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Airflow visualization and air purifier positioning optimization in potentially COVID-19 contaminated classrooms

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Abstract

Given the pandemic infection risk in classrooms and given the potential to purify COVID-19 prone air, this research team has visualized the flow of air to find the optimal position in a room. Through Schlieren imaging the air flow was studied to establish the circulation in the tested room. With a variation of air purifier positions in a model classroom, the imaging sensors have taken profiles of airflow and therefore contributed to identifying the optimal placings in heated classrooms. Given a random position of a potentially infected and COVID-19 infectious person, the systematic research measured concentrations of artificially produced particles that emulated aerosol distributions. The research established contaminations stabilizing after a quarter of an hour. The concentrations are only a fraction of the emitted effluents. In this way, the risk of superspreading can be mitigated and so the results allow continued academic work during the Corona pandemic

Context, Occasion

The SarsCov2 pandemic, which was declared on 07 March 2020 by UN's World Health Organization WHO has not only cost the lives of millions within a year, but affected millions more in their health, income, or general life [1]. What does the appearance of the COVID-19 virus teach us about life after the pandemic? As a consequence, amongst many aftermaths, younger generations in Universities and schools were affected in their learning opportunities, while the worldwide crisis would actually require qualifying them more profoundly for an undetermined future after the pandemic. On December 31st 2019, the World Health Organization WHO reported the appearance of this unknown COVID-19 virus, which triggered medical researchers identifying chains of infection. Already initially and based on other viral epidemics, schools and universities were suspected replicating the viral infection by contact, droplets and aerosols, by March 2020, research suggested the infection through exhaled aerosols as being the most pertinent [1]. The suspicion of a sociable youth multiplying the virus in schools and university was seen logically as a health risk, especially in the 5-10% rare superspreaders [2].

Universities and schools were affected by these precautions significantly in their teaching and learning function. For instance, the Berlin Senate for Education and research issued instructions to air out classrooms or revert to online teaching. Background is that especially indoor meetings of teachers and students pose a risk, because of aerosols accumulate the longer infectious person are indoor [3]. The already established distance of over two meters between persons prevents droplet transmission, but the finer droplets between 0,1 and 5 µm can accumulate in the area volumes where people breathe. An infected student or teacher would therefore represent a risk for the teaching / learning community, especially inside closed rooms.

In this way, preventative measures lead either to students being far from teachers or sitting in cold classrooms during cold or hot seasons with open windows with jackets on, taking notes with cold hands and ears.

During the first lockdown in spring 2020, effects of the distance learning could be observed. While the general approach to distance learning through video / online teaching seems fashionable, on a second glance it should be observed more critically. In the absence of the direct teacher / student contact isn't learning limited to information acquisition? To what degree teaching learning can enable deeper grasping of topics under the pandemic restrictions, is questionable. On the other hand, what risk is acceptable putting children and teachers in classrooms? While preventing the epidemics of course is of highest importance if not condition-sine-qua-non, wouldn't it be of high importance to return to presence classroom work as early as safety is sufficiently high?

In sight of this, during September 2020 the idea emerged in context of project management lecture to clean the air in a classroom. Through air purification -or in other words- mechanical filtering the risk is to be reduced, and its effectiveness studied here. During the final writings of this article in Mid December 2020, first reports about mutations of the original wild type COVID-19 virus were reported. Only after the presentation of this research at the EI2021 on 19 January medical, scientists established a 35% higher infectiousness [4]. This higher infectiosness does not hamper the qualitative findings, but requires a higher quantitative response, which is discussed in the conclusion chapter.

Established knowledge

Daily, humans ingest 0,8 to 1,5 kg solid foods, 1,5 to 3 kg liquids but inhale also 20 to 30 kg air [5]. The inhaled air of up to 30 kg weight daily corresponds to some 0,2 m³ in quarter an hour or less than 1 m³/hr. If in this ongoing pandemic a student, teacher or other attendant of a lecture talks loudly, which is often the case, significant amounts of aerosol partles are emmitted into a lecture hall. Aerosols from a COVID-19 infectious person generally float through the room with a general downward tendency of 3mm/sec [6] and rises above humans. The Massachusetts Medical Society published Dr. van Doremalen's research establishing the half time of COVID-19 aerosol being 1,1 hours [7], meaning that half of the aerosol is not infectious after a bit more than an hour. Already before the pandemic, Asadi determined the aerosol droplet size distribution and found the majority exhaled during speech at a particle size of 1 µm with 2 particles per second and with 0,15 particles/cm³ [8]. Citing the research of Shaman et. al, one finding was "evaporative drying of 1-micron diameter droplets " can take place "in the order of 100 milliseconds". Especially in dry environment aerosols evaporate and expose the virus leading to an inactivation of the virus, which in other words reduces the infection risk. Moist, and body-warm exhaled air contains a whole spectrum of particles including aerosols in a size from 0,1 to 20 µm. The highest proportion of this spectrum is between 0,1 and 1 µm [9] [10]. If these particles carry virus of a size between 0.003 and 0.05 µm, a person next to them might inhale the contagious air and could get infected if the minimum virus load is exceeded. This leads to an indoor risk calculated in [8]. Based on these probability estimations for the wildtype virus, the infection risk for 10 persons in a 155 m³ room in a four-hour period, amounts to 12%. Given the groundwork above, this research aims at breaking the chain of infection.

Filtering

On August 5th 2020, Prof. Kähler and his team reported on their research of effects by purifying devices and found the devices in position to half the concentration the latest within 12 minutes with a room air exchange rate of 5hr-1 [9]. In his article, Kähler and his team of the military university in Munich experimented with filling a 200 m³ (80 m²) room with Dioctyl sebacate (DEHS) and pumping the room air through a filter of the H14 Standard according to the European standard EN1822 with a throughput that amounts to multiple of the room volume in an hour. The parameters were set to three, five and 7,5 times per hour and the direction of the purified air was nearly vertically up fore- and backward. With a similar approach the Goethe University Frankfurt came to the conclusion that air purifiers according to the H13 or H14 standard and an Air Change per Hour (ACH) of six room's volumes hourly [13].

That research went on to study purifiers that work on the physical principle of ionized air, where virus is inactivated at contact [10] and based on surgical theatres, Prof. Kählers research suggested H14 filtering. Consitently, with an ACH=5,7 h^{-1} it was found in Frankfurt that aerosols were sufficiently removed from classrooms [11].

Another solution presented by the Max Planck Institute for Chemistry in Mainz of suction of air outside classrooms was presented in the International Journal of Environmental Research and Public Health on 31. October 2020 [12]. considered in September but rejected for several reasons. Firstly, pumping the air out of lecture halls requires openings in the windows that are not trivial to build or impossible altogether. Secondly the energy of a heated classroom atmosphere is "blown out of the window" or lost in other words. This might even still be acceptable, but the research assumes that exhaled air rises and can be absorbed above a given classroom. The last argument needs to be seen in context of aerosols sinking with the most 3 mm per second without thermal induction, as the RWTH university reports [6]. Despite the upward sucktion and air drift, there is a significant risk that the contaminated air is aspired because not all COVID-19 aerosol is removed.

This suggestion above needs also to be seen critically in light of the research shown assembled by Detlef Lohse [13], who describes the fluid dynamic aerosol transmission from one person to another as a turbulent dispersive multiphase flow. A human with some seventy to hundred Watt thermal power will create an uplift air stream above the human yes, but many other streams prevail in a room due to heating, speaking, moving or coughing, which are complex, if not chaotic in an undisturbed room [14].

In contrast to relatively high ACH of at least six per hour, and transferring theoretically from α spread in Kindergartens, [6] concluded that much lower ACH would already reduce the infection risk to more acceptable levels. This circumstance rendered filtering more interesting because of much lower purifier cost.

While surgical theatres would require an air exchange rate of 18 times the room's volume, an at least six-fold rate would significantly reduce the infection risk. This recommendation was based on the required time duration, to remove the test aerosol from a once loaded room, in contrast to a continuously contaminated room, when a infectious person keeps exhaling.

Furthermore, this save assumption needs to be seen in terms of feasibility and airflow in lecture halls or classrooms. In both research, Prof. Kähler's institute for fluid mechanics and aerodynamics have contributed significantly to better understanding effects of filters in rooms. However, in both experimental setups, the COVID-19 contamination was modelled in a one-off load with particles. Indeed, this allows an evaluation of the filter's effect because the experiments measured the drop of particle contamination in several positions in the room, i.e. vis-à-vis the purifier(s).

In contrast to the previously mentioned research, this study looked at the more realistic case of a COVID-19 positive person sitting in a room, where that subject continuously contaminates the room over time. With a purifier of a given throughput, a balance is achieved between the exhaled and contaminated air volumes and the air that is purified. Furthermore, the position and attitude of the purified air-jet determines, which part of the room benefits from a purifier to what extent. Therefore, this research studied in a complementary fashion the purifier's outcome on particle concentrations in relation to a continuous contamination.

The aim to have students and pupils back in class with the necessity of effectively protecting the attendants of classes was the initial point of research, but puts a lot of responsibility on the design. It is imperative to achieve the highest possible safety, so that people in the education system develop confidence. That can only be attained by evidence based careful considerations of the risks. Given the need to prevent potentially infected persons inhaling the contaminated exhaled breath of a COVID-19 positive person, several principles were studied.

Theoretical considerations

While meeting people outside in the open air is 18 times less dangerous, exhaled breath of an infectious person indoor can accumulate above and around contagious concentrations and contaminate other persons.

Four assumptions led the experiments and this research altogether. The first assumption is made that the forced airflow is diluting any particles and aerosol in a room. Diluting only helps over a short time but needs to be followed by removing aerosol swiftly enough. Diluting and dispersing also prolongs the time period that oral fluid droplets "….disappear from the window of view with time constants in the range of 8 to 14 min, which corresponds to droplet nuclei of ca. 4 µm diameter, or 12 to 21 µm droplets prior to dehydration" as Stadnytskyi found [16]. Here it is assumed that the virions lose their degree of infectioness within minutes. Second assumption is that most aerosol is filtered away to that extend that the concentration or virus load remains below the 500 to 2000 virus that a person inhales at a given position, which would be necessary to probably infect a person. As described in chapter 6.1, a second research was performed in parallel finding the studied filter being 99,97% effective. (2021 Pfeiffer et.al.: “Optical determination of filter effectiveness in potentially aerosol contaminated filter during COVID-19 pandemic”) A third assumption is that aerosol movements through the room with a purifier can be emulated by smoke, which in turn can be visualized. The fourth assumption is that the purified air blown into a classroom displaces the potentially contaminated air. Such contaminated air is eventually pushed towards the filter, where it is filtered clean. If sufficient air is filtered per time in relation to the contaminating rate, then infections get prevented effectively.

Hereby a person has a throughput of about two cubic meter per hour. In the studied room of 155 m³ this amounts to some one and a half percent. Multiplied by the number of persons in the room, the exhaled volume with potentially infectious aerosol could accumulate at a person’s location and take a proportion significant to infectious levels. In a non-ventilated room aerosol might rise initially above the warmer human bodies of 37°C but settles over time and distance. Because generally aerosol tends to sink, the lower strata of the room fill and accumulate aerosol. The purifier, however, sets the room’s air volume is in motion stabilizing in a circulation after a while, also utilizing the rooms volumes below the ceiling. Therefore, this research aims at finding the best position, so that the stabilized circulation in the room pushes potentially contaminated room back towards the purifier.

With a purifier blowing from a given position in the room $(x \quad y \quad z)$ in a particular direction with an elevation angle α and an azimuth angled β $(\alpha \quad \beta)$, the jet influences the entire room. After some initial blowing, a circulation stabilizes involving a proportion of the room’s volume. However, once the stream finds a wall, deflection sets in rendering the circulation more complex. How the stream changes, once it finds a table, beamer or a person is a more multifaceted issue, depending to a large degree on the room’s geometry. That question is here only researched in so far as the entire room, or the largest part of the room is involved, so that any present aerosol is filtered soonest. In the very case of the experiments reported about here, a simple cubic room geometry was chosen. One condition is however, that an already filtered stream should not be filtered again too soon but displace air volumes that have not been filtered after being potentially contaminated.

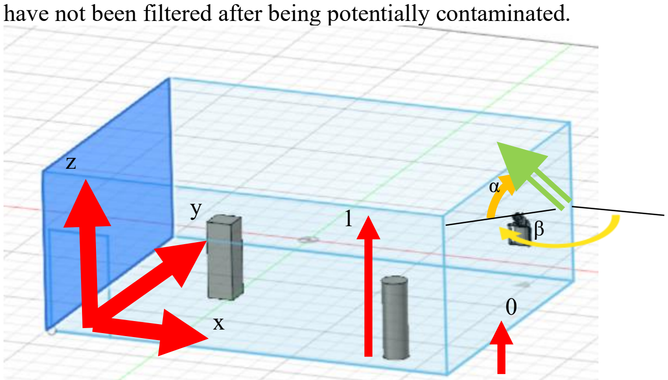

***Figure 1**: Coordinate system and labels of angles. Distances in meters [m] angles in [°] at the example of a “diagonal” setting. Levels zero (L0: z=0,9m) and (L1: z=2,8m) are marked.*

To maximize the effect in the way described in this paragraph, the purifier needs to be positioned and given the most useful attitude in terms of reducing a COVID-19 propagation. How effective a position / attitude is, depends on a whole set of parameters, like position $(x \quad y \quad z)$, attitude $(\alpha \quad \beta)$, the cross section A and flow speed v , which corresponds to a volumetric flow rate equivalent to ACH.

Methodology

This article aims at optimizing the purifier positioning in a room with a given geometry. However, the necessary condition of the purifier working effectively is its filtering function. Therefore, and as discussed in chapter 4, besides the optimal filter positioning in a room treated here, it is important to establish the degree to which a filtering system effectively removes particles from an air stream. That is done in an adjacent research that concluded that more than 99,97% of particles with a 0,3 µm size are removed. A choice of positions in the room was tested, relevant to the typical frontal setting in a lecture hall with standing teaching staff and sitting students. In distinction to commercial machines and existing research, an elevation angle α was tested of 60° and compared to 90°. In this way, the assumption was tested that with α=60° a wider air circulation in the room is more effective and reduced dwell times of aerosols.

Smoke shadow imaging

Smoke generated by incense sticks was utilized to visualize the air streams and qualitatively understand the patterns in the lecture hall. This easier method served preparing the more labor intensive Schlieren Imaging. Since the air stream in the room is deviated or reflected on walls or any obstacles like a ceiling mounted beamer, the corners were chosen. By emulating, tracing and visualizing the path followed by classroom’s air in the presence of the air purifier’s air stream. In horizontal direction, observations made while observing the deflection of a candle flame in the classroom with the presence of an air purifier were fed as input for deciding the points of interest. These were mostly along the wall and in the corners, because the air stream turns around. The smoke from an incense stick was used to trace the path of air in working conditions.

Though the ambient air and smoke from the incense stick have different densities, as discussed in chapter 4, the path traced by both fluids in this phenomenon is comparable and indicatively helps in visualization and mapping of flow patterns in complex room geometries.

Schlieren Imaging

To visualize the ambient air flow direction in the presence of an air purifier, density differences needed to be utilized. Schlieren imaging is visualizing density variations in a transparent medium was one of the main considerations for this research. The smoke from the incense stick helped track the flow of ambient air qualitatively. The incense stick smoke being similar in density to ambient air, helped to observe the ambient air flow as it follows the general air flow.

In addition, the Schlieren optical visualization technique, however, produces a neutral image easily-interpretable image of refractive-index gradient fields. The Schlieren system provides a method to viewing the flow through the transparent media [21]. As Vasilev describes, “the inhomogeneity is visualized by means of viewing a diaphragm causing a phase or amplitude change in a part of the light beam, which result in a redistribution of the illumination in the image plane” Invalid source specified. This optical visualization photography made it possible to capture the incense stick smoke flow direction in the presence of an air purifier. Schlieren technique is based on imaging light reflects by using a concave mirror in two focal length's distance.

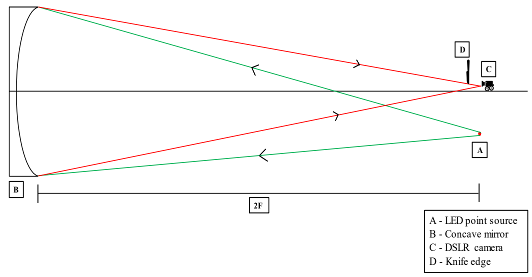

***Figure 2**: A typical Schlieren concept with the mirror left and the light source and camera opposite.*

A typical Schlieren of a plane perpendicular to the image axis the assembly consists of a concave mirror, a point light source, a knife edge and a camera (Fig 2). The system was set-up by initially arranging the components as shown in figure 1 and then carefully adjusting the position of each component for optimal results. The LED light was carefully positioned as to obtain perfect alignment and a distance two times the focal length of the mirror i.e., at a distance of 150 mm. The concave mirrors are of 200 mm diameter and a 1000 mm focal length, normally used in astronomic telescopes. Two mirrors were used to picture two planes in one setting, as is visualized on the image below.
The smaller the light source, the more sensitive the whole arrangement and hence better imaging. For this reason, this research group opted for an LED point light source placed laterally of the main axis. A knife edge was placed right in front of the camera to block out a portion of the light to increase contrast. The major reason for this is that in flows of varying densities, there is imperfect focusing of the distorted beam, and portion that has been focused in an area covered by the knife edge is blocked. [21].
This results in contrasting dark and light patches aiding in better flow visualization, as can be seen in fig. 3 below.

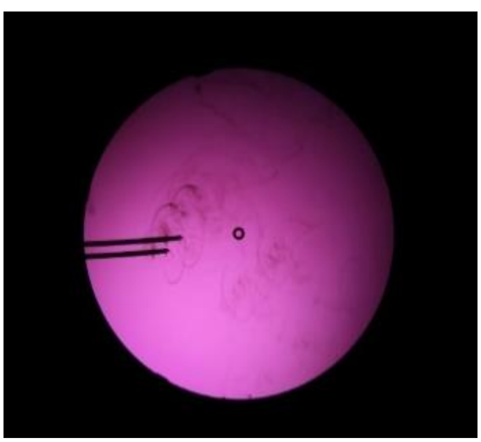

***Figure 3**: Result of using color filter instead of a knife in Schlieren imaging.*

A knife edge can be replaced by a color filter in the Schlieren system which assists in better flow visualization. A colored filter was used in one of the directions on the frame, which resulted in the following Schlieren imaging. This variation of classical Schlieren yielded better visualization of the flow. The objective behind using Schlieren imaging for this experiment was visualizing the three dimensional air flow along all three planes (x&y ; z&y ; z&x). For this purpose, the research group constructed a frame that is visualized in the tested room.

Particle counting

The particle counting experiment aims at finding out the optimal purifier position vis-à-vis a continuously emitting smoke source modeling a contaminating person. A commercial particle counter or laser-egg was utilized to measure the particle concentration. The particle counter from the Origins/Kaitera brand can measure particles in the PM 2,5 category with [µg/m³ air] and in a second mode in particles per 0,1 liter of that particle size above 2,5 µm and above 0,3 µm [21]. To emulate the contamination of an imaginary infectious person producing exhaled volume from a position in the room, incense sticks were lit that produced smoke. The produced particles of 2,5 µm size were used as an indicator for the relevant part of the aerosol size spectrum. This is eight times larger than the assumed COVID-19 aerosol particle size, but the similarity in its behavior is plausible. Each particle counting measurement with the small movable counter in a position of interest was done vis-à-vis the purifier's the contaminant's position long enough to observe constant concentrations.
Three main criteria served in evaluating the particle concentrations. Firstly, the time elapsing after the incense started and the particle concentration rises indicates the free time, before the contamination of one person reaches another. Secondly, the top particle concentration was noted for each setting. That top value was reached typically after a quarter of an hour and settled thereafter. Thirdly, to compare two settings thirdly, the integrative difference was calculated. Since the infection risk rises not only with the concentration, but also with the duration of the exposure, the product of the two variables was taken. This dosis equivalent, that a person is exposed to, should remain below the D50 [12].

Observation and results

The qualitative smoke experiments determined where the Schlieren images should be taken of the flow and the particle counting observations enhanced quantitatively the observations.

Smoke and Schlieren experiments

The smoke images in the fifteen points depicted the flows in three planes and allowed to visualize the airflow under the blower's influence as shown below. The circulation is induced by the upward elevated outflow of the purifier, that returns towards the purifier lower:

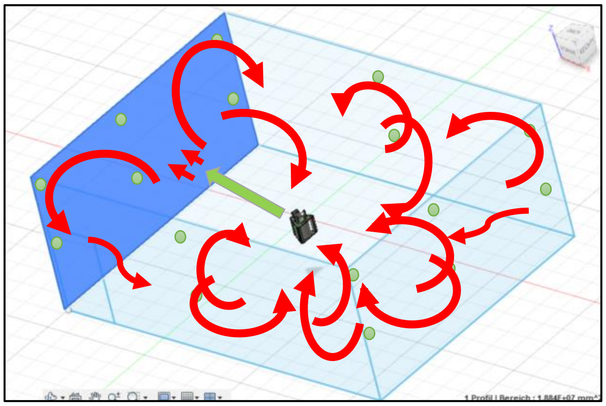

Figure 4: Summary of all smoke observations indicating that the forward circulation dominates and the flow of cleaned air is reflected at the ceiling and flows towards the center on lower levels.

Schlieren

Following a first coarse determination of the airflow by smoke observation, images of the finer density variations were made visible by the 42 Schlieren images in three planes. Sparing the reader from these details, one exemplified coordinate shall be reported about here.

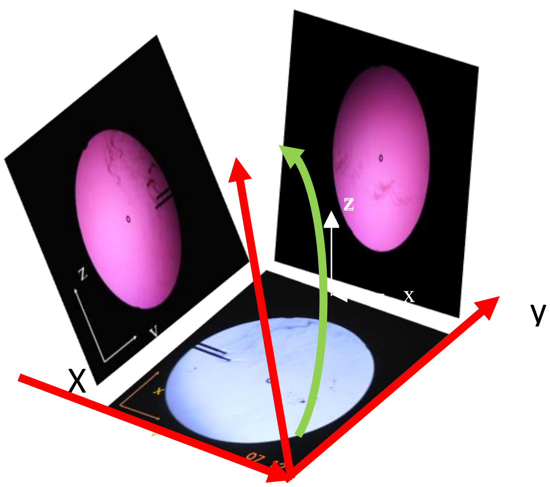

***Figure 5**: Schlieren Images 3 planes at Point F0= (■(7,8, 0,5, 0,9)) with the observed main stream depicted with the green arrow.*

The image above places the three Schlieren images that were taken in the right corner of the studied room in the corresponding coordinate system's position in the lower of the studied layers F0= (7,8 0,5 0,9). The purifier's setup can be described with the matrices: Pc= (5,1 3 1,3)(60 180), expressing a rear/central position amongst imaginary students and the blower's outflow being elevated to 60° and pointing towards the teacher. In this situation, the Schlieren images indicate that the purifier induces an airflow in the room that reflects at the walls. In corners, including in the upper corners, the airflow gets turbulent suggesting that the aerosols assemble there or turn around. That finding might play a role why high lecture halls bear less risk for attendants reaching the necessary infective dose.

Particle counting experiments

A selection of three experimental findings shall be presented here. Firstly, we studied the influence of the elevation angle and secondly the outcome of diagonal and frontal orientations.

Elevation

The research group designed the purifier with an elevation α=60° with the assumption that it would more effectively reach the opposite side of the room. Therefore, vertical blowing was tested versus the 60° forward blowing.

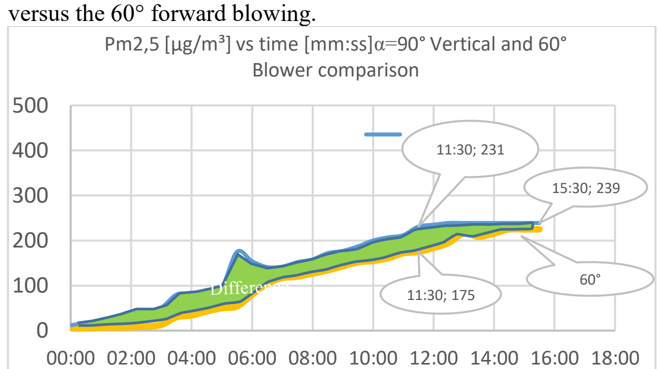

***Diagram 1:** Particle concentration over time with the variation of the elevation α angle. The lower orange line is the record of the particle concentration with a 60° elevation. The particle concentrations settle with 225 after some 14 minutes. The upper blue line represents the blower directed to the ceiling α=90° and saturates at 239 µg/m³.*

In order to perform this experiment, the blower was positioned in (5,0 3,0 1.3) and the contaminator on the left at (5,0 4,7 1,3) and measured on the opposite right side. In one setting with the elevation of α=90° the blower directed the clean air stream straight to the ceiling. In fact, this proved to be less effective as the diagram above illustrates:

The infection risk of the equivalent to the contaminating concentration multiplied with the exposition time, the integrate serves in evaluating with the result of the 60° forward blowing angle is superior. Comparing the two runs in diagram 1, the advantage is obvious. The 60° forward blowing purifier achieves a 27% integrative advantage over the blower that is directed towards the ceiling.

Diagonal

Aiming at orientating the purifier parallel to the longest axis of a room seems justified and suggests placing the purifier in one corner. This case was tested with the contaminant being in a forward position, corresponding to a teacher who is speaking and potentially posing a risk for students.

As diagram 2 shows, the particle concentrations are rising within the first quarter of an hour and settle. An emulated student in front of a contaminating teache would experience the lowest concentration settling at 242 µg/m³ for the 2,5 µm particles (PM2,5)

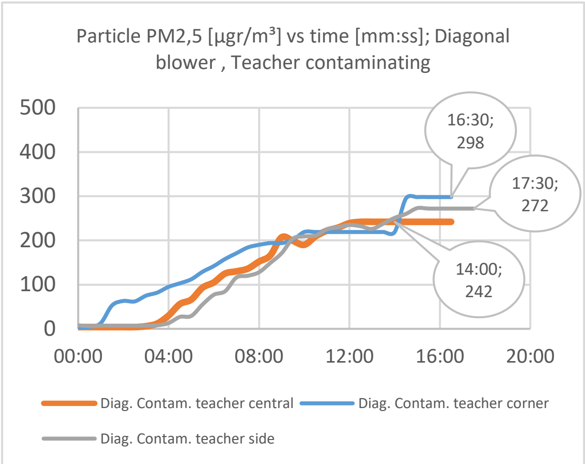

***Diagram 2**: Particle concentrations Pm2,5C [µg/m³] over time [m:s] with Diagonal Purifier orientation in left corner the teacher being the contaminant.*

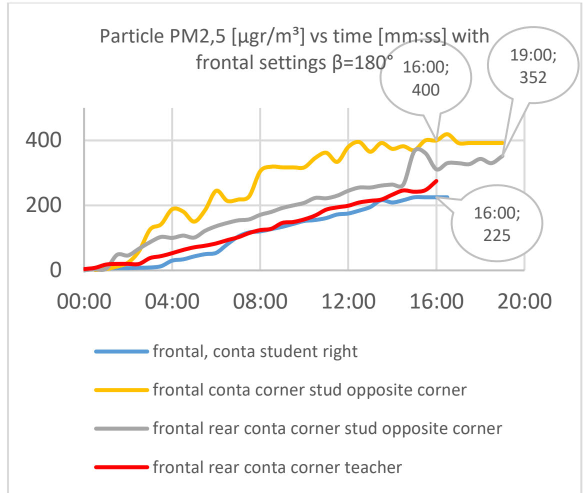

***Diagram 3**: Particle concentration Pm2,5C [µg/m³] over time [m:s] for a frontal setting shows the best settings where the purifier sits at the wall.(blue and yellow).*

The highest concentration in the diagonal setting can be found in the oposite corner, i.e. on the right with 298 µg/m³. This suggests that the air circulation deposits aerosol in corner with a 23% higher concentration compared to the lowest measured concentration. In complement to the diagonal setting, the next chart shows the purifier facing to the end wall, which is shown in the following figure.

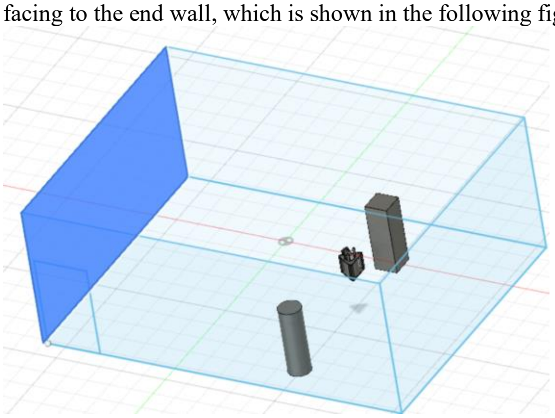

***Figure 6**: "Frontal" Purifier setting orientating at β=180° air streaming towards the end wall of the room; the contaminant in "student" position, particle counter on the mirrored or opposite side.*

Figure 6 displays the studied setup of purifier displayed by the prismatic model, the infectuous person represented by the cuboid body and the measuring point depicted by the cylindical body. The purifier blows towards the bluish wall, where a teacher stands. The measuring situation therefore would be an infectuous student in the same row like the position of a person of interest, separated by a purifier. In this situation exhaled aerosol should be aspired by the purifier in a better way in comparison with a diagonal setting, where one of the two purifiers is operated like in figure 7.

Diagram 3 shows the particle concentrations at a frontal setting of β=180° rising within 12 to 16 minures and leveling the highest at 419 µg/m³, in the case that the purifier sits forward of an imaginary student poluting in one corner. A lower particle concentration of is achieved with the purifier sitting between a potentially contaminating student and other students.

In conclusion, it is more advantegous to place the purifier opposite the end wall between the rearmost sitting students and point if "frontally" to the opposite side. This is plausible because of the circulation of the purified air stream being more effective than the air stream on the suction side.

One more observation can be made in relation to the purifier induced circulation with the onset of contamination. Between 01:30 and 05:00 Minutes after the contamination starts, the sensors detect 10% of the maximum concentration settled after 12 to 18 minutes. In average 2:50 minutes after contamination the contamination can be measured in the positions where the counter was placed. It can be safely assumed that a significant proportion of room's air circulates within three minutes.

Multiple and alternate purifier settings

Whereas in the chapters above effects of one purifier in a room were discussed, it is worthwile researching operating several small purifiers in a room. It can be suspected that the effectiveness of multiple small purifiers with a total ACH corresponding to single big one, unifying the total capacity of multiple purifiers, would be superior to a single purifier in terms of risk reduction. While such multiple purifier would require more cost and efforts in setting up, the corners could be better reached. Absorbing aerosols closer to a potential emmittent shorten their pathways, streams and retention times.

With placing 2 purifiers in a classroom the question arises how they could be placed so that the largest possible proportion of the room is involved in the circulation without cleaning purified air again. For instance, by positioning one purifier diagonally, a stream is induced that risks being aspired by the opposite purifier.

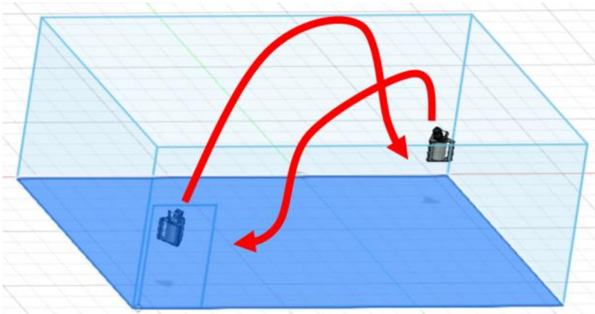

***Figure 7**: Double diagonal with two purifiers setting blower1@ (8,2 6 1,3) , (60° 140°), blower2@ (1,5 1 1,3) , (60° 320°).*

The setting displayed in Figure 7 risks blowing purified air towards the opposite purifier's intake. This would significantly reduce the efficiency of filtering the priority aerosol air volumes. More promising and definite would be creating a suction zone and a pressure zone as figure 8 shows.

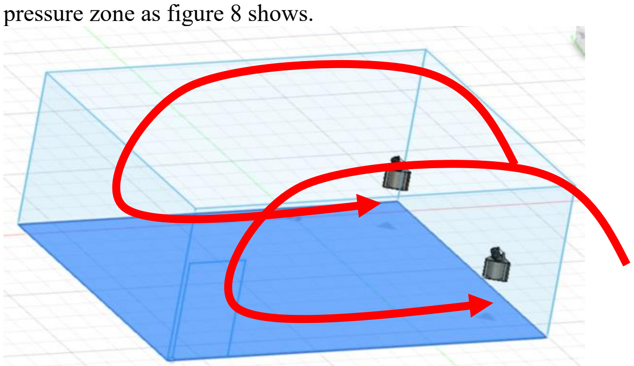

***Figure 8**: Double Longitudinal with two purifiers setting superior because of definitive high- and low-pressure zones. blower1@ (8,2 6,0 1,3), (60°180°), blower2@ (8,2 1,0 1,3), (60° 180°).*

Figure 8 shows the two purifiers blowing along the long axis and therefore creating a pressure zone oposite the purifier's position. Would more contageous virus mutations appear, like the B1.1.7, the corresponding aerosol would get aspired before being inhaled by other attendants in the room. This more definite setting was researched.
In order to compare the double-longitudinal, the double-diagonal and the single purifier setting, the particle counting experiment was utilized.

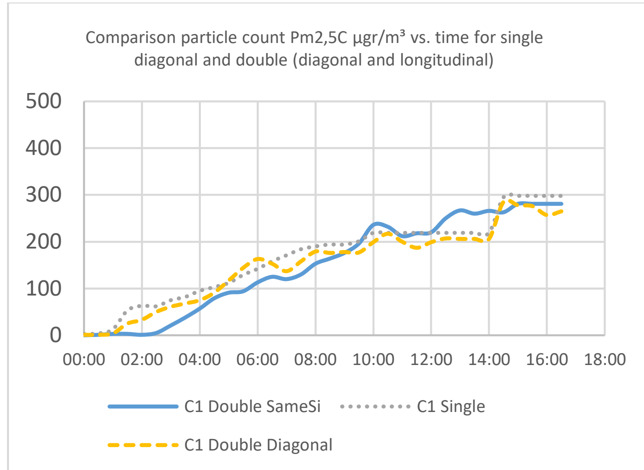

***Diagram 4**: Shows the comparative particle count Pm2,5C [µgr/m³] vs. time [m:s] for single diagonal and the double diagonal and longitudinal setting (same side). As expected, the 2 purifiers on the same side are reducing to the lowest concentration, which is 10% lower than the single purifier setting.*

Diagram 4 shows the particle concentration [Pm2,5C µg/m³] over time in Minutes for the single diagonal blower marked with dots, the double-purifier setting orientated diagonal marked with dashes and the solid line for the double-purifier setting on the same side directed to the other side longitudinally. While the lines trend similarly in grand order, the longitudinal double line with a similar ACH value that the single purifier has, it remains below those concentrations. On a second look the solid longitudinal setting adds up with the integrated curve 10% lower, compared to the double diagonal setting. As discussed in chapter describing the elevation, the infection risk is proportional to the concentration times the exposure time. Therefore, the lowest infection risk can be linked to the purifier setting displayed in figure 9. Blower1@(8,2 6,0 1,3), (60° 180°), Blower2@ (8,2 1,0 1,3), (60° 180°), i.e. the purifiers blow towards the opposite wall. However, such a setting would probably create higher aerosol concentrations on the downwind side, should an infectuous person be producing aerosol on that side. It makes sense to utilize the downwind side as a buffer zone without attendants.

Conclusion and recommendation

Summary

This research was launched to explore opportunities to allow students savely back to their classrooms, despite the COVID-19 virus aerosol possibly being exhaled among other students. Depending on where it stands and blows, the studied purifier induces an air stream that mixes different strata and dilutes them in the lecture hall, which -if tall like the 3,14 m high subject of study- allows aerosols to flow where humans are not breathing. By stiring up, such a machine contributes to the aerosol floating longer and it should dehydrate faster, in this way not reaching room attendants at risk. In complement to the literature recommending a room air exchange rate above six, a purifier with an ACH of 2,5 hr^{-1} induces already an air flow that was made visible with the smoke images. Based on how swiftly contaminations can be measured in the room, the circulation of air seems to have a relative turn-around cycle of about three minutes. It showed that most of the room's volume is well participating in the circulation, so transporting aerosol towards the filtration, which is needed to protect attendees from an excessive aerosol inhalation, would one attendant be infectuous. The Schlieren

images seem to confirm that picture of the entire room's volume being involved in the circulation. Nevertheless the corners are aerodynamically 60,9% less ventilated and purified, which was also shown by the particle counting tests. With the dwell time of aerosol particles in the corners higher, the ACH could be increased or more than one purifier could be installed. The particle counting experiments also support the argument of abandoning the corners, so securing the majority of the room. The majority of the room would be sufficiently well involved in the airflow even with a small ACH and the aerosol kept from other attendands. With a single machine in a room, the purifer with the α=60° forward blowing angle was found 27% more effective than blowing straight to the ceiling. The diagonal and frontal positioning of the purifier bring similar purifying results with low particle concentrations in central positions with 225 to 296 µg/m³ PM2,5 indicating aerosols remaining less concentrated.
For the double-purifier setting, comparative results displayed in diagram 4 show that two purifiers in a room with a total ACH comparable to the ACH of one purifier can be more effective. Especially if the purifiers are positioned on one side and blow towards the opposite side, a ten percent reduction can be achieved in comparison to a single setting. However, room attendants should be positioned at a distance to that opposite wall. All of the results above can probably be transferred to a rectangular room of the same proportion or are at least similar.

Discussion and Safety assessment

With the purifier in the classroom blowing filtered air across the classroom a circulation is induced that displaces potentially contaminating aerosol towards the filter. Its effective removal of aerosol above 1µm was clearly shown in the adjacent filter effectiveness article. More critical are the smaller particles of <0,3 µm, because some 0,2% could theoretically pass. However, at the same time, the amount of particles emitted by a speaking person at that size is smaller. While during speech about 100 aerosol particles are produced by a person saying "a", only 1 aerosol particle with a size less than 0,5 µm is released into the room's atmosphere [8]. One more argument in favor of purifiers offering a safe learning environment concerns the comparison of volumes exhaled by an infectuous person and the throughput of the purifier. With a maximum air exhaled of two m³ per hour by an infectuous human, the purifier's throughput 360 $m^3\ hr^{-1}$ is nearly two hundred times higher. The assessment of safety is therefore a matter of probability that sufficient aerosol reaches a room attendant times exposure time with a given concentration. To the designers of this purifier, the risk is arguably also a matter of acceptance by the individuals that trust the devices.
One more potential improvement concerns the vertical movement. The studied purifier aspires and ejects air in the same point of a room. This design was chosen to obtain a handy device with short paths for the air passing through the purifier. However, by dropping this reqirement, a more effective design can probably be achieved that utilizes the natural rise of air and would be effective in rooms with high ceilings.

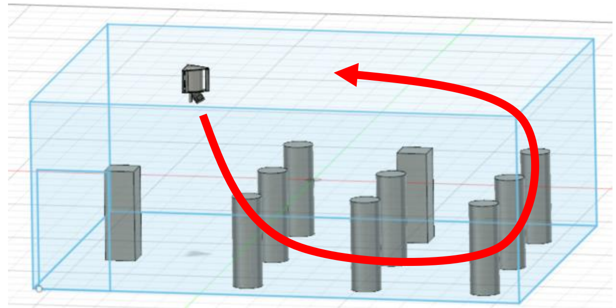

***Figure 9**: Purifier mounted at ceiling to utilize natural rise of warm air.*

By aspiring under the ceiling, where warmer air and much of the aerosol accumulates, the average dwell time in the room before filtering shrinks. Clean air would be blown downward towards the plane where attendants in the lecture hall are breathing. Despite the efforts necessary to hang the purifier on the ceiling, this would be worth studying for its effectiveness.

Mutated virus addendum

The B1.1.7 mutation that were discovered in late 2020, was found being around 35% more contageous than the COVID-19 wild type by 15 January 2021 [20] [21]. This increased infectiousness results from the virions entering host cells more easily. This evolution is normal for virus and might not be the last mutation, but still does not render this research obsolete. While new experiments can only be made after closure of the conference, the measurements hint at the possibility of solving this higher infectiousness with at least two purifiers being distributed in classrooms.
Finally, the entire effectiveness of the purifier strongly depends on the amount of virions that a human needs to inhale for a likely infection. Existing literature has determined that threashold for the COVID-19 wildtype more precisely than 300 to 3000, but experiments are planned to intentionally infect healthy persons. While the ethics of these experiments with the new mutations like B.1.1.7 are questionable, they might shed more light on the effectiveness of purifiers in classrooms.

Recommendation

- The purifier with 60° elevation seems effective in aerosol filtering a classroom, if placed at the end of the long axis and pointing to the opposite end. With an ACH of 2,5 hr^{-1} placing the attendants out of the corner and between the purifier and the opposite wall seems advisable.
- A biological survey should confirm the filter effectiveness with real but safe virus material and a lower and hopefully more efficient ACH of at least 2,5 room volumes hr^{-1}.
- Given more contagious virus mutations like the B1.1.7, it is worth studying the operation of more than one purifier in a classroom, so to absorb aerosols closer to a potential contaminant.
- In the eyes of the researcher team, employing purifiers in class and lecture halls is worth studying further and allowing. If possible, most students and especially children would benefit by allowing them back to classrooms if sufficient purifiers are installed.

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Prof. Dr. Michael Hartmann is the Academic Director of SRH Berlin School of Technology; Head of the Study Programs: Engineering and International Business; Engineering and Sustainable Technology Management. He is a theoretical physicist by background and did his doctoral research in semiconductor physics at the Humboldt Universität zu Berlin.

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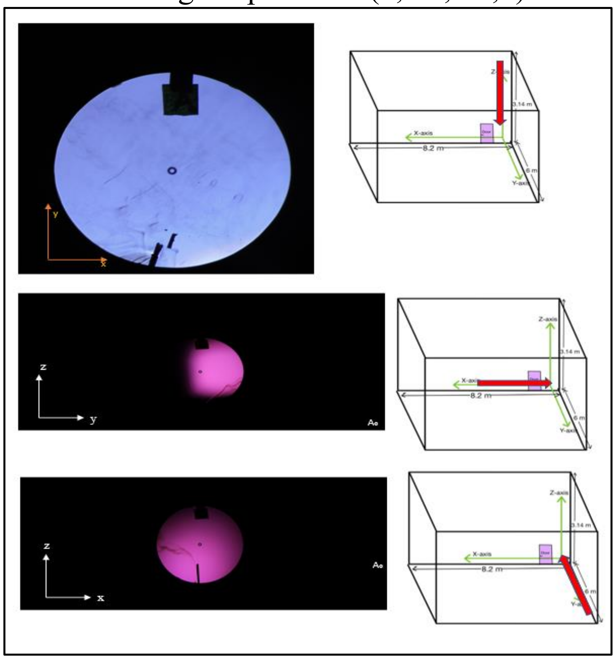
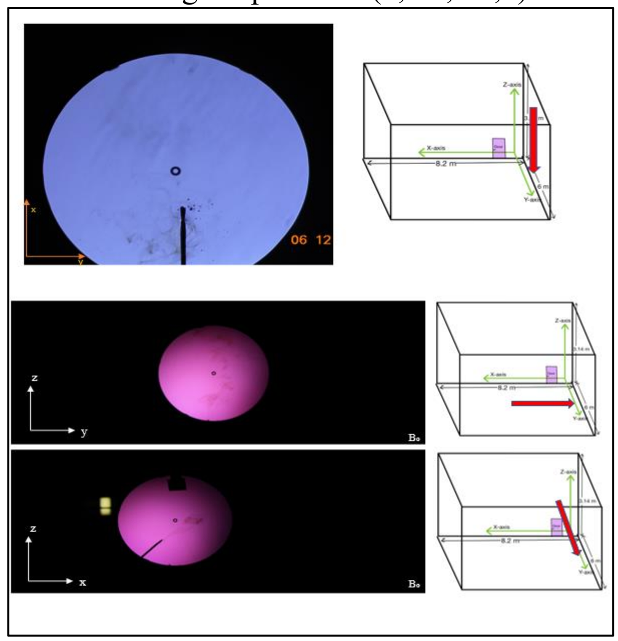
Annex I Schlieren Images

The Schlieren images are shown on the following pages of the annex with the coordinate position and a visualization:

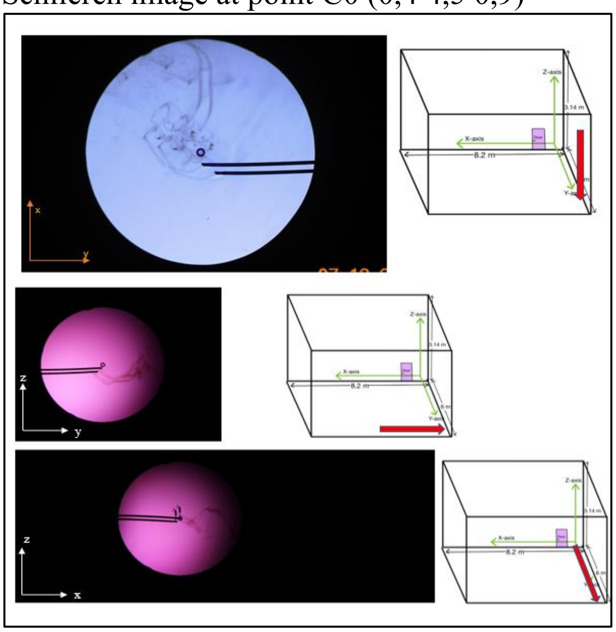
Schlieren image at point A0 (0,4 0,4 0,9)



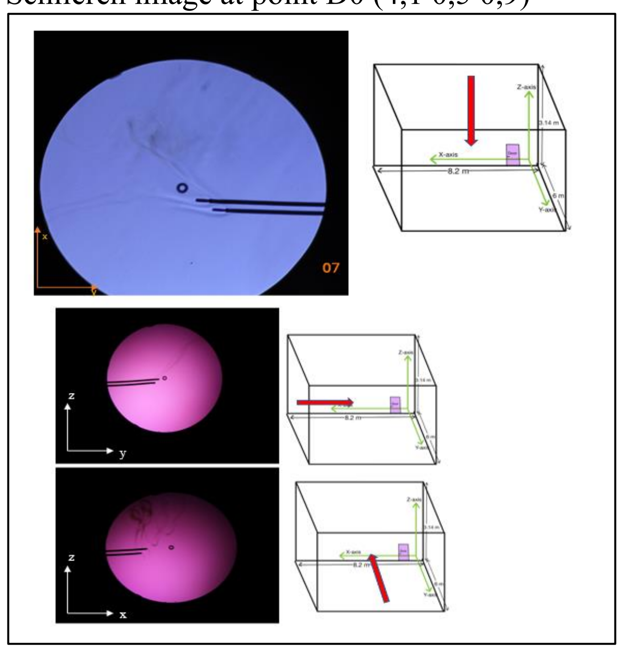
Schlieren image at point B0 (0,4 3,0 0,9)



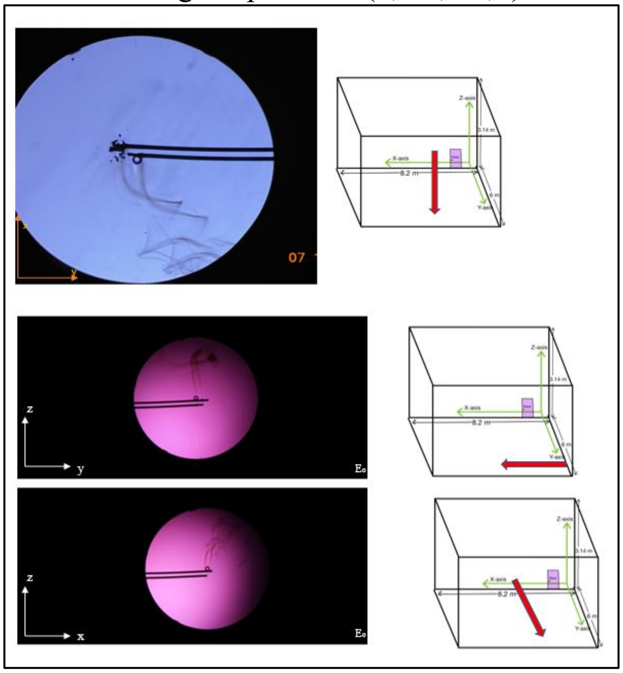
Schlieren image at point C0 (0,4 4,5 0,9)



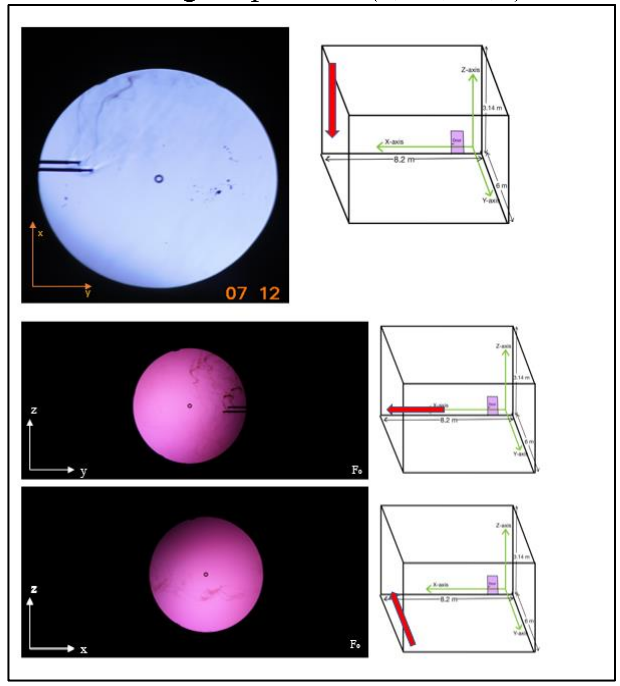
Schlieren image at point D0 (4,1 0,5 0,9)



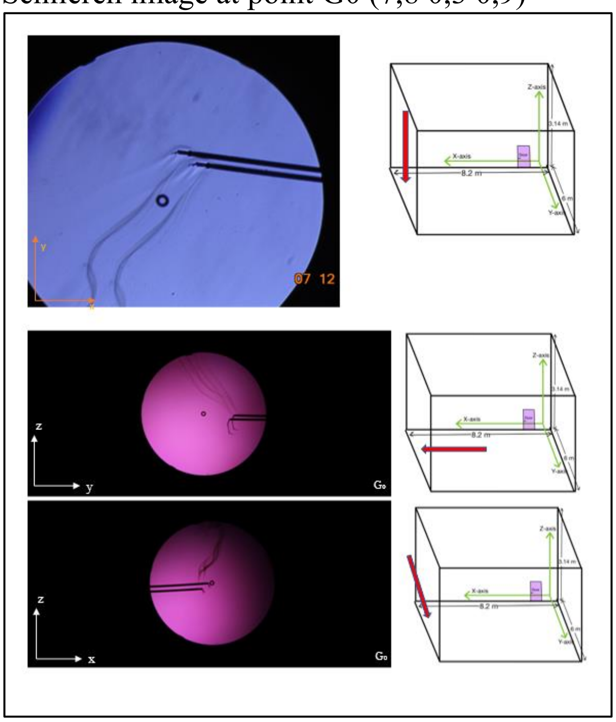
Schlieren image at point E0 (3,4 0,5 0,9)



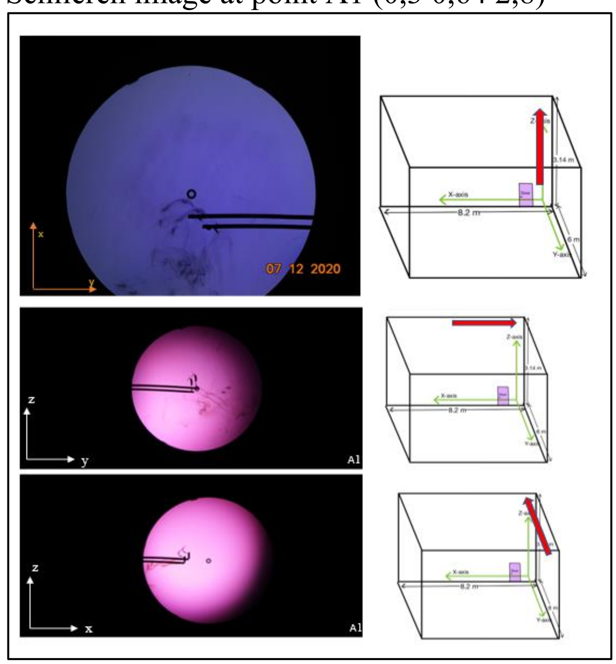
Schlieren image at point F0 (7,8 0,4 0,9)



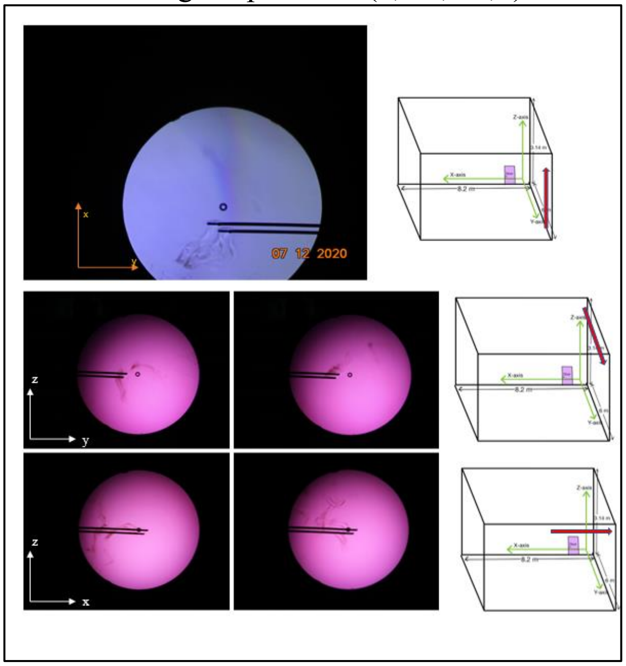
Schlieren image at point G0 (7,8 0,3 0,9)



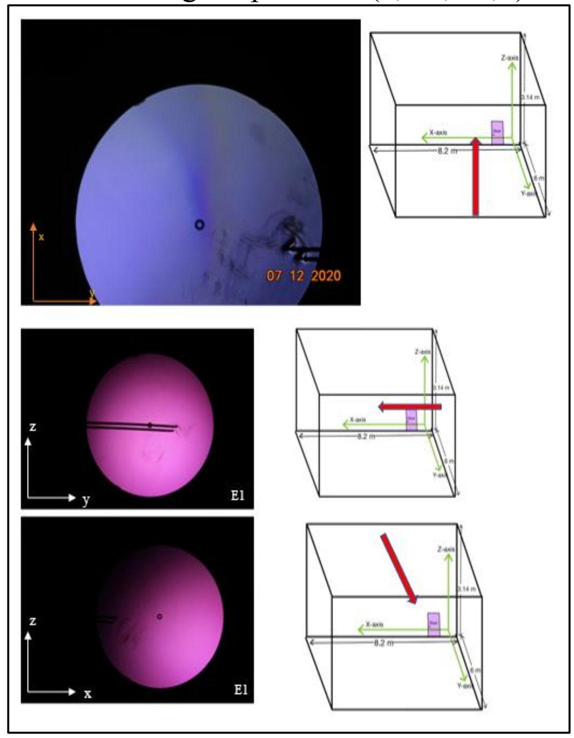
Schlieren image at point A1 (0,3 0,64 2,8)



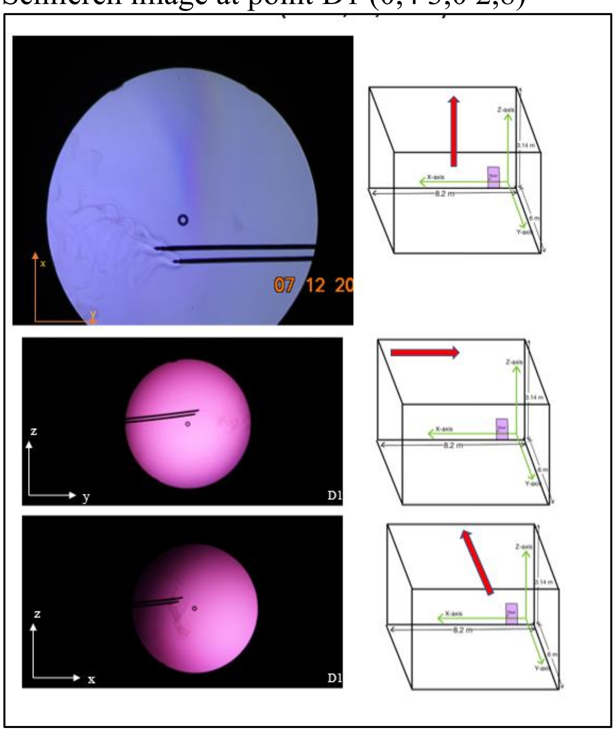
Schlieren image at point C1 (0,4 4,5 2,8)



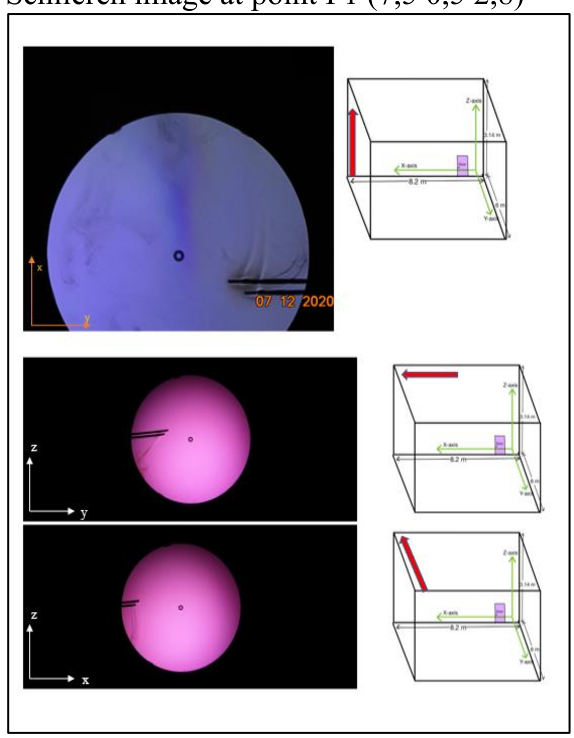
Schlieren image at point E1 (4,1 4,5 2,8)



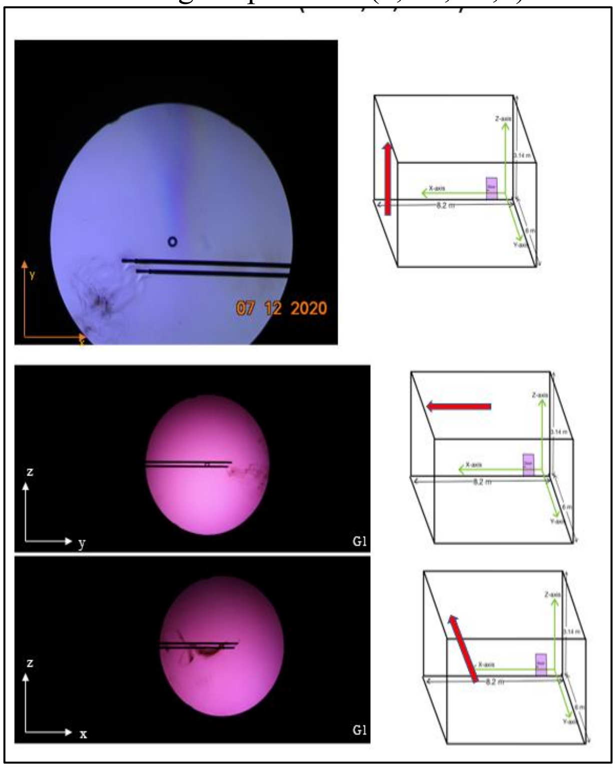
Schlieren image at point D1 (0,4 3,0 2,8)



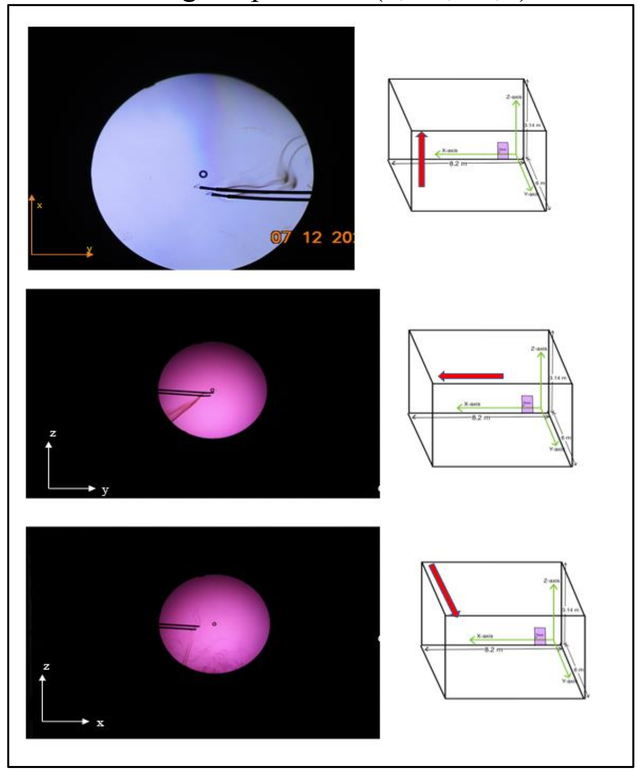
Schlieren image at point F1 (7,5 0,5 2,8)



Schlieren image at point G1 (7,8 3,0 2,8)



Schlieren image at point H1 (7,8 4,5 2,8)



Annex II
Images of Air-Purifier or filtering devices

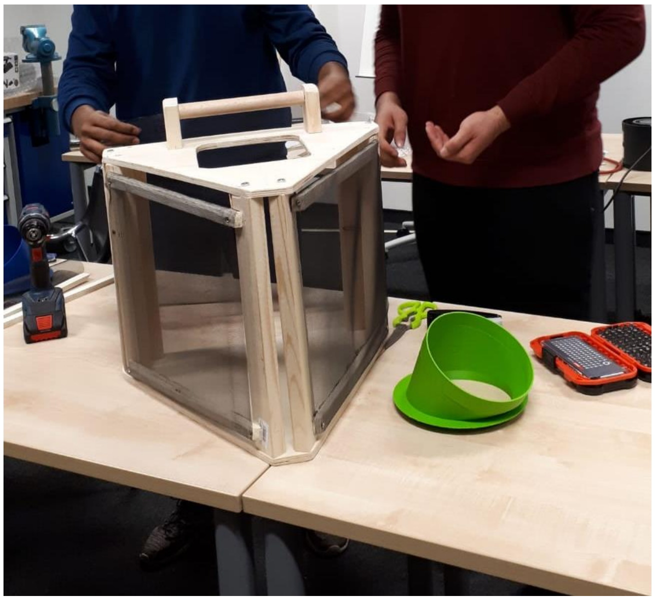


Figure 10: Building team of the Purifier frame made of wood worth 150 EUR. The adapter between filter and fan blower was 3D-printed.

Figure 11: Purifier frame holding the filter and the 44 W fan blower. The fan's cross section of 0,0123 m² and wind speed 9 m/sec results in a flow rate of

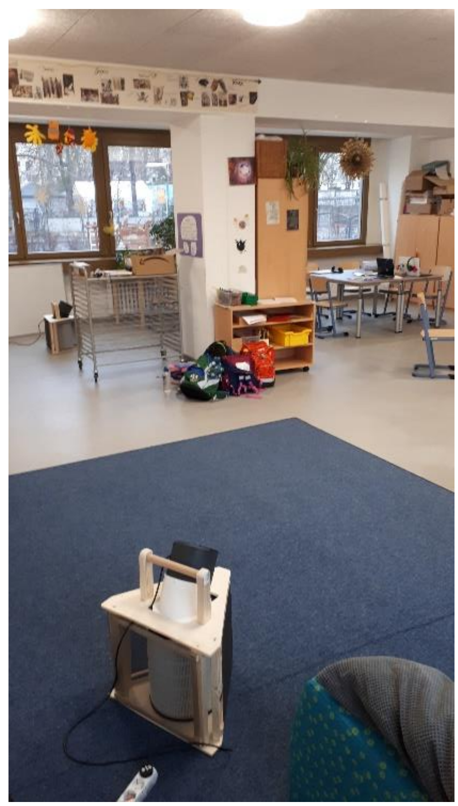


Figure 12: Test Application of the purifier in a classroom. Given the room's geometry and separation, two purifiers were necessary.

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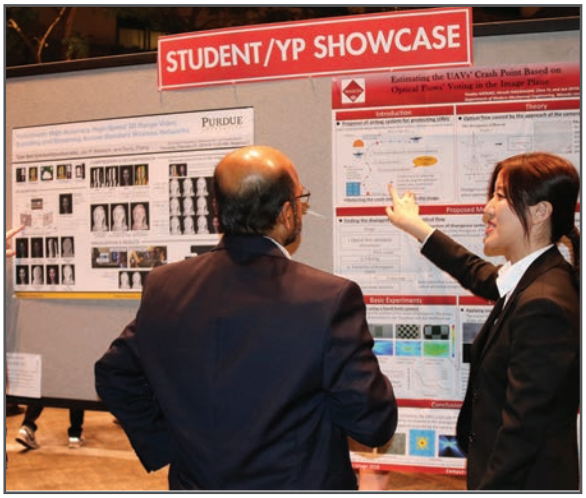

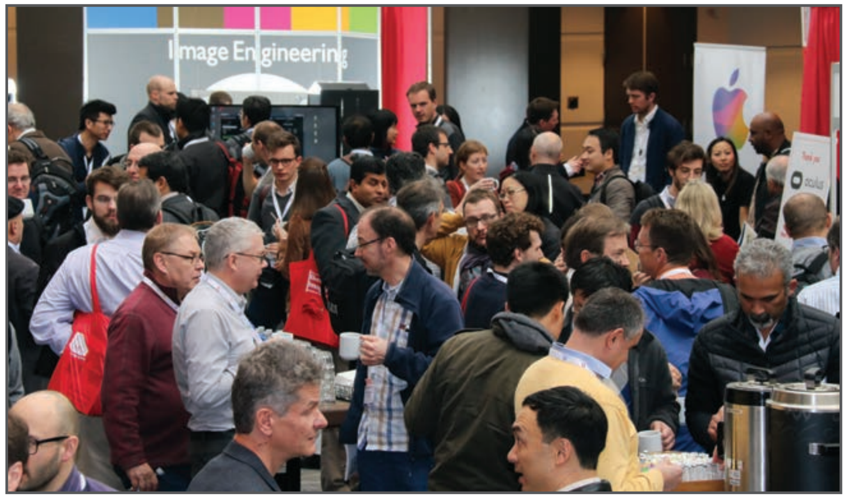

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