Comparing HVAC Fan Operation with a Ceiling Fan and Room Air Cleaner Combination for Indoor Air Quality, Thermal Comfort, and Energy Use in a Multizone Residence

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ABSTRACT

We humans spend most of our time indoors, and most of that time in residences, where we are exposed to airborne particulate matter that can lead to a wide range of mild to serious adverse health effects. Air filtering with continuous Heating, Ventilation, and Air-Conditioning (HVAC) fan operation or room air cleaners can reduce human exposure to airborne pathogens and other particulates. In addition to filtering, HVAC fan operation mixes the air, breaking up localized high contaminant concentrations. Air mixing and elevated airspeeds from HVAC fan operation also aid thermal comfort. Due to its lower airflow than an HVAC fan and confinement in the lower part of the room, a portable air cleaner has limited mixing effect. Ceiling fans are commonly used to mix air for thermal comfort at higher temperature set points. Modern ceiling fans and room air cleaners typically use much less energy than a typical HVAC fan, and because they can be turned on only in occupied spaces, they likely have an energy conservation advantage over continuous HVAC fan operation. An alternative to continuous HVAC fan operation is a combination of room air cleaners and ceiling fans for (i) filtering, (ii) mixing, and (iii) thermal comfort associated air movement.

This study compares combinations of ceiling fans and air cleaners with continuous HVAC fan operation in residential environment for air quality, thermal comfort, and energy use. This study shows how to normalize data across experiments to compare HVAC filtration and various combinations of ceiling fans and room air cleaners from one test to another. One combination of ceiling fans and a portable air cleaner was slightly more effective and much more energy efficient than continuous HVAC operation for ultrafine particle removal, but continuous HVAC operation outperformed the portable air cleaner in all configurations for particles in the 1-2.5 μm and 2.5-5 μm size ranges. This study points the way to further testing to explore air cleaner and ceiling fan combinations that could be more effective and energy efficient than HVAC operation across all particle sizes of concern.

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INTRODUCTION

Indoor environmental quality (IEQ) includes indoor air quality (IAQ), thermal comfort, and other considerations for healthy and comfortable indoor spaces. Building energy performance is so interleaved with IEQ that IAQ, thermal comfort, and energy performance must be considered holistically.

If residents are especially concerned about particulate pollutants because of allergies, asthma, or airborne pathogens, they can open doors and windows to increase ventilation, but in some times and places that may be inadvisable due to weather or outdoor air pollutants. HVAC filters can be effective at cleaning indoor air, but residential HVAC systems typically only run an annual average of 20% of the time [1] and may not be needed for days or weeks at a time in some regions and seasons. Running the HVAC fan continuously can be effective for more thorough indoor air cleaning; however, that technique uses significantly more energy than normal temperature control operations. A HEPA Room Air Cleaner (RAC) is an energy efficient alternative to remove particles from the air during the 80% of the time when the HVAC is not running.

Thermal comfort also has energy efficiency considerations. Ceiling fans are commonly used for low-energy thermal comfort, allowing a higher temperature set-point. Some light air movement can have a cooling effect, but too much air movement can be objectionable, and it is far too windy when papers blow off desks. ASHRAE 55-2020 specifies upper airspeed limits for seated and standing averages as a function of operative temperature [2]. Ceiling fan speeds can be adjusted to generate airspeeds ranging from 0.2 to 0.8 m/s (40 to 160 fpm) for a useful cooling effect.

If a HEPA RAC is used for energy-efficient IAQ, and ceiling fans are used for energy-efficient thermal comfort, then some optimization may be achieved by considering pollutant removal and thermal comfort energy efficiency for various combinations of HEPA RACs and ceiling fans. In addition to their thermal comfort function, air mixing by ceiling fans may improve the performance of a HEPA RAC.

This study focuses on determining the particle removal effectiveness and energy efficiency for of five test conditions: 1) 0.5 ACH mechanical ventilation only, 2) HEPA RAC alone, 3) HEPA RAC with Living Room ceiling fan Speed 1, 4) HEPA RAC with Living Room ceiling fan Speed 3 and all Bedroom ceiling fans Speed 1, and 5) HVAC fan on at 6.4 ACH with 1-inch MERV-13 filter installed. To the authors' knowledge, this is the first study to examine the impact of ceiling fan operation on room air cleaner performance.

METHODOLOGY

We tested the five conditions listed above in the UTest House, a 110 m² (1184 ft²), 250 m³ (8829 ft³), three-bedroom, two-bath prefabricated house on the Pickle Research Campus of the University of Texas at Austin.

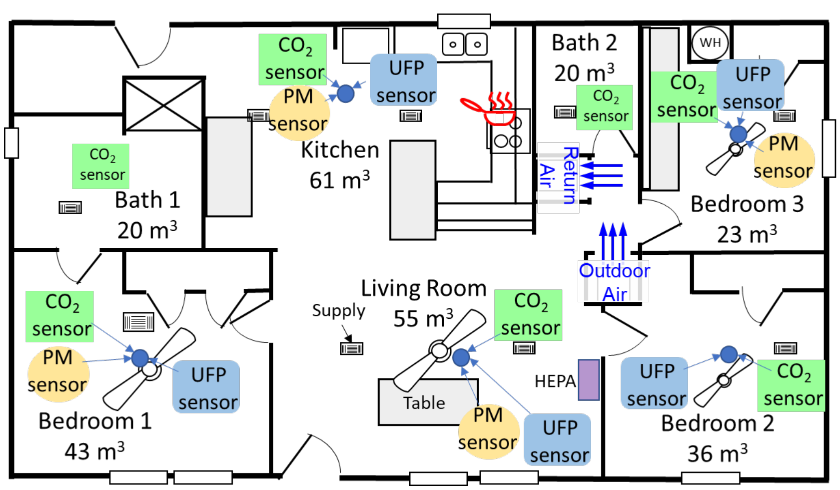

Figure 1. UTest House Floor Plan with Test Equipment Layout.

Figure 1 shows the floor plan of the UTest House with the source on the stove, ceiling supply vent locations, positions of AE2-60 ceiling fans in Bedroom 1 and the Living Room and AE2-43 ceiling fans in Bedrooms 2 and 3, and sensor types and locations. A LI-COR LI-7000 Closed Path CO_2/H_2O Gas Analyzer measured CO_2 concentrations in the Kitchen. It was also used as a truth source to calibrate TelAire 7000 CO_2 Monitors used in all other rooms. A TSI Aerodynamic Particle Sizer (APS) Model 3321 was used in the Kitchen for the large particles. The other large PM sensors are TSI AeroTraks (Model 9306A in the Living Room and Bedroom 1, and Model 8220 in Bedroom 3) capable of counting particles in six size bins ranging from 0.3 μm to > 10 μm. The bins used in this study were 1-2.5 μm and 2.5-5 μm. Particles larger than 5 μm were too few to establish meaningful trends. Particles smaller than 1 μm were measured by TSI P-Traks, shown as UFP (Ultrafine Particle) sensors in the figure.

The RAC is a HEPA Air Purifier operated at its highest speed, for which the manufacturer reports 231 cfm (374 m^3/hr) airflow and 220 cfm (392 m^3/hr) clean air delivery rate (CADR). We measured it power used at the top speed as 66 W, giving it a CADR/W of 3.3 cfm/W, which exceeds Energy Star requirement of 2.9 cfm/W [3].

A RAC is most effective when located near the source [4] for the same reason that exposure is greatest near the source [5]: the highest concentration occurs near the source, which is the best place to ventilate or filter before particles spread. These tests, with an emission release near the stove simulates a cooking event, but residences have irregular episodic events in unforeseen locations often unrecognized by occupants. If the occupants only use one air cleaner, they are likely to place it in a central location, usually near a wall and out of the way. We located the RAC in the Living Room beside the door to Bedroom 2 to avoid biasing results toward the propitious events when the cleaner is near the emission.

We had two Aeratron AE2-60 1.5 m (60 inch) diameter and two AE2-43 1.1 m (43 inch) diameter ceiling fans available for these tests. The Aeratron AE2-60 is listed by Energy Star as the most efficient ceiling fan in terms of airflow cfm/W [6]. Both the AE2-60 and the AE2-43 exceed the Energy Star requirements for airflow per Watt [7]. The UC Berkley CBE Ceiling Fan Design Guide recommends a fan diameter for a space with an aspect ratio less than or equal to 1.5:1 that is 0.2 to 0.4 times the characteristic length, which is the square root of the area [8]. Based on these criteria, Bedroom 1 and the Living Room are large enough to accommodate the AE2-60 1.5m (60 inch) diameter fans, and the other two bedrooms are large enough to accommodate the AE2-43 1.1 m (43 inch) diameter fans.

Prior to testing pollutant removal strategies, we measured airspeeds at four heights using HT-428 thermoelectric airspeed sensors at four heights as specified in ASHRAE 55-2020 at 54 positions and calculated seated and standing average airspeed at each position. We found that the maximum recommended speed for the Living Room ceiling fan is Speed 3 (out of 6 speeds), and that the maximum for each of the Bedroom ceiling fans is Speed 1. We previously measured volumetric airflow and power used by these ceiling fans in a test chamber using the Energy Star Ceiling Fan test methods [9] adapted to a smaller chamber (and a smaller budget) using Siemens airspeed sensors. The condition for minimum ceiling fan air mixing is the Living Room ceiling fan at Speed 1 with all other ceiling fans off, which delivers 4620 m^3/hr (2719 cfm), or 18.5 ACH. Maximum ceiling fan mixing is achieved with the Living Room fan at Speed 3 with the Bedroom ceiling fans at Speed 1, which delivers 18,550 m^3/hr (10,920 cfm), 74.2 ACH.

We used CO2 as a tracer gas to determine when the house air is well-mixed and to evaluate the ventilation and exfiltration rate. We used incense smoke for ultrafine particles, and Arizona Test Dust (Medium Grad) for larger particles. AHAM AC-1-2020, Method for Measuring Performance of Portable Household Electric Room Air Cleaners also recommends using Paper Mulberry Pollen for 5-11 μm particles [10], but we did not use pollen on these initial tests.

The HVAC fan, ceiling fans, and RAC were on conditions before the emission to stabilize airflow patterns. Each test began with a brief release, or burst event of CO_2, incense smoke, and Test Dust. We burned incense in a closed container for about 10 minutes before the event. An air pump supplied low-rate airflow to the container and a relief tube vented a small amount of smoke outdoors. For the burst, we stopped the air pump, removed the lid from the incense canister, and extinguished the incense. The Arizona Test Dust was then released from a plastic sauce bottle with a tube through the bottom of the bottle attached to an air pump. The burst event was an approximately 1-second burst that shot dust out the nozzle at the top of the bottle. Longer dust bursts tended to exceed the concentration limits of the AeroTraks. We released CO_2 from two 30-gallon trash bags we had filled outside while the incense was burning.

All tested conditions included 0.5 ACH provided by mechanical ventilation which maintained a slight positive pressure to mitigate day-to-day infiltration variations due to different wind conditions. Mechanical ventilation is required for new homes, but most existing homes do not have it. ASHRAE 62.2-2019 specifies residential ventilation requirements based or floor area and number of bedrooms [11]. For the UTest House, the required ventilation is 30.5 L/s (65.5 cfm), or 0.45 ACH. For these tests, we provided 34.7 L/s (73.6 cfm), or 0.5 ACH of HEPA filtered outside air. ASHRAE 62.2-2019 does not require ventilation filtration, but we used the filter to eliminate outside particle sources.

Figure 2 shows the size distribution of the incense and the Arizona Test Dust used in these tests. The incense particles typically far-outnumber the Arizona Test Dust particles. The <1 μm particles counted with the P-Traks are mostly less than 0.1 μm, and therefore are a reasonable representation of ultrafine particles.

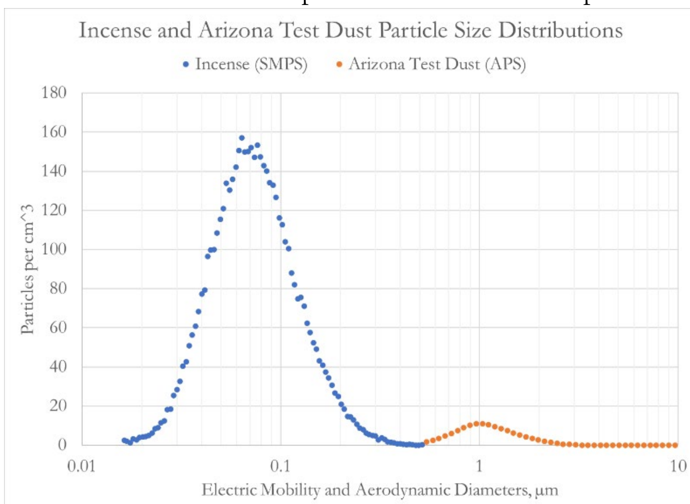

Figure 2. Incense and Arizona Test Dust Particle Size Distributions

Loss Rate Determination

Air pollutant loss rates are determined using the average reading starting at the well-mixed point, because until the house is well-mixed, we do not have a good estimate of the house average concentrations.

The material balance for pollutants is

$$C(t) - C_{out} - \frac{E}{\lambda V} = \left(C_{init} - C_{out} - \frac{E}{\lambda V}\right) e^{-\lambda t}$$

Where $C(t)$ is the average concentration at time, t

C_{out} is outdoor concentration

E is an indoor emission rate per hour

λ is the ventilation rate or pollutant loss rate

V is the space volume

C_{init} is the initial concentration, in this case, the house average at the well-mixed point

$t = 0$ at the well-mixed time

The material balance may be simplified by assuming no indoor sources after the initial event, so $E = 0$. Rearranging the remaining material balance equation, we have

$$\lambda t = -ln\left(\frac{C(t) - C_{out}}{C_{init} - C_{out}}\right)$$

If we plot $-ln\left(\frac{C(t)-C_{out}}{C_{init}-C_{out}}\right)$ versus time, then the slope of the line gives us the loss rate, λ.

We measured outdoor CO_2 for thirty minutes before and after each test, which typically ranged between 430 and 450 ppm, and used the average of those samples as the outdoor concentration. For particles, we assume no outdoor source since the mechanical ventilation system is fitted with a HEPA filter and the slight positive pressure should limit infiltration, so we only need to plot $-ln\left(\frac{C(t)}{C_{init}}\right)$. As the concentration approaches zero, so does the loss rate, since we can't lose what is not present, so the plot must eventually curve down to zero slope. To avoid distorting the loss rate with the flatter portion of the plot, good practice is to only use the first time constant, $\tau = \frac{1}{\lambda}$, to calculate the loss rate. Since τ is used to determine λ and vice versa, this requires some iteration, but it converges quickly if the value of $-ln\left(\frac{C(t)}{C_{init}}\right)$ at $t = 1$ hour is used as the initial estimate for λ.

Modeling the Average Trendline

After determining the loss rate, we can generate an average trend using

$$C(t) = (C_{init} - C_{out})e^{-\lambda t} + C_{out}$$

where $C_{out} = 0$ for particles. Time zero is at the well-mixed time, and the curve is projected backwards to the event time to find the trend peak, representing the average concentration in the house if it were immediately well-mixed at event time. Data from one test to another may be compared by converting data from each test to a normalized fraction of its trend peak. This allows valid comparisons without the time and expense of setting up precisely equal emission events.

RESULTS AND DISCUSSION

Figure 3, the CO_2 concentration coefficient of variation (CoV, the standard deviation divided by the average for all sensors) versus time from burst event, shows mixing time and mixing thoroughness of the five test conditions. The CoV spikes up to greater than 100% shortly after the burst event and then falls rapidly until it approaches some steady-state level. The well-mixed time is the time it takes for the rapid drop in the coefficient of variation to suddenly slow and settle out at some steady-state level.

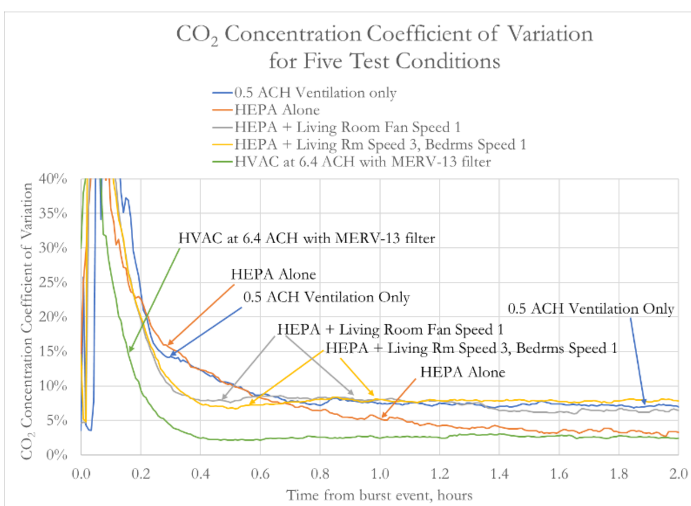

Figure 3. CO2 Concentration Coefficient of Variation

The HVAC Fan and both HEPA + Ceiling Fan configuration CoVs level out about 24 minutes after the event.

The HVAC configuration settles at a much lower CoV, indicating more thorough mixing. The CoV for 0.5 ACH ventilation only slows its descent at 15 minutes but does not level out until 42 minutes after the event, near the level of the ceiling fan conditions. The HEPA RAC alone CoV slows its descent about the same time as the ventilation only condition and levels out about 1.4 hours after the event at nearly the same level as the HVAC condition.

Figure 4 shows that for particles less than 1 μm in diameter, all mixing and filtering conditions are much better than Ventilation Only, which achieves 0.8 ACH as a baseline. The HEPA RAC with the minimum ceiling fan mixing is almost the same as the HEPA RAC alone. The HEPA RAC with maximum ceiling fan mixing improves performance to match the HVAC fan for ultrafine particles.

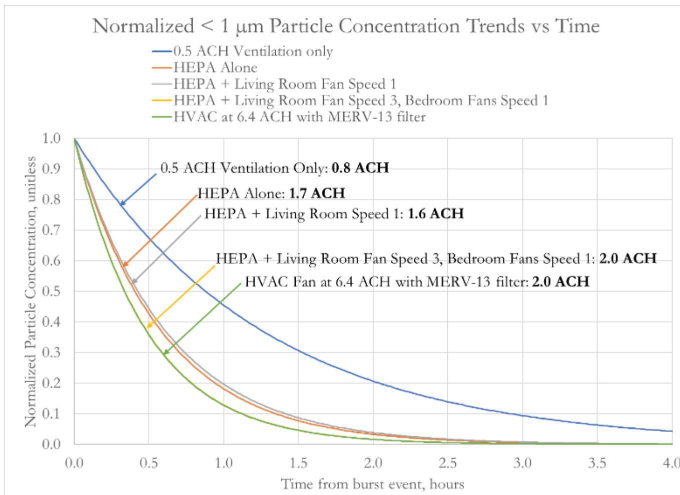

Figure 4. Comparing test conditions for ultrafine particle removal.

Figure 5 shows that HVAC outperforms all HEPA conditions for 1-2.5 μm and 2.5- 5 μm particle removal. Ceiling fans have little effect on RAC performance at 1-2.5 μm. Maximum ceiling fan mixing matches the HEPA alone for 2.5-5 μm particle removal, while minimum ceiling fan mixing degraded HEPA performance. Although HVAC clearly outperforms HEPA for the larger particles, the removal rates by all HEPA conditions are high enough that any of them might be considered excellent for normal residential requirements.

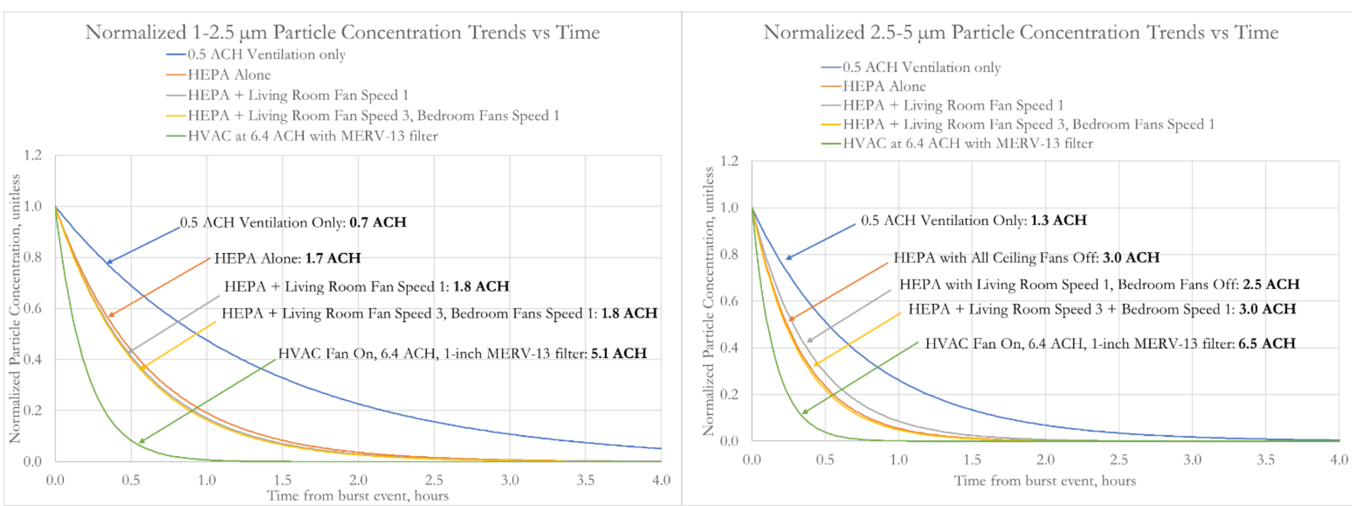

Figure 5. Comparing test conditions for 1-2.5 μm and 2.5-5 μm particle removal.

Mechanical ventilation with no other mixing or filtering achieved 0.8, 0.7, and 1.3 ACH for the <1 μm, 1-2.5 μm, and 2.5-5 μm particles, respectively. To compare the effects of each strategy and determine energy efficiency, we subtract the loss rate that occurs with only the mechanical ventilation from the total loss rate to yield the effective loss rate in ACH. We then divide that effective loss rate by the power in kW to determine efficiency in air changes/kW-hr.

Table 1 shows the effective air exchange rates and air exchange energy efficiency for each of the mixing and filtering strategies. The maximum mixing with HEPA strategy is slightly more effective and more than three times as energy efficient as the continuous HVAC strategy for ultrafine particle removal. We can also see that some amount of mixing improves the effectiveness of the HEPA RAC for ultrafine particle removal, though the effect is negligible at the lowest mixing level tested.

Continuous HVAC with the 1-inch MERV-13 filter is clearly more effective than the single HEPA RAC in all conditions, though the energy efficiency of the HEPA strategies is close to that of the HVAC. The great advantage of the HVAC is that it moves 6.4 ACH through its filter versus 0.9 ACH through the HEPA filter.

Table 1. Power, Effective Air Changes per Hour, and ACH/Power for Filtering Methods.

	HEPA Alone	**HEPA + Living Room Fan Speed 1**	**HEPA + Living Room Fan Speed 3, Bedroom Fans Speed 1**	**HVAC at 6.4 ACH with MERV-13 filter**
Power (W)	66	68.5	82	249
< 1 μm ACH, eff	0.9	0.8	1.2	1.2
1-2.5 μm ACH, eff	1	1.1	1.1	4.4
2.5-5 μm ACH, eff	1.7	1.2	1.7	5.2
< 1 μm /kW hr, eff	13.6	11.7	14.6	4.8
1-2.5 μm /kW hr, eff	15.2	16.1	13.4	17.7
2.5-5 μm /kW hr, eff	25.8	17.5	20.7	20.9

CONCLUSION

Running a HEPA RAC with ceiling fans can be as effective and more energy-efficient than continuous HVAC fan operation for ultrafine particle removal from indoor air. For removal of 1-2.5 and 2.5-5 μm particles, none of the HEPA RAC strategies were as effective as continuous HVAC operation. An additional HEPA RAC might help, and it would still use less energy than continuous HVAC. Adding a second RAC might be much more effective than the HVAC for ultrafine removal and only slightly less effective for larger particles.

It then becomes a medical question as to how much removal is recommended for each particle size range. On the one hand, we did not evolve in a dust-free air environment, so our bodies have some protections and filters built in. We probably have less protection against ultrafine particles because early humans were mostly exposed to them after they discovered fire and started cooking with it. So perhaps the focus should be more on the ultrafine particles for indoor air quality. On the other hand, allergy sufferers are particularly concerned with large particles like pollen, which we have yet to test. The goal is to filter effectively across the particle size range, but some trade-offs may need to be considered and evaluated by medical professionals.

We can also test other ceiling fan conditions. The Living Room ceiling fan at Speed 1 moves 4,620 m^3/hr (2,719 cfm) of air while the Living Room ceiling fan at Speed 3 plus the Bedrooms ceiling fans at Speed 1 moves a total of 18,548 m3/hr (10,917 cfm) of air, based on test chamber measurements. With Living Room fan Speed 1-3 available and Bedroom fans either off or at Speed 1, we have six combinations. We could create six more conditions by running only one or two bedroom ceiling fans. Perhaps some intermediate airflow mixing condition with the one or two RACs is the most effective and energy-efficient strategy.

More energy-efficient RACs might have acceptable CADR and an energy-efficiency advantage over continuous HVAC. Some RACs have Smoke-Free Clean Air Delivery Rate per Watt 3 to 4 times as high as the one we tested at up to double the CADR.

This analysis does not include possible energy savings of using a higher temperature set point. We would need to calculate the cooling effect of each ceiling fan condition tested and perform some energy modeling to estimate the energy savings from operating at a higher temperature set point during the cooling season. We can also experiment with running the fans in reverse, as is commonly done during the heating season. Air mixing helps with thermal comfort during the heating season by preventing stratification of air temperature. Energy savings may be achieved in the heating system by operating at a lower temperature set point, but at that point the maximum desired airspeed is about 0.2 m/s (40 fpm). Forward ceiling fan operation results in a relatively high-speed jet of air in the center down towards the floor and then a draft across the floor until the flow slows and climbs back up the walls. That's fine in the cooling season at a high temperature set point, but unwanted during the heating season at low temperatures. The ceiling fan operating in reverse directs the jet upwards where it spreads across the ceiling before sliding down the walls at lower speeds. This keeps the fastest air off the humans and other occupants and still provides good mixing. We would need to perform ceiling fan reverse flow testing to determine its effect on RAC performance and then perform the same energy analysis to determine the extra energy savings that might be possible during the heating season.

Another aspect of IEQ that we have not yet tested is acoustics. A well-known aerosol researcher stated that his daughter's teacher turned the portable air cleaner off on the third day because of the noise. We do know that RACs are completely ineffective in the off condition, so acoustics can be an important factor affecting performance. The RAC used in these tests was not noticeably louder than the HVAC fan, but we have not measured sound levels to make any objective comparisons.

Finally, with only one run of each test condition, the repeatability is unknown. More testing will help to determine the uncertainty of the results, and to understand the importance of the RAC power efficiency and other strategies. This study has shown that the combined ceiling fan and room air cleaner concept has potential for energy savings and acceptable IAQ, but that more work is needed to find a strategy that is both more effective and more efficient than continuous HVAC fan operation with a good, properly installed filter.

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