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Minimizing Indoor Infection Risk by Airborne Pathogens with Nanofiltration and Vertical Flow

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Abstract
The risk of infection between people can be significantly reduced with targeted vertical flow control in the room and nano-filtration of the recirculated air. This cannot be achieved with any other air purification device or ventilation system.

In the work described, three examples of preventing the risk of infection - a classroom ventilation system, ventilation of an elevator cabin and securing a hospital bed - were physically implemented and evaluated experimentally and numerically.

In addition to the results of these examples, the currently applicable regulations were critically discussed, as well as the difficulties involved in the widespread introduction of the innovations developed.

Keywords: Ventilation for Virus Protection, Vertical Laminar Flow, Virus Filtration, Virus De- Activation, Ceramic Wall Flow Filter, Requirements for Ventilation.

Abbreviations

- **ASHRAE:** American Society of Heating Refrigerating and Air Conditioning Engineers
- **BAFU:** Bundesamt für Umwelt (FOEN)
- **BAG:** Bundesamt für Gesundheit, CH (www.bag.admin.ch)
- **CAST:** Combustion Aerosol Standard
- **CEN:** Comité Européen de Normalisation
- **EASA:** European Union Aviation Safety Agency
- **EPA:** Efficient Particulate Air filter
- **FOEN:** Swiss Federal Office of Environment (www.bafu.admin.ch)
- **GAEF:** Gesellschaft für Aerosolforschung (www.info.gaef.de)
- **HEPA:** High-Efficiency Particulate Air filter (down to 0.3 µm)
- **HKL:** Heizung Kühlung Lüftung
- **HVAC:** Heating Ventilation and Air Conditioning
- **IARC:** International Agency for Research on Cancer
- **ISO:** International Organization for Stanardization
- **MERV:** Minimum Efficiency Reporting Value (classification of the ASHARE); MERV Ratings 13 to 20 (down to 0.3 µm)
- **NCA:** NanoCleanAir GmbH (www.nanocleanair.ch)
- **PNFE:** Particle Number Filtration Efficiency
- **PN:** Particle Number
- **PMP:** Particle Measuring Program
- **REHVA:** Federation of European Heating, Ventilation and Air Conditioning Associations
- **SWKI:** Schweizer Verein Wärme Klima Ingenieure
- **UBA:** Umweltbundesamt, D (www.umweltbundesamt.de)
- **UFP:** Ultra Fine Particles
- **ULPA:** Ultra-Low Penetration Air filter (down to 0.12 µm)
- **UTF:** Umwelt-Technologie-Fonds
- **WHO:** World Health Organisation (www.who.int)

Introduction

The importance of virus protection was made clear by the past pandemic, but it is still very important in normal times. The authors have confidently proven that nanofiltration of exhaust gases, which comes from automotive technology, is also very effective in eliminating viruses from the ambient air. Nanofiltration, i.e. the separation of particles in the nanometer size range, is nothing new. There is an overwhelming amount of information on the Internet about nanofiltration in air and water or in other gases and liquids. For extreme air purity in cleanrooms, HEPA and ULPA 1) filtration qualities were defined and standardized [1-4]. Already in the early days of the electronics industry in the second half of the XX century measuring technics and high requirements concerning nano-aerosol purity were established.

ULPA filters trap smaller particles (U15, U16, U17…down to 0.1.2-micron diameter) than HEPA filters, which are effective for eliminating particulate matter of 0.3-micron diameter or larger (H13 & H14). The higher ISO-classes (EN ISO 14644-1) certify the filtration quality down to 0.1-micron equivalent particle size [4, 5].

The filter materials are usually replaceable packets of fiber filters. The typical lifespan of a HEPA/ULPA filter in a cleanroom depends on numerous factors such as the level of air pollution (and pre-filtration), frequency of use, and maintenance practices. Generally, HEPA/ULPA filters in cleanrooms can last anywhere from 1 to some years. Afterwards, the valuable filters often have to be disposed of, which contradicts the principle of the circular economy.

However, all these highest filtration qualities have so far only been reserved for special applications in medicine and industry and have a high price, which has kept them away from general use by the public.

The corona pandemic from the beginning of 2020 has shed new light on the importance of nano air purification and stimulated new interdisciplinary technical solutions. The measurement and filtering of harmful nano-aerosols has been known in the exhaust technology of combustion engines for three decades. The authors of this paper have used sound scientific research to prove that the ceramic filter substrates used in exhaust technology separate viruses in the same way as other nanoparticles and deactivate them within 1 to 2 days [6]. This paves the way (also from an economic point of view) for the widespread introduction of nanofiltration and the utilization of its advantages (combined with targeted flow management) for the health of all.

The paper briefly describes the methods for developing and monitoring the new improvement measures, describes some approaches and suggests ideas for their wider introduction.

Materials and Methods

Filtration of Nanoparticles, Viruses, Bacteria, Spores

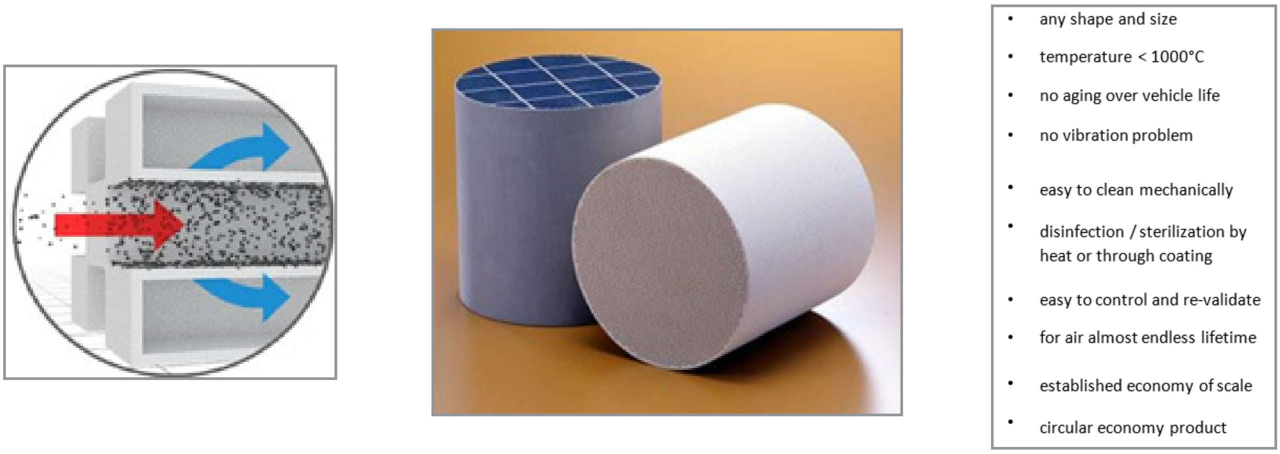

Figure 1: Ceramic Wall Flow Multicell Filter Substrate (Source: Corning)

During the development of exhaust gas filtration (since 80-ties) different filtration materials were used, like braided, or coiled fibers, sintered porous metal materials, metallic wire mashes and of course ceramic monoliths, usually Cordierite, or Silicium Carbid. The last are shown in Figure.1, invented 1979, now > 200 Mio in Diesel cars and machines. Thanks to their flexibility in designing the external shape, pore size and porosity, their ever-improving mechanical and thermal properties and, finally, their price, ceramic monoliths have now become almost completely established on the market for filtration of exhaust gas from combustion engines [7-13]. Particularly noteworthy in recent years is the development of filter substrates with a hierarchical pore structure, which guarantee the highest particle separation efficiency even without preconditioning of the filter [12, 13].

The pore size used is 10 to 25 microns, depending on the application. Through diffusion filtration, these substrates excellently separate particles in nanometer size. Adapted to bioaerosols in air ventilation systems, they can be cleaned or regenerated if necessary and never need to be changed. The ceramic filter substrates are therefore the only ones that fulfill the requirements of a circular economy product.

Covid viruses are between 50 and 150 nm in size. Exhaled by the patient, they often occur in agglomerates together with proteins and water. These conglomerates can be up to a few microns in size. However, the moisture evaporates in milliseconds and agglomerates in the size range mainly around 300 to 700 nm remain. This mixture of individual viruses and agglomerates has hours of suspension time in the ambient air, follows the flow like the gas molecules and can be separated by diffusion filtration.

The experimental demonstration of nanofiltration was carried out several times and repeatedly with Cordierite substrates as follows (always with the same substrate at time) [6].

- **For the Particles from Combustion:** The soot particles from a CAST generator were introduced and homogenized in a flow channel upstream of the filter. The particle separation efficiency PNFE was determined from the PN measurement before and after the filter [14, 15].
- **For the Viruses:** A special method had to be used. Working with pathogenic viruses, and especially with highly transmissible viruses, presents very significant technical challenges. Due to the high contagiousness and virulence of SARS-CoV-2 viruses in general, experiments would have to be carried out under the highest biosafety measures, which makes an experimental facility with aerosols practically impossible. Therefore a surrogate virus, the Escherichia coli bacteriophage.

MS2 was applied. MS2 is an RNA virus, slightly smaller, than SARS-CoV-2 and can be used together with biological safety laboratory strains of Escherichia coli bacteria as host cells, both of them being safe for humans, animals, plants and the environment. For these reasons, using bacteriophages as surrogate viruses is state of the art in environmental biology research [16-18].

Viruses are not living organisms, but "biological particles with a short genome". They attach themselves to bacterial cells, penetrate them, use the bacterial cytoplasma for their own reproduction and thus also destroy these cells.

In a flow channel, the Escherichia coli bacteriophages MS2 were introduced in a solution upstream of the filter and aerosolized. The aerosol samples before and after the filter were collected on special gelatin support, eluted and subsequently serially diluted, mixed with the receptor cells Escherichia coli bacteria and plated on a semi-solid growth medium. During the 24-hour incubation period, each active virus multiplied in the surrounding receptor bacteria, resulting in visible plaques. Counting these plaques and multiplying with the applied dilution factor, before and after filter, makes it possible to determine the viral clearance rate of the active viruses, see example in Figure 2.

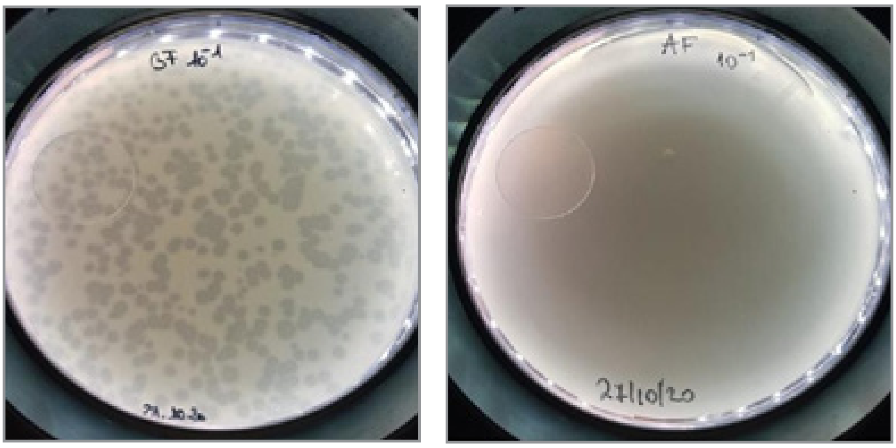

Figure 2: Agar plates, from which the number of plaques are counted before (A) and after filter (B). The solution was highly diluted to make the plaques countable, [6].

In both series of experiments: for the combustion particles and for the viruses, equally high separation efficiencies of more than 99%, typical for this filtration material, were demonstrated. It was also found, that the viruses deposited in the filter are about 95% deactivated after 24 h and completely deactivated after 48 h [6].

Requirements for Ventilation

In a static ambient atmosphere, the air exhaled by a person moves upwards due to natural thermal convection. If this upward movement is supported by a low-turbulence displacement flow that is also oriented upwards, the exhaust air from this person cannot reach the neighboring persons. If this exhaust air is contaminated with infectious pathogens, the protection of the neighboring persons is almost one hundred percent guaranteed.

If, on the other hand turbulences or cross components of the flow are allowed in the room, this automatically leads to the cross-transfer of the exhaust air cloud and thus potentially of the pathogens. These cross flows can typically be caused by window ventilation or by air purification devices. In both cases, the positive effect of global air dilution in the ventilated room is offset by the negative effect of cross-transmission of the local, polluted gas cloud.

In cases with continuously operating air purification devices, which blow the purified air into the room, or in systems with ventilation nozzles (such as bus or airplane cabins), an inhomogeneous flow field can form, which supplies some people with highly diluted gas or clean air, but others with undiluted and contaminated gas.

From these considerations, the advantages of vertical, upward flow with the greatest possible avoidance of air mixing in the room compared to other ventilation systems based on mixing are clear. However, this fact is diametrically opposed to the current "state of the art" of conventional ventilation and air conditioning technology. Fresh air is almost always fed into the room from above, precisely so that the room air can be mixed and diluted as efficiently as possible. According to the logic of coarse dust, this prevents it from rising from the floor and supports possible sedimentation downwards. The needs outlined above, which are geared towards nano-aerosols, are new and represent a paradigm shift for the HVAC industry, at least in some areas.

Important principles, helpful orientation values and terms, as well as requirements for ventilation systems, whether for general or specific cleanroom use, are given in various standards [19-21]. The following are examples: air exchange rate, 1 or 2-stage filtration or pre-filtration, heat recovery, pre-conditioning of outside air, CO2 control, types of flow (low-turbulence or turbulent), recommendations for air routing, maintenance regulations, safety measures for infectious aerosols and more.

Numerous recommendations and guidelines were issued at the beginning of the pandemic by various organizations, authorities (BAG, UBA) and industry associations (such as EASA, REHVA, SWKI, or GAeF), [22-25].

The possibility or recommendation to protect people through the air flow in the room is sometimes mentioned, especially in the case of ventilation systems in the healthcare sector, but is not specified in more detail. The use of higher filtration rates is also sometimes recommended, but this is ultimately left to the (mostly commercial) decision of the user. The existing standards are of a recommendatory nature and there are few or no official control mechanisms.

Results and discussion

Prototype Measures Implemented

The authors of this paper, with the support of the Swiss Federal Office of Environment (FOEN) and various interdisciplinary specialists (NCA Scientific Advisory Board see www.nanocleanair.ch), have developed three prototype measures for consequent infection control in enclosed spaces.

These measures, which relate to different situations, are: ventilation of a classroom, ventilation of an elevator cabin and the ventilation protection of a hospital bed. In all cases, ventilation and filtration systems were implemented and their efficiency was confirmed both experimentally and theoretically by flow simulation.

Classroom

NCA with its partners University of Applied Sciences Northwestern Switzerland (FHNW), Adolphe Merkle Institute (AMI) and Combustion Flow Solutions (CFS) have developed a concept for virus protection for indoor areas. The aim is to achieve the most vertical flow possible by extracting air at the ceiling and recirculating it, after efficient filtration, near the floor, thus minimizing the exchange of air between people. The effectiveness of this approach was demonstrated in a pilot installation in a classroom at the Rudolf Steiner Special School in Lenzburg (RSSL).

Figure 3: The classroom at RSSL.

The picture in Figure 3 shows the realization in the classroom: The air is extracted from the room through perforated pipes suspended from the ceiling, fed into a collection duct (above the wall panel) to the 'technology cabinet' (left of the wall panel). The cabinet contains a fan for extraction, after which the air is filtered and returned to the room via a duct near the floor (below the blackboard). The scheme of the ventilation system is shown in Figure 4.

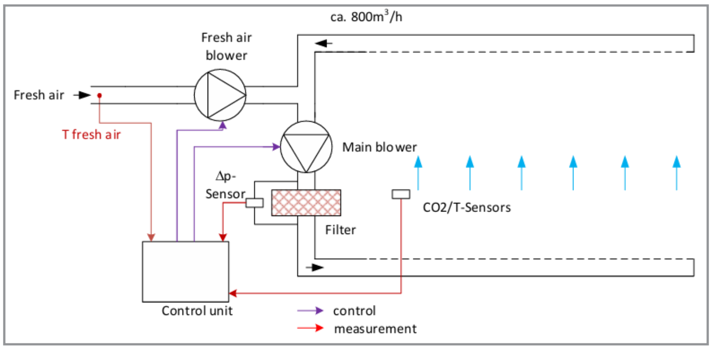

Figure 4: Layout of the System.

Via a radial fan (main fan), the air extracted from the ceiling is fed to the nano-filter, which also has the role of a sound absorber. The system is activated via a motion detector. The pressure drop across the filter is monitored; if it is too high (filter occupied) or too low (problem with the fan), an error message is issued. The CO2 concentration in the room is measured and used to regulate the supply of fresh air via another fan. The air from outside is also filtered and all the purified air is introduced back to the room near to the floor.

NCA uses ceramic 'wall-flow' filters, such as those used for exhaust gas purification in combustion engines. Such filters are produced in large quantities and are therefore inexpensive, they achieve efficiencies well above 99%, can be easily heated and thus sterilized in hygienically demanding applications (hospital), are easy to clean and therefore have a very long service life in contrast to fiber filters, which have to be changed when they are plugged. Experiments show that these filters can also filter viruses highly efficiently [5].

The efficiency was investigated in three ways:

- Flow simulations
- Flow visualization using smoke
- Aerosol measurements using a salt aerosol generator.

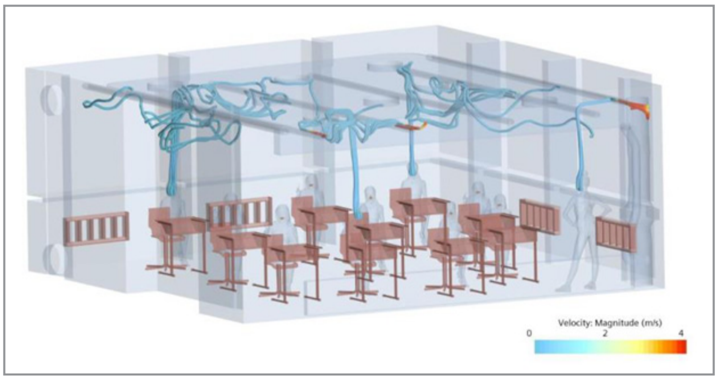

Figure 5. Flow Simulation in A Classroom

Example of a flow simulation in Figure 5 shows that a good vertical flow and no exchange of gases between the persons are achieved.

Figure 6: Salt Aerosol Generator and Hot Plates in The Classroom Simulating the Body Heat.

For the aerosol measurements, a source (salt particles by spraying a salt solution) was installed on one desk and sensors measuring the particle concentration were installed on each desk. Measurements were taken in an empty classroom, with body heat simulated by hot plates, as shown in the Figure 6, but also during class. The results are very similar.

Figure 7 shows an example of the results for a measurement according to Fig.7 with the ventilation fan switched on. The blue curve shows the particle concentration at the source, the others show the concentration at the individual desks. It can be seen that the concentration at the tables is even and also very much reduced and that this reduction is achieved at all desks.

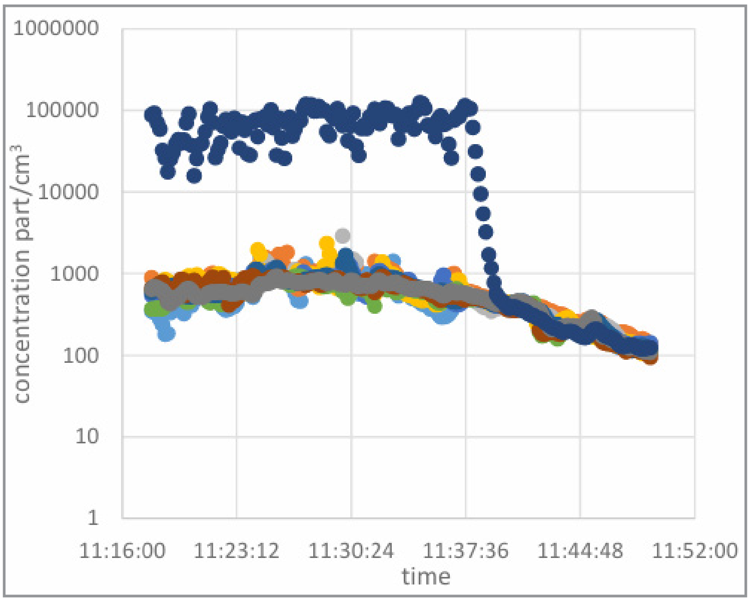

Figure 7: Particle Number Concentrations at The Source and on Individual Places.

Figure 8 shows the important influence of the ventilation fan, which contributes to a significant reduction in particle numbers at all locations.

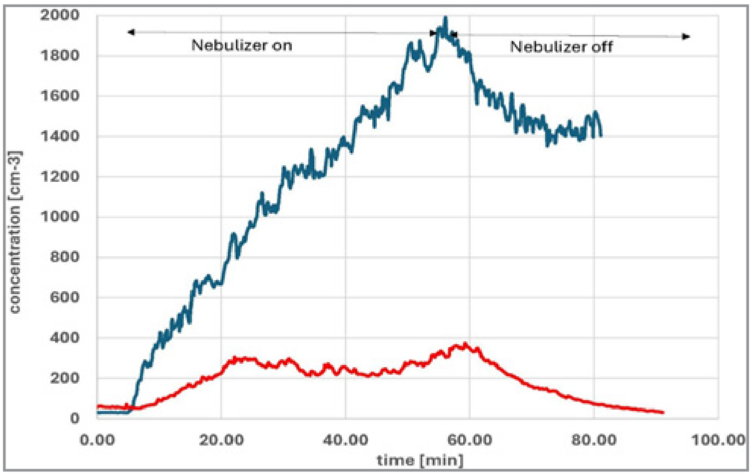

Figure 8: Average Values of The Particle Number Concentrations Across All Sensors; Blue: Fan "off"; red: fan "on".

Lift Cabin

Flow simulations show that the minimizing of air exchange between people can be realized very well also in an elevator cabin, Figure 9. When the recirculated air passes through the nano-filtration, the protection of healty person becomes very efficient.

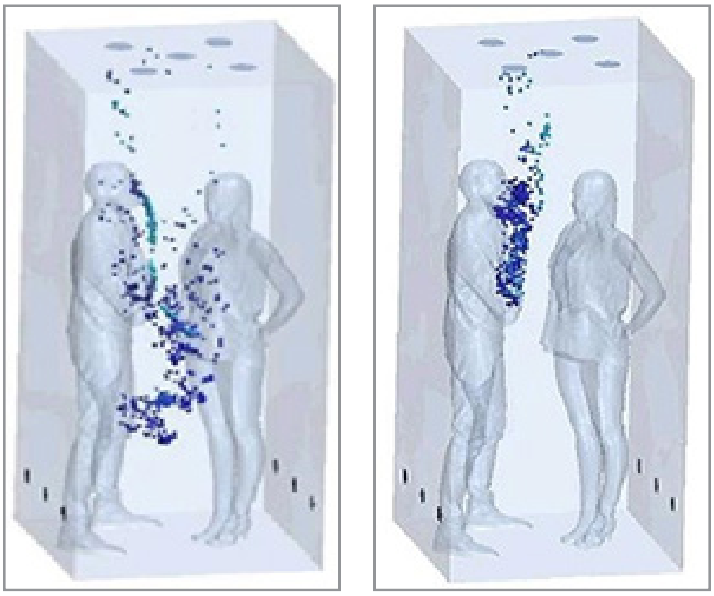

Figure 9: Flow simulation in a lift cabin. Left without vertical flow, right with a vertical flow of 10 cm/s.

An example of implementation of such a ventilation system for a real tested lift cabin is given in Figure 10. A filter/blower unit was installed on the roof, which extracts air from the cabin through perforated plates on the cabin ceiling. The filtered air is led through a duct on the outside of the cabin to the cabin floor, where it is re-introduced into the cabin.

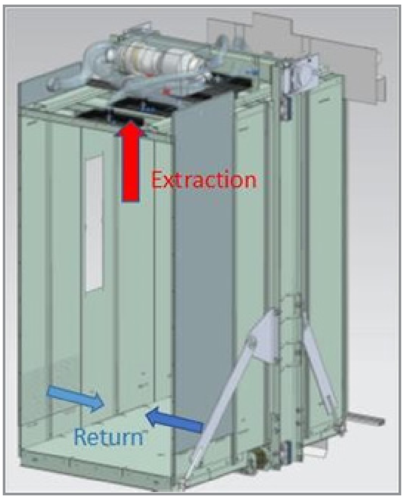

Figure 10: Schematic Representation of The Lift Cabin. The Ventilation Has an Air Exchange Rate of 27/H, The Mean Vertical Flow Velocity is 1.6 cm/s.

Flow visualizations using smoke show that a largely vertical flow is achieved. Although the suction does not reach all the way to the edge of the booth, no flow reversal is visible at the side walls.

Quantitative results were obtained by aerosol measurements. For this purpose, six scattered light sensors were suspended from the ceiling at about head height to measure particle concentration. A nebulizer used to spray a saline solution serves as the aerosol source. Another sensor measures the aerosol concentration near the source, Figure 11.

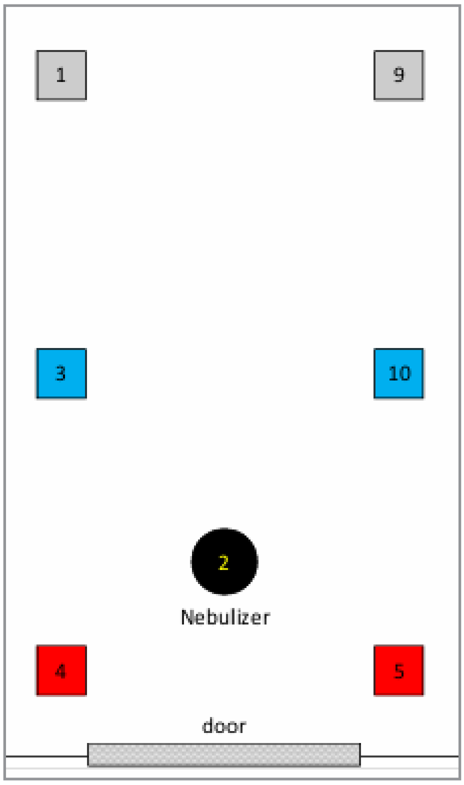

Figure 11: The Arrangement of The Sensors and The Aerosol Source.

The concentrations shown in Figure 12 are related to the value near the source. Already in the front part of the booth, i.e. close to the source (red), the concentration of the sensors is only 20% of the concentration of the source. Towards the back, the concentration drops significantly and in the rear part (gray) it is only 5% of the concentration near the source.

The two sensors in the back, in the middle and in the front each showed very similar values, therefore only the average values of the two sensors are shown.

This shows that the horizontal dispersion in the cabin is reduced very efficiently

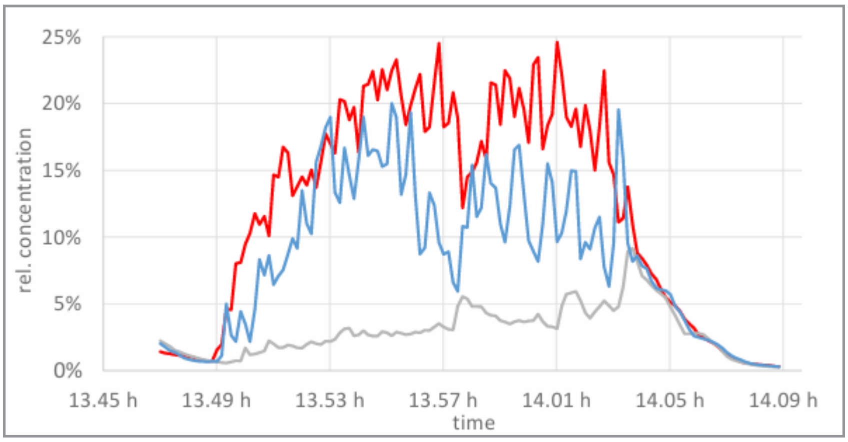

Figure 12. Concentration in the front (red), in the middle (blue) and in the back of the lift cabin (gray) in relation to the concentration near the source.

Baldachin for Hospital Bed

A system for protection against infectious aerosol from hospital beds was developed. Here, the air exhaled by the patient is extracted above the bed in a kind of baldachin, filtered and returned below the bed.

Figure 13 shows a schematic of the system: the air is extracted through perforated tubes above the bed. A Plexiglas hood prevents air exchange further up. In the two supports on the left and right of the bed, the extracted air is fed to the filter and radial blower and blown out again at the bottom behind the bed. The system is easy to fold up and transport.

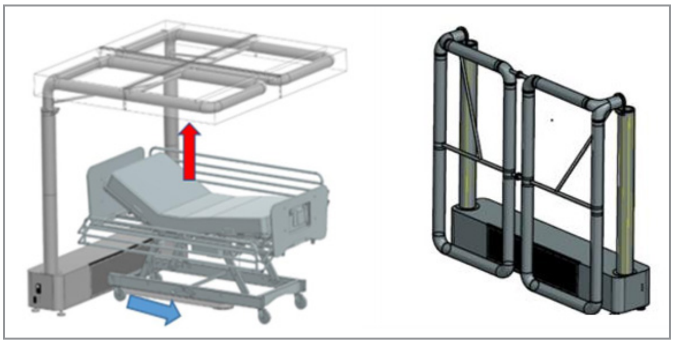

Figure 13: Protection Baldachin for a Hospital Bed

Silencers are housed in the two support tubes, and the filter also acts as a silencer. The pressure drop across the filter can be measured to provide information about the occupancy of the filter.

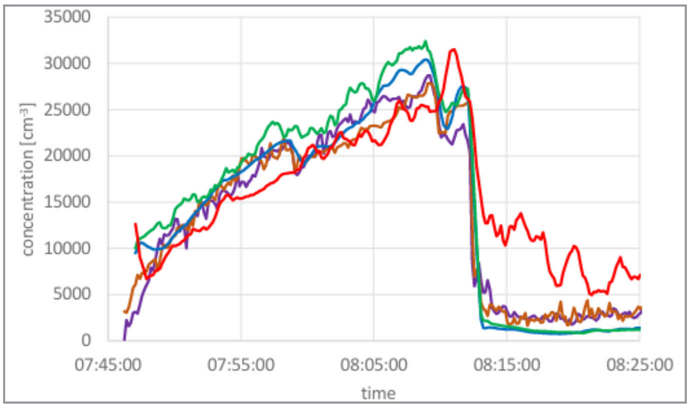

Figure 14: Results of Aerosol Measurements.

Figure 14 shows the efficiency of the system. With the ventilation initially switched off, aerosol particles are generated by spraying a saline solution of 30nm -100 nm solid particles. In this measurement, four sensors were placed in the corners of the canopy and one under the canopy roof (red curve). The particle concentration increases continuously. As soon as the fan is switched on, however, it drops again very quickly. The four sensors in the corners show negligible concentrations after a few minutes, but cleaning is also very effective under the baldachin.

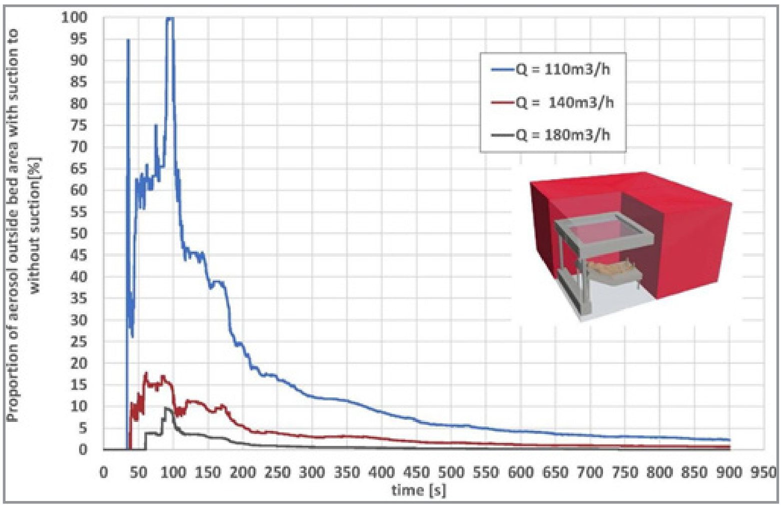

Figure 15: Results of Numeric Simulation – Reduction of the "Outside Nanoaerosol" (In the Red Area) After Switching-In the Ventilation.

Flow simulations were used to investigate how much aerosol can enact the space outside of the canopy. The bed with the patient under the canopy is in a corner of a patient room. Figure 15 shows the ratio of aerosol particles leaving the baldachin space with and without suction. The ventilation is turned on at the time points 40s to 60s, it then takes a few minutes for the flow to build up, then the proportion of 'escaped' aerosols becomes very small. "Escaped" means that the particles enter the red area of the room where the nurses, the doctors or other patients may be situated. Since the suction has to always be switched on, only the final value is of practical importance and this is in the range of one to two percent. The figure shows very well that with increasing volume flow the equilibrium is established much faster. This is of very great practical importance, since we will always have disturbances in clinical operation (nursing, sitting up of the patient, air blast from a neighboring bed, etc.).

Applications and paradigm shifts

The principles of these solutions, i.e. highly efficient purification of the breathing air from all particulate matter by nano-filtration and permanent recirculation, as well as ensuring a nearly laminar vertical flow, which even avoids contagion of neighbor patients, are generally applicable and can be used in a similar form in waiting rooms of medical practices, in restaurants or meeting rooms. Even the secondary conditions, such as maintaining an extremely low noise level of 40 dB(A) and controlling the CO2 concentration, have been solved. Since the ceramic filters are easy to clean, there are hardly any maintenance costs and a long service life can be assumed. We do not know of any competing systems that even come close to the protection efficiency of these presented systems and we recommend the installation in existing rooms as well as the consideration of this conception in new planning.

The Wider Introduction of The Presented Improvements Needs Some Paradigm Shifts

As already mentioned in the introduction, first of all the nano-filtration quality must be considered, as available, affordable and recommendable for general application in buildings and public spaces. Nano- filtration is a very efficient measure that always adds to the other conceivable measures and removes the pathogens as quickly as possible. Nano-filtration not only affects viruses and nanoparticles, but also bacteria, fungi, germs, allergens and other organic and inorganic air pollution. Nanofiltration and its maintenance may cause additional costs and an increase in the energy of the fans, it can, however, reduce the use of outside air in air conditioning / heating systems and thereby reduce energy loss. Finally, nano- filtration is easy to measure and control with today's portable measuring devices for the vehicle emissions.

A second important change of idea must consider the introduction of fresh, filtrated air at a floor of the room. The flow guidance should be quasi laminar and preferably from bottom to top, so that it supports convection through body heat and the probability of the cross-exchange of the pollutant would be minimized. The traditional idea of (larger) dusts that sediment downwards is no more applicable to clean rooms with nanoparticles-and bio-aerosol filtration.

These technical changes nevertheless will be hardly considered by the industry and by the clients without any recommendation, or even regulation from an independent authority. In the pandemic emergency, severe restrictions were introduced in public places in many countries. This could be largely mitigated with the new, target-oriented design of the ventilation systems. These facts result in the need for further improvements in the area of public law and procedures and bring us to the next paradigm shifts:

- **Quality Control & Consumer Protection:** damages, material- or assembly errors can destroy the effectiveness of the best filter systems. Inspection and maintenance (I&M) of the filter systems is crucial and should be publicly organized for important ventilation systems especially in times of health risks (similar to the control of the heaters, or vehicles).
- **Regulatory Precautions:** Official recommendations, regulations, incentive measures. The official introduction and quality control of nano-filtration is crucial. Experience from DPF introduction has shown that market forces alone cannot achieve this satisfactorily.

An interesting and motivating looking back at some of the milestones in the development of knowledge and regulations on nanoaerosols and their harmfulness is given in the Appendix.

Nanoaerosols - Knowledge and Regulation Development

The technology and regulations of conventional indoor air purification have been developed for decades: a technology for cleaning indoor spaces of dusts in the micron range or larger, microfiltration so to speak, without considering the properties of the substances in these dusts.

In the meantime, however, the focus has shifted to air purification under the primacy of health protection, without classic room ventilation having taken note of this.

It is interesting and motivating to look back at some of the milestones in the development of knowledge and regulations on nanoaerosols and their harmfulness.

Since the 1990s, it has been proven that the alveolar-penetrating fraction is decisive for health effects, in particular particles < 100 nm, the UFP [26-30].

In Switzerland, SN 277206, which shifts filtration to the nanoscale (from 10 nm) and takes into account the toxicity of aerosols, has been in force since 2009 [31].

In the EU, exhaust gases from vehicle engines, which are considered the most important source of UFP in urban air, are limited from 23 nm according to the PMP protocol (2011) and with Euro7 this value is shifted even further to 10 nm (2024) [32].

IARC declares diesel particulate emissions (2012) as (certainly) carcinogenic [33].

WHO recommends from 2022 (as "good practice") the testing of UPF in breathing air from 10 nm and has specified guideline values according to the number [34].
A CEN technical specification describes the PN measurement in ambient air (2016) and a more recent CEN standard for testing air quality in vehicle cabins also specifies the UPF indoors (2022) [35,36].

The measurement technology for these tests is mature, see examples in [35-41].

In the recent past (also in the milestones shown), nanoparticles originating from combustion, traffic or industrial processes have been considered. However, the pandemic has also shifted the focus in engineering circles to bio-nanoaerosols. As shown in this article, it has been proven that nanofiltration also effectively filters bio-nanoaerosols. This means that viruses, bacteria, fungi, allergens and others are effectively eliminated.

The task now is to introduce nanofiltration into indoor air purification and to use technologies that are ideally suited for this purpose. This will enable us, as a society, to meet the requirement of protecting human health in accordance with the latest findings and possibilities.

Conclusions

This article presents the experiences and results of Nano CleanAir GmbH in connection with the radical reduction of the risk of infection in enclosed spaces. The information ranges from the general normative situation of filtration quality and requirements for ventilation systems, to the technical-scientific developments of three prototype measures and to the difficulties and the necessary paradigm shifts for the general introduction of the presented innovations.

With the introduction of fresh air in the floor area, with the low-turbulence parallel upward flow and with the nano-filtration of the recirculated air, the risk of cross-infection between people can be very much reduced, which cannot be achieved with any other measures. Air and heat exchange with the outside environment can be kept to a minimum, which also leads to energy savings when heating or cooling.

The general introduction of the proposed measures faces economic obstacles in particular and should be expediently initiated or accelerated by opinion-forming in the public legal sphere. This would reduce the surprise effects of the next possible pandemics and certainly also the intensity of the yearly flu epidemics.

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