Visualisation of the airflow pattern of exhaled droplets in a classroom

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Abstract. The airborne transmission of SARS-CoV-2 in educational buildings has raised concerns during the current COVID-19 pandemic. In this study, a portable fog generator system was designed and assembled to visualise the airflow pattern of exhaled droplets in a classroom. The system consists of five components: medium, fog generator, buffer, pump, and manikin head. The medium was made of glycol and demineralised water, which produced a fog composed of droplets. The fog was produced with the fog generator and passed through a pipe into the buffer for build-up. After accumulation, the fog is pumped through another pipe and is exhaled out of the mouth of the manikin. Experiments were conducted with the portable fog generator system in a simulated classroom under four different ventilation regimes: no ventilation, natural ventilation (open windows and door), mixing ventilation (600 m^3/h), and a combination of natural + mixing ventilation. The experiments were recorded with a camera and analysed to determine the horizontal distance of the path taken by the fog and to measure the time it remained visible after exhalation from the mouth. During the experiments, it could be observed with the naked eye that the glycol droplets linger in the air longer than what was captured in the recordings. Not all the droplets were visible with the camera. The recordings showed that with open windows and door (natural ventilation), the droplets travelled the furthest distance (1.8 m) and stayed the longest in the air, while with mixing and natural ventilation, the droplets travelled the shortest (0.5 m) and stayed the least time in the air. These findings confirm that mechanical mixing ventilation increases the removal of aerosols in the air. It is concluded that the portable fog generator system provides a quick method in understanding the duration and distance droplets can travel after being exhaled.

Keywords. Covid-19, SARS-CoV-2, aerosol, respiratory droplets, visualisation, laser, breathing
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1. Introduction

Since the beginning of the COVID-19 pandemic, ventilation has been recommended as a measure to reduce transmission of SARS-CoV-2 in indoor environments with a high occupancy, such as educational buildings [1]. In a study initiated by the National Ventilation Coordination Team (LCVS) in which CO_2 monitors were placed in educational buildings, the outcome showed that only 38% of the tested schools (7340 elementary and secondary schools in the Netherlands) meet the ventilation requirements from the Building Decree of 2012 [2]. Furthermore, only a third of the schools have natural ventilation, which is often inadequate to supply enough fresh air in the classroom. Controlling the temperature while the windows are open during periods of cold weather can be challenging as it has a negative effect on thermal comfort. Mechanical ventilation is an option to increase the fresh air supply, while controlling the indoor temperature. Other measures are to reduce the number of occupants, the use of air cleaning devices and/or use of facial masks.

To be able to determine whether in a certain situation additional measures are required, the aim of this study was to design and assemble a portable fog generator system to visualise the airflow pattern of aerosols produced by pupils in a classroom. This system should mimic human breath and it should be possible to apply at schools, in a classroom. To test whether this fog generator system can be applied, the system was tested in an experimental setting under different ventilation regimes.

2. Research method

2.1 The portable fog generator system

The portable fog generator system consists of five main components: medium, fog generator, buffer, pump, and manikin head. The medium was made of glycol and demineralised water (9:1 ratio). The medium was put inside the container of the fog generator. The fog was produced with the fog generator and passed through a pipe into the buffer for accumulation. The lid of the buffer had to be airtight to prevent leaks. After the built-up, the fog is transferred from the buffer to the mouth of the manikin with a manual pump. The final setup can be seen in Figure 1.

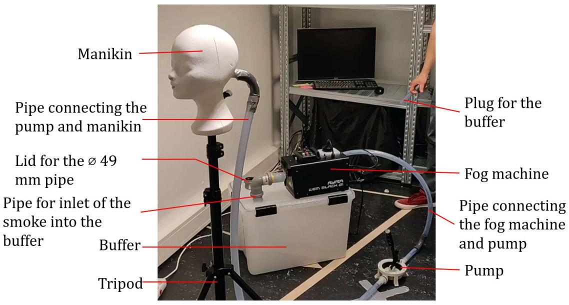

Fig. 1 – Setup of the portable fog generator.

2.2 Ventilation regimes

Four ventilation regimes were applied to visualise how the glycol droplets disperse after exhalation: no ventilation, natural ventilation with windows and door open, mixing ventilation with a ventilation rate of 600 m^3/h and the combination of natural + mixing ventilation. An overview is shown in Figure 2. Two data loggers were placed in the room to examine if the basic indoor parameters deviated too much during the experiment between each attempt and the different ventilation regimes. The baseline measurements (including the air velocity) were measured with the Dantec ComfortSense monitor and HOBO MX1102 data loggers at different locations throughout the Experience room of the SenseLab [3].

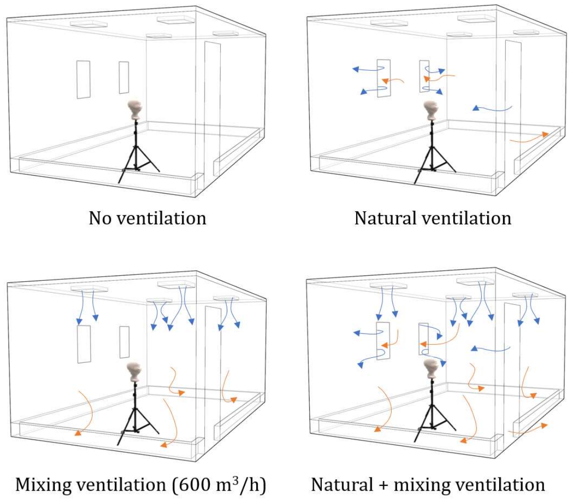

Fig. 2 - Four tested ventilation regimes. The blue arrows indicate air being supplied to the room. The orange arrows are for the air leaving the Experience room.

2.3 Setup for the airflow pattern visualisation

The experiments were conducted in the Experience room of the SenseLab, which is an experimental room decorated as a classroom with the possibility to adjust the indoor environmental conditions. The manikin head was placed at the back of the Experience room (see Figure 3). Five lasers (Huepar BOX-1G) were put on the table, facing towards the ceiling. Another laser was placed at the end of the table. The distances between the manikin's mouth to the lasers were measured with a measuring tape and written on the table. The lights of the room were turned off during the experiment to increase the effect of the lasers. The visualisation of the fog was recorded with a mirrorless camera (E-M10 Mark II) with a wide-angle lens (Lumix G Vario 7-14mm f/4.0 ASPH). Two attempts were taken for each ventilation regime. Each attempt was one minute long. To mimic the respiratory system as realistic possible, the operator based the pumping movement on its breathing. This resulted in 15 breaths per minute.

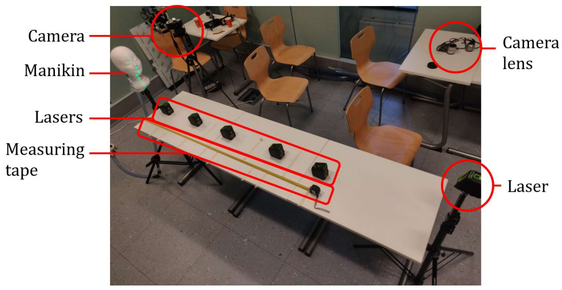

Fig. 3 – Setup of the airflow pattern visualisation experiment.

2.4 Data analysis

The attempts were recorded and reviewed to determine how far the droplets travel in the air, how long it takes before they are no longer visible and the percentage of fog plume visible after each exhalation.

The program VLC was used to review the recordings frame by frame. When the droplets do not progress more than a certain distance after a single exhalation, it is noted as the furthest distance. The duration was measured by how long it took before the droplets were no longer visible in the recording. It was observed with the naked eye that the glycol droplets linger in the air longer than what was captured by the recordings. Therefore, it was decided to time that as well with a stopwatch. To quantify the percentages of the droplets detected by the laser per respiratory cycle an image processing program (named Fiji) was used. The subtraction method was applied to compare each frame with the frame before exhaling the fog plume. This method results in a frame showing only the droplets (depicted in grey/white pixels). The program assigns a value between 0–100% for each frame, depending on the amount of non-black pixels. The mean grey intensity can be computed by summing the grey values of all the pixels in the selection divided by the number of pixels.

3. Results

3.1 Travel distance of glycol droplets

The measurement results of the droplet distances are shown in Figure 4. The corresponding frames of the video which were used to determine the distance can be found in the appendix. The droplets reached a distance of 1.3 metres without any ventilation. By opening the windows and door in the natural ventilation regime, a distance of 1.8 metres was recorded. Applying only mechanical ventilation in the mixing ventilation regime made the droplets travel 0.9 metres. The droplets reached the shortest distance of 0.5 metres in the natural + mixing ventilation regime.

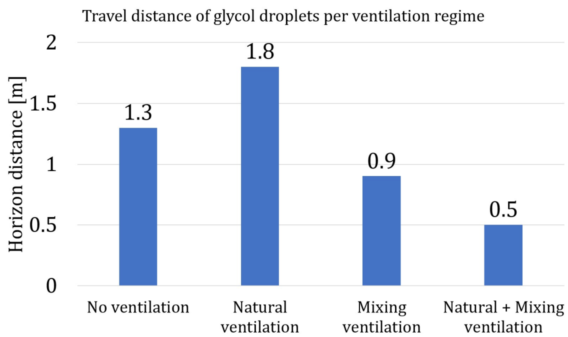

Fig. 4 – The droplets travelled furthest with natural ventilation (1.8 metres) and shortest with natural + mixing ventilation (0.5 metres).

3.2 Visibility time of glycol droplets

Figure 5 presents the time that the glycol droplets were visible for the different ventilation regimes. In the 'no ventilation' regime, the droplets remained suspended in the air for 12.7 seconds according to the video recordings and 15.5 seconds by personal observation. It was observed that the fog plume in the natural ventilation regime was less concentrated than in the no ventilation regime. The droplets lingered in the air for 12.2 seconds according to the video recordings and 13.8 seconds visually. In the only mixing ventilation regime, the fog plume seemed less concentrated and dissipated in both horizontal and vertical directions. It was visible for 9.5 seconds in the video recordings and 11.2 seconds in person. The fog plume disappeared the fastest during the natural + mixing ventilation regime. The droplets travelled upwards and spread even faster when it nearly reached the ceiling, with a lingering time of 5.4 seconds in the video recordings and 7.2 seconds visually.

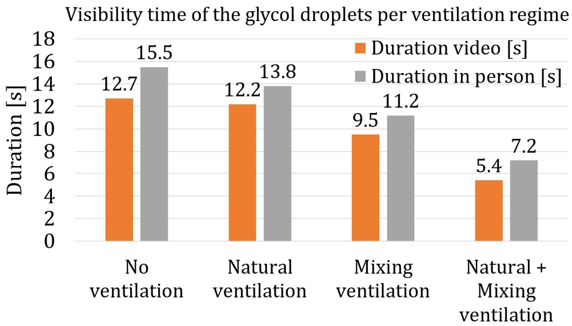

Fig. 5 – The droplets settled or evaporated faster in the recordings than with the naked eye. Increasing the indoor air velocity decreases the visibility of the droplets.

3.3 Percentage of fog plume

Figure 6 presents the mean grey intensity over time, the percentage of fog plume per frame calculated with Fiji. The analysed images with only the fog plumes consisted of almost only black pixels. This resulted in a low mean grey intensity value. The peak and valley in the graph indicate exhalation and inhalation, respectively. The mean grey intensity starts to decrease at t=50s for all ventilation regimes. This is because the amount of fog in the buffer decreased during each exhalation. The natural + mixing ventilation regime had the lowest average mean grey intensity value (0.74%). The fog plume was immediately dispersed by the high air velocity caused by the open door, windows and the presence of mechanical ventilation. Therefore, the majority of the droplets were not detected by the laser. The average mean grey intensity of no ventilation and natural ventilation was 0.86% and 0.90%, respectively. More droplets were detected by the laser in the natural ventilation regime because it passes a longer distance than with no ventilation. The mixing ventilation regime had the highest value (1.22%). The fog plume was mainly dispersed horizontally, causing the total concentration of droplets per exhalation to spread out even more, thus making it easier for the lasers to visualise the droplets.

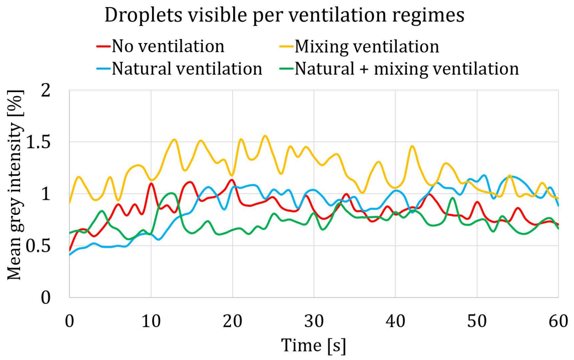

Fig. 6 – The respiratory cycle is represented in the graph with peaks and valleys.

4. Discussion and conclusions

4.1 The portable fog generator

The visualisations of the portable fog generator system provided a quick method in understanding the duration and distance the droplets travel before they settle down. Visualisation studies mostly occurred in hospitals or dental clinics, of which the results were reviewed with numerical studies [8-11]. Others used a more practical approach to examine how well for example face masks obstruct the respiratory jets [12-13]

The reliability of the portable fog generator system may be constrained by the fact that it needs to be manually operated. This results in inconsistent outcomes as it depends on the skill of the operator to use the pump. Although the essence of the airflow pattern of the droplets was recorded in the recordings, we were unable to record all of the exhaled fog plumes. The camera cannot capture single droplets, only clouds of multiple droplets. This makes it impossible to determine the actual droplet sizes from the recordings. The same applies to estimating the time it took for the droplets to evaporate or disappear in the video. Also, timing the experiment with the stopwatch likely caused inaccuracy in time measurements due to human reaction time to mainly start and stop the stopwatch.

4.2 Ventilation and lifespan of the droplets

The chances of getting infected with diseases through airborne transmission are especially high in low ventilation enclosed environments. In such environments, respiratory droplets immediately shrink after exhalation and become droplet nuclei. The majority of the respiratory droplets are smaller than 75 μm and according to Stokes' law, droplets of these sizes can linger in the air from a few seconds to many hours in rooms with low indoor air velocity while holding viable infectious viruses [4]. The results of the airflow pattern visualisation show that the droplets can reach much further than the 1.5 metres guidelines in natural ventilation (1.8 metres). Simultaneously, the droplets lingered the longest in the air. Unfortunately, a third of the Dutch schools only have this type of ventilation, which is often not sufficient to provide adequate indoor air quality for the whole school day [2]. Various research has shown the importance of adequate ventilation in rooms with a high occupancy [5-7].

The findings from this study suggest that there is a correlation between the lifespan and the airflow pattern of droplets under different ventilation regimes. The results showed that the exhaled droplets from the portable fog generator system tend to reach a shorter distance from the source when the airflow pattern becomes more turbulent (characterised by chaotic movements and contains swirling regions), which is visible in the recordings, and the mean grey intensities calculated.

In conclusion, this research contributed to the understanding of how the aerosols and droplets disperse after exhalation under different ventilation regimes. Firstly, it provides awareness and gives direct feedback on the effect of how droplets disperse at different ventilation regimes. Secondly, the fact that the setup is portable creates the convenience of taking it anywhere to visualise the airflow pattern of the droplets. Thirdly, the materials are accessible everywhere and relatively easy to assemble.

5. Acknowledgement

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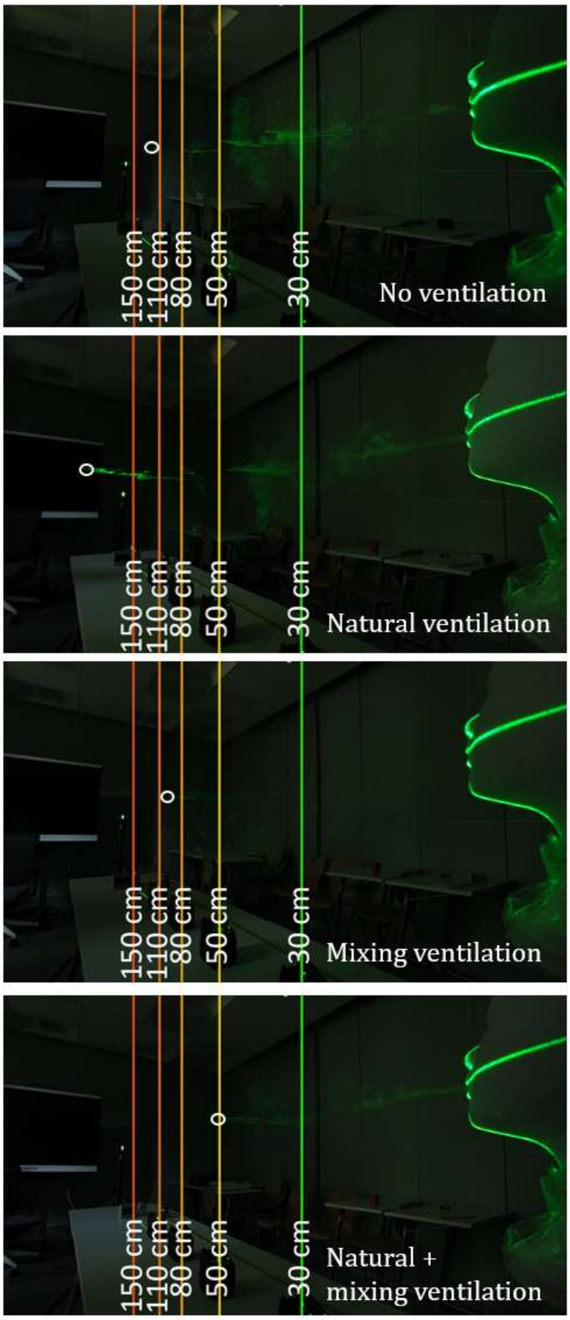
6. Appendix

Video frame of the maximum travel distance of glycol droplets per ventilation regime



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Data Statement

The datasets generated during and/or analysed during the current study are available in the TU Delft Research Repository, http://resolver.tudelft.nl/uuid:73d08938-da05-47c7-89c1-0a497ab990ad.