition under practical indoor airflow conditions [5]. This threshold distinguishes differences in air mixing across HVAC operating modes, and lower thresholds (e.g., 10% [1,2]) require substantially longer times to reach in a full-size room.

Long air mixing times indicate slower mixing. Since the horizontal sensor resolution at the mid and lower level was not spatially resolved similarly to the upper level, those sensors were given greater weight in the RSD calculation. Welch's t-test was used to compare mean air mixing times between different HVAC operation conditions ($p<0.05$).

We calculated the exposure relative to perfectly mixed (ERM) or time-integrated normalized value relative to perfectly mixed (for sensors were not at occupant zone) for 10 min as the ratio of the time-integrated normalized value (V_{norm}) at each sensor to that calculated under complete and instantaneous room mixing conditions (V_{ideal}) [5,7].

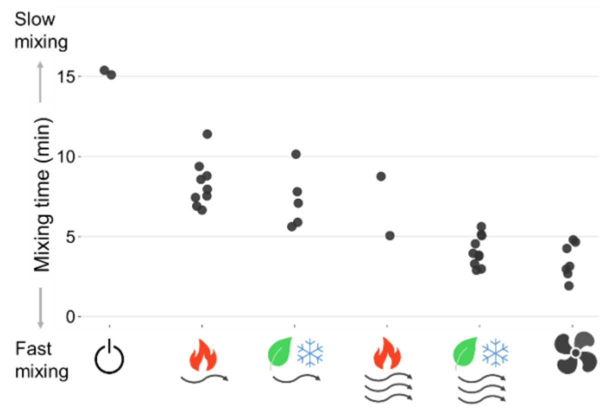
$$ERM = \frac{\int_0^{10} V_{norm} dt}{\int_0^{10} V_{ideal} dt} \qquad (1)$$

3 Results

3.1 Effect of supply air conditions on air mixing

Fig. 2 summarizes air mixing times under various supply airflow rates and air temperatures. Air mixing was slowest with the HVAC off, followed by conditions with a low supply airflow rate at all temperatures, and was fastest under high airflow at neutral/cooling temperatures or when mixing fans were added. Under low airflow conditions, mixing times ranged from 6.6–11.4 min during heating and 5.6–10.1 min under neutral/cooling conditions, indicating the low kinetic energy of air discharged from the supply grilles. High airflow neutral/cooling conditions and operation of mixing fans without HVAC resulted in fastest mixing times of 2.9–5.6 min and 1.9–4.8 min. Mixing times under high airflow neutral/cooling and mixing-fan conditions were significantly shorter than those under low airflow conditions (Welch's t-test, $p < 0.05$).

Fig. 2. Air mixing times under different airflow conditions: HVAC off, low heat, low neutral/cool, high heat, high neutral/cool, and mixing fan on.

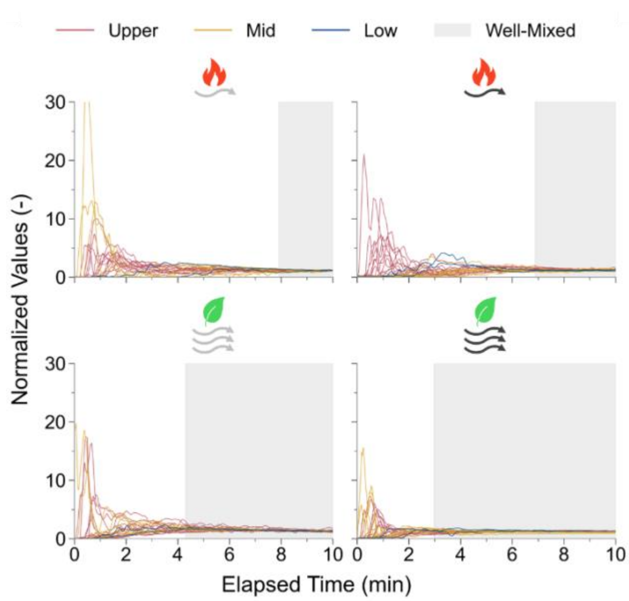


3.2 Effect of outdoor airflow rate on air mixing

Fig. 3 shows the effect of outdoor airflow rate (100% or 20% outdoor air) did not significantly affect spatial heterogeneity or air mixing time. Under low-airflow heating conditions, whole-room mixing required 7.9 and 6.9 min for 100 and 20% outdoor air, respectively, whereas under high airflow at neutral temperature, the mixing times decreased to 4.3 and 3.0 min.

Under slow mixing conditions (low airflow rate) and with releases associated with heaters simulating occupants, several upper or mid-level sensors peaked after the release, and mixing into the upper room and occupied space was slow. Under good mixing conditions (high airflow rate with neutral settings), air reached and mixed in the upper room more quickly and spread faster in the occupied zone.

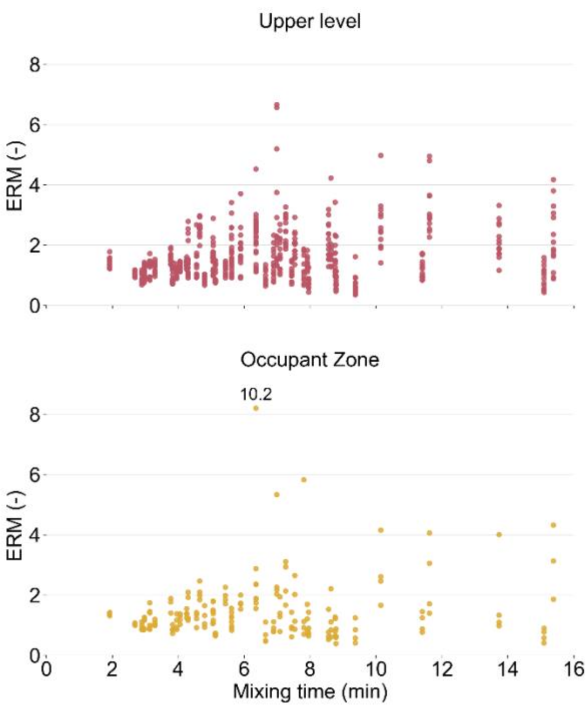
Fig. 3. Normalized values from sensors in the upper, mid, lower levels of the room under different outdoor airflow rates (100% - left, 20% - right). Top two are under low airflow rate at heating; bottom two are under high airflow rate at neutral temperature.



3.3 Effect of air mixing time on spatial variability

Fig. 4 presents the spatial variability of ERM calculated for 10 min at the upper level and occupant zone. When air mixing was fast (mixing time of 2–4 min), ERMs at both the upper level and occupant zone were close to 1 with low variability, because the space was well mixed for more than half of the exposure period. As mixing time increased, the variability of concentrations increased up to the mixing time of 6–7 min. And when exceeding 8 min, ERM variability no longer increased, indicating that spatial variability of ERMs does not differ further when the exposure duration is shorter than the mixing time.

Fig. 4. ERMs at each location at upper and mid-level of the room by air mixing times.



3.4 Effect of release location on air mixing

Fig. 5 shows the effect of release location on air mixing, comparing tracer release away from a table and release near the central table influenced by strong thermal plumes. When released in the south corner of the room, the tracer reached the upper room sensors to a limited extent and had a low impact on the occupied zone under both HVAC-off and mixing fan conditions. When released near the central table, the tracer reached and peaked at upper room sensors, presumably due to the strong thermal plume and mixed into both the upper room and occupied zone.

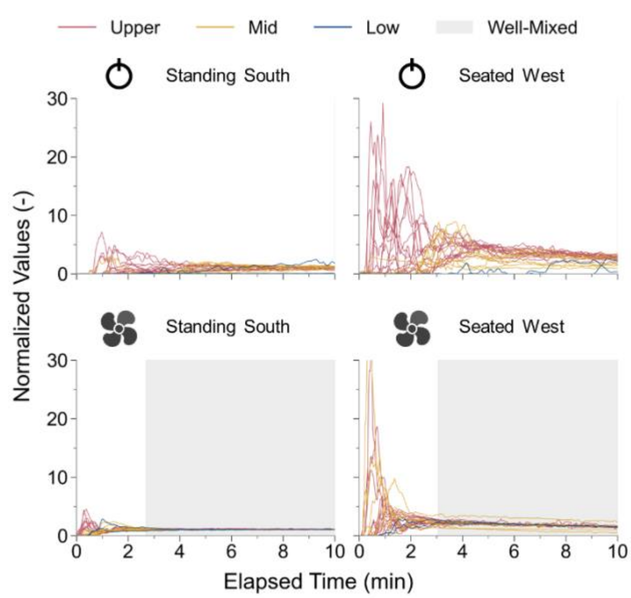
4 Discussion and Conclusion

Consistent with prior work on a novel tracer gas method [5], this study measured the effects of supply airflow rate and supply air temperature on air mixing time in a room with overhead mixed ventilation. We quantified the influence of air mixing on spatial concentration variability and the role of release location on contaminant transport.

The results show that the effective air cleaning rate of within-room air cleaning systems, such as upper-room GUV, depends on mixing conditions that can occur in normally operated rooms. High effective air cleaning rates are more likely to be achieved under fast mixing conditions, including high airflow at neutral or cooling supply temperatures and cases with added mixing fans. Under slow mixing conditions (HVAC off or low airflow rates), effective air cleaning rates vary widely, depending on whether releases occur in stagnation zones where contaminants are poorly transported, or at locations that enabled direct transport to the removal or disinfection zone.

For systems with a target air cleaning rate of 4 h^{-1}, the effective rate may not be achieved under HVAC-off conditions. Achieving target air cleaning rates of 6–11 h^{-1} may require additional mixing (with fans for example) under low airflow conditions. For higher target rates of 11–32 h^{-1}, even high airflow at neutral or cooling temperatures, or the use of mixing fans, may be insufficient.

Fig. 5. Normalized values from sensors in the upper, mid, and lower levels of the room, with tracer releases at a distance from a table (standing south, left) and near the table (seated west, right). The top panels show data under HVAC-off conditions; the bottom two are under mixing fan conditions.



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References

1. A.V. Baughman, A.J. Gadgil, W. W Nazaroff, Mixing of a point source pollutant by natural convection flow within a room. Indoor Air **4**, 114–122 (1994). https://doi.org/10.1111/j.1600-0668.1994.t01-2-00006.x
2. A.C. Drescher, C. Lobascio, A.J. Gadgil, W. W Nazaroff, Mixing of a point-source indoor pollutant by forced convection. Indoor Air **5**, 204–214 (1995). https://doi.org/10.1111/j.1600-0668.1995.t01-1-00007.x
3. I. Arvelo, F. Pagone, J. Persky, C.E. Carpio, P. Arnold, N. Clements, Decay rates of two tracer gases compared to DNA-tagged liquid aerosol tracer particles: impact of varying dilution rate and filtration. Indoor Environ. **212**, 108819 (2022). https://doi.org/10.1016/j.buildenv.2022.108819
4. I. Arvelo, E.R. Blatchley, W.P. Bahnfleth, P. Arnold, A. Fry, M. Topete, L. Zhou, W. Palmer, P.J. Piper, J. Zhang, W.A. Dexter, N. Palma, N.J. Heredia, Investigation of a DNA-tagged aerosol tracer method for in situ evaluation of germicidal UV air cleaner effectiveness. Build. Environ. **262**, 111828 (2024). https://doi.org/10.1016/j.buildenv.2024.111828
5. C.Y. Um, W.W. Delp, R.C. Blacklock, B.C. Singer, Demonstration of a novel tracer gas method to investigate indoor air mixing and movement. Indoor Environ. **2**, 100081 (2025). https://doi.org/10.1016/j.indenv.2025.100081
6. C.Y. Um, M. Russell, W.W. Delp, S. Schiavon, B.C. Singer, M.D. Sohn, Field demonstration of a tracer method to track simulated exhaled air trajectories and mixing in three connected rooms with upper-room GUV, in Proceedings of the Indoor Air 2024 Conference, Honolulu, HI, USA, June 30–July 4 (2024). https://escholarship.org/uc/item/5rg8307n
7. B.C. Singer, H. Zhao, C.V. Preble, W.W. Delp, J. Pantelic, M.D. Sohn, T.W. Kirchstetter, Measured influence of overhead HVAC on exposure to airborne contaminants from simulated speaking in a meeting and a classroom. Indoor Air **32**, (2022). https://doi.org/10.1111/ina.12917