Preliminary testing of a simplified methodology for indoor environments evaluation correlated to airborne transmission: the case of a university classroom with vertical low-velocity ventilation

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Abstract. This work presents and tests a simplified evaluation methodology for indoor environments in relation to airborne transmission. The tests were carried out in a university classroom with vertical low-velocity ventilation. The methodology is focused on aerosols that are one of the most dangerous carriers of infectious disease being able to transport pathogens for long distances. It consists in tracing the aerosols generated through an ultrasonic emitter as well as in the correlation between their dispersion and the artificial ventilation. The methodology aims to identify the critical zone of an indoor volume and to give useful suggestions on how to improve the ventilation of the environment. The tests carried out in a university room show a negligible difference between the deposition occurred with and without ventilation, accordingly with the extremely low velocity measured. These results show that in the specific case study the actual ventilation system does not alter the propagation of small droplets in the environment and does not create critical spots, therefore it is advisable to maintain the ventilation turned ON.

1. Introduction

The airborne transmission refers to the transmission of pathogen or disease caused by the dissemination of aerosols, droplets, droplet nuclei or other viral particles by an infected human, via sneezing, coughing, speaking, which remain infectious when suspended in air over a long distance and time, and their subsequent inhalation by a susceptible individual [1,2].

From the epidemiological point of view, airborne transmission is probably the most challenging infection pathway to prevent [1], therefore the spread and the outbreaks of this kind of diseases need to be studied with a multidisciplinary approach that takes into account various factors such as the impact of indoor air environments [3].

In this work a simplified tracing methodology for airborne transmission diffusion tracing is proposed and tested in a university room. The authors of this work already filed a patent based on the proposed methodology (patent application number 102020000032021 [4]). The goal of the method is to provide relevant information about the ventilation in a specific indoor environment in relation to the distribution of infectious droplets.

Ventilation is the process of distributing and introducing outdoor or treated air into a space or a building by natural or mechanical means [3,5] and it is recognized as the most important engineering method used to control airborne transmission in indoor environments [6,1]. In mechanical ventilation, air flows are usually controlled by heating, ventilating and air conditioning systems (HVAC) taking into account health, thermal comfort and productivity goals [5,3].

There are different air distribution methods such as displacement ventilation (DV), mixing ventilation (MV), under-floor air distribution (UFAD), downward ventilation (DnV), personalized ventilation (PV) and personalized exhaust (PE) [6]. Each of these methods has pros and cons that guide their application to specific environments covering a wide range of applications from auditoriums to aircraft cabins. Different air distribution strategies lead to different influences on airborne transmission between persons in a room: e.g. PV is capable of reducing the risk of cross infection, however, the use of PV by an infected individual could be dangerous due to a higher dispersion of exhaled droplet nuclei [6].

There are various strategies that can be implemented on the ventilation systems to reduce the possibility of airborne transmission [5]. During an epidemic or a pandemic like COVID-19, air recirculation should be avoided as much as possible and, when it is not, filtration systems or ultraviolet germicidal irradiation should be applied on recirculated air [5].

Increasing the existing ventilation rates and introducing air from the outdoors can enhance ventilation effectiveness in limiting the spread of COVID-19 [5], but this particular recommendation is perhaps more controversial compared to the others.

Ai et al. [6] assert that the influence of air changes per hour on the risk of airborne transmission is not straightforward even if it is a widely used method of diluting infected exhaled air, and under specific conditions, increasing the number of air changes per hour could increases the risk of cross infection.

Furthermore, Ding et al. [7] assert that there is a strong lack of knowledge regarding the proper ventilation rate and designs that would make indoor environments, such as classrooms, reasonably safe from airborne transmission infectious diseases.

In measurement of airborne transmission, literature reports various methods including tracer gases such as N_2O and CO_2 that can be reliably used to mimic the movement of infectious aerosol droplets [6,8].

There is also the possibility of directly tracing the small droplets and aerosols emitted by one or more persons. This can be done through a combination of Schlieren imaging and multi-magnification digital inline holography, providing an instantaneous average and ensemble average flow field [9]. However, this approaches have the limitation of being quite expensive and difficult to be reproduced by not highly trained personnel.

In the presented context there is the need for simple methods that allow an assessment of the transmission mechanisms within indoor environments, that can be easily implemented in a large spectrum of applications such as the identification of critical spots or the evaluation of the possible countermeasures to be taken to improve the safety of an environment.

This work is focused especially on aerosols and droplet nuclei due to their capacity to carry viable viruses to considerable distances [2].

While large droplets follow a ballistic trajectory and fall to the ground quickly within a limited radius, as shown by the well-known Wells evaporation-falling curve [10], gravity and inertia play a weak role in the dynamics of small droplets, especially with a diameter ≤ 10 μm [2], and therefore they can travel longer distances.

The methodology proposed in this work exploits the aerosolized particles emitted by an ultrasonic emitter to properly mimic the droplet dispersion behaviour, since the the droplets generated by such devices has usually a diameter in the range of 1 - 10 μm [11,12] a size consistent with the one of typically exhaled droplets during speech or cough (diameter ≤ 20 μm) that can linger in air for more than an hour [13].

2. Methodology setup

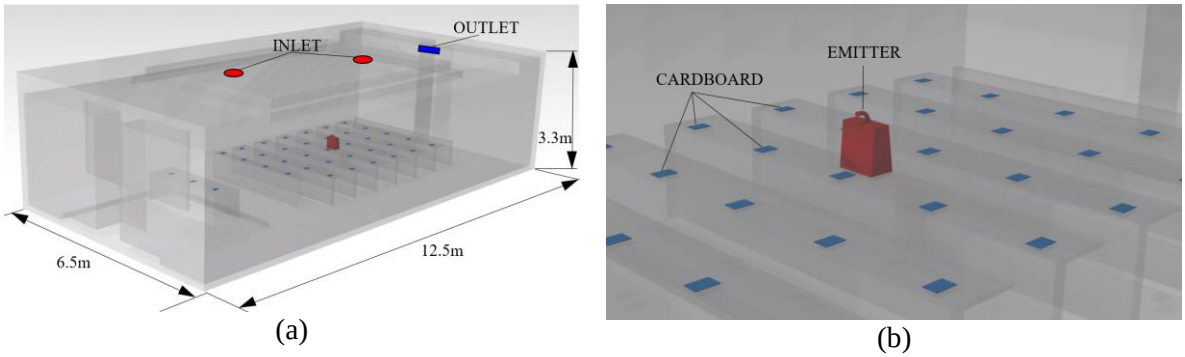
The developed methodology can be applied to various indoor volumes (e.g. a classroom) to estimate the droplet nuclei and aerosols dispersed by a single or multiple individuals and it focuses on tracing aerosols and droplet nuclei generated through an ultrasonic emitter.

The ultrasonic emitter used was the Levoit LV550HH ultrasonic humidifier. This device features an ultrasonic atomizer with frequency of operation of 1.7 MHz leading to a median diameter of the emitted aerosol droplets of about 6 μm [12], consistent with the dimension investigated in this and other works on airborne transmission. The instrument is positioned in the spot (or the spots) considered more meaningful or interesting to analyze. A hot sphere anemometer was used to measure the air velocity in the proximity of the emitter. The water tank is filled with a mixture of deionized water (98% w/w) and solid phase black pigment (2% w/w). This concentration follows the proportion between solid and liquid matter in human saliva [14]. The pigment used is the Maximum Concentrated Paste Colour "Black Extra" produced by Sugarflair Colour. The humidifier is set on emitting about 80 mL h^{-1}.

The emitter is equipped with a fan that guarantees an air flow velocity of 1 m s^{-1} at the outlet of the corrugated pipe implemented to replicate the position of a human mouth.

Such velocity is in line with the velocity of the air exhaled by a person during breathing [15].

The emitter was placed on the fourth line of the desks, in a central position. Arrays of 0.15x0.10 m white ultra-glossy inkjet cardboard (240 g m^{-2}) are positioned on the desks all around the emitter and on the professor's desk as represented in Figure 1 (a) and (b).



(a) (b)

Figure 1. Aerosol tracing operation layout: example of the positioning of the cardboards (a) and the aerosol emitter (in red) (b).

The aim is to numerically quantify the amount of aerosol and droplet nuclei deposited on the various cardboards by measuring the average variation in their color after the exposure.

To do so, the NH300 Colorimeter [16] with an aperture diameter of 8 mm was used to measure the lightness parameter L of the CIE 1976 $L \times a \times b$ colour space [17]. The lower is the lightness, the higher is the amount of pigment deposited, and therefore the aerosol and droplet nuclei that impacted the surface.

To ease the data reading, the B parameter, equal to $(1 - L)$, was considered. A calibration phase is necessary to correlate the amount of aerosol to the color of the paperboard. The calibration was performed using a laboratory scale, weighting the paperboard after a series of tests in order to make a calibration curve. Due to the possible color inhomogeneity of the paperboards, the color is measured in six places of it, and then the average is calculated. The position of the measuring spots is indicated in Figure 2.

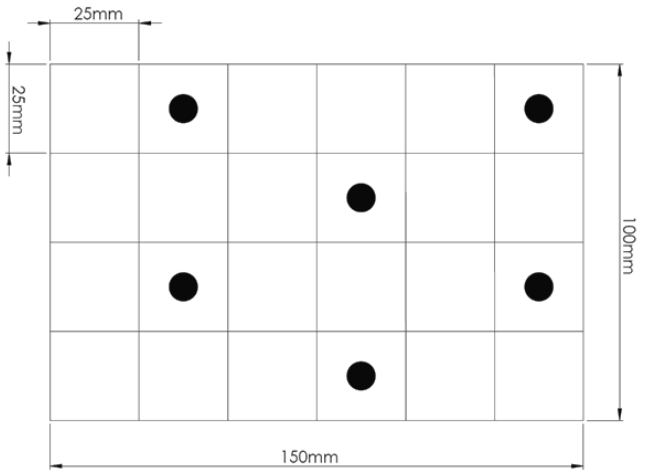
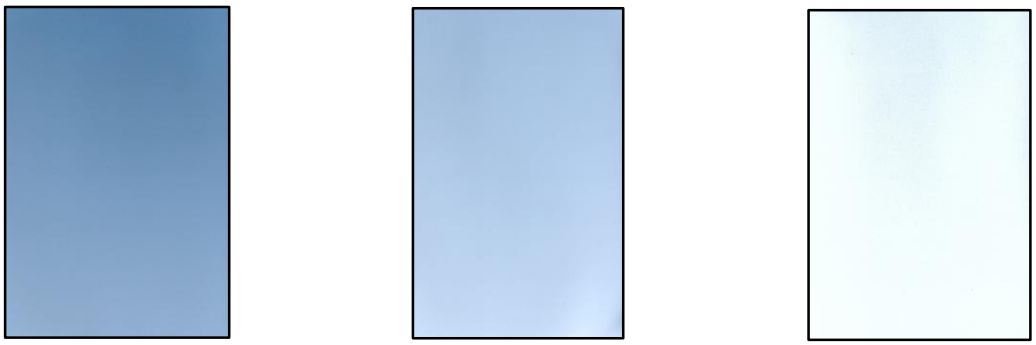


Figure 2. Color measurement spots on the paperboard

As depicted in Figure 2, every board is divided into 24 squares and the *B* parameter is measured in 6 of them. During the preliminary testing, it was ascertained that measuring 6 or 12 rather than 24 spots gives the same results as the average color of the paperboard.

The average *B* value obtained for each board was then used as the basis input for a Delaunay 2D triangulation carried out using Paraview [18] software and reported in Section 3.

The classroom ventilation is vertical low velocity ventilation with two inlet vents and one outlet vent. placed on the ceiling. The test was performed twice with the room ventilation turned off and twice with the ventilation turned on. As an example, in Figure 3 three of the cardboards used during one of the tests are shown, while in Figure 4 a magnified portion of a cardboard is reported, showing the trace dimension of the deposited droplets.



(a) (b) (c)

Figure 3. Three of the cardboards after a test. The *B* value resulted in (a) 40.2, (b) 26.3 and (c) 15.6.

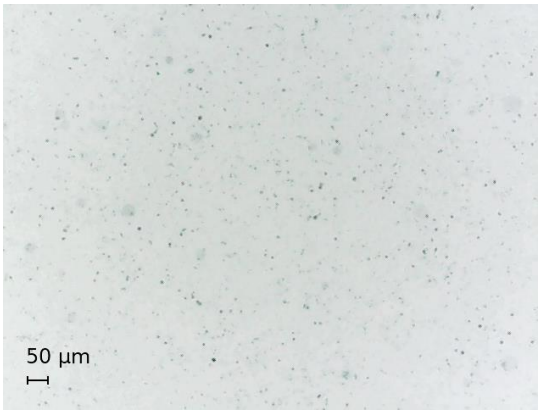


Figure 4. Portion of a cardboard under microscope magnification

As shown in Figure 4, the dimensions of the pigment marks are in the order of 10 µm.

3. Results

The tests were carried out both in the room under normal ventilation and in the room with the mechanical ventilation system turned off. Two color maps of the aerosol concentration are reported in Figure 5 where only the cardboards that presented a *B* value greater than the one of the blank cardboards were used to generate the plots.

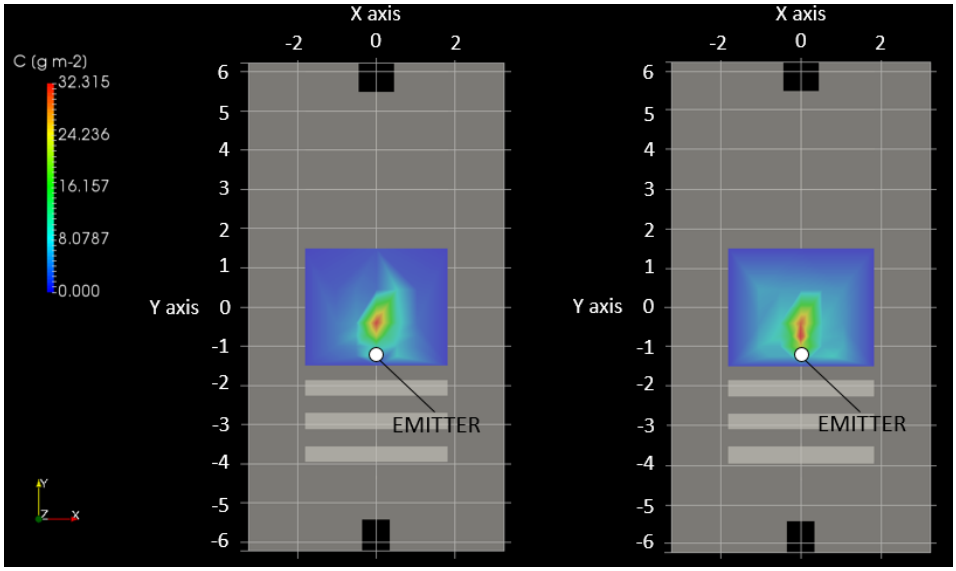


Figure 5. Color map of the deposited aerosol concentration after the test with (left) room ventilation OFF and (right) room ventilation ON.

The two color maps are similar. This can be attributed to the extremely low air velocity measured (below 0.05 m s^{-1}) with the hot sphere anemometer (Testo hot-sphere 0635 1051, with an accuracy of ± 0.03 m s^{-1} + 5% of the measured velocity [19]).

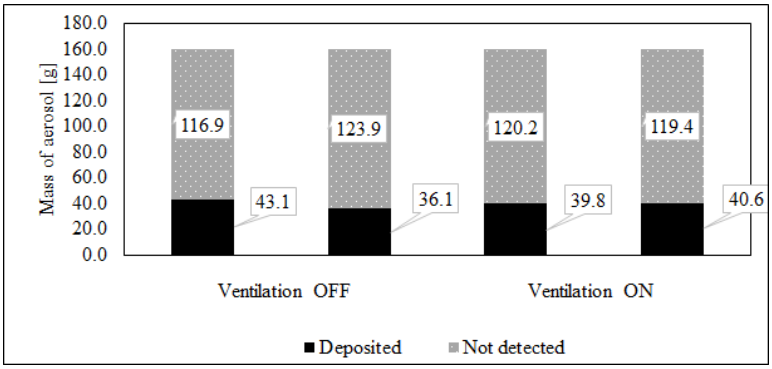


Figure 6. Representation of the mass of aerosol both deposited and not detected after the 2 tests in the classroom.

As reported in Figure 6, the fraction of the overall detected water-pigment solution ranged from 36.1 to 43.1 g after the tests in the classroom with the ventilation system OFF while it ranged between 39.8 to 40.6 g in the tests with the ventilation ON.

The not detected fraction was calculated considering the emission of 80 g h^{-1} of aerosol from the emitter outlet and considering the test length of 2 hours.

The not detected fraction represents, on the average, 67% of the total when the ventilation is OFF and 66% when the ventilation is ON.

These not detected fractions were in part removed by the ventilation system and in part settled down inside the room where there were no cardboards. In order to detect the pigment in a larger area it would be necessary to extend the test duration as well as the area covered with target cardboards.

Similarly to the color maps distribution, no appreciable differences on the aerosol deposition were observed between the two couples of tests with and without ventilation and this is again consistent with the extremely low air velocity at the height of a seated person. These results indicate that ventilation has a very little effect on the diffusion of small droplets in the considered room. Furthermore, ventilation does not create critical spots, therefore it is advisable to maintain the ventilation turned ON and, if possible, verify if increasing the extracted flow could reduce the risk of cross infection between individuals.

4. Concluding remarks

In this paper, a simplified methodology for the evaluation of indoor environment in relation to airborne transmission is presented and tested in a university classroom with vertical low-velocity ventilation. The proposed methodology has been designed to be simple and easily reproducible. The work has been used by the authors as the basis for a patent application (number 102020000032021 [4]).

While the deliverable of proposing a tool that can be easily and widely used is satisfied, the present methodology presents few limitations that need to be properly discussed.

The humidifier is designed to emit a water flow rate 16 times greater than the droplets emission rate for a standing or speaking person [20], therefore the goal of using this tool is to release a sufficient amount of particles that can be easily detected and measured rather than reproducing the same amount of droplets emitted by an individual.

This approximation can be considered consistent with a precautionary principle since in this way the measured droplets concentration is less susceptible to the dilution caused by ventilation.

At this stage, the method does not aim to numerically quantify the risk to be infected in every position of the room but to compare different situations. In the presented methodology, the thermal plumes produced by the occupant of the room were not reproduced, but due to the presence of the outlet vent near the ceiling this approximation can be considered again consistent with a precautionary principle.

Despite the limitations of the proposed solution, the tests carried out in a university room lead to important results showing how this method can lead to meaningful insights to better control the HVAC

systems. At low ventilation velocities there is a negligible difference between the amount of deposited aerosol and droplet nuclei as well as their spatial diffusion with and without ventilation. These results show that the ventilation does not modify the propagation of small droplets in the considered room and does not create critical spots.

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