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Methods for air cleaning and protection of building occupants from airborne pathogens

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ABSTRACT

This article aims to draw the attention of the scientific community towards the elevated risks of airborne transmission of diseases and the associated risks of epidemics or pandemics. The complexity of the problem and the need for multidisciplinary research is highlighted. The airborne route of transmission, i.e. the generation of pathogen laden droplets originating in the respiratory tract of an infected individual, the survivability of the pathogens, their dispersal indoors and their transfer to a healthy person are reviewed. The advantages and the drawbacks of air dilution, filtration, ultraviolet germicidal irradiation (UVGI), photocatalytic oxidation (PCO), plasmacluster ions and other technologies for air disinfection and purification from pathogens are analyzed with respect to currently used air distribution principles. The importance of indoor air characteristics, such as temperature, relative humidity and velocity for the efficiency of each method is analyzed, taking into consideration the nature of the pathogens themselves. The applicability of the cleaning methods to the different types of total volume air distribution used at present indoors, i.e. mixing, displacement and underfloor ventilation, as well as advanced air distribution techniques (such as personalized ventilation) is discussed.

1. Introduction

Most people live, work and enjoy their leisure activities in densely populated environments, which increase their exposure to many pathogens. The risk of cross-infection is a psychological stress factor as well as a health issue. It reduces the well-being of the population and has a powerful economical impact due to absenteeism and reduced productivity. Human history records many pandemics, e.g. the Spanish influenza epidemic in 1918–1919 (H1N1 virus), which was by far the most lethal flu pandemic of the 20th century, infecting about a quarter of the global population and killing more than 40 million people [1]. Increased mobility permits a rapid dissemination of new diseases and elevates the risk of further pandemics, e.g. of Severe Acute Respiratory Syndrome (SARS), as well as the emergence of old and well-known diseases that have developed resistance to existing drug treatment, e.g. tuberculosis [2]. Another threat imposes the rapid mutation of some microorganisms and their adaptation as a cause of human diseases, e.g. ebola, the H5N1 strain of avian flu, etc. [3].

All these factors increase the importance of making the indoor air as clean from any pathogens, and with high perceived air quality, as the cleanest outdoor air, or even better. Unfortunately, most of our indoor work places are not designed to prevent the spread of airborne pathogens. Furthermore, air distribution systems may even enhance transmission. In order to solve this multidisciplinary problem successfully, knowledge in different fields needs to be combined: the type of pathogen, its generation and survival mechanism before affecting the host, possible disinfection methods to eradicate it, and transmission mechanisms among people. Engineering solutions can be proposed in order to efficiently reduce the pathogen loads released in air, disable their virulence, and make them harmless for healthy inhabitants. The methods applied should be neither life nor health threatening, nor should they reduce in any way occupants' perceived air quality or thermal comfort. They should also be user friendly (if people are to operate them), with low noise emission, energy efficient, highly ergonomic and aesthetic.

The following discussion is limited to the generation, survival and airborne transmission of pathogens, the methods and technologies for removing microorganisms and viruses, from indoor air and their compatibility with existing HVAC practice.

2. Airborne pathogens

2.1. Generation and airborne transmission

Airborne pathogens are those pathogens generated in the respiratory system and released in exhaled air as a way of

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propagation. In her review article Morawska [4] describes the generation mechanism and the sites of pathogens' droplet formation. The factors influencing this process, and the fate of the expelled respiratory droplets are also considered. She concludes that although a great deal is known, more knowledge is needed on the mechanism of pathogen transfer in occupied places. There are 4 parts in the respiratory tract where microorganisms may multiply and be dispersed in exhaled air: nose, oral cavity, throat and lungs. Each provides different habitats to which different pathogens have adapted: tuberculosis in the lungs, *Streptococcus agalactiae* in the throat, etc. Dispersal may take place through the nose and the mouth. Most frequent aerial dispersal takes place from the mouth, when talking, coughing or even sneezing, and involves primarily the saliva [5]. Fiegel et al. [6], on the other hand, identifies the pulmonary region as the main source for deep lung generation of bio-aerosols and the ensuing environmental transport of airborne pathogens. She states that applying "saline therapy" (aerosol approach to immobilize bio-aerosols within the lungs), would reduce airborne pathogen generation, allowing for natural clearing mechanisms. It is clear that the contamination of the generated droplets with pathogens depends on the preferred habitat of the pathogen: coughing will produce droplets with deep lung pathogens, while talking, sneezing, etc., will disperse pathogens inhabiting mainly the mouth, the nose or the throat of the host individual.

According to Tellier [7] the latest medical findings suggest that influenza A virus is more likely to be transferred by the airborne route through aerosolization and to thus penetrate the lower lung region of the exposed occupant. The airborne transmission route has been shown to be predominant for three respiratory diseases: measles, varicella and tuberculosis [8]. When coughing, sneezing, talking or breathing, people generate particles of different sizes and air jets with different initial characteristics. Nicas et al. [9] summarized the scarce data on the particle size distribution of respiratory aerosols. Evaporative water loss was also taken into account. After evaporation is complete the particle retains half of its original diameter. However the authors are skeptical about the existing data on droplet size distribution based on previous experiments. They propose a new fitted mixture model of two log normal distributions to describe the particle size distribution for coughing based on the findings of Loudon and Roberts [10]. According to this model there is a distribution of "small" particles with geometric mean (GM) and geometric standard deviation (GSD) of 9.8 μm and 9.0 μm, respectively, and a distribution of "large" particles with GM of 160 μm and GSD of 1.7 μm. The small particles constitute 71% of all particles emitted by coughing. Particles with a diameter of 10 μm and less are able to penetrate into the lungs [11]. Thus coughed droplets with diameters up to 20 μm should be considered in the case of airborne cross-infection because after full evaporation of the water content in them they attain a diameter of 10 μm or less. If the inhaled particles carry any pathogens the risk of infection is greatly increased. A recent experiment performed by Yang et al. [12] shows that the droplet size distribution is in the range 0.62–15.9 μm. In their experiment they used two methods to identify the size distribution of coughed droplets. In the first method, the droplets expelled by coughing were mixed with clean air with low RH (35%) in a testing column. To avoid interference from the surrounding environment the subjects wore a mask with a P100 filter, which was connected to the testing column. In the second method subjects coughed directly into a sample bag. However, it was found out that more particles were retained in the bag compared to the first method. They also studied the effect of age and gender on droplet generation. In both cases no significance was found ($p > 0.1$). Their findings agree with the conclusions of Nicas et al. [9], but for the small particle range only. This was probably due to the fact that the bigger particles were caught in the filter media or stuck on the walls of the sampling bags. The ambiguity remaining is such that more research is required in the field of droplet generation and size distribution.

A simple physical model proposed by Xie and Li [13] was employed to investigate the coupled evaporation and movement of droplets released during respiratory activities. The effect of droplet size, exhaled air velocity and temperature, and the relative humidity of the ambient air on droplet evaporation and dispersion were all taken into account. The prediction, which applies only to still ambient air, was that expelled droplets move more than 6 m when sneezing (initial velocity of 50 m/s), more than 2 m when coughing (initial velocity of 10 m/s), and less than 1 m when breathing (initial velocity of 1 m/s). Compared to small droplets, large droplets evaporated more slowly and sedimented more rapidly. These processes were strongly dependent on the initial velocity of the respiratory jet: the higher the initial velocity the faster they would evaporate and the faster they would deposit on surfaces. More droplets would be suspended in air at lower initial jet velocities (i.e. talking, laughing etc.). However different air distribution patterns may affect differently the heat and mass transfer from the droplets as well as their dispersion.

Another form of airborne contamination with infectious bio-aerosols could occur when vomiting and when flushing toilets in public premises. Barker et al. [14] showed that a sick person can produce 10^7 viruses per 1 ml of vomit and 10^{12} viruses per 1 g of stool material. So for pathogens that cause vomiting of the host or diarrhea (SARS, *Escherichia coli*, *Neisseria meningitidis* etc.), there is a greatly increased risk of spreading the disease. Rusin et al. [15] found that droplets produced by flushing the toilet could either be inhaled or deposited on surfaces.

The virulence, pathogen generation and the infective dose are other important factors determining the infectivity of a pathogen. Different microorganisms have different methods of overcoming the defence mechanisms of their host and successfully hiding. Also the generation of pathogens is different depending on the stage of the disease (early, advanced or latent). Another point of importance is the infective dose: sometimes a single organism can cause a disease. But this factor is strongly dependent on the immune system and/or age of the host: immuno-compromised people as well as old and very young are more susceptible [16].

2.2. Survival of pathogens in air

In order to be able to reach and infect their host, the airborne pathogens need to survive in the surrounding environment, which makes factors like air temperature and relative humidity important. So far, knowledge on the influence of relative humidity on pathogenic bacteria is scarce and the little data available is for opportunistic representatives (studies were performed on innocuous strains from the same families as the pathogens themselves). In general, mid-range humidity conditions (40–60%) have been shown to be more lethal to non-pathogenic bacteria [17]. Viruses with more lipids tend to be more persistent at lower relative humidity, while viruses with less or no lipid content are more stable at higher relative humidity [18]. Loosli [19] showed that humidity levels of 80–90% for 30 min could render the influenza virus noninfectious to mice, while exposure to lower humidity levels (17–24%) provided the greatest infectivity. Lowen et al. [20] confirmed that the transmission efficiency of influenza A virus is dependent on relative humidity by conducting experiments with guinea pigs in an environmental chamber. The four infected animals were separated from the four healthy ones: each animal was in a cage to avoid any possible contact. Thus the only possible transmission route was airborne. The transmission was highly efficient at low RH (20% or 35%), and less effective at 65%. At 50% only one animal was infected and at 80% RH no transmission of the virus was observed. In all five cases the

temperature was kept constant: 20 °C. The authors suggest that the dry air could desiccate the nasal mucosa, lead to epithelial damage and/or reduction in mucociliary clearance, thus making the host susceptible to respiratory infections. This obviously depends also on the stability of the virus as well as the droplet nuclei formation mechanism: at low RH droplets evaporate faster, shrink and change their size, increasing the possibility of being inhaled if their diameter is less than 10 μm. In other studies the survival of some viruses has been shown to be independent of relative humidity [21]. Harper [22] and Miller and Artenstein [23] showed that picornaviruses and adenoviruses, respiratory disease causatives and members of non-enveloped virus groups, survive better at high relative humidity. Measles and influenza, both enveloped viruses, survive best in aerosols at low relative humidity [24,25].

Studies also report that the effects of relative humidity on virus survival can be influenced either positively or negatively by temperature. At 20 °C human coronavirus (upper respiratory tract diseases) was reported to be most stable at intermediate humidity, but was also relatively stable at low humidity [26]. The same study also found that virus survival at 6 °C and 80% humidity was very similar to the best survival at intermediate humidity. Lower temperatures have also been shown to enhance rhinovirus survival at high relative humidities [27]. Lowen et al. [20] reported that influenza virus transmission is inversely proportional to the temperature. At 5 °C, the transmission of influenza A virus was more effective compared to 20 °C or 30 °C. At 5 °C the infected guinea pigs shed the virus for a longer period compared to the other two conditions and more viable viruses were found in their nose secretions. The authors believed that at low temperature the cooling effect on the cilia slows their beats, reducing mucociliary clearance and diminishing immune defence mechanisms. It was suggested that in cool and temperate climates the predominant route of infection with influenza is airborne, which implies that in tropical and warm environments the direct contact route is dominant. This bold hypothesis may not be true; it is in full contradiction to the findings of Tellier [7] (as already mentioned above). Enveloped viruses and their patterns of survival at different temperatures, [28,29], may not be the same as those of non-enveloped viruses, especially when the viruses are on surfaces [30].

For safety reasons scientists have until now performed studies with non-pathogenic organisms, which have a different structure from their pathogenic relatives [16]. Therefore more research is needed on this topic.

3. Cleaning methods

Chen et al. [31] showed by applying mathematical models (the Well–Riley model, competing-risk model and Von Foester equation), that public health interventions (vaccination, insulation, tracing down of the contacts of infected people etc.) are not enough to stop the outbreak of a disease in a modern society. They concluded that more advanced methods need to be applied to help people fight the diseases, namely engineering techniques combined with public health interventions.

A great effort has been made to find engineering techniques to keep airborne pathogens away from occupants in buildings, or at levels low enough to be unable to cause a disease: dilution, filtration, Ultra Violet Germicidal Irradiation (UVGI), etc. The airborne pathogens might originate from a sick person, from the building itself (infected/polluted HVAC system, infected building materials etc.) or from an intentional release, i.e. a terrorist attack [32,33].

3.1. Dilution

Dilution of room air with clean disinfected air is one of the easiest and best known methods to remove pathogens and to decrease the risk of infections in rooms. Natural, mechanical and hybrid ventilation are often used to supply clean air in rooms. However, this method has its limitations, related to air distribution pattern, occupants' thermal comfort, etc., which is discussed later in this paper. Moreover, if one assumes perfect mixing, a reduction of contaminants' concentration by a factor requires an increase of the air change rate by the same factor.

3.2. Filtration

A method widely used today is the filtration of air in HVAC systems. Classifications and guidelines exist for applying filtration as part of the ventilation system. They are widely used by designers [34,35]. Studies show that filtration is a good method to prevent outside pathogens from penetrating the building envelope through the mechanical ventilation. Kowalski and Bahnfleth [36,37] showed that 80- and 90-per-cent filters can produce air quality improvements that approach those achieved with HEPA filters, but at much lower cost. Another finding is that microorganisms capable of penetrating HEPA filters are predominantly nosocomial infections (HEPA filters remove 99.97% of all particles 0.3 μm or larger in diameter).

Enzyme filters eradicate microbes by attacking the microbial cell membrane, but this assumes that they come into close contact with the microbes. Yamada et al. [38] studied the performance of such an enzyme filter. They used two filters: with and without enzymes, and found out that the performance of the enzyme filter did not differ much from that of a control filter, due to adhesion of particles over time on the filter surface, preventing close contact between the enzymes and any microbes retained by the filter.

3.3. Ultraviolet germicidal irradiation (UVGI)

UVGI light is emitted at wavelength of 253.7 nm by low-pressure mercury vapour arc lamps. UVGI damages the DNA/RNA of pathogens and makes them harmless: they cannot reproduce once they have entered their host. Laboratory research has shown that the germicidal effect of UVGI is primarily a function of two factors: the intensity of the UVGI energy and the duration of exposure [39–42]. These studies also found some influence of pathogen susceptibility, of the presence or absence of a cell wall and its thickness. Since smallpox, influenza and adenovirus lack a cell wall they are more easily inactivated [43], while spores, such as Bacillus anthracis, are the most difficult to inactivate due to their protective cover [44]. There are two ways to use UVGI application in practice: ceiling/wall mounted or in-duct application.

Disinfection of air by ceiling/wall mounted UVGI started in the 30 s in USA [45,46]. The inactivation process occurs when the pathogens enter the UVGI zone: 1.8 m above the floor (the height above which UVGI systems should be installed to avoid any health risks for occupants). The inactivation rate of UVGI in rooms could be enhanced by increasing the intensity of light, by promoting better mixing in rooms, or by generating an upward flow to facilitate the upward transport of pathogens [47–49]. Another important factor for UVGI efficiency is the level of relative humidity. Studies [50,51] show that with increased humidity in the environment the pathogens are more likely to survive the germicidal effect of the UVGI lamp. Xu et al. [51] evaluated the impact of room ventilation rates, UV effluence rates and distribution, airflow patterns, relative humidity, and photoreactivation on the effectiveness of UVGI systems. They suggested that in order to obtain maximum benefit from a ceiling/wall mounted UVGI system, an adequate level of UV radiation of at least 6 W of UV-C per m^3 in the upper zone should be provided. Moreover, the UV radiation should be evenly distributed and good room air mixing should be provided. Room relative humidity should be kept around 50%. Values above 75%

significantly reduce UVGI performance: the effectiveness is reduced by more than 40%. Photoreactivation, a process by which DNA damaged by UV light is repaired by an enzyme that requires light, is not likely to be an issue with any significance for full-scale operation. The amount of photoreactivation has been reported to increase at a high level of relative humidity (RH > 75%). However, there is a threshold dose of UV above which photoreactivation will not occur in airborne bacteria [52].

The adverse health effects of UVGI on humans include a mild form of reddening of the skin (erythema) and painful photokeratitis of the eyes (sensitization to light, as in snowblindness). UVGI lights are therefore mounted in deep louver enclosures to prevent overexposure at eye level or excessive reflection from ceilings, but such casings absorb a large amount of the useful UV energy, making the unit less efficient. Guidelines for upper-room UVGI application are available [53,54]. In buildings with ceilings lower than 2.4 m duct UVGI irradiation must be applied. The problems of direct eye contact or skin contact are not relevant here, so the systems could be operated at even higher intensities. Good mixing and the use of reflective surfaces is an economical way to increase the effectiveness of the induct UVGI systems [55,56]. Exposure duration is also important factor. Kujundzic et al. [57] reported that under the same other conditions culturability of the bacteria was reduced by up to 87% and culturability of fungi by 75% at an air stream velocity of 2.2 m/s. The higher velocity (5.1 m/s) rendered the UVGI system ineffective.

3.4. Photocatalytic oxidation

Photocatalysis is the acceleration of a photoreaction by the presence of a catalyst (TiO_2, WO_3, ZnS, etc.). In photogenerated catalysis the photocatalytic activity depends on the ability of the catalyst to create electron–hole pairs, which create free short-lived radicals able to undergo secondary reactions. Photocatalytic oxidation (PCO) could be achieved by either using fluorescent or UV light. PCO is an emerging technology in the HVAC industry, especially in purging airborne bacteria, which is performed by utilizing short-wave ultraviolet light (UVC). The results are somewhat encouraging, since some pathogens are readily destroyed after treatment with a TiO_2 coated PCO unit [58,59]. However only small portion of the pathogens will be absorbed on the catalyst and chemically attacked from a single pass system. Also with time there will be accumulation of "dead" pathogens on contact surface, which will reduce the effectiveness of the method as the UV light will be stopped from activating the catalyst layer. An enhancement of the germicidal effect can be achieved by doping a TiO_2 photocatalyst with Ag^+ ions [60]. On the other hand, a possible problem of the whole PCO approach is that some of the resulting short-lived radicals react to form secondary chemical species (aldehydes, ketones etc.) that reduce the indoor air quality and may reach high unacceptable levels from health point of view [61]. The process of pathogen inactivation by PCO is still under exploration and further research is required [59].

3.5. Desiccant rotor

A new approach to clean volatile organic compounds (VOCs) from indoor air is to apply a dehumidifier with a silica gel desiccant rotor. As reported in Ref. [62], measured levels of VOCs downstream of the rotor indicate efficiency of approximately 94% or higher. This method could be applied to purge airborne pathogens from indoor air, however, this needs to be investigated further.

3.6. Plasmacluster ions

A new technology, plasmacluster ions technology (PCI) that has recently reached the market claims to neutralize 26 kinds of harmful airborne substances. The ion generator uses an alternating plasma discharge (between two electrically charged plates: anode and cathode) to split the airborne molecules of water into positively charged hydrogen (H^+) and negatively charged oxygen (O_2^-). A chemical reaction occurs, and the collision of hydrogen with oxygen ions creates groups of highly reactive OH radicals that react with proteins/polysaccharides in the cell wall or surface structure of the pathogen, thus damaging it and rendering it incapable of causing infection [63]. The molecules of water formed as a result of this reaction are returned back into the air. It is possible that elevated levels of ozone (O_3) may be providing some of these benefits. PCI is a promising method for dealing with harmful airborne substances but it must be further investigated in terms of its effect on human health and on air quality.

3.7. Essential oils

Recent studies have shown that essential oils used in pharmaceutical, cosmetics and food and beverage industries have a strong germicidal effect and could be applied in the ventilation industry. Furthermore, the antimicrobial effect of essential oils' is greater in air than in solution [64–66]. Their application is still under intensive investigation. A hypersensitivity reaction of some occupants to certain essential oils (mint, thyme, oregano etc) and the fact that some of those oils also exhibit cytotoxic activity, i.e. being toxic to human cells as well as to microbial cells may limit the application of essential oils for air cleaning in occupied spaces [66].

3.8. Nanotechnology (silver nanoparticles)

A new method utilizing silver nanoparticles atomized in the air and used to control the viability of pathogens has been suggested [67]. The method was tested by injecting silver nanoparticles together with the aerosolized bacteria in a small glass chamber. Though highly effective (more than 99% of the tested bacteria lost culturability), this methodology still needs further investigations regarding its applicability indoors because of its possible negative effects on health.

4. Protection by ventilation

The current awareness of new emerging diseases serves to emphasise the need to design indoor conditions that prevent cross-infection. A simple way to limit the spread of pathogens is by supplying clean outdoor air, reducing the harmful concentrations indoors. The review article of Li et al. [68] shows strong evidences demonstrating the association between ventilation and the control of airflow directions in buildings and the transmission and spread of infectious diseases. The authors conclude that there is insufficient data on the minimum ventilation requirement for ventilating public premises such as hospital infectious wards, schools, offices, etc. to minimize the spread of airborne infections.

Airflow patterns are of great importance indoors, because they determine the path of the droplet distribution generated from the occupants' respiratory activities. Depending on the airflow pattern, the ventilation process of supplying fresh air indoors may decrease the risk of airborne cross-infection, or it may increase the spread of diseases in occupied volumes. The following discussion, on the importance of airflow distribution in rooms for the airborne transmission of diseases, is limited to mechanically ventilated rooms.

4.1. Total volume air distribution

Two main principles of room air distribution are commonly used in practice: mixing and displacement ventilation. Mixing

ventilation aims to create a homogeneous environment in the occupied zone. The clean air is supplied at high velocity to promote mixing with the room air and thus with the pathogens generated by a sick occupant. In rooms with mixing air distribution the level of exposure to infected air exhaled from another person is independent of the location of the person [69].

Displacement ventilation introduces the clean air at a slightly lower temperature (3–6 °C lower than room temperature), through floor or wall mounted diffusers. The cold air, supplied at relatively low velocity, spreads over the floor and moves upwards, entrained by flows generated from heat sources (people, equipment etc.), and then it is exhausted close to the ceiling from the better-mixed upper region of the ventilated space. Under these conditions airborne cross-infection between occupants (who are not too close to each other) will be low since the warm exhaled air which may carry viruses will rise upward to the ceiling. The problem arises in a dynamic environment, i.e. when people move and cough and the boundary layer around their bodies is disturbed. The airflow pattern is much dependent on local disturbances because air velocity is quite low (except near the floor and in thermal plumes generated by people, office equipment etc.). For example, in a room with a standard height of 2.6 m and an air change rate of unity approximate calculation gives an average upward velocity of $0.7 \times 10–3$ m/s, i.e. the height of the room per hour. A walking person (with speed of 1 m/s) in room with displacement ventilation may cause air mixing close to that of mixing ventilation [70]. Mundt [71] studied particle resuspension at 2 and 4 air changes per hour (ACH) in a room with displacement ventilation. She used talcum powder as a "carpet" in front of the air supply, on which a person walked either normally or vigorously. Data for only three particle size ranges (greater than 0.5 μm, 5 μm and 10 μm) were presented although the particle counter used had four ranges, recording also particles greater than 0.25 μm (one reason might have been that the number of particles smaller than 0.5 μm was low). The size distribution of the talcum powder particles used was not specified. The results in all cases indicated elevated levels of particles in the room and within the convection flow of the heated cylinders used to simulate occupants. It may be concluded that when a person walks in a room with displacement ventilation the dispersion of resuspended particles (with diameter from 0.5 μm to 25 μm) resembles that of mixing ventilation. Settled particles on the floor are resuspended in air and brought by the convection flow into the breathing zone of the occupants. This is valid for those particles for which the settling velocity is smaller than the velocity of the free convection flow. The settling velocities (Stoke's Law) reported by Mundt [71] for talcum powder particles with a density of 2700 kg/m^3 and diameter 0.5 μm, 5 μm and 10 μm was respectively 2×10^{-5} m/s, 2×10^{-3} m/s and 8×10^{-3} m/s. With the density of 1746 kg/m^3 for talcum broken, these velocities will be respectively 1.3×10^{-5} m/s, 1.3×10^{-3} m/s and 5.1×10^{-3} m/s. The diameters of resuspended particles of respiratory origin calculated for these settling velocities and the dry density of nonvolatile species in saliva (Na^+, K^+, Cl^-, lactate and glycoprotein) of 88 kg/m^3 (suggested by Nicas et al. [9]) corresponds respectively to 2.2 μm, 22 μm and 45 μm. The latter two diameters are outside the penetration range for the human lungs (only particles with a diameter less than 10 μm can penetrate the lungs) and are easily resuspended by human activities indoors. Therefore particles of respiratory origin, resuspended from the floor, could increase the risk of infection if they carry viable pathogens.

Denés et al. [72] showed that with mixing ventilation the inlet and outlet positions influence particle deposition, and have an accumulative effect with that of increased airflow velocity. Wan and Chao [73] compared four different types of supply-exhaust positions in regard to dispersion of droplet aerosols indoors: ceiling (supply and exhaust located in the ceiling), floor-return (both supply and exhaust placed in the floor), upward (supply in floor, exhaust in ceiling) and downward (supply in ceiling, exhaust in floor). It was found that the downward system performed best in controlling the transmission of infection by exhaled droplets by achieving the best dilution and reducing lateral dispersion indoors. However, no heat sources were present in the room. The convection flow above heat sources would definitely influence the airflow interaction in the room and the dispersal of droplets indoors.

A comparison of the performance of three ventilation supply systems (mixing, displacement and downward air distribution) was carried out in a hospital environment, to determine which was most capable of protecting patients and health care workers from cross-infection due to the inhalation of droplet nuclei [8]. The downward ventilation performed like the mixing ventilation, due to the counter flow from the free convection around the human body. So although it is recommended for clean rooms, infectious wards and operating theaters, downward air distribution may not always protect people from cross-infection. Displacement ventilation performed worse when patient was lieing face sideways, because the exhalation jet persisted over a very long distance, assisted by the thermal stratification.

Underfloor ventilation has been shown to provide air quality similar to that achieved by displacement ventilation when supplied air was discharged vertically upwards and not horizontally [74]. The inhaled air quality was found to deteriorate when increasing the throw of the supply jet from the floor diffuser. The supply jet promotes mixing close to the floor, which can promote resuspension of particles (including particles carrying pathogens of respiratory origin) from the floor into the air and up into the breathing zone.

Dilution could solve to some extend the problem of controlling the level of pathogens in rooms with total volume ventilation but the limiting factor here would be local thermal discomfort: both mixing and displacement ventilation can cause draught problems. Another issue could be the low cost effectiveness of this approach, due to increased energy use and increased initial costs (bigger ducts, more powerful fans, over-sizing of the HVAC unit etc.). In densely occupied spaces, like theaters, aircraft or vehicle cabins, etc., dilution does help but the risk of transmission of diseases by contact and by droplet transmission, remains high due to proximity of people.

To avoid some of the associated problems of increased dilution, UVGI technology could be used instead. Mounted at the ceiling level, a UVGI unit with louvers would work quite well with mixing ventilation. The enhanced air mixing would transport any pathogens more rapidly to the upper part of the room, where they would be inactivated, but this approach would clearly be less effective when applied to displacement ventilation. Once they had been transported by the warm convection flow around humans, the pathogens would be exhausted close to the ceiling. This would be the case when the gravity forces acting on the droplets are small compared to the velocity of the free convection flow, or they would leave the jet and be deposited in the room. The appropriate UVGI technology here is in-duct installation, provided recirculation is available. This approach is therefore useful for large halls with displacement ventilation, where people spent most of the time seated: theaters, concert halls, offices, etc. [75,76]. Filtration could also be used to control the pathogen levels in such buildings. However filters are not efficient in protecting occupants if pathogens are generated inside the occupied space. In duct installation they are effective at removing the microorganisms or toxins present in the outside air. Sometimes filters themselves can become a source of bacterial growth and thus contribute to high pathogen levels in the respirable range: less than 1.1 μm, especially at elevated humidity, higher than 80% RH [77]. As mentioned above, PCO may generate by-products which can reduce perceived indoor

air quality or in themselves are hazardous. Economy is another important point for consideration: filters need to be regularly changed, as does the catalytic coating of the PCO unit and both types of unit add additional flow resistance to the HVAC system, resulting in a requirement for more powerful fans. In rooms with mixing ventilation an alternative solution can be the usage of chilled-beams or convectors, recirculating part of the room air through a heat exchanger and a local HEPA filter or a UVGI unit.

4.2. Advanced air distribution methods

There is a need for new air distribution systems that reduce to a minimum the airborne route of pathogens in occupied volumes and protect occupants from cross-infection to be developed. One possible solution is personalized ventilation (PV) that provides clean air to the breathing zone of each occupant, and thus improves perceived air quality. Improved thermal comfort, by providing individual control of velocity, temperature and direction of the personalized flow to each occupant, is another benefit of PV. PV may thus increase occupants' satisfaction, decrease SBS symptoms, and increase work performance [78]. When properly applied, PV has greater potential than total volume air distribution to protect occupants from airborne pathogens. Research in this area started only recently but there is already evidence that PV in conjunction with mixing ventilation can protect occupants from airborne pathogens and is superior to mixing air distribution alone [79]. Cermak and Melikov [79] applied the model for prediction of the risk of airborne transmission of diseases suggested by Rudnick and Milton [80] to compare the performance of mixing ventilation, underfloor ventilation and personalized ventilation in conjunction with background mixing ventilation. An air terminal device installed on a movable arm and supplying clean air to the face from in front was used. The comparison was based on the reproductive number calculated for influenza in case of a quantum generation rate of 100 quanta per hour. The reproductive number represents the number of secondary infections that arise when a single infectious case is introduced into a population where everyone is susceptible. The calculation was made when one of 30 persons occupying the same room for eight hours was infected. The results are shown in Fig. 1 and indicate that in the case of mixing ventilation and a supply rate of 10 l/s per person, it is likely that 7 out of 30 occupants will contract influenza in the course of one working day. The number of possibly infected persons decreases to just two (one already infected and one secondarily infected) if either the ventilation rate is increased to 40 l/s per person or an underfloor system (UFAD) with a short throw is employed. The use of PV is shown to reduce the risk of any cross-infection to a very low level.

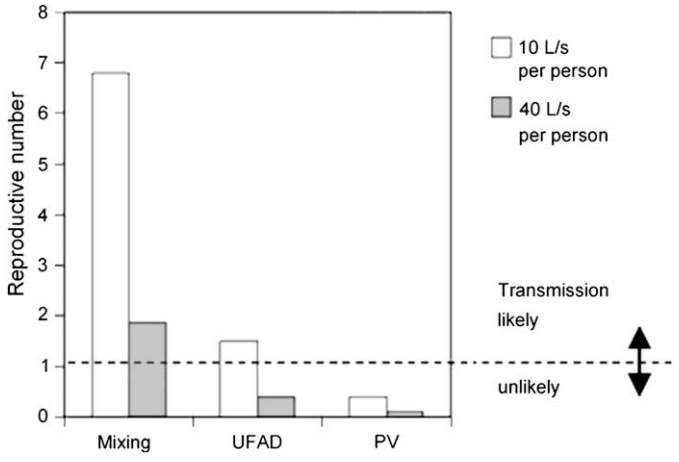

Fig. 1. Reproductive number for influenza, for different ventilation systems and outdoor air supply rates. The normalized concentration was 1, 0.2, and 0.05 in the cases shown from left to right [77].

Apart from protecting occupants, PV may also facilitate the transport of exhaled pathogens, in the case where the host individual uses PV while the other occupants do not use any PV for protection. In rooms with displacement ventilation, PV promotes mixing of the exhaled air with room air [81,84]. This is also true for rooms with underfloor ventilation [79,82–84]. There is therefore a risk of transmission of airborne infections to occupants who are not protected by high efficiency PV, e.g. occupants who are not at their work places. PV has been reported to improve the perceived air quality as well as to protect the user from cross-infection when applied with downward ventilation in rooms with textile air terminals [85].

Most existing PV designs are for desk mounted air supply devices. Bolashikov et al. [86] reported on an air terminal device (named Round Movable Arm, RMP) for installation on a desk, providing nearly 100% clean air for inhalation. A solution that incorporates the PV air supply diffusers into the headrest of the user's chair has recently been proposed [87]. In this case, over 90% of the inhaled air was clean air at PV flow rates above 8 l/s per person. The performance of this system was found to be dependent on the position of the head relative to the diffusers, the angle of the diffusers themselves, the clothing insulation of the occupant, the thermal insulation of the seat and the ambient air temperature. Niu et al. [88] studied a ventilated seat with an adjustable personalized air supply nozzle. Eight different nozzles were studied in terms of their effectiveness in reducing exposure to pollutants and personalized air utilization efficiency (the proportion of actual personalized air in inhaled air to the total supplied personalized air). The best nozzle managed to achieve 80% of clean PV air in the air inhaled. Human subject tests were also performed. People found the air quality better, but at high flow rates (1.6 l/s) they felt draught. Nielsen et al. [89] proposed a low velocity personalized ventilation system (LVPV) discharging supply air at very low velocities (laminar flow) and relying on the entrainment of this clean PV air from the natural convection flow around the human body. Their designs were for a person seated in a chair and included a neck support pillow and a complete seat cover (placed on the seat and backrest of the chair, with the whole surface being the air outlet) and a seat cover which was partially open in areas along the two sides of the seat. The effectiveness of the pillow reached 94% of clean air in the air inhaled and 80% for the seat cover, in both cases for flow rates above 14 l/s.

Among other factors, the performance PV systems installed in desks and chairs depends on their users' activity, body posture and movement. Such designs protect occupants from airborne transmission of infectious agents only when the user is seated at the desk. This narrows their usefulness. Bolashikov et al. [86] used a headset to supply clean air just in front of the mouth and the nose, in order to overcome the disadvantages described above. They achieved up to 80% clean air in inhalation. The close proximity of the Headset supply orifice to the breathing zone makes it applicable in places where there is high occupation density and hence an elevated risk of airborne infection (theaters, cinemas, airplanes etc.).

Low velocity personalized ventilation, based on a ventilated pillow and a ventilated blanket for application in the hospital environment as a way of limiting cross-infection, was studied and reported by Nielsen et al. [90]. The performance of these devices was studied in regard to the patient and not the health care workers or visitors. The efficiency of both devices was found to be dependent on the position of the patient: lying on one side or on the back. The highest efficiency was achieved for a patient lying on his side: almost 95% of the inhaled air was clean PV air. When lying on the back less clean air was able to reach the breathing zone of the

patient. This was due to the low supply velocities: the entrainment rate of the clean PV air by the natural convection flow was low and it was pushed aside before reaching the nose/mouth.

The positive feature of the advanced air distribution methods discussed above is their feasibility and the relatively small flow rates used, as well as their close proximity to the occupant. A HEPA filter or UVGI unit can be included in PV systems that use room air to ensure that each occupant receives air that is clean and free from pathogens. This would further improve the efficiency of the PV system. However field studies are required to evaluate the magnitude of this improvement.

5. Concluding remarks

The concern of airborne transmission of respiratory diseases and the associated risks of epidemics or pandemics increases. The successful solution of the problem requires multidisciplinary research involving epidemiologists, hygienists, engineers and experts in other fields. The knowledge on generation of pathogen laden droplets due to respiratory activities, survivability of the pathogens, their dispersal indoors and their transfer to a healthy person is incomplete. There is need for development of new and efficient technologies for disinfection of air in spaces. Present methods for air distribution indoors are inefficient with regard to decreasing the risk of airborne transmission of diseases. Advanced methods for air distribution indoors are needed for protecting people from cross-infection.

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