Ceiling-Fan-Integrated Air Conditioning (CFIAC): Age-of-air, Air Pollution, and Airflow Distribution

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Abstract. Ceiling-Fan-Integrated-Air Conditioning (CFIAC) is a heating ventilation and air conditioning (HVAC) design approach that jets supply air into the vicinity of ceiling fans to be mixed and distributed within the room. This eliminates terminal ductwork and diffusers and provides very efficient cooling for the occupants. Two previously published papers have described the air velocity, temperature, and thermal comfort fields in a space conditioned by CFIAC. This paper is the third in this series, to evaluate CFIAC ventilation effectiveness and its effect on air pollution. In a test chamber, HVAC supply air was jetted from a high-side wall vent into the centreline of a ceiling fan. The ceiling fan was operated at various conditions (off, level 2-downward, level 4-downward, and blowing upward). Carbon dioxide (CO2) was used as a tracer gas for the age-of-air evaluation, and as a proxy for an indoor air pollutant. For the age-of-air measurement, the CO2 source was injected into the side wall jet, and the age-of-air was monitored in various locations in the chamber. For the air pollution test, CO2 as the pollution source was released near a thermal manikin’s nose that was located in the middle of the chamber. The CO2 concentrations were measured at different locations around the ceiling fan and the thermal manikin. The ventilation effectiveness and health exposure are represented by the age-of-air and intake fraction (IF). At level 2 and level 4 downward fan operations, the age-of-air is reduced in the measured locations compared to the fan-off operation. The age-of-air for upward fan operation is equal to the age-of-air in fan-off operation, except for one location that is farthest from the fan. The IF results are very similar among all 4 fan operations, with level-4-downward and upward-fan operations slightly lower than the fan level-2 downward and fan-off operations. The study is considered preliminary, but at this point, we can say that fans reduce age-of-air and cross-infection risk.

1 Introduction

This study is one of the three-paper series introducing a novel air ventilation system, which is called ceiling fan-integrated air conditioning (CFIAC). Two previously published papers described air velocity and temperature distributions [1], and thermal comfort [2]. This paper investigates the age-of-air and air pollution distributions of the CFIAC system.

In a CFIAC system, conventional terminal supply ducts and diffusers are replaced with vents or nozzles, e.g. on side walls, that jet supply air into the vicinity of a ceiling fan for mixing and distribution. Such a system fan can provide thermally comfortable conditions and more energy efficiency while reducing the cost of ductwork and diffusers. The use of ceiling fans has received recent attention: review papers [3, 4] summarized field studies of fan use on thermal comfort, energy use, and human productivity. Several researchers have experimentally evaluated how ceiling fans distribute temperature in spaces [5-7]. Alizadeh et al. examined the reduction of vertical temperature stratification within a room with a ceiling fan [8]. Lin found that a downward-directed fan jet at a speed of 0.3 m/s disrupted the thermal plume produced by a human body, and the heat generated by the body diffused in all directions. If a ceiling fan was used in a space with an air conditioner, a 90 m³ workplace might potentially save 1804.8 kWh of power annually by raising the cooling setpoint of the air-conditioning of the space [9]. Since CFIAC is a new concept, no papers describe its impact on age-of-air and air pollution distribution within a room. Relationships between a ceiling fan and indoor air movement have been developed by experiments and numerical simulations [10, 11], and results showed that raising the rotational speeds of a ceiling fan could enhance average air speeds in the occupied zone. These studies did not examine the age-of-air and air pollution distributions, and they only consider cases of an empty room and omit the human body effects that are key to exploring real indoor conditions. It is necessary to look...
into how the human body affects indoor air movements together with the ceiling fan and the supply of airflow.

This paper summarizes results from two experiments examining the ventilation effectiveness and air pollution distributions within a room under a CFIAC system. The ceiling fan airflow rate and downward or upward operations were varied. For the air pollution distribution tests, the thermal manikin, releasing CO₂ via its nostrils and mouth, was positioned in the middle of the experimental chamber, near but not directly within the ceiling fan jet, to serve as the pollution source.

2 Method

Chamber setup. The configuration of the CFIAC system, the age-of-air experimental setup, and the CO₂ pollution experimental setup are illustrated in Section 2.1. Section 2.2 introduces two indoor environmental evaluation indexes: the age-of-air, and the health exposure index: intake fraction (IF).

2.1 Experimental setup

The experiments were carried out at the Center for the Built Environment (CBE) at the University of California, Berkeley. The configuration of the CFIAC in an environmental chamber is depicted in Figures 1 (a) and (b).

Fig. 1. Configuration and dimensions of the CFIAC chamber: (a) chamber layout and (b) horizontal section.

The dimensions of the chamber are 5.5 m (length) x 5.5 m (width) x 2.53 m (height). A small box on the side wall sized 0.33 m (length) x 0.36 m (width) x 0.36 m (height), contained the supply vent. The vent was 0.184 m (width) x 0.133 m (height) and was located 2.15 m high above the floor. The supply vent register (Price Industries 520 Grille) allowed the supply air throw direction to be adjusted vertically. The ceiling fan (Haiku 60, Big Ass Fans, Inc.) with a diameter of 1.5 m was positioned 2.15 m from the floor. The distance between the center of the supply vent and the center of the ceiling fan was 1.775 m. A square exhaust grille with length and width dimensions of 0.61 m was 0.9 m away from the nearest side wall (the right side wall in Figure 1 (a)).

Air pollution test setup. The CO₂ pollution experimental setup is shown in Figure 2. Figure 2 (a) shows the test configuration. A thermal manikin was located in the middle of the chamber with a seated position. One CO₂ tube connected to a CO₂ gas tank was put near the manikin’s nose at a height of 1.1 m above the floor. The tube served as the CO₂ source. It released the CO₂ with a mass flow rate of 0.3667 L/min, representing a typical breathing flow rate. The manikin’s skin temperature was controlled at 34°C across its entire body. The CO₂ measurements were conducted under stable conditions. The CO₂ source released CO₂ for one hour before the measurement started.

Fig. 2. Configuration of the CO₂ pollution experiment setup: (a) experimental setup; in the picture, the tripod with velocity sensors and CO₂ tubes are seen in the Line 1 position; (b) line layout with the heights of thermos-anemometers and tracer gas pickups indicated by grey short lines.

Figure 2 (b) shows four different measurement vertical lines around the manikin symmetrically located:
Line 1 (-1.375 m, -1.375 m, z), Line 2 (-1.375 m, 1.375 m, z), Line 3 (1.375 m, 1.375 m, z), and Line 4 (1.375 m, -1.375 m, z), taking the manikin center as the origin. The manikin was facing Line 2 and Line 3 direction. Note that the ceiling fan was not placed in the middle of the chamber, but closer to the air-conditioning supply vent. Therefore, the ceiling fan was not directly above the manikin. Line 1 and Line 2 were closer to the ceiling fan than Line 3 and Line 4. In each line, eight omnidirectional anemometers (AirDisSys5000, Sensor Inc., Poland) were used to measure the air velocity and temperature at a sampling frequency of 1 Hz with heights of 0.1m, 0.6m, 0.9m, 1.1m, 1.5m, 1.7m, 2.0m, and 2.3m, respectively. The sensor detection accuracy is ±0.02m/s or 1% of the reading (0.05-5.00 m/s).

Eight CO2 sampling tubes connected to a CO2 detector were put in the same locations as the eight anemometers, and CO2 concentrations were collected every second. The CO2 detector had a pump drawing air through the sample tubes to a CO2 concentration measurement meter. The pump drew air from one tube at a time and the detector measured the CO2 level over a period of 2 minutes. Then the pump switched connection automatically to draw a gas sample from another tube until samples from all 8 tubes were measured. Then we moved the measurement tripod to the next measurement line. We waited for 20 minutes to start the CO2 sample measurement at the eight locations in the next measurement line. In addition, three additional CO2 tubes were located near the supply vent, exhaust vent, and outdoors.

Age-of-air test setup. Figure 3 illustrates the experimental setup for testing the age-of-air. The positions of the four detection lines were the same as in the CO2 pollution test. For each line, two omnidirectional anemometers and two CO2 tubes were placed at heights of 1.1m and 1.7m to detect the air velocity, temperature, and CO2 concentration. The reason for choosing 1.1 m and 1.7 m was that these two values represented typical sitting and standing heights of people [12, 13]. One CO2 tube connected to a CO2 tank was put in the center of the supply vent releasing a mass flow rate of 1L/min, and the releasing time lasted for 45 minutes, which guaranteed that the chamber achieved a steady-state condition. The CO2 tank was turned off after 45 minutes, and the decay period was used to calculate the values of the age-of-air for each of the eight measurement locations. When calculating the age-of-air for all 8 measurement points, the start time is the time when CO2 was turned off. Again, three extra CO2 tubes were put near the supply vent, exhaust vent, and outdoors to collect the CO2 concentrations.

The ceiling fan was operated at four modes: off, Level 2 downward, Level 4 downward, and blowing upward (Level 4, the maximum speed for the upward fan operation), and airflow rates of each mode are shown in Table 1. The rotational speeds of Level 2, and Level 4 downward were 72 rpm and 122 rpm, respectively, and the corresponding fan air speeds were 0.6 m/s and 1.2 m/s, respectively measured at [14].

Table 1. Ceiling fan airflow rate of each mode.

<table>
<thead>
<tr>
<th>Mode</th>
<th>Airflow rate (m³/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>off</td>
<td>0</td>
</tr>
<tr>
<td>Level 2 downward</td>
<td>1.2</td>
</tr>
<tr>
<td>Level 4 downward</td>
<td>2.2</td>
</tr>
<tr>
<td>Blowing upward</td>
<td>1.3</td>
</tr>
</tbody>
</table>

### 2.2 Indoor environmental evaluation indices

The age-of-air is used to evaluate the ventilation effectiveness of the CFIAC system, and the intake fraction (IF) is responsible for calculating the health risk.

#### 2.2.1 Age-of-air index

Fresh air ventilation has the ability to purify the indoor air in buildings [15], and the effectiveness of the HVAC system, which distributes the fresh air across an occupied space, is crucial to maintaining indoor air quality and thermal comfort. The age-of-air index measures how long it takes for fresh air to move from the supply vent to any location in the room, and is a reliable indicator of the freshness of the room air [16]. The shorter it takes for the air from the supply vent to a location, the smaller the age-of-air, and the more effective the ventilation system. The calculation equation is as follows [17]:

\[
A_i = (t_{end} - t_{start}) \frac{C_{i avg}}{C_i(t_{start})}
\]

where \(t_{end}\) is the last detecting CO2 time used; \(t_{start}\) is the time when the CO2 source is turned off; \(C_i(t_{start})\) is the tracer-gas concentration at location \(t\) at time \(t_{start}\), and \(C_{i avg}\) is the time-averaged tracer-gas concentration at location \(i\) between the time start and end.

#### 2.2.2 Intake fraction index

The intake fraction (IF) index is used to evaluate cross-infection risk [18]. The IF index is defined as the proportion of pollutant mass exhaled from the pollution source that is then inhaled by the exposed human, the smaller the IF, the less risk. The formula is as follows:

\[
IF = \frac{C_h M_h}{C_i M_i}
\]

where \(C_h\) is the inhaled CO2 concentration for the exposed human, and \(C_i\) is the exhaled CO2 concentration from the source; \(M_h\) and \(M_i\) are the mass flow rates of
inhalation for the exposed human, and exhalation from the source, respectively.

3 Results and Discussions

The supply vent air velocity and temperature were set at 1.2 m/s, and 15°C, respectively. These low values were chosen because, without the ceiling fan running, the supply air will be least mixed within the room. So this test condition provides conservative results for the evaluations of the age-of-air and pollution distribution.

3.1 Air velocity distribution

Figure 4 shows the air velocities of four detection lines at various heights. Level 4 produces the highest velocities in comparison to other fan operation modes, and the air velocities of the without-fan mode are the lowest. Level 2 has a higher air velocity than blowing upward mode in most circumstances. The mean air velocity of Level 4 is 9.2 times larger than without fan mode, and Level 2 and blowing upward are 5.1 times, and 2.6 times larger, respectively. The results demonstrate that the CFIAC system increases interior air movements. The higher the fan rotational speed, the higher the air movements achieved.

For downward flows, the maximum air velocity is found at 0.1 m height, where the fan’s downward jet spreads out across the floor. The lowest air velocity occurs at 1.1 m. When the fan mode is downward, the air velocity of Line 1 is higher than that of Line 4, because Line 1 is closer to the fan. Line 1 and Line 2 have similar air velocities, while Line 3 and Line 4 have similar air velocities. When the fan mode is blowing upward, the air velocities of Line 3 and Line 4 are slightly higher than those of Line 1 and Line 2, because the presence of the opposite wall increases velocities in Line 3 and Line 4.

Overall, the velocities at the four locations are fairly low. For level 2, upward direction, and fan-off operations, most velocities are 0.2 m/s or lower, except at 0.1 m height, which could reach 0.3-0.6 m/s. For level 4 fan operation, the velocities at Line 1 and Line 2 could reach 0.3 m/s or 0.4 m/s, except at the 0.1 m height, which reached 0.5 to 0.9 m/s.

3.2 CO2 concentrations from pollution sources in various locations

When using CO2 as a tracer gas, because there is CO2 in the supply air of the air-conditioning system, and this CO2 level changes slightly with outdoor conditions, it is necessary to use the relative CO2 concentration. It is defined as the difference between actual indoor CO2 concentration and supply vent CO2 concentration. It represents the CO2 concentration at measurement locations removing the CO2 effect from the supply air.
Fig. 5. Relative CO₂ concentrations of four detection lines.

Figure 5 shows the relative CO₂ concentrations of four detection lines when the CO₂ tracer gas is supplied from the pollution source near the nose of the thermal manikin located in the middle of the test chamber. The CO₂ concentrations of Level 4 fan operation mode are significantly lower than those with no fan for all four lines, and the average relative CO₂ concentrations for Level 4 are reduced by 14% compared to the fan-off operation mode. For the other three fan operation modes (fan-off, level 2 downward, upward), the CO₂ concentrations are very similar for Line 3 and Line 4. For Line 1 and Line 2, the upward fan direction creates the lowest CO₂ concentrations, 25% and 11% lower than the fan-off condition. For level 2, the concentration in Line 1 is 13% lower than the no-fan condition, but in Line 2, the CO₂ concentration is 9% higher than the no-fan condition. The higher concentration in Line 2 is due to the low air velocities (between 0.1–0.2 m/s) and the manikin’s facing direction (facing toward Line 2). Under the blowing-upward condition, the lower relative CO₂ concentrations in Line 1 and Line 2 than in Lines 3 and 4 due to Lines 1 and 2 being closer to the ceiling fan.

3.3 Age-of-air

The age-of-air index is used to evaluate the purifying efficiency of the CFIAC system. Figure 6 shows the results of eight locations: four Lines at 1.1 m and 1.7 m (seated and standing breathing zones). It shows that the age-of-air value of Level 4 is the lowest among all four tested conditions. The average age-of-air at Level 2 and blowing upward are 1.3 times and 1.6 times larger than at Level 4, respectively. The average age-of-air is 12.7 minutes under no-fan conditions, which is reduced to 8.8 minutes of Level 4, to 10.8 minutes of Level 2, but is increased on average by 1 minute to 13.7 minutes of an upward fan-blowing direction. In Line 1 and Line 2, under level 4, the age-of-air is reduced to 6-8 minutes.

Fig. 6. Age-of-air results for eight detected positions.
(Position 1&2: 1.7 m and 1.1 m, at Line 1; Position 3&4: 1.7 m and 1.1 m, at Line 2; Position 5&6: 1.7 m and 1.1 m, at Line 3; Position 7&8: 1.7 m and 1.1 m, at Line 4)

The values of Lines 1 and 2 (positions 1-4 in Figure 6) are lower than those of Lines 3 and 4 (positions 5-8 in Figure 6). This difference is related to the location: the closer to the ceiling fan, the smaller value of the age-of-air. The above findings demonstrate that the CFIAC can improve the air exchange effectiveness of the ventilation system. For the upward blowing direction, the age-of-air is similar in Line 1 and Line 2, and higher
in Line 3 and Line 4 compared to the no-fan mode, meaning that the upward direction equals the time of fresh air delivered to Lines 1 and 2 in no-fan condition, but increased about 2-3 minutes in Line 3 (1.1 m and 1.7 m) and Line 4 (1.1 m). The age-of-air is similar for Line 4 at 1.7 m height.

3.4 Health exposure index

The intake fraction (IF) is shown in Table 2. The IF values for all fan operations and all line locations are very similar. The IF values at level 4 of fan downward operation are slightly smaller than the other conditions. The similar IF for all fan operation modes means that the fan doesn’t affect the risk of pathogen cross-infection.

Table 2. Intake fraction (IF) of all fan operations and at 4 lines.

<table>
<thead>
<tr>
<th></th>
<th>Line 1</th>
<th>Line 2</th>
<th>Line 3</th>
<th>Line 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>without fan</td>
<td>0.10</td>
<td>0.10</td>
<td>0.10</td>
<td>0.10</td>
</tr>
<tr>
<td>level 2</td>
<td>0.09</td>
<td>0.11</td>
<td>0.10</td>
<td>0.11</td>
</tr>
<tr>
<td>level 4</td>
<td>0.09</td>
<td>0.09</td>
<td>0.08</td>
<td>0.09</td>
</tr>
<tr>
<td>upwards</td>
<td>0.07</td>
<td>0.09</td>
<td>0.10</td>
<td>0.10</td>
</tr>
</tbody>
</table>

4 Conclusions

This study investigates the ventilation effectiveness and air pollution distributions of the CFIAC system using the age-of-air and IF indexes. The conclusions are summarized as follows.

(1) At the Level 4 fan speed, the age-of-air is the smallest compared with no-fan, Level 2, and upward-directed airflow. The fresh air from the supply vent of the air-conditioning system is delivered to the receptor locations on average 4 minutes faster than the no-fan condition. The health exposure indexes (IF) are slightly smaller than the no-fan condition for all Lines at the Level 4 fan speed, meaning the cross-infection risk is reduced slightly.

(2) At the Level 2 fan speed, the age-of-air values for Lines 1 and 2 are reduced significantly, but not for Lines 3 and 4. The reason is that Line 1 and Line 2 are closer to the ceiling fan than Line 3 and Line 4. The cross-infection risk is similar to the fan-off condition.

(3) With the upward fan direction, the age-of-air is similar compared to the no-fan condition in Line 1 and Line 2, but increased in Line 3 and Line 4. This indicates that the upward direction delays the fresh air delivered to those more distant measurement locations. The blowing air upward reduces the cross-infection risk in Line 1 and Line 2 to the lowest levels compared to no-fan, Level 2, and Level 4 fan operation conditions.

(4) The airflow distributions are mostly influenced by the rotation speed of the ceiling fan. When the ceiling fan is in the high-speed downward mode, the indoor air velocity is higher than in the other modes and a lower age-of-air value is obtained.

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References

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