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Published in:
E3S Web of Conferences

DOI:
10.1051/e3sconf/202235605007

Published: 01/01/2022

Document Version
Publisher's PDF, also known as Version of record

Temporal and spatial aerosol transmission from the exhalation of an infected person in an office environment

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Abstract. The paper reports office test chamber experiments with an exposed breathing thermal manikin (6 L/min) and an infected exhalation simulator (6 L/min) connected with a thermal dummy. The motivation was to investigate effects of different protection methods at workstation when an infected person is working in the room. The protection methods were room air purifier, personal air purifier, FFP2-mask, and workstation partition panels. The objective was to measure temporal and spatial concentration characteristics at the exposed breathing zone. The exhale of infected model was aerosolized by using a Blaustein atomizer (BLAM), syringe pump and paraffin oil (0.6 mL/h). The concentrations were measured with TSI optical particle sizers. The ventilation method was mixing ventilation from a perforated duct. The indoor air change was 1.7 1/h (ACH). The experimental set-up was carried out at 6 workstations around the infected person. The temporal and spatial evolution was measured from zero concentration to steady concentration level. The results indicate that the room air purifier and the facemask can efficiently reduce exposure whereas the personal air purifier had a moderate reduction. The partition panels had only a minor effect on exposure. The lowest exposure was found when the individuals were sitting at the same side far from each other.

1 Introduction

Airborne transmission is one route for pathogens from infected person to exposed person [1]. Furthermore, the recent COVID-19 epidemic has changed working modes in office indoor environments. People may want to work remotely, but the convenience can be insufficient because of the limited face-to-face discussion possibilities. Therefore, practical protection methods could be a relevant choice at workstations, such as room air cleaner or facemasks. The protection methods can be classified as passive or active methods. The active methods clean the room air, and the passive methods make structural barrier for aerosols to reach susceptible person.

Earlier studies have found that face masks may capture 40–60% of exhaled aerosols and are more effective for the larger particles than the smaller particles [2]. However, the face masks may worsen the working performance by increasing the breathing resistance and CO_2 rebreathing and by decreasing the inhaled O_2 concentration [3-4].

Air purifiers, in turn, circulate and clean indoor air. Although their efficiency may be reduced with variable airflow rates, the HEPA-filter and the electrostatic precipitator have been found effective [5-7]. There are several types of air purifiers in the market. For instance, the air purifier can be a personal and wearable air purifier or larger room air purifier that circulates the indoor air.

Generally, characterizing human exposure can be rather complex highlighting the generation, survival, and transmission of pathogens [8]. The unclear is how much viable pathogens the droplet nuclei contain. The large droplets fall rapidly to workstation and smaller ones may dry to droplet nuclei level that can transfer along the airflow patterns unspecified long time.

In this study, different protection methods were compared at office workstation. The office room layouts were a workstation setup and a meeting setup. The motivation was to characterize the aerosol transmission in the room when an infected person is working under the mixing ventilation conditions. The objective was to examine a protection potential of each method by measuring the concentration level at the exposed inhaling of thermal manikin. The infected model was transferred to the different workstations around a table to detect the spatial differences.

2 Methods

The following paragraphs define the exhaling simulator used as the infection source and the breathing thermal manikin used as the exposed model. Furthermore, the measuring instruments, the experimental setup and the test cases are discussed.

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2.1 Infected thermal model

The infected thermal model was built by combining a respiratory exhalation simulator (CHεST, CH Technologies Inc.) to a seated thermal dummy including light bulbs and fan to equalize the inside heat source. The paraffin oil of 0.6 mL/h was released from the syringe pump and aerosolized in the Blaustein atomizer (BLAM). The supplied exhalation was 6 L/min. The aerosol distribution had similarities with Morawska et al. [9] and Johnson et al. [10].

2.2 Exposed thermal manikin

The male breathing thermal manikin (P.T. Teknik Limited, Denmark) was seated to an office chair. The 26 body segments were heated under the 'comfort mode' that should maintain the surface temperature equal to the average human skin temperature. The breathing mode describing a light office work was set at 6 L/min with a breathing cycle of 2.5 s inhalation, 1 s break, 2.5 s exhalation and 1 s break. The exhaled air temperature was set at 35°C with around 85% of relative humidity.

2.3 Measuring instruments

The aerosol concentration of the breathing zone of thermal manikin was measured by using a TSI optical particle sizer. The sizer used laser technology and had an optical scattering from single particles. The suction of the TSI meter was 1 L/min continuously. The concentrations at the workstations were measured with a TSI Dusttrak DRX 8533 optical counter. The sampling frequency of both concentration measurements was 1 Hz. The measurement uncertainty of the optical sizer was on the order of ±10%. The zero calibration of Dusttrak was driven before each measurement.

The air velocity and the thermal conditions were measured with a Dantec Comfort sense transducers that are the temperature compensated omnidirectional probes. The air temperature and the air humidity were measured from the floor, table and each wall with a Tinytag plus 2 meter, in which the sensor was around 2 cm from a solid surface of the measured location, thus reflecting merely the boundary layer conditions. Table 1 shows the measuring instruments and accuracy level.

Table 1. Measuring instruments and accuracy.

Instrument	Accuracy
TSI Optical particle Sizer (OPS) Model 3330	Count 100% >0.3µm Air flow ±5%
TSI Dusttrak DRX 8533 optical counter	Resolution ±0.1%, min 1 µg/m^3 Air flow ±5%
Dantec comf.sense transducers 54T33 omnidir. probe	Air velocity ±2%±0.02 m/s Air temperature ±0.5 C
Dantec comf.sense transducers 54T38 oper.temp.	Operative temperature ±0.2°C
Tinytag plus 2 TGP-4500	Air temperature ±0.5°C RH ±3% if 25 C

2.4 Experimental setup

The test chamber had the internal length of 5.5 m, the width of 3.8 m and the height of 3.6 m. Hence, the floor area was around 21 m^2 and the indoor air volume around 75 m^3.

Figure 1 shows a side-view of the test chamber. The measurement locations were at the breathing zone and at the workstations. The distance between each location was 40 cm from the mouth of infected dummy towards the mouth of exposed thermal manikin (40 cm-40 cm-40 cm, see Fig. 1). The breathing zone was measured two centimetres beside the mouth of exposed manikin through which the inhaling occurs. The infected source was measured at the mouth of seated dummy through which the exhaling occurs.

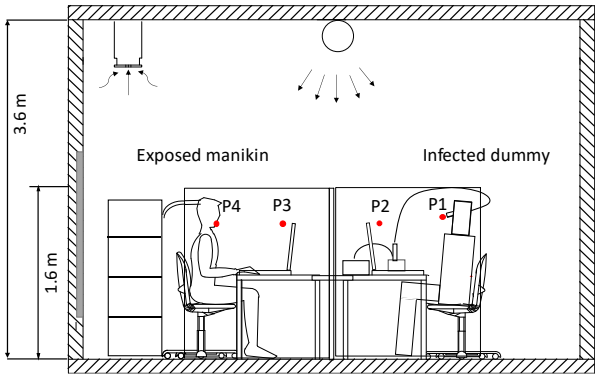

Fig. 1. Side-view layout of the test chamber. Red dots describe the measurement locations (P1-P4).

Figure 2 shows a top-view of the test chamber with the workstation layout. In this layout, the table had four workstations. The red dots describe the concentration measurements whereas the orange and blue dots describe the location of thermal condition and air velocity measurements, respectively. The air velocity conditions were measured above the table at the height of 0.8 m, 1.1 m, 1.4 m and 1.7 m focusing on the zone above table at each workstation. The table-top was at the height of 0.75 m.

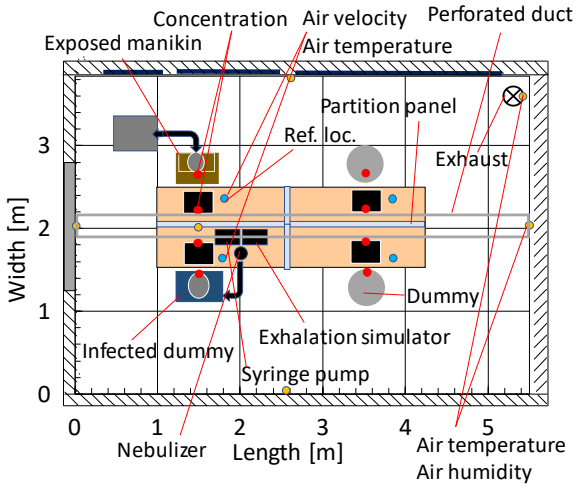

Fig. 2. Top-view layout of the workstation setup.

The air distribution method was mixing ventilation. The supply air was introduced from a perforated duct

diffuser of the diameter of 0.2 m that was installed in the middle of the ceiling extending the entire length of the test chamber. The supplied airflow pattern was 180° downwards to the occupied zone. The smoke visualization depicted that the supply airflow is reached the table level and mixing well to surrounding indoor air. The exhaust air device was at the ceiling corner.

Figure 3 shows a top-view of the test chamber with the meeting layout. In this layout, the table had six workstations around the table. The measurement locations and ventilation setup follow the same logic than with the workstation layout.

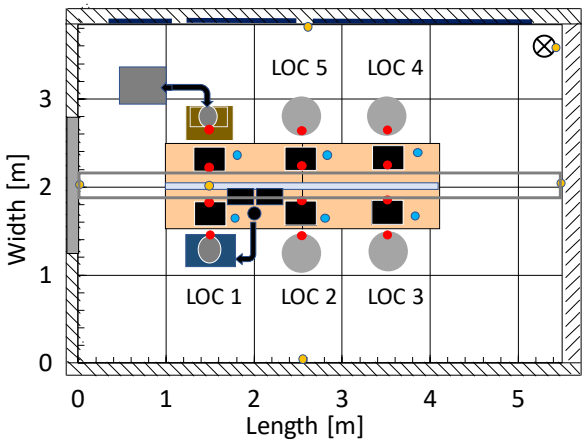

Fig. 3. Top-view layout of the meeting setup.

Table 2 shows the internal heat gain and ventilation parameters of the test cases. The heat power was pre-measured. The total heat flux was 12.5±0.6 W/m^2 describing a low heat load condition. The heat loss was through the structures mainly. The ventilation was 36±3 L/s describing office ventilation of 6 L/s per person. The supply air temperature was 17±0.5°C and the indoor air temperature 23±1°C in the reference location.

Table 2. Heat gain and ventilation parameters.

Parameter	Heat flux (W/m^2)	Parameter	Value
Thermal manikin	3.8±0.2	Persons max.	6
Thermal dummy	4.1±0.2	Ventilation (L/s)	36±3
2 x lap-top	3.8±0.2	Supply air (°C)	17±0.5
Light	4.3±0.2	Room air (°C)	23±1
Heat loss	-3.5±0.2	ACH (1/h)	1.7±0.1
Total heat gain	12.5±0.6	Total cooling	-12.5±0.6

2.5 Test cases

Test cases compare different protection methods at the workstation (Table 3). The measured period was 1 hour and 40 minutes (6000 s) under the air change conditions of 1.7 1/h (ACH). This consists of the concentration development from the zero level to the statistically steady-state conditions, as well as the time-averaging of 1000 s with the sampling frequency of 1 Hz.

During measurements, the indoor air temperature was on average 23.0±0.6°C, and the air humidity was 26±5%. The operative temperature was 23.0±0.5°C. Hence, the thermal radiation was at a low level. The average air velocity was also low 0.09±0.02 m/s whereas the turbulence intensity was 59±12%. The average draft rate falls to 6.8±3.2% reflecting low heat-gain conditions.

Table 3. Test cases.

Test case	Protection method
Case 1	Without protection (meeting setup)
Case 2	Room air purifier (meeting setup)
Case 3	Personal air purifier (meeting setup)
Case 4	FFP2-mask (meeting setup)
Case 5	Low partition panel (meeting setup)
Case 6	High partition panels (workstation setup)

3 Results and discussion

3.1 Concentration characteristics

Figure 4 shows the concentration level in the steady-state conditions. The concentration was 166±11 µg/m^3 (avg±sd) at the exposed breathing zone without any protection method (1.2 m from the infected person, Figure 1, P4). At the workstation, the concentration was 173±15 µg/m^3 (80 cm from the source, P3). At the infected workstation, the concentration was larger 487±845 µg/m^3 (40 cm from the source, P2). The results reveal that although the ventilation was highly mixing, the exposure logically increases near the source due to the wide range of aerosols.

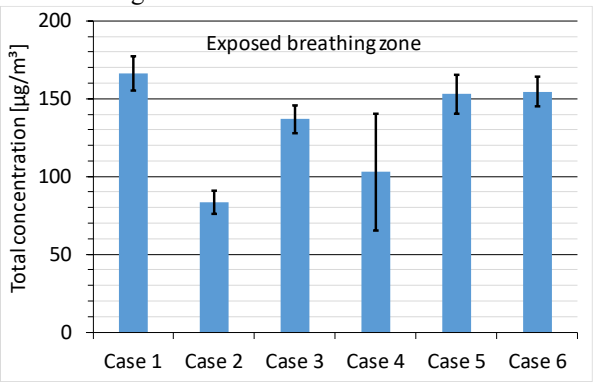

Fig. 4. Time-averaged concentration at the exposed breathing zone (AVG±SD) in the office.

According to the results, the exposure concentration was 84±7 µg/m^3 with the room air purifier and the 137±9 µg/m^3 with the personal air purifier representing namely the active protecting methods. Those results indicate that the room air purifier can reduce the average

concentration level by 50% and the personal air purifier by 20%. The noteworthy is that the given room air purifier included the HEPA-filter and the electronic sterilizer, and that the circulating airflow rate was adjusted cleaning 2.5 times the ventilation airflow rate, which increases the effective indoor air change rate significantly. Noteworthy was also that the location of personal air purifier was a key matter because the clean air jet was small compared to the room air purifier.

The passive structural protection methods had the following results. The average concentration falls with the FFP2-mask to 103±38 µg/m^3 meaning approximately 40% decrease to the exposure concentration. In this stage, the breathing of thermal manikin caused rather reasonable variation in results.

The location of infection source (Figure 5) had a low effect on concentrations under the fully mixed conditions. However, the lowest exposure was found when the infected and exposed persons were seated in the same side of table far from each other (Figure 3, LOC 4). The standard deviation, in turn, was highest near the source (LOC 5) indicating that downward air distribution can transmit aerosols workstation next to the infected person.

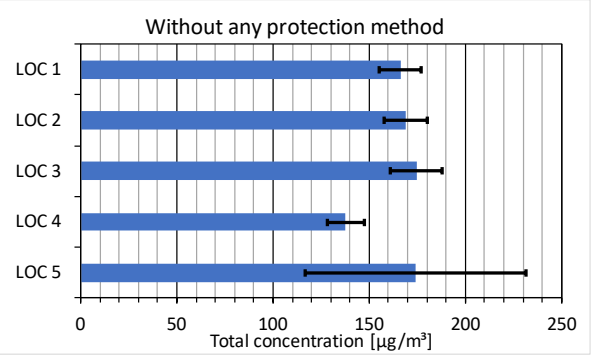

Fig. 5. Time-averaged concentration at the exposed breathing zone (AVG±SD). The locations are defined in Figure 3.

3.2 Temporal evolution

The results show that the concentration reached the steady-state conditions within an hour if there was not air cleaning device installed in the room space (Figure 6, without protection). However, the steady-state conditions were reached faster with active protection methods. For instance, the room air cleaning device caused steady conditions after half an hour of exposure (Figure 6, Room air purifier). This shows clearly how the cleaning device, and the ventilation had a combined effect on the concentration level. In the cleaning device, the circulating airflow rate was 2.5 times the ventilation rate, which means the circulation airflow of around 325 m^3/h. This covers rather well the indoor air volume of 75 m^3 under the fully mixing conditions.

3.3 Conclusions

The room air purifier and facemask reduced efficiently the exposure. The personal air purifier had moderate reduction whereas the partition panels had only minor effects on exposure. The lowest exposure was found when individuals were sitting at the same side of table, far from each other.

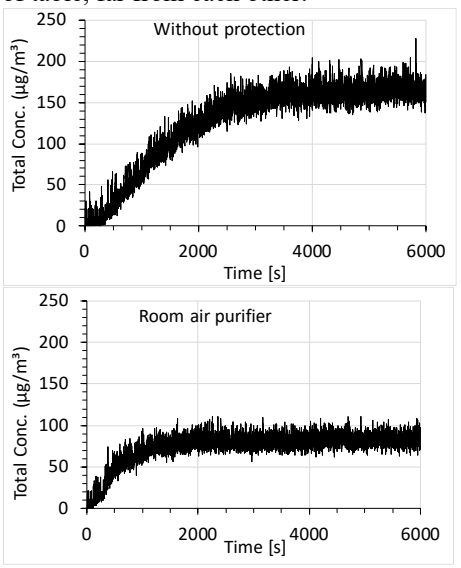

Fig. 6. Temporal evolution at the exposed breathing zone.

The authors acknowledge the Finnish Work Environment Fund (Grant No. 210099, SUOJAILMA), the Aalto University Campus & Real Estate (ACRE) and the city of Helsinki for the financial support. The authors acknowledge the Filha ry, the Finnish institute for health and welfare, and the Finnish society of indoor air quality and climate for the comments. Lifa Air Ltd is acknowledged for providing the protection solutions.

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