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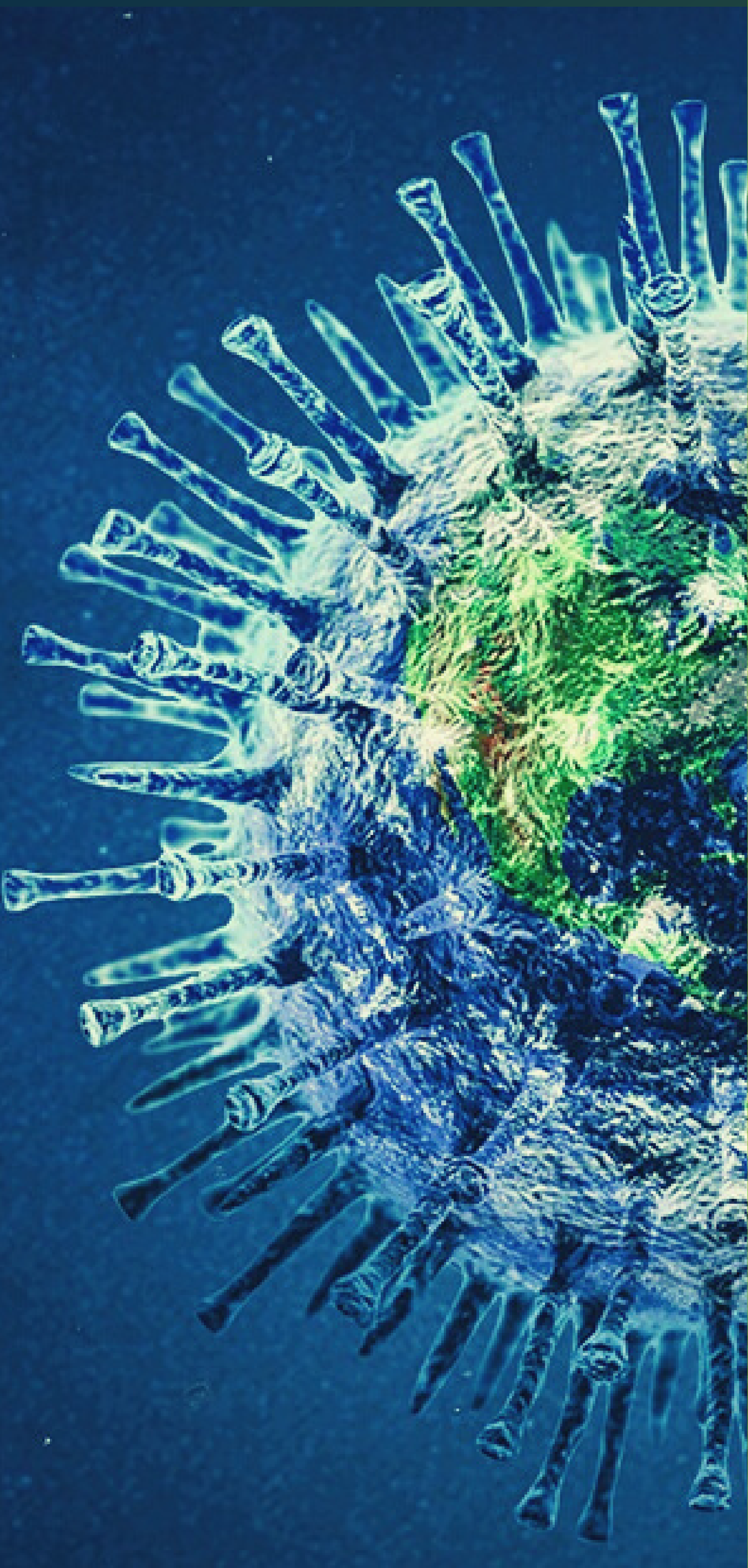

REHVA COVID19 GUIDANCE

version 4.0

How to operate HVAC and other building service systems to prevent the spread of the coronavirus (SARS-CoV-2) disease (COVID-19) in workplaces

REHVA
Federation of European Heating, Ventilation and Air Conditioning Associations

REHVA COVID-19 guidance document

How to operate HVAC and other building service systems to prevent the spread of the coronavirus (SARS-CoV-2) disease (COVID-19) in workplaces

November 17, 2020

This document updates all previous versions, i.e.: August 3, April 3, and March 17. Further updates will follow as necessary.

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1 Introduction

In this document, REHVA summarises advice on the operation and use of building service systems during an epidemic of a coronavirus disease (COVID-19), to reduce the risk of transmission of COVID-19 depending on HVAC (Heating, Ventilation, and Air Conditioning) systems related factors. The advice below should be treated as *interim* guidance; the document may be complemented with new evidence and information when it becomes available.

The suggestions below are meant as an addition to the general guidance for employers and building owners that are presented in the WHO document 'Getting workplaces ready for COVID-19'. The text below is intended primarily for HVAC professionals and facility managers. It may be useful for occupational and public health specialists and other professionals involved in decisions on how to use buildings.

In this document, building services related precautions are covered. The scope is limited to commercial and public buildings (e.g., offices, schools, shopping areas, sports premises, etc.) where only occasional occupancy of infected persons is expected, and some advice is given for temporary hospital and healthcare settings. Residential buildings are out of the scope of this document.

The guidance is focused on temporary, easy-to-organise measures that can be implemented in existing buildings that are in use during or after epidemic with normal or reduced occupancy rates. Some long-term recommendations are also presented.

Disclaimer:

This document expresses REHVA expert advice and views based on the available scientific knowledge of COVID-19 available at the time of publication. In many aspects, SARS-CoV-2 information is not complete and some evidence[1] from previous airborne viruses may have been used for best practice recommendations. REHVA, the contributors and all those involved in the publication exclude all and any liability for any direct, indirect, incidental damages or any other damages that could result from, or be connected with, the use of the information presented in this document.

[1] In the last two decades we have been confronted with three coronavirus disease outbreaks: (i) SARS in 2002-2003 (SARS-CoV-1), (ii) MERS in 2012 (MERS-CoV) and COVID-19 in 2019-2020 (SARS-CoV-2).

Summary

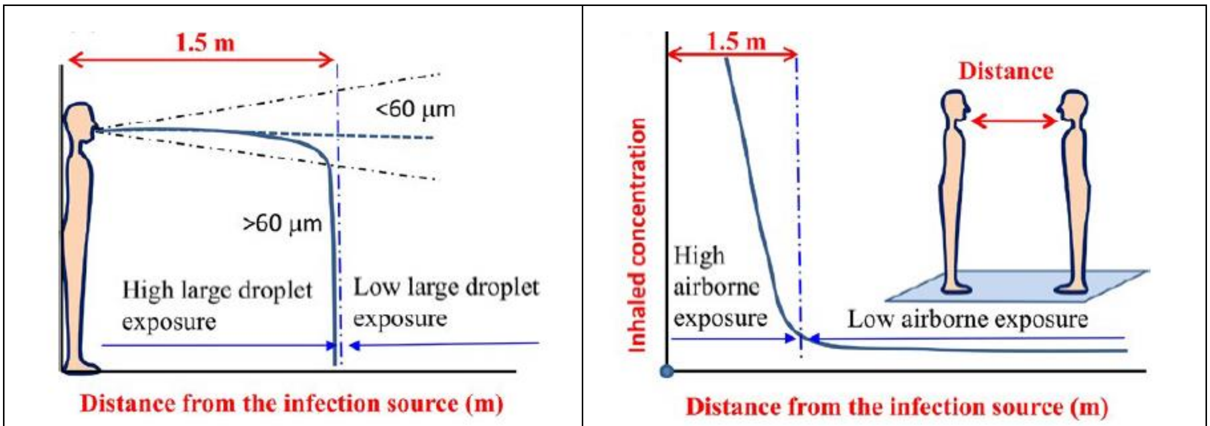
New evidence on SARS-CoV-2 airborne transmission and general recognition of long-range aerosol-based transmission have developed recently. This has made ventilation measures the most important engineering controls in the infection control. While physical distancing is important to avoid a close contact, the risk of an airborne transmission and cross-infection over distances more than 1.5 m from an infected person can be reduced with adequate ventilation and effective air distribution solutions. In such a situation at least three levels of guidance are required: (1) how to operate HVAC and other building services in existing buildings right now during an epidemic; (2) how to conduct a risk assessment and assess the safety of different buildings and rooms; and (3) what would be more far-reaching actions to further reduce the spread of viral diseases in future in buildings with improved ventilation systems. Every space and operation of building is unique and requires specific assessment. We make 15 recommendations that can be applied in existing buildings at a relatively low cost to reduce the number of cross-infections indoors. Regarding airflow rates, more ventilation is always better, but is not the only consideration. Large spaces such as classrooms which are ventilated according to current standards tend to be reasonably safe, but small rooms occupied by a couple of persons show the highest probability of infection even if well ventilated. While there are many possibilities to improve ventilation solutions in future, it is important to recognise that current technology and knowledge already allows the use of many rooms in buildings during a COVID-19 type of outbreak if ventilation meets existing standards and a risk assessment is conducted as described in this document.

2 Transmission routes

It is important for every epidemic to understand the transmission routes of the infectious agent. For COVID-19 and for many other respiratory viruses three transmission routes are dominant: (1) combined droplet and airborne transmission in 1-2 m close contact region arising from droplets and aerosols emitted when sneezing, coughing, singing, shouting, talking and breathing; (2) long-range airborne (aerosol-based) transmission; and (3) surface (fomite) contact through hand-hand, hand-surface, etc. contacts. The means to deal with these routes are physical distance to avoid the close contact, ventilation to avoid airborne transmission and hand hygiene to avoid surface contact. This document mainly focuses on reduction measures of airborne transmission while personal protective equipment such as wearing masks is out of the scope of the document. Additional transmission routes that have gained some attention are the faecal-oral route and resuspension of SARS-CoV-2, which are also addressed in this document.

The size of a coronavirus particle is 80-160 nanometre[2,i] and it remains active on surfaces for many hours or a couple of days unless there is specific cleaning[ii,iii,iv]. In indoor air SARS-CoV-2 can remain active up to 3 hours and up to 2-3 days on room surfaces at common indoor conditions[v]. An airborne virus is not naked but is contained inside expelled respiratory fluid droplets. Large droplets fall down, but small droplets stay airborne and can travel long distances carried by airflows in the rooms and in extract air ducts of ventilation systems, as well as in the supply ducts when air is recirculated. Evidence suggests that airborne transmission has caused, among others, well known infections of SARS-CoV-1 in the past[vi,vii].

Expelled respiratory droplets that are suspended in air (which means airborne), range from less than 1 μm (micrometre = micron) to more than 100 μm in diameter, which is the largest particle size that can be inhaled. They are also referred to as aerosols, i.e. particles suspended in air, since droplets are liquid particles. The main airborne transmission mechanisms are illustrated in Figure 1.



Close contact: combined exposure from droplets and droplet nuclei (aerosols)

Long range: exposure from droplet nuclei (aerosols) can be controlled with sufficient ventilation

Figure 1. The distinction between close contact combined droplet and aerosol transmission (left) and long-range aerosol transmission (right) which can be controlled with ventilation diluting the virus concentration to a low level. (Figure: courtesy L. Liu, Y. Li, P. V. Nielsen et al.xii)

Airborne transmission depends on the droplet size[viii,ixx] and is usually divided into close contact and long-range regions as follows:

1. Short-range droplet transmission region for close contact events can be defined through the distance travelled before the drops and large droplets (up to 2000 μm = 2 mm) fall down to surfaces. At an initial droplet velocity of 10 m/s larger droplets fall down within 1.5 m.

[2] 1 nanometer = 0.001 micron

Respiratory activities correspond to a droplet velocity of 1 m/s for normal breathing, 5 m/s for talking, 10 m/s for coughing and 20-50 m/s for sneezing. Expelled droplets evaporate and desiccate in the air so that the final droplet nuclei shrink to roughly a half or one-third of the initial diameter[xi]. Droplets with initial diameter smaller than 60 μm do not reach the ground before they desiccate entirely and may be carried further than 1.5 m by airflows.

2. Long-range airborne transmission applies beyond 1.5 m distance for droplets <60 μm. Droplet desiccation is a fast process; for instance, 50 μm droplets desiccate in about two seconds and 10 μm droplets in 0.1 s to droplet nuclei with roughly a half of the initial diameter[3]. Droplet nuclei <10 μm may be carried by airflows for long distances since the settling speeds for 10 μm, and 5 μm particles (equilibrium diameter of droplet nuclei) are only 0.3 cm/s and 0.08 cm/s, so it takes about 8.3 and 33 minutes respectively to fall 1.5 m. Because of instant desiccation, the term "droplet" is often used for desiccated droplet nuclei which still include some fluid explaining why viruses can survive. Droplet nuclei form a suspension of particles in the air, i.e. an aerosol. With effective mixing ventilation, the aerosol concentration is almost constant from 1-1.5 m distance onward. This concentration is most dominantly affected by air change rates in adequately ventilated rooms but is also reduced by deposition and decay of virus-laden particles.

The distance of 1.5 m for large droplets to fall, shown in Figure 2, left, applies if there is no air movement in the room. Usually, air distribution of ventilation and convection air flows of heat gains cause air velocities between 0.05 – 0.2 m/s in typical rooms with human occupancy. Using these velocities as lower and upper bounds together with particle settling velocities allows an estimate of how far droplets can travel before falling 1.5 m under the influence of gravity. These estimates illustrate that even larger than 30 μm droplets can travel much more than 1-2 meters.

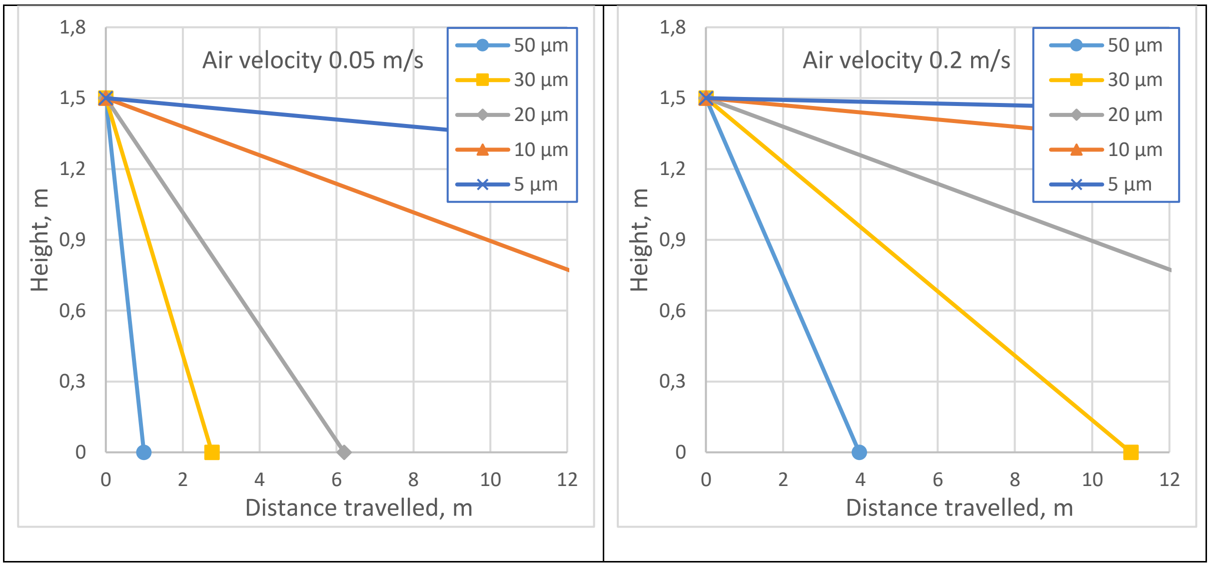


Figure 2. Traveling distance estimates for different sizes of droplets to be carried by room air velocities of 0.05 and 0.2 m/s before settling 1.5 m under the influence of gravity. The travelled distance accounts for movement after the initial jet has relaxed and is calculated with the equilibrium diameter of completely desiccated respiratory droplets (μm values in the figure refer to equilibrium diameters). With turbulence distance travelled is less, but settling time is longer.

More important than how far different size droplets travel, is the distance from the source or infected person at which a low, an almost constant aerosol concentration will be reached. As shown in Figure

[3] Physics of suspended respiratory droplets in air shows that a droplet with initial diameter of 20 μm will evaporate within 0.24 seconds in room air with 50% RH shrinking at the same time to a droplet nuclei with equilibrium diameter of about 10 μm. For this droplet nuclei of 10 μm, including still some fluid, it takes 8.3 minutes to fall down 1.5 m in still air.

1, right, the concentration of droplet nuclei will decrease rapidly within the first 1-1.5 meter from a person's exhalation[xii]. This effect is due to the aerodynamics of the exhalation flow and the flow in the microenvironment around people (plume). The droplet nuclei distribution depends on the position of people, air change rate, the type of air distribution system (e.g., mixing, displacement, or personal ventilation), and other air currents in the space[xiii]. Therefore, close contact within the first 1.5-meter creates high exposure to both large droplets and droplet nuclei that is supported by experimental and numerical studies[xii]. Aerosol concentrations and cross-infection from 1.5 m or more from an infected person can be controlled with adequate ventilation and air distribution solutions. The effect of ventilation is illustrated in Figure 3.

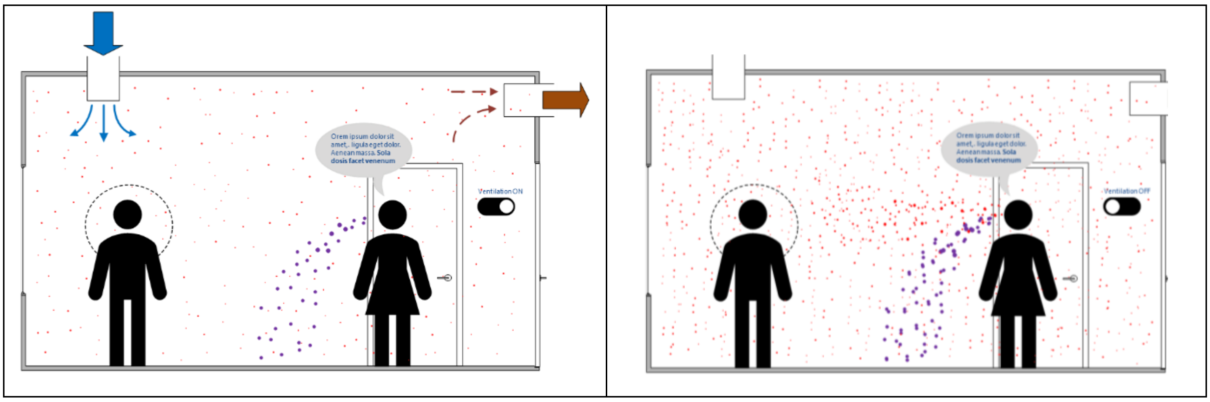


Figure 3. Illustration of how an infected person (speaking woman on the right) leads to aerosol exposure (red spikes) in the breathing zone of another person (man on the left in this case). Large droplet exhalation is marked with purple spikes. When the room is ventilated with mixing ventilation system, the number of virus-laden particles in the breathing zone is much lower than when the ventilation system is off. Left figure: ventilation system on, right figure: ventilation system off.

For SARS-CoV-2, the long-range aerosol-based route with infection through exposure to droplet nuclei particles was first acknowledged by the WHO for hospital aerosol-generating procedures and was addressed in the guidance to increase ventilation[xiv]. Japanese authorities were one of the first to address the possibility of aerosol transmission under certain circumstances, such as when talking to many people at a short distance in an enclosed space, and associated risk of spreading the infection even without coughing or sneezing[xv]. After that, many other authorities have followed including the US CDC, UK Government, Italian Government and the China National Health Commission. Important evidence came from a study[v] concluding that aerosol transmission is plausible, as the virus can remain viable in aerosols for multiple hours. Analyses of superspreading events have shown that closed environments with minimal ventilation strongly contributed to a characteristically high number of secondary infections[xvi]. Well known superspreading events reporting aerosol transmission are from a Guangzhou restaurant[xvii] and Skagit Valley Chorale event[xviii] where outdoor air ventilation rate was as low as 1–2 L/s per person. The fact that substantial evidence has quickly emerged indicating that SARS-CoV-2 is transmitted via aerosols has been required to be generally recognised by many scientists[xixxx]. To date, the European Centre for Disease Prevention and Control (ECDC) review on HVAC-systems in the context of COVID-19 as well as the German Robert-Koch-Institut have recognised aerosol transport[xxixxii]. Finally, after an open letter by 239 scientists[xxiii],the WHO in June 2020 added aerosol transmission to their transmission mode scientific brief[xxiv]. Generally, a long-range aerosol-based transmission mechanism implies that keeping 1-2 m distance from an infected person is not enough, and concentration control with ventilation is needed for effective removal of particles in indoor spaces.

Surface (fomite) contact transmission may occur when expelled large droplets fall on nearby surfaces and objects such as desks and tables. A person may be infected with COVID-19 by touching a surface or object that has the virus on it and then touching their mouth, nose, or possibly their eyes, but US CDC and other have concluded that this route is not thought to be the main way this virus spreads[xxv].

The WHO recognises the faecal-oral, i.e. aerosol/sewage transmission route for SARS-CoV-2 infections[xxvi]. The WHO proposes as a precautionary measure to flush toilets with a closed lid. In this context, it is essential to avoid dried-out drains and U-traps in floors and other sanitary devices by regularly adding water (every three weeks depending on the climate) so that the water seal works appropriately. This prevents aerosol transmission through the sewage system and is in line with observations during the SARS 2002-2003 outbreak: open connections with sewage systems appeared to be a transmission route in an apartment building in Hong Kong (Amoy Garden)[xxvii]. It is known that flushing toilets are creating rising air flows containing droplets and droplet residue when toilets are flushed with open lids. SARS-CoV-2 viruses have been detected in stool samples (reported in recent scientific papers and by the Chinese authorities)[xxviii,xxix,xxx].

Conclusion about the aerosol (airborne) transmission route:
New evidence and general recognition of the aerosol-based transmission route have been developed recently. When the first version of this document was published on March 17, 2020, REHVA proposed following the ALARP principle (As Low As Reasonably Practicable) to apply a set of HVAC measures that help to control the aerosol route in buildings. To date, there is evidence on SARS-CoV-2 aerosol-based transmission, and this route is now recognised worldwide. The relative contribution of different transmission routes in the spread of COVID-19 is still under discussion. It also very much situation-dependent whether one transmission route or the other is dominant. For instance in hospitals with an excellent 12 air changes per hour (ACH) ventilation rate, aerosol transmission is mostly eliminated, but in poorly ventilated spaces, it may be dominant. Transmission routes remain an important research subject, and it has already been reported that the short-range aerosol-based route dominates exposure to respiratory infection during close contact[xxxi]. Medical literature has started to talk about a new paradigm of infectious aerosols. It is concluded that there is no evidence to support the concept that most respiratory infections are primarily associated with large droplet transmission, and that small particle aerosols are the rule, rather than the exception, contrary to current guidelines[xxxii]. In the context of buildings and indoor spaces there is no doubt that cross-infection risk may be controlled up to 1.5 m from a person with physical distancing and beyond that distance with ventilation solutions.

3 Heating, ventilation & air-conditioning systems in the context of COVID-19

There are many possible measures that may be taken to mitigate COVID-19 transmission risks in buildings. This document covers recommendations for ventilation solutions as the main ‘engineering controls’, as described in the traditional infection control hierarchy (Figure 4.) to reduce the environmental risks of airborne transmission. According to the hierarchy, ventilation and other HVAC & plumbing related measures are at a higher level than the application of administrative controls and personal protective equipment (including masks). It is therefore very important to consider ventilation and other building services system measures to protect against airborne transmission. These may be applied in existing buildings at a relatively low cost to reduce indoor infection risk.

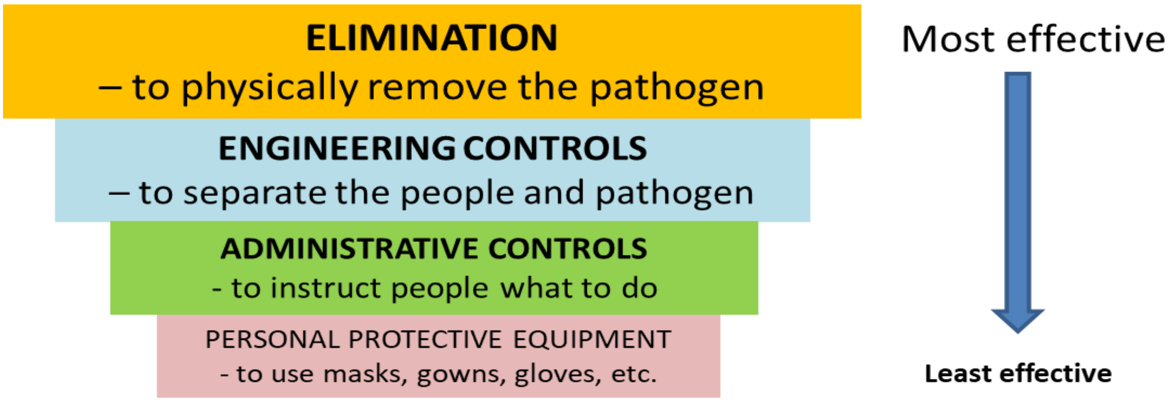


Figure 4.Traditional infection control pyramid adapted from the US Centers for Disease Controlxxxiii.

The European Centre for Disease Prevention and Control (ECDC) has prepared guidance for public health authorities in EU/EEA countries and the UK on the ventilation of indoor spaces in the context of COVID-19[xxi]. This guidance is targeted at public health professionals and serves as a basis for REHVA to provide technical and system-specific guidance for HVAC professionals. The main evidence and conclusions by ECDC can be summarised as follows:

- *The transmission of COVID-19 commonly occurs in enclosed indoor spaces.*
- *There is currently no evidence of human infection with SARS-CoV-2 caused by infectious aerosols distributed through the ventilation system air ducts. The risk is rated as very low.*
- *Well-maintained HVAC systems, including air-conditioning units, securely filter large droplets containing SARS-CoV-2. COVID-19 aerosols (small droplets and droplet nuclei) can spread through HVAC systems within a building or vehicle and stand-alone air-conditioning units if the air is recirculated.*
- *The airflow generated by air-conditioning units may facilitate the spread of droplets excreted by infected people longer distances within indoor spaces.*
- *HVAC systems may have a complementary role in decreasing transmission in indoor spaces by increasing the rate of air change, decreasing the recirculation of air, and increasing the use of outdoor air.*
- *Building administrators should maintain heating, ventilation, and air-conditioning systems according to the manufacturer's current instructions, particularly concerning the cleaning and changing of filters. There is no benefit or need for additional maintenance cycles in connection with COVID-19.*
- *Energy-saving settings, such as demand-controlled ventilation controlled by a timer or* CO_2

<u>detectors, should be avoided</u>.

- *Consideration should be given to <u>extending the operating times of HVAC systems</u> before and after the regular period.*
- *<u>Direct air flow should be diverted away from groups of individuals to avoid pathogen dispersion</u> from infected subjects and transmission.*
- *Organizers and administrators responsible for gatherings and critical infrastructure settings should explore options with the assistance of their technical/maintenance teams to <u>avoid the use of air recirculation as much as possible</u>. They should consider reviewing their procedures for the use of recirculation in HVAC systems based on information provided by the manufacturer or, if unavailable, seeking advice from the manufacturer.*
- *<u>The minimum number of air exchanges per hour, following the applicable building regulations, should be ensured at all times. Increasing the number of air exchanges per hour will reduce the risk of transmission in closed spaces. This may be achieved by natural or mechanical ventilation, depending on the setting</u>.*

In the guideline[xxxiv] ECDC stresses the importance of ventilation by concluding that ensuring the implementation of optimal ventilation adapted to each particular indoor setting could be critical in preventing outbreaks and transmission amplification events. In the guideline the minimum number of air exchanges per hour, in accordance with the applicable building regulations, is required to be ensured at all times. It is stated that increasing the number of air exchanges per hour, by means of natural or mechanical ventilation, will reduce the risk of transmission in closed spaces. Ventilation has seen as a major method because there is no evidence on the effectiveness of methods for decontamination of air (e.g. UV light irradiation) for use in community settings.

4 Practical recommendations for building services operation during an epidemic for infection risk reduction

This REHVA guidance on building services operation covers 15 main items, as illustrated in Figure 5:

1. Ventilation rates
2. Ventilation operation times
3. Overrule of demand control settings
4. Window opening
5. Toilet ventilation
6. Windows in toilets
7. Flushing toilets
8. Recirculation
9. Heat recovery equipment
10. Fan coils and split units
11. Heating, cooling and possible humidification setpoints
12. Duct cleaning
13. Outdoor air and extract air filters
14. Maintenance works
15. Indoor air quality (IAQ) monitoring

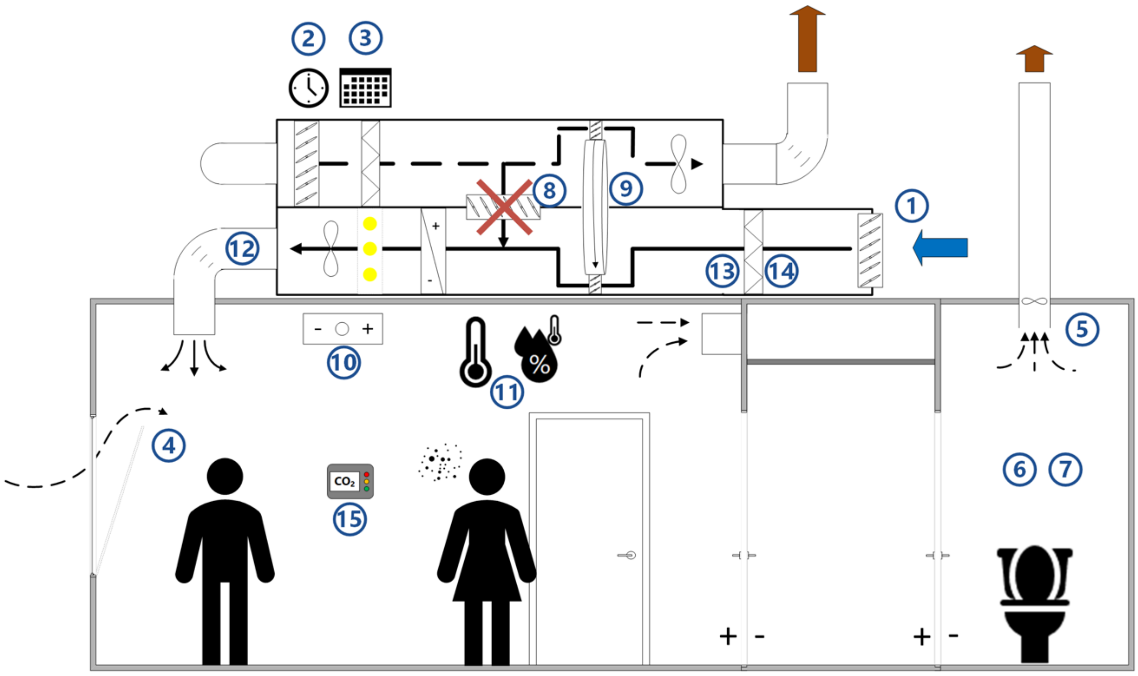


Figure 5. Main items of REHVA guidance for building services operation.

4.1 Increase air supply and exhaust ventilation

In buildings with mechanical ventilation systems, extended operation times are recommended for these systems. Adjust the clock times of system timers to start ventilation at the nominal speed at least 2 hours before the building opening time and switch off or to a lower speed 2 hours after the building usage time. In demand-controlled ventilation systems, change the CO_2 setpoint to 400 ppm in order to maintain the operation at nominal speed. In buildings that have been vacated due to the pandemic (some offices or educational buildings), it is not recommended to switch ventilation off, but to operate continuously at reduced speed during normal operation hours. Extended operation time helps to remove virus particles from the building and to remove released virus particles from surfaces. In winter and summer, increased energy use has to be accepted, because ventilation systems have enough heating and cooling capacity to fulfil these recommendations without compromising thermal comfort.

The general advice is to supply as much outside air as reasonably possible. The key aspect is the total outdoor air flow rate, typically sized as supply air flow rate per square meter of floor area or per person. Clean air delivery rate from an air cleaner adds on to the supply air flow rate (see Appendix 1 for details).

If the number of occupants is reduced, do not concentrate the remaining occupants in smaller areas but maintain or enlarge the physical distance (min 2-3 m between persons) between them to improve the dilution effect of ventilation. More information about ventilation rates and risks in different rooms is provided in Appendix 1.

Exhaust ventilation systems for toilets should be operated in similar mode to the main ventilation system. It should be switched to the nominal speed at least 2 hours before the building opening time and may be switched off or to a lower speed 2 hours after the building usage time.

Additional ventilation guidance for patient rooms is provided in Appendix 3 and for school personnel in Appendix 4.

4.2 Use openable windows more

The general recommendation is to stay away from crowded and poorly ventilated spaces. In buildings without mechanical ventilation systems, it is recommended to actively use openable windows (much more than normal, even when this causes some thermal discomfort). Window opening is then the only way to boost air exchange rates. Windows should be opened for approximately 15 min when entering the room (especially when the room was occupied by others beforehand). Also, in buildings with mechanical ventilation, window opening can be used to boost ventilation further.

Open windows in toilets with a passive stack or mechanical exhaust systems may cause a contaminated airflow from the toilet to other rooms, implying that ventilation begins to work in the reverse direction. Open toilet windows should be avoided to maintain negative pressure in the toilets and the right direction of mechanical ventilation. If there is no adequate exhaust ventilation from toilets and window opening in toilets cannot be avoided, it is important to keep windows open also in other spaces to achieve cross flows throughout the building.

4.3 Humidification and air-conditioning have no practical effect

Relative humidity (RH) and temperature contribute to virus viability, droplet nuclei forming, and susceptibility of occupants' mucous membranes. The transmission of some viruses in buildings can be altered by changing air temperatures and humidity levels to reduce the viability of the virus. In the case of SARS-CoV-2, this is unfortunately not an option as coronaviruses are quite resistant to environmental changes and are susceptible only to a very high relative humidity above 80% and a temperature above 30 ˚C[ii,iii,iv], which are not attainable and acceptable in buildings for reasons of thermal comfort and avoiding microbial growth. SARS-CoV-2 has been found viable for 14 days at 4℃; for a day at 37℃ and for 30 minutes at 56℃[xxxv].

SARS-CoV-2 stability (viability) has been tested at a typical indoor temperature of 21-23 ℃ and RH of 65% with very high virus stability at this temperature and RH[xxxvi]. Together with previous evidence on MERS-CoV, it is well documented that humidification up to 65% may have very limited or no effect on the stability of the SARS-CoV-2 virus. The current evidence does not support the view that moderate humidity (RH 40-60%) will be beneficial in reducing the viability of SARS-CoV-2 and so humidification is NOT a method to reduce the viability of SARS-CoV-2.

Small droplets (0.5 – 50 μm) will evaporate faster at any relative humidity (RH) level[xxxvii]. Nasal systems and mucous membranes are more sensitive to infections at very low RH of 10-20 %[xxxviii,xxxix], and for this reason some humidification in winter is sometimes suggested (to levels of 20-30%), although the use of humidifiers has been associated with higher amounts of total and short-term sick leave[xl].

In buildings equipped with centralised humidification, there is no need to change humidification systems' setpoints (usually 25 or 30%[xli]). Usually, any adjustment of setpoints for heating or cooling systems is not needed, and systems can be operated normally, as there is no direct implication for the risk of transmission of SARS-CoV-2.

4.4 Safe use of heat recovery sections

Virus particle transmission via heat recovery devices is not an issue when an HVAC system is equipped with a twin coil unit or another heat recovery device that guarantees 100% air separation between the return and supply side[xlii].

Some heat recovery devices may carry over particle and gas phase pollutants from the exhaust air side to the supply air side via leaks. Rotary air to air heat exchangers (i.e., rotors, called also wheels) may be liable to significant leakage in the case of poor design and maintenance. For properly operating rotary heat exchangers, fitted with purging sectors and correctly set up, leakage rates are very low, being in the range of 0-2% that is in practice insignificant. For existing systems, the leakage should be below 5% and should be compensated with increased outdoor air ventilation, according to EN 16798-3:2017. However, many rotary heat exchangers may not be properly installed. The most common fault is that the fans have been mounted in such a way as to create a higher pressure on the exhaust air side. This will cause leakage from the extract air into the supply air. The degree of uncontrolled transfer of polluted extract air can in these cases be of the order of 20%[xliii], which is not acceptable.

It has been shown that rotary heat exchangers which are properly constructed, installed, and maintained have almost zero transfer of particle-bound pollutants (including air-borne bacteria, viruses, and fungi), and the transfer is limited to gaseous pollutants such as tobacco smoke and other smells[xliv]. There is no evidence that virus-laden particles larger than about 0.2 μm would be transferred across the wheel. Because the major part of the leakage is caused by the pressure differences between supply and exhaust air, stopping the rotor will have only a minor impact of the leakage. Therefore, its not necessary to switch the rotor off. The normal operation of rotors makes it also easier to keep ventilation rates higher. It is known that the carry-over leakage is highest at low airflow, so higher ventilation rates should be used as recommended in Section 4.1.

If critical leaks are detected in the heat recovery sections, pressure adjustment or bypassing (some systems may be equipped with bypass) can be an option to avoid a situation where higher pressure on the extract side will cause air leakage to the supply side. Pressure differences can be corrected by dampers or by other reasonable arrangements. In conclusion, we recommend inspecting the heat recovery equipment, including measuring the pressure difference and estimating leakage based on temperature measurement, see Appendix 2.

4.5 No use of central recirculation

Viral material in extract (return) air ducts may re-enter a building when centralised air handling units are equipped with recirculation sectors. The general recommendation is to avoid central recirculation during SARS-CoV-2 episodes: close the recirculation dampers either using the Building Management System or manually. This is especially important in buildings that are used by susceptible end-users[4] (e.g. nursing homes).

[4] In hospitals the use of recirculation is strictly forbidden in many countries.

Sometimes, air handling units and recirculation sections are equipped with return air filters. This should not be a reason to keep recirculation dampers open as these filters normally do not filter out viral material effectively since they have coarse or medium filter efficiencies (G4/M5 or ISO coarse/ePM10 filter class).

In air systems and air-and-water systems where central recirculation cannot be avoided because of limited cooling or heating capacity, the outdoor air fraction has to be increased as much as possible and additional measures are recommended for return air filtering. To completely remove particles and viruses from the return air, HEPA filters would be needed. However, due to a higher pressure drop and special required filter frames, HEPA filters are usually not easy to install in existing systems. Alternatively, duct installation of disinfection devices, such as ultraviolet germicidal irradiation (UVGI) also called germicidal ultraviolet (GUV), may be used. It is essential that this equipment is correctly sized and installed. If technically possible, it is preferred to mount a higher-class filter in existing frames and to increase exhaust fan pressure without reducing the airflow rate. A minimum improvement is the replacement of existing low-efficiency return air filters with ePM1 80% (former F8) filters. The filters of the former F8 class have a reasonable capture efficiency for virus-laden particles (capture efficiency 65-90% for PM1).

4.6 Room level circulation: fan coil, split and induction units

In rooms with fan coils only or split units (all-water or direct expansion systems), the first priority is to achieve adequate outdoor air ventilation. In such systems, the fan coils or split units are usually independent of mechanical ventilation which in some cases even might not exist, and there are two possible options to achieve ventilation:

1. Active operation of window opening together with the installation of CO_2 monitors as indicators of outdoor air ventilation;
2. Installation of a standalone mechanical ventilation system (either local or centralised without recirculation, according to its technical feasibility). This is the only way to ensure a sufficient outdoor air supply in the rooms at all times.

If option 1 is used, CO_2 monitors are important, because fan coils and split units with both cooling or heating functions improve thermal comfort, and it may take too long before occupants perceive poor air quality and lack of ventilation[xlv]. During hours of occupation leave windows partially open (if openable) to increase the level of ventilation. See an example of a CO_2 monitor in Appendix 4, Figure 17.

Fan coil units have coarse filters that practically do not filter smaller particles but may still collect potentially contaminated particles. Standard maintenance procedures are to be followed with recommendations provided in Section 4.9.

Split units and sometimes fan coils may cause high air velocities. In common spaces (larger rooms with fan coil or split units occupied by many persons), in the case of local air velocities of 0.3 m/s or more, directed air flows from one person to another should be avoided with workplaces arrangements or air jet adjustments.

4.7 Duct cleaning has no practical effect

There have been some overreactive statements recommending cleaning ventilation ducts to avoid SARS-CoV-2 transmission via ventilation systems. Duct cleaning is not effective against room-to-room infection because the ventilation system is not a contamination source if the above guidance about heat recovery and recirculation is followed. Viruses attached to small particles will not deposit easily in ventilation ducts and will normally be carried out by the airflow.[xlvi]. Therefore, no changes are needed to normal duct cleaning and maintenance procedures. Much more important is to increase the outside air supply and to avoid recirculation of air according to the recommendations above.

4.8 Additional change of outdoor air filters is not necessary

In the COVID-19 context, questions have been asked about filter replacement and the protective effect in very rare cases of outdoor virus contamination, for instance, if air exhausts are close to air intakes. Modern ventilation systems (air handling units) are equipped with fine outdoor air filters right after the outdoor air intake (filter class F7 or F8[5] or ISO ePM2.5 or ePM1), which filter particulate matter from the outdoor air well. The size of the smallest viral particles in respiratory aerosols is about 0.2 μm (PM0.2), smaller than the capture area of F8 filters (capture efficiency 65-90% for PM1). Still, the majority of viral material is already within the capture area of filters. This implies that in rare cases of virus-contaminated outdoor air, standard fine outdoor air filters provide reasonable protection for a low concentration and occasional occurrence of viral material in outdoor air.

Heat recovery and recirculation sections are equipped with less effective medium or coarse extract air filters (G4/M5 or ISO coarse/ePM10) whose aim is to protect equipment against dust. These filters have a very low capture efficiency for viral material (see Section 4.4 for heat recovery and 4.5 for recirculation).

From the filter replacement perspective, normal maintenance procedures can be used. Clogged filters are not a source of contamination in this context, but they reduce supply airflow, which has a negative effect on reducing indoor contamination levels. Thus, filters must be replaced according to the normal procedures when pressure or time limits are exceeded, or according to scheduled maintenance. In conclusion, it is not recommended to change existing outdoor air filters and replace them with other types of filters, nor it is recommended to change them sooner than usual.

4.9 Safety procedures for maintenance personnel

HVAC maintenance personnel may be at risk when conducting scheduled maintenance, inspection or replacement of filters (especially extract air filters) if standard safety procedures are not followed. To be safe, always assume that filters, extract air ducts, and heat recovery equipment may have active microbiological material on them, including viable viruses. This is particularly important in any building where there has recently been an infection. Filters should be changed with the system turned off, while wearing gloves and respiratory protection and disposed of in a sealed bag.

4.10 Room air cleaners and UVGI can be useful in specific situations

Room air cleaners remove particles from the air, which provides a similar effect compared to the outdoor air ventilation. To be effective, air cleaners need to have HEPA filter efficiency, i.e., to have a HEPA filter as the last step. Unfortunately, most attractively priced room air cleaners are not effective enough. Devices that use electrostatic filtration principles instead of HEPA filters (not the same as room ionizers!) often work with similar efficiency. Because the airflow through air cleaners is limited, the floor area they can serve is usually quite small. To select the right size air cleaner, the airflow capacity of the unit (at an acceptable noise level) has to be at least 2 ACH and will have positive effect until 5 ACH[xlvii] (calculate the airflow rate through the air cleaner in m^3/h by multiplying the room volume by 2 or 5). If air cleaners are used in large spaces, they need to be placed close to people in a space and should not be placed in the corner and out of sight. Special UVGI disinfection equipment may be installed in return air ducts in systems with recirculation, or installed in room, to inactivate viruses and bacteria. Such equipment, mostly used in health care facilities needs to be correctly sized, installed and maintained. Therefore, air cleaners are an easy to apply short term mitigation measure, but in the longer run, ventilation system improvements to achieve adequate

[5] An outdated filter classification of EN779:2012 which is replaced by EN ISO 16890-1:2016, Air filters for general ventilation - Part 1: Technical specifications, requirements and classification system based upon particulate matter efficiency (ePM).

outdoor air ventilation rates are needed.

4.11 Toilet lid use instructions

If toilet seats are equipped with lids, it is recommended to flush the toilets with lids closed to minimize the release of droplets and droplet residues from air flows[xlviii,xxvi]. Building occupants should be clearly instructed to use the lids. Water seals must work at all times[xxvii]. Regularly check the water seals (drains and U-traps) and add water if required, at least every three weeks.

4.12 Risk of Legionellosis after shut-down

Throughout the duration of the SARS-CoV-2 (COVID-19) epidemic, many buildings have been experiencing reduced use or complete shut-down over extended periods of time. This includes, for example, hotels/resorts, schools, sports facilities, gyms, swimming pools, bath houses and many other types of buildings and facilities equipped with HVAC and water systems.

Depending on a variety of factors, including system layout and design, prolonged reduced (or no) use can lead to water stagnation in parts of the HVAC and water systems, enhancing the risks of an outbreak of Legionnaires' disease (Legionellosis) upon reassuming full operation.

Before restarting the system, a thorough risk analysis should be carried out to assess any Legionellosis risks involved. Several relevant authorities provide information on related risk assessment and restart procedures, including[xlix,l,li,lii,liii].

4.13 IAQ monitoring

The risk of indoor cross-contamination via aerosols is very high when rooms are not ventilated well. If ventilation control needs actions by occupants (hybrid or natural ventilation systems) or there is no dedicated ventilation system in the building, it is recommended to install CO_2 sensors at the occupied zone that warn against underventilation especially in spaces that are often used for one hour or more by groups of people, such as classrooms, meeting rooms and restaurants. During an epidemic it is recommended to temporarily change the default settings of the traffic light indicator so that the yellow/orange light (or warning) is set to 800 ppm and the red light (or alarm) up to 1000 ppm in order trigger prompt action to achieve sufficient ventilation even in situations with reduced occupancy. In some cases, standalone CO_2 sensors or 'CO_2 traffic lights' can be used, see an example in Appendix 4. Sometimes it may work better to use CO_2 sensors that are part of a web-based sensor network. The signals from these sensors can be used to warn building occupants to use operable windows and mechanical ventilation systems with multiple settings in the right way. One can also store the data and provide facility managers with weekly or monthly data reports so that they know what is going on in their building and in rooms with high concentration, helping them to identify the infection risk.

5 Summary of practical measures for building services operation during an epidemic

1. Provide adequate ventilation of spaces with outdoor air
2. Switch ventilation on at nominal speed at least 2 hours before the building opening time and set it off or to lower speed 2 hours after the building usage time
3. Overrule demand-controlled ventilation settings to force the ventilation system to operate at nominal speed
4. Open windows regularly (even in mechanically ventilated buildings)
5. Keep toilet ventilation in operation at nominal speed in similar fashion to the main ventilation system
6. Avoid opening windows in toilets to maintain negative pressure and the right direction of mechanical ventilation air flows
7. Instruct building occupants to flush toilets with closed lid
8. Switch air handling units with recirculation to 100% outdoor air
9. Inspect heat recovery equipment to be sure that leakages are under control
10. Ensure adequate outdoor air ventilation in rooms with fan coils or split units
11. Do not change heating, cooling and possible humidification setpoints
12. Carry out scheduled duct cleaning as normal (additional cleaning is not required)
13. Replace central outdoor air and extract air filters as normal, according to the maintenance schedule
14. Regular filter replacement and maintenance works shall be performed with common protective measures including respiratory protection
15. Introduce an IAQ (CO_2) sensor network that allows occupants and facility managers to monitor that ventilation is operating adequately.

Appendix 1 - Airborne transmission risk assessment and far-reaching actions to reduce the spread of viral diseases in future buildings with improved ventilation systems

1 Introduction

This appendix summarises available information on ventilation rates and provides a method for cross-infection risks assessment which can be applied for typical rooms in non-residential buildings. Available information on COVID-19 allows to argue that transmission of this disease has been associated with close proximity (for which ventilation isn't the solution) and with spaces that are simply inadequately ventilated. The latter is supported by evidence from superspreading events where outdoor air ventilation has been as low as 1–2 L/s per person[xvii,xviii], that is by factor 5–10 lower than commonly recommended 10 L/s per person in existing standards. The question, how much ventilation would be needed to substantially reduce airborne transmission of SARS-CoV-2 and what are other factors such as air distribution and room size that matter is discussed in the following paragraphs. It is important to understand that this topic includes high uncertainties given the current state of knowledge and scientific developments may provide new information quickly. The scope of this appendix applies for long-range airborne transmission reduction only, so the ventilation solutions discussed do not affect 1-2 m close contact and surface contact transmission modes.

2 Ventilation rate, room size and activity effects on infection risk

As discussed in Section 2, at a greater distance than 1.5 m from an infected person, control of virus-containing aerosol concentrations depends on ventilation solutions. The overall dose when exposed to a virus, (for example, when sharing a room with somebody infected) is equal to the product of concentration and time. Thus, to reduce the dose and infection risk, ventilation has to be increased and the occupancy time to be reduced. In existing ventilation systems, it is typically not possible to increase the fan speed significantly, so the system can deliver the performance for which it is sized. Sometimes, it may be possible to increase total airflow rates by 10-20% overall and by balancing possibly more significantly in specific rooms. Other improvement measures are limited to those discussed in Section 4.1.

From a legal point of view, the outdoor air ventilation rate must fulfil at least national minimum requirements set in the local building code or other regulatory documents (which may also include specific regulation for COVID-19). If a national ventilation regulation does not exist, then typically local building laws will always contain a provision for "good building practice", referring to the use of national, European or international standards and guidelines. Typical sizing according to ISO 17772-1:2017 and EN 16798-1:2019 results in default Indoor Climate Category II to 1.5 – 2 L/s per floor m^2 (10–15 L/s per person) outdoor airflow rates in offices and to about 4 L/s per floor m^2 (8-10 L/s per person) in meeting rooms and classrooms.

Ventilation improvement in existing or new buildings brings the question: Are the ventilation rates of Category II enough, or more outdoor air ventilation is needed to reduce the risk of cross-infection? Infection risk is currently not addressed in these standards as a design criterion. On the other hand, cross-infection risk is well known and applied in the design of hospital buildings where it leads to ventilation with a 6-12 ACH rate (see Appendix 3). Hospital ventilation systems have worked well in COVID-19 conditions as cross-infections have been under control, illustrating that high capacity ventilation is capable to keep aerosol concentration at low level. In non-hospital buildings, there are evidently lower emission rates and smaller numbers of infected persons per floor area. So, a lower ventilation rate than in hospitals, for instance Category I ventilation rate, could be considered as a starting point for the risk reduction. It is also worth noting that 4 L/s per floor m^2 in meeting rooms and classrooms corresponds to 5 ACH and is not much below the air change rate of patient rooms with precautions against airborne risks.

Infection risk can be calculated for different activities and rooms using a standard airborne disease transmission Wells-Riley model, calibrated to COVID-19 with correct source strength, i.e., quanta emission rates. In this model, the viral load emitted is expressed in terms of quanta emission rate (E, quanta/h). A quantum is defined as the dose of airborne droplet nuclei required to cause infection in 63% of susceptible persons. With the Wells-Riley model, the probability of infection (p) is related to the number of quanta inhaled (n) according to equation (1)[xi]:

$$p = 1 - e^{-n} \tag{1}$$

The quanta inhaled (n, quanta) depends on the time-average quanta concentration (C_{avg}, quanta/m^3), the volumetric breathing rate of an occupant (Q_b, m^3/h) and the duration of the occupancy (D, h):

$$n = C_{avg} Q_b \mathrm{D} \tag{2}$$

The airborne quanta concentration increases with time from an initial value of zero following a "one minus exponential" form, which is the standard dynamic response of a fully mixed indoor volume to a constant input source. A fully mixed material balance model for the room (equation (3)) can be applied to calculate the concentration:

$$\frac{dC}{dt} = \frac{E}{V} - \lambda C \tag{3}$$

where

E quanta emission rate (quanta/h);

V volume of the room (m^3);

λ first-order loss rate coefficient[liv] for quanta/h due to the summed effects of ventilation (λ_v, 1/h), deposition onto surfaces (λ_{dep}, 1/h), virus decay (k, 1/h) and filtration by portable air cleaner if applied ($k_{filtration}$, 1/h), $\lambda = \lambda_v + \lambda_{dep} + k + k_{filtration}$;

C time-dependent airborne concentration of infectious quanta (quanta/m^3).

The surface deposition loss rate of 0.3 1/h may be estimated based on data from Thatcher[lv] and Diapouli[lvi]. For virus decay Fears[lvii] shows no decay in virus-containing aerosol for 16 hours at 53% RH, whereas Van Doremalen[v] estimated the half-life of airborne SARS-CoV-2 as 1.1 h, which equates to a decay rate of 0.63 1/h. An average value of these two studies is 0.32 1/h.

For portable air cleaner, the filtration removal rate ($k_{filtration}$) depends on the rate of airflow through the HVAC filter (Q_{filter}), and the removal efficiency of the filter (η_{filter}):

$$k_{filtration} = \frac{Q_{filter} \eta_{filter}}{V} \tag{4}$$

For portable cleaners with a High-Efficiency Particle Air (HEPA) filter, the Clean Air Delivery Rate (CADR, m^3/h) is provided and the filtration removal rate can be calculated as $k_{\text{filtration}} = CADR/V$. It should be noted that the removal efficiency of filters and the CADR are particle-size dependent. These parameters are to be estimated based on the size distribution of virus-containing particles. Calculation examples provided in the following are conducted without air cleaners.

Assuming the quanta concentration is 0 at the beginning of the occupancy, equation (3) is solved and the average concentration determined as follows:

$$C(t) = \frac{E}{\lambda V}\left(1 - e^{-\lambda t}\right) \quad (5)$$

$$C_{avg} = \frac{1}{D}\int_0^D C(t)\,dt = \frac{E}{\lambda V}\left[1 - \frac{1}{\lambda D}\left(1 - e^{-\lambda D}\right)\right] \quad (6)$$

where

t time (h).

Calculation examples can be found from papers analysing the Skagit Valley Chorale event[lviii] and quanta generation rates for SARS-CoV-2[lix]. Quanta emission rates vary over a large range of 3 – 300 quanta/h depending strongly on activities so that higher values apply for loud speaking, shouting and singing and also for higher metabolism rates, as shown in Table 1. Volumetric breathing rates depend on the activity being undertaken as shown in Table 2.

Activity	Quanta emission rate, quanta/h
Resting, oral breathing	3.1
Heavy activity, oral breathing	21
Light activity, speaking	42
Light activity, singing (or loudly speaking)	270

Table 1. 85th percentile quanta emission rates for different activitieslx.

Activity	Breathing rate, m^3/h
Standing (office, classroom)	0.54
Talking (meeting room, restaurant)	1.1
Light exercise (shopping)	1.38
Heavy exercise (sports)	3.3

Table 2. Volumetric breathing rateslxilxii.

Although SARS-CoV-2 quanta/h emission values include some uncertainties, it is already possible to calculate infection risk estimates and conduct comparisons on the effect of ventilation and room parameters. Results from such calculations are shown in Figure 6 for commonly used ventilation rates and rooms. It is assumed that in all calculated rooms, there is one infected person. The following time-averaged quanta emission rates calculated from activities shown in Table 1 were used: 5 quanta/h for office work and classroom occupancy, 15 quanta/h for a restaurant, 10 quanta/h for shopping, 21 quanta/h for sports and 19 quanta/h for meeting rooms. While typical COVID-19 infection rates in the general population have been in the magnitude of 1:1000 or 1:10 000, the assumption that only one infected person is in a room that is used by, e.g., 10 (office), 25 (school) or 100 persons (restaurant) is highly valid.

A risk assessment as shown in Figure 6. helps to build a more comprehensive understanding of how virus laden aerosols may be removed by ventilation. The results show that with Category II ventilation rates according to ISO 17772-1:2017 and EN 16798-1:2019, the probability of infection is reasonably low (below 5 %) for open-plan offices, classrooms, well-ventilated restaurants, and for short, no more than 1.5-hour shopping trips or meetings in a large meeting room. Small office rooms occupied by 2-3 persons and small meeting rooms show a greater probability of infection, because even in well ventilated small rooms the airflow per infected person is much smaller than that in large rooms. Therefore, in an epidemic situation small rooms could be safely occupied by one person only. In normally ventilated rooms occupied by one person there is no infection risk at all because of no emission source. There is also a very visible difference between 1 L/s m^2 and 2 L/s m^2 ventilation rate in an open plan office (note that 1 L/s m^2 is below the standard). Speaking and singing activities are associated with high quanta generation, but also physical exercises increase quanta generation and breathing rate that directly affects the dose. Thus, many of indoor sports facilities (excluding swimming pools and large halls) are spaces with higher probability of infection if they are not specially designed for high outdoor ventilation rates.

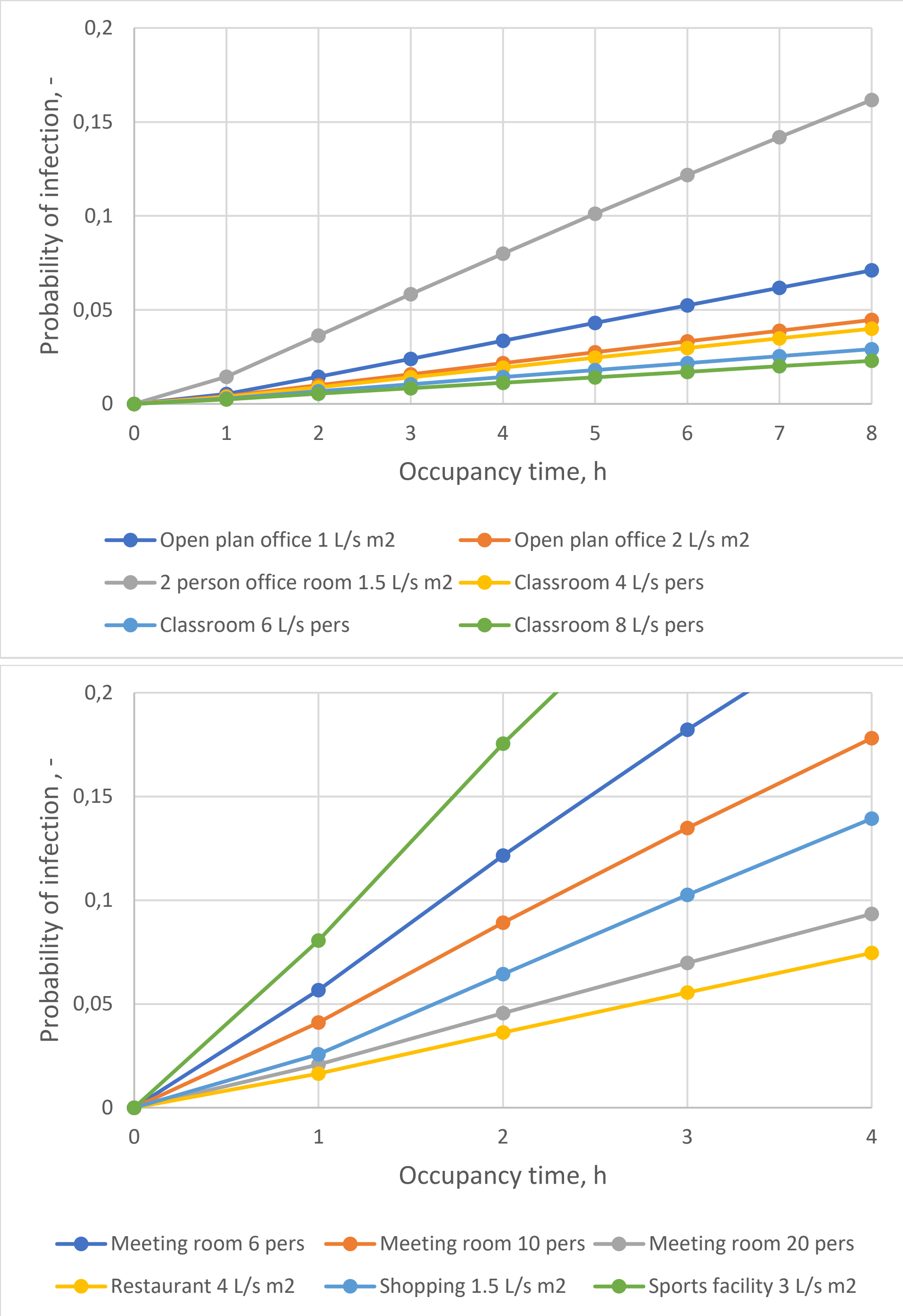


Figure 6. Infection risk assessment for some common non-residential rooms and ventilation rates calculated with the REHVA COVID-19 ventilation calculator. 1.5 L/s per m2 ventilation rate is used in 2 person office room of 16 m2, and 4 L/s per m2 in meeting rooms. Detailed input data is reported in Table 3.

Infection risk probability calculation workflow is illustrated in Table 3. The total airflow rate is calculated as a product of L/s per floor area ventilation rate value and the floor area, therefore the larger the room the larger the total airflow rate per infected person (1 infected person is assumed in all rooms). It should be noted that the number of occupants has no effect because the calculation is per infected person. The room height (volume) matters on the concentration development so that the source E is switched on at time t = 0 and the concentration starts to build up. In the calculation, 8-hour occupancy was considered and the average concentration is quite close to the steady state as the value in the parentheses is higher than 0.9 in all cases (1.0 will correspond to the steady state).

Case Specific Input Parameters													
	Floor area	Height	Ventilation rate per floor area	Qunta emission rate	Breathing rate	Occupancy time	Air change rate	Total first order loss rate	Room volume	x steady state concen-tration	Average concen-tration	Quanta inhaled (dose)	Probability of infection
	A (m^2)	h (m)	L/(s m^2)	quanta/h	m^3/h	Δt (h)	k_{ven} (h^{-1})	k_{tot} (h^{-1})	V (m^3)	[]	quanta/m^3	quanta	-
Open plan office 1 L/s m^2	50	3	1	5	0.54	8	1.2	1.82	150	0.93	0.02	0.07	0.071
Open plan office 2 L/s m^2	50	3	2	5	0.54	8	2.4	3.02	150	0.96	0.01	0.05	0.045
2 person office 1.5 L/s m^2	16	3	1.5	5	0.54	8	1.8	2.42	48	0.95	0.04	0.18	0.162
Meeting room 6 pers	18	3	4	19	1.1	8	4.8	5.42	54	0.98	0.06	0.56	0.428
Meeting room 10 pers	25	3	4	19	1.1	8	4.8	5.42	75	0.98	0.05	0.40	0.331
Meeting room 20 pers	50	3	4	19	1.1	8	4.8	5.42	150	0.98	0.02	0.20	0.182
Classroom 4 L/s pers	56	3	2	5	0.54	8	2.4	3.02	168	0.96	0.01	0.04	0.040
Classroom 6 L/s pers	56	3	3	5	0.54	8	3.6	4.22	168	0.97	0.01	0.03	0.029
Classroom 8 L/s pers	56	3	4	5	0.54	8	4.8	5.42	168	0.98	0.01	0.02	0.023
Restaurant 4 L/s m^2	50	3	4	15	1.1	8	4.8	5.42	150	0.98	0.02	0.16	0.147
Shopping 1.5 L/s m^2	50	3	1.5	11	1.38	8	1.8	2.42	150	0.95	0.03	0.32	0.272
Sports facility 3 L/s m^2	50	3	3	21	3.3	8	3.6	4.22	150	0.97	0.03	0.85	0.573

Table 3. Infection risk probability calculation workflow for the cases reported in Figure 6.

It is important to understand the limitations of the probability calculation:

- Results are sensitive to quanta emission rates which can vary over a large range, as shown in Table 1. The uncertainty of these values is high. Also, there are likely to be super spreaders that are less frequent but may have higher emission rates (as in the choir case[lviii]). This makes absolute probabilities of infection uncertain, and it is better to look at the order-of-magnitude (i.e. is the risk of the order of 0.1% or 1% or 10% or approaching 100%). The relative effect of control measures may be better understood from this calculation, given the current state of knowledge;
- Calculated probability of infection is a statistical value that applies for a large group of persons, but differences in individual risk may be significant depending upon the individual's personal health situation and susceptibility;
- Assuming full mixing creates another uncertainty because, in large and high-ceiling rooms, the virus concentration is not necessarily equal all over the room volume. In the calculation, a 50 m^2 floor area is used for an open-plan office. Generally, up to 4 m high rooms with a maximum volume of 300 m^3 could be reasonably well mixed; however, it is more accurate to simulate concentrations with CFD analyses. Sometimes, thermal plume effects from occupants may provide some additional mixing in high spaces such as theatres or churches.

These limitations and uncertainties mean that rather than predicting an absolute infection risk, the calculation is capable of comparing the relative effectiveness of solutions and ventilation strategies to support the most appropriate choice. The calculation model can show which strategy offers the lowest load for non-infected persons. The model can be applied to show low and high-risk rooms in existing buildings that is highly useful in the risk assessment of how buildings should be used during the outbreak. Calculation results are easy to convert to the form of relative risk. In Figure 7 this is done for an open plan office where 2 L/s per person ventilation rate (0.2 L/s per m^2) with occupant density of 10 m^2 per person is considered as 100% relative risk level. This ventilation rate that is a half of an absolute minimum of 4 L/s per person can be used to describe superspreading events. Results in Figure 7 show that a common ventilation rate of 2 L/s per m^2 will reduce the relative risk to 34% and doubling that value to 4 L/s per m^2 will provide relatively smaller further reduction to 19%.

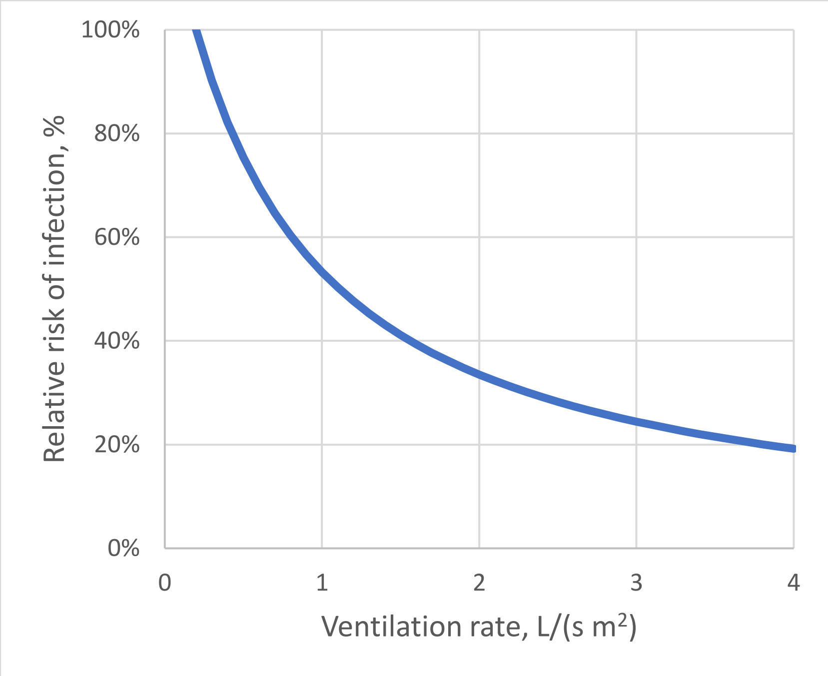


Figure 7. Relative risk in open plan office of 50 m2 where 2 L/s per person (0.2 L/s per m2) ventilation rate is considered as a reference level for a superspreading event with 100% relative risk.

Finally, Figure 7 allows to estimate what is the difference between Category II and I ventilation rates. With 10 m^2 per person occupant density, the airflow rates become 1.4 and 2.0 L/s per m^2 in Category II and I respectively when low polluting materials are considered. Thus, Category II ventilation results in 43% relative risk and Category I in 34% that shows significant improvement as the curve has quite deep slope at that range.

3 CO_2 concentration as a ventilation indicator

An easy way to monitor the ventilation performance is to use CO_2 sensors as recommended in Section 4.13. CO_2 readings describe outdoor ventilation rate adequately under normal occupant density. When persons enter a room, it takes some time before the concentration builds up and reaches the steady state value. In well ventilated rooms, CO_2 concentration builds up quickly, in meeting rooms and classrooms within 30 minutes and in offices less than in one hour. More specifically, the speed of the concentration build-up depends on the room time constant which is reciprocal of air change rate (63% of concentration change happens within 1 time constant and 95% within 3 time constants). Thus, CO_2 readings provide reliable indication about the ventilation sufficiency after the time of couple of the time constants.

At the same ventilation rate, the CO_2 concentration is lower if occupancy is reduced for instance, because of physical distancing or administrative measures. CO_2 concentration dependency on occupant density is illustrated in Figure 8 for an office with two ventilation rates. 2 L/s per m^2 ventilation corresponds to good practice of indoor climate Category I which is capable to keep CO_2 concentration below 800 ppm if there is at least 7 m^2 floor area per occupant. In the case of smaller ventilation rate of 1 L/s per m^2, at least 10 m^2 per person is needed to keep CO_2 concentration below 1000 ppm.

On the CO_2, the bottom line is that high CO_2 indicates poor ventilation without question. Low CO_2 is good, but it's not by its own a confirmation of a low risk of aerosol transmission; occupant density, occupancy duration and room size are to be considered too.

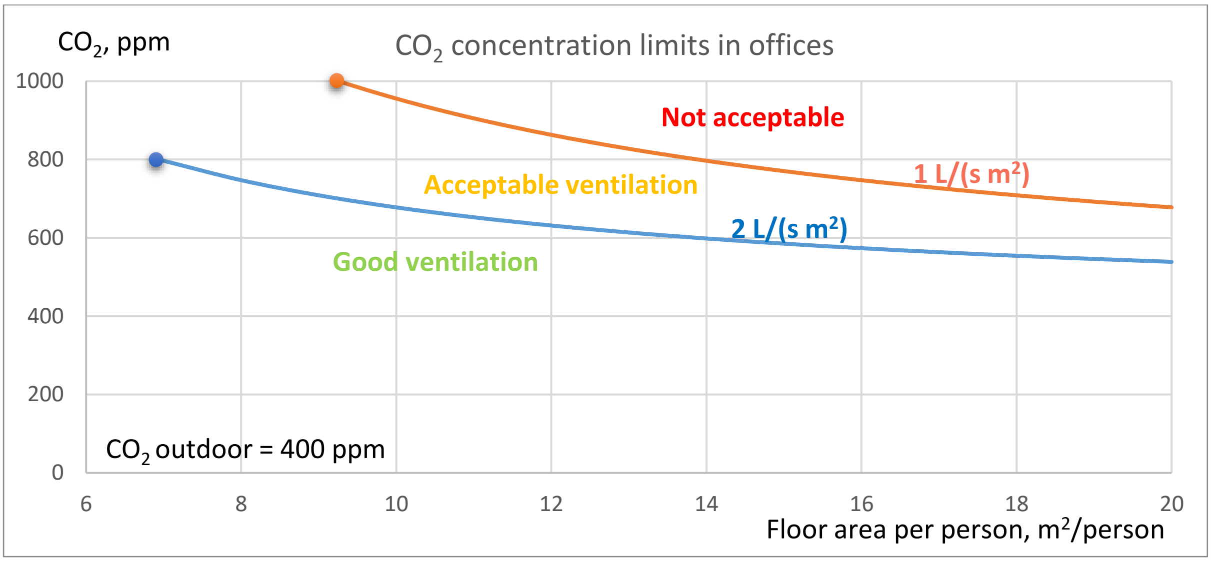


Figure 8. CO_2 concentration (absolute values that include outdoor concentration) dependency on ventilation rate and occupancy in offices.

4 Propagation and spread by air currents directed to a person

While air movement is commonly treated as a draught that is a local thermal discomfort issue, in rooms with an infected person, this can take on a new meaning. Because of studies of a Guangzhou restaurant and some previous airplane infections, this phenomenon of spread by air movement is well known. A strong directed airflow toward an infected person may carry little-diluted viral material in an aerosol towards a susceptible person in a very high concentration, which may propagate the virus within a specific part of the room, as shown by Figure 9. The ECDC addresses this possibility (see Section 3), concluding that "Air flow generated by air-conditioning units may facilitate the spread of droplets excreted by infected people longer distances within indoor spaces." However, in this specific case, it is not known what were the relative contributions of the directed air flow of split unit and the poor ventilation to the infections in the Guangzhou restaurant. Only the combined effect of these two factors is known along with the fact that the ventilation was negligible, being only about 1 L/s per person. This indicates that the very low level of ventilation was likely the main cause of the outbreak in the restaurant.

Although the air conditioning unit was not likely to be the main contributor in this specific case, the issue of directed air flow should be taken seriously in future air distribution design. Low velocity air distribution solutions which do not provide either strong air currents or draughts are already widely available and should now be applied more widely.

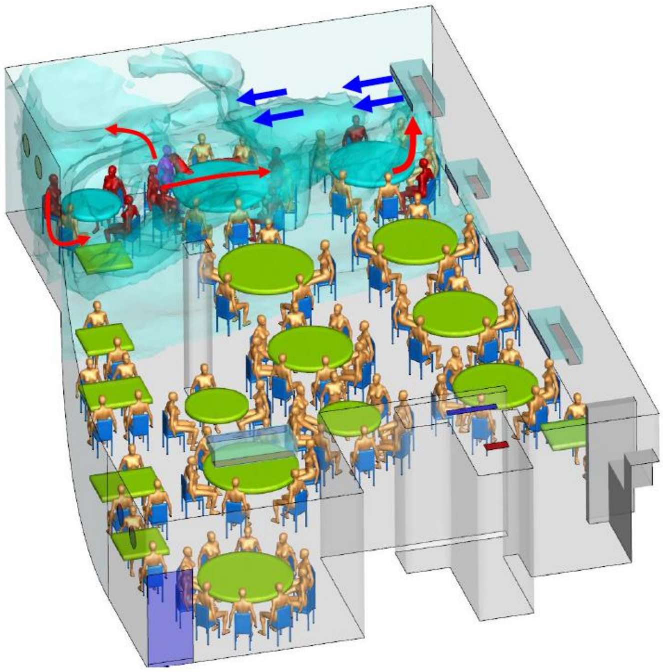


Figure 9. CFD simulated air distribution by split unit in Guangzhou restaurantxvii. The index person is shown with magenta-blue and nine infected persons with red. (Figure: courtesy Yuguo Li

Air distribution may have a crucial effect on the concentration of viral material in room air. It can both locally reduce or increase concentrations remarkably. A number of papers show that assuming well-mixed air in a space is in many cases an oversimplification that fails when it comes to particles and aerosol concentrations. Increasing the ventilation rate may in some situations even increase the concentration in the breathing zone because of unfavourable airflow patterns. Such evidence is reported for some displacement and underfloor systems[lxiii][lxiv].

Generally, viral aerosol concentration control is a new consideration for room air distribution where viral material from a point source (an infected person with unknown location) should be effectively diluted and locally removed at the same time. Therefore, a fully mixing air distribution system, capable of completely mixing contamination from a point source in a large room in one hand, and vertical stratification and exhausts capable of removing the higher concentration before it is completely mixed, would be beneficial. Additionally, personal ventilation solutions can be useful as they help to reduce concentrations locally in workplaces. There is no obvious way to combine such mutually contradictory features. Thus, dilution rates, effectiveness of contaminant removal and efficiency of air changes for all possible types of air distribution including personal ventilation solutions should be the subject for air distribution research. This should consider the situation of one randomly located point source instead of a common situation with more or less equally distributed emission sources distributed in rooms with no infected persons.

5 Cross-contamination aspects of ventilation and AC systems

High ventilation hygiene levels and strict avoidance of any cross-contamination are well known aspects of hospital and industrial ventilation design. In other non-residential buildings the issue is more speculative because of contaminants with lower risks and the more economical and energy-efficient solutions used. The need for more widespread infection control, however, will raise new questions for the use of recirculation and potential leakages in heat recovery equipment, as well as about safe distances between exhaust and intake air openings. Recirculation is technically easy to avoid in any climate, and there are available alternatives, such as more energy-efficient heat, cold, and humidity recovery solutions. However, further research into pollutant transfer may be needed. For instance, pollutant transfer studies of rotors (enthalpy wheels) are more than 20 years old, and more studies about particle and gas-phase transfer and the effects of hygroscopic coatings may also be needed. The same applies to air cleaning technologies for which research and standardization are in the development phase.

6 Summary and the research agenda

While there are many possibilities to improve ventilation solutions in future, it is important to recognise that current technology and knowledge already allows the use of many rooms in buildings during a COVID-19 type of outbreak as long as ventilation rates correspond to or ideally exceed existing standards and a cross-infection risk assessment is conducted (as shown in Section 2). Regarding the airflow rates, more ventilation is always better, but to dilute the aerosol concentration the total airflow rate in L/s per infected person matters. This makes large spaces ventilated according to current standards reasonably safe, but smaller rooms occupied by fewer people and with relatively low airflow rates pose a higher risk even if they are well ventilated. Limiting the number of occupants in small rooms, reducing occupancy time and applying physical distancing will in most cases keep the probability of cross-infection to a reasonable level. For future buildings and ventilation improvement, Category I ventilation rates can be recommended as these provide significant risk reduction compared to common Category II airflow rates.

Proposed research agenda:

- Future research should tackle cross-contamination, air distribution, and outdoor air ventilation capacity aspects as the first priority;
- Quick and affordable retrofit solutions of improved ventilation efficiency resulting in reduction of risk of infection should be a specific focus for existing buildings (that can be developed as a part of energy efficient low carbon retrofit to meet 2030/2050 goals);
- Risk management may be improved by dedicated use of IAQ monitoring systems designed not just to detect high CO_2 concentration situations but designed to translate CO_2 concentration trends (depending upon room size, a normal number of persons present in the room, etc.) into an evaluation of Wells-Riley infection risks;
- Research funding agencies and industry should invest in developing practical technical solutions to protect against the aerosol transmission of infectious diseases in indoor environments, buildings, and on public transport systems;
- Building codes, standards, and guidelines should be revised and updated to improve preparedness for future epidemics;
- The proposed actions will provide concurrent benefits for reducing the risk of airborne transmission of viral diseases and general health in times between epidemics.

Appendix 2 – Inspection of rotary heat exchangers to limit internal leakages

The main indicator of internal leakage of contaminated air leaving the room to supply air through the exchanger is expressed by Exhaust Air Transfer Ratio (EATR) in %. EATR is a function of the pressure difference between the supply air side downstream of the exchanger (p_{22}) and the extract air side upstream of the exchanger (p_{11}), and its value depends on the type of sealing and conditions. But also, the rotor speed and purge sector have an impact on EATR. The main target is to keep over pressure on the supply air side, and in this way, maintain any possible leakage from supply to exhaust air (i.e. EATR = 0%). In well-equipped air handling units (AHUs), pressure taps to measure p_{11} and p_{22} are normally available.

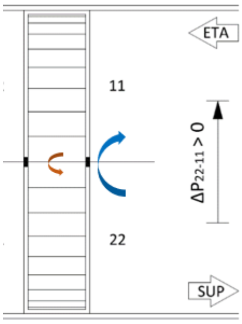


Figure 10. $\Delta P_{22\text{-}11}$ in AHU

For a correctly designed, set-up and maintained rotary heat exchanger, the leakage of potentially contaminated by pathogens extract air to supply air stream is typically very low and without practical meaning. Nevertheless, in the case of incorrect layout of AHU fans or lack of a correct pressure balance setting within the AHU, the leakage may be significantly higher.

Measures to keep the exhaust air leakage low

The air leakage across a rotary heat exchanger depends on a number of factors described below. The facility management staff normally have no impact on the location of fans, but other measures to eliminate or minimise leakage should be taken during commissioning, inspection and regular maintenance.

Correct position of fans

A prerequisite for minimising internal leakages is the correct positioning of fans. The available fans position configurations are shown on Figures 11-14. The most recommended configuration includes both fans located downstream within the exchanger (see Figure 11), In this configuration, with correctly balanced pressures ($p_{22\text{-}11} > 0$) and properly set-up purge sector, EATR is usually below 1%. In contrast, the most adverse configuration in terms of leakage includes both fans on the building side (see Figure 12) In the worst case, for this configuration EATR can amount to as much as 10–20%[6].

[6] Eurovent Recommendation 6-15. Estimation based on Eurovent Certified data.

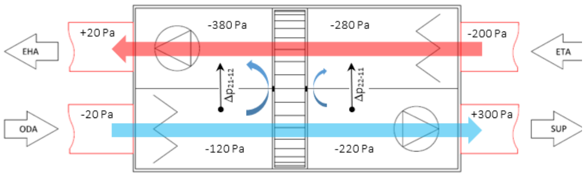


Figure 11. Best configuration. Both fans after the rotor

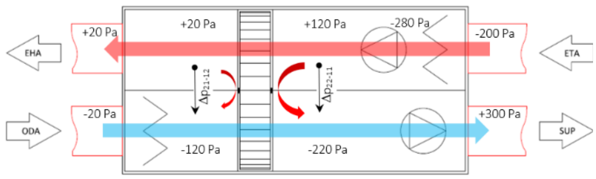


Figure 12. Both fans on building side

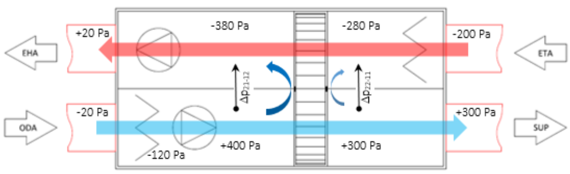


Figure 13 Both fans on the outdoor side

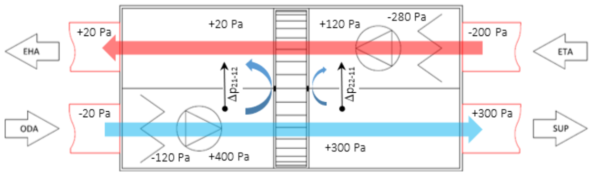


Figure 14 . Both fans upstream the exchanger.

Balancing pressure difference

The next step to minimise a leakage is to set the correct difference between pressures p_{22} and p_{11}. Pressure p_{11} should be at least 20 Pa less than the pressure p_{22}. Depending on the configuration of fans, this can be done by throttling as follows:

- If both fans are placed after the rotor (Figure 11): adjust the throttle in the extract air so p_{11} will become at least p_{22} – 20 Pa. If the throttling device (e.g. damper) is not available in an AHU, it should be installed in the ductwork.
- Both fans on the building side (Figure 12): There is no possibility to use throttling in this case.
- Both fans on the outdoor side (Figure 13): There is no need to use throttling in this case.
- Both fans upstream of the rotor (Figure 14): adjust the throttle in the supply air so p_{11} will become at least p_{22} – 20 Pa. If the throttling device (e.g. damper) is not available in an AHU, it should be installed in the ductwork.

Correct application of the purge sector, position and setting

The purge sector is a device that can practically eliminate the leakage resulting from the rotation of the wheel (carry-over leakage). Its location and setting (angle) must be arranged according to the AHU manufacturer's guidance depending on the configuration of fans and pressure relations.

Effective sealing of the rotor

Perimeter and middle beam sealing prevent air leakage from the supply side to the exhaust side. Seals are subject to wear and their performance deteriorates with time. The condition of the seals should be checked during periodic inspection and, if necessary, the seal should be restored to its original state in accordance with the manufacturer's instructions.

Method to estimate leakage (EATR) for on-site tests

The precise testing of internal air leakage must be carried out in the laboratory. However, a draft of the new upcoming standard prEN308 provides a simple method for estimation of EATR in service using temperature measurements that can be performed on-site. The test procedure includes measurements of temperatures t_{11}, t_{21} and t_{22} in steady-state conditions with the rotor stopped (heat transfer deactivated). Next, EATR is calculated as:

$$EATR = \frac{t_{22} - t_{21}}{t_{11} - t_{21}}$$

Where,

t_{11} is temperature exhaust air inlet;

t_{21} is temperature supply air inlet;

t_{22} is temperature supply air outlet.

Leakage related to the rotation of the wheel (carry-over) cannot be determined by this method.

Appendix 3 - Ventilation in patient rooms

Ventilation systems for special patient rooms like airborne infectious isolation rooms (AIIR) have been well developed for infection risk control[7]. These rooms apply two principles: by preventing the spread of airborne microbes adjoining rooms and the surrounding area and by reducing the amount of airborne microbes in patient room with efficient ventilation. To prevent the spread by airborne transmission from a source patient to susceptible patients and other persons in a patient room, it is important to keep the patient room with negative pressure comparing with adjacent rooms in hospitals. Patient rooms with negative pressure are also known as 'Class N isolation room', 'airborne infection isolation' and 'infectious isolation units'. A few recommendations are presented here specifically for the operation of patient rooms during COVID-19 temporary hospital settings according to several national regulations/standards[8][9][10][11][12]. Generally, hospital ventilation systems designed according to these regulations/standards have provided adequate airborne infection risk control for COVID-19 disease so that no cross-infections have been reported from modern hospitals.

For normal areas/patient rooms:

- Normal patient rooms that are not intended for patients with infectious diseases, need at least 4 air changes per hour (ACH).
- If used for airborne precaution, it should be updated to meet the requirement for isolation rooms, where adequate ventilation is considered to be at least 6 ACH (equivalent to 40 L/s/patient for a 4x2x3 m^3 room).

For temporary areas/wards for patients with infectious diseases:

- Healthcare facilities without enough single isolation rooms in emergency departments should designate a separate, well-ventilated areas/wards where patients with suspected COVID-19 can wait.
- If feasible, ventilation system should be updated to meet the requirement for isolation rooms.

For isolation rooms with airborne infections:

- AIIR air shall be exhausted directly to the outdoors, using HEPA filter whenever it is possible to avoid possible cross contamination if the exhaust air outlet are nearby windows or outdoor air intakes.
- Ensure supply air ducts are independent of the common building supply air system.
- The supply airflow rate should be 6-12 ACH (e.g. equivalent to 40-80 L/s/patient for a 4x2x3 m^3 room) for existing isolation rooms, ideally at least 12 ACH for new constructions. See Figure 15 for illustration of the effect of high airflow rates.
- Recommended negative pressure differential is ≥5 Pa to ensure that air flows from the corridor

[7] Guidelines for the classification and design of isolation rooms in health care facilities, Victorian Advisory Committee on Infection Control 2007. http://docs2.health.vic.gov.au/docs/doc/4AAF777BF1B3C40BCA257D2400820414/$FILE/070303_DHS_ISO%20RoomGuide_web.pdf

[8] ASHRAE Standard 170-2013

[9] VDI 6022 https://www.vdi.de/richtlinien/unsere-richtlinien-highlights/vdi-6022

[10] https://www.fhi.no/publ/eldre/isoleringsveilederen/

[11] https://www.cdc.gov/infectioncontrol/guidelines/environmental/appendix/air.html#tableb2

[12] https://www.who.int/publications/i/item/WHO-2019-nCoV-IPC-2020.4

into the patient room.

- Exhaust air shall be located directly above the patient bed on the ceiling or on the wall.
- Ensure the room is as airtight as possible
- Extract air from the patient room and toilet should not be recirculated and returned to the room.
- Fit a local audible alarm or local visual means in case of fan failure and negative differential pressure is not maintained.
- A separate exhaust system dedicated to each room that removes a quantity of air greater than that of the supply system.
- If possible, anteroom or air lock should be used to prevent the transmission of infectious agent from the door opening of the AIIR.

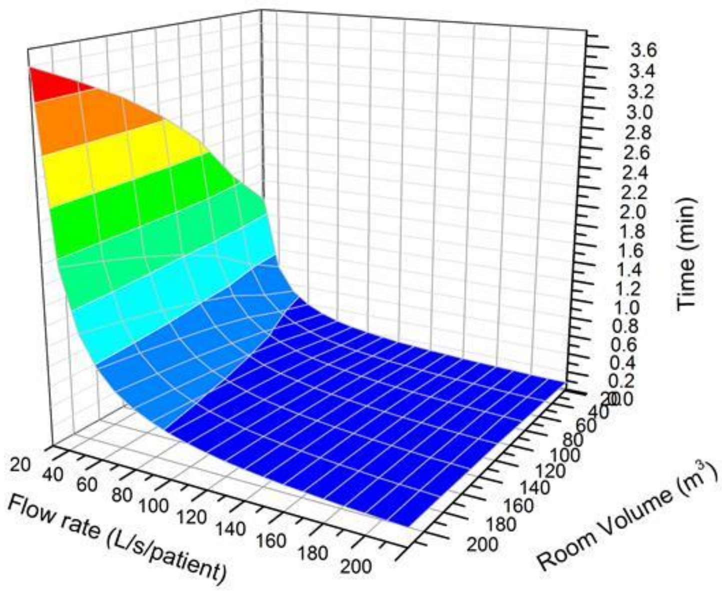


Figure 15. illustration of high airflow rates. Time to replace the air in the room as a function of airflow rate and room volume.

If natural ventilation is used, higher ventilation rates are recommended because of unstable operation of ventilation where sufficient ventilation cannot be guaranteed at all times. Natural ventilation is suitable for the use only in favourable climate conditions. Comprehensive natural ventilation guidance is provided by WHO[13].

[13] Natural Ventilation for Infection Control in Health-Care Settings. WHO 2009. https://www.who.int/water_sanitation_health/publications/natural_ventilation.pdf

Appendix 4 - COVID-19 ventilation and building services guidance for school personnel

In this document we summarise advice on the operation and use of building services in schools, in order to prevent the spread of the coronavirus disease (COVID-19) virus (SARS-CoV-2). This guidance is focussing on school principals, teachers and facility managers.

Before taking preventive measures, it requires some basic understanding of transmission of infectious agents. In relation to COVID-19 four transmission routes can be distinguished:

1. in close contact of 1-2 m via large droplets and aerosols (when sneezing or coughing or talking);
2. via the air through aerosols (desiccated small droplets), which may stay airborne for hours and can be transported long distances (released when breathing, talking, sneezing or coughing);
3. via surface contact (hand-hand, hand-surface etc.);
4. via the faecal-oral route.

More backgrounds on transmission routes of SARS-CoV-2 can be found in Section 2 of this document.

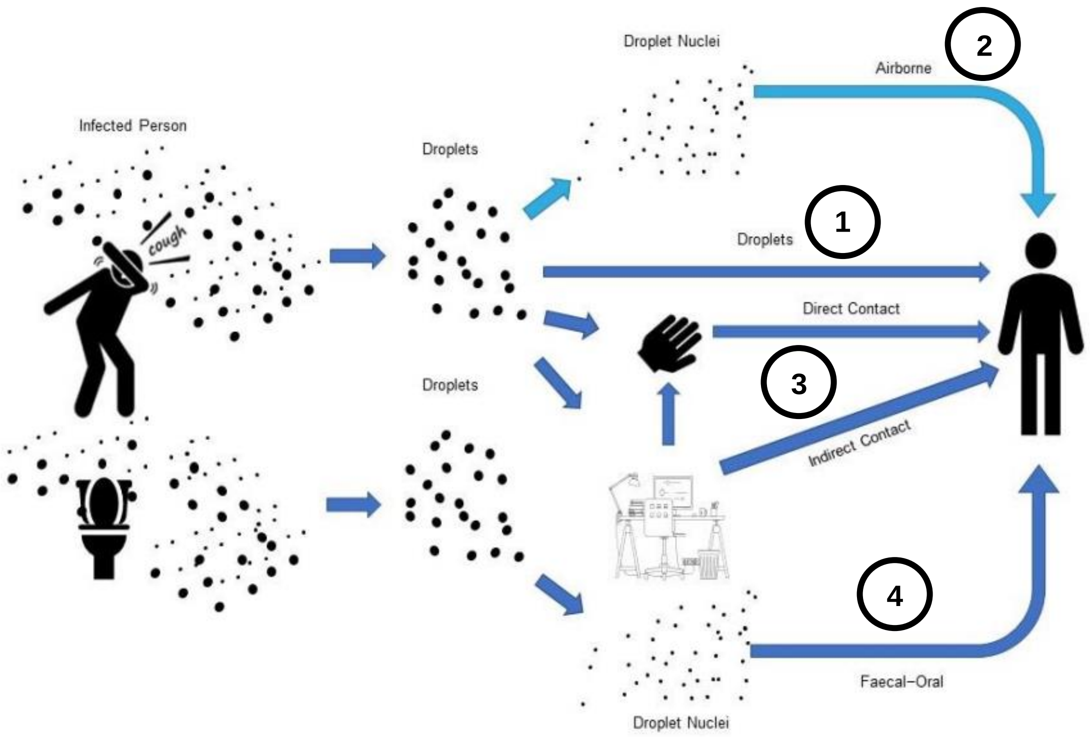


Figure 16. Exposure mechanisms of COVID-19 SARS-CoV-2 droplets. (Figure: courtesy Francesco Franchimon)

General guidance for employers and building owners that is presented in e.g. the WHO document '[Guidance for COVID-19 prevention and control in schools]' and national guidelines focus on monitoring of symptoms, keeping distance and good hygiene practices (transmission routes via large droplets and via surface contact). In order to keep the risk of infection as low as reasonably achievable, we additionally recommend measures on ventilation (airborne transmission) and sanitary installations (faecal-oral transmission).

Ventilation

In many European schools sufficient ventilation is a challenge. Today, many schools in Europe are naturally ventilated (e.g. using windows). Natural ventilation significantly depends on the temperature difference between the indoor and the ambient air and the current wind situation. As a result, a sufficient natural ventilation cannot be guaranteed at all times. Mechanical ventilation systems can ensure a continuous air exchange throughout the year.

Below some practical instructions are given to optimize ventilation in the short-term:

- Secure ventilation of spaces with outdoor air. Check whether the ventilation systems in classrooms, either natural or mechanical, are functioning well:
    - ✓ Check whether windows and grilles can be opened;
    - ✓ Clean ventilations grilles so that the air supply is not obstructed;
    - ✓ Have mechanical ventilation systems checked for their functioning by your maintenance company;
- Install a CO_2 monitor with traffic light indication (Figure 17) at least in the classrooms in which ventilation depends on opening windows and/or outdoor grilles. This visualises the need for extra ventilation by opening windows. Make sure that the CO_2 monitor is placed at a visible position in the classroom, away from fresh air inlets (e.g. open windows), typically on the internal wall at occupied zone height of about 1.5 m. In times of Corona, we suggest to temporarily change the default settings of the traffic light indicator (yellow/orange light up to 800 ppm and red light up to 1000 ppm) in order to promote as much ventilation as possible.

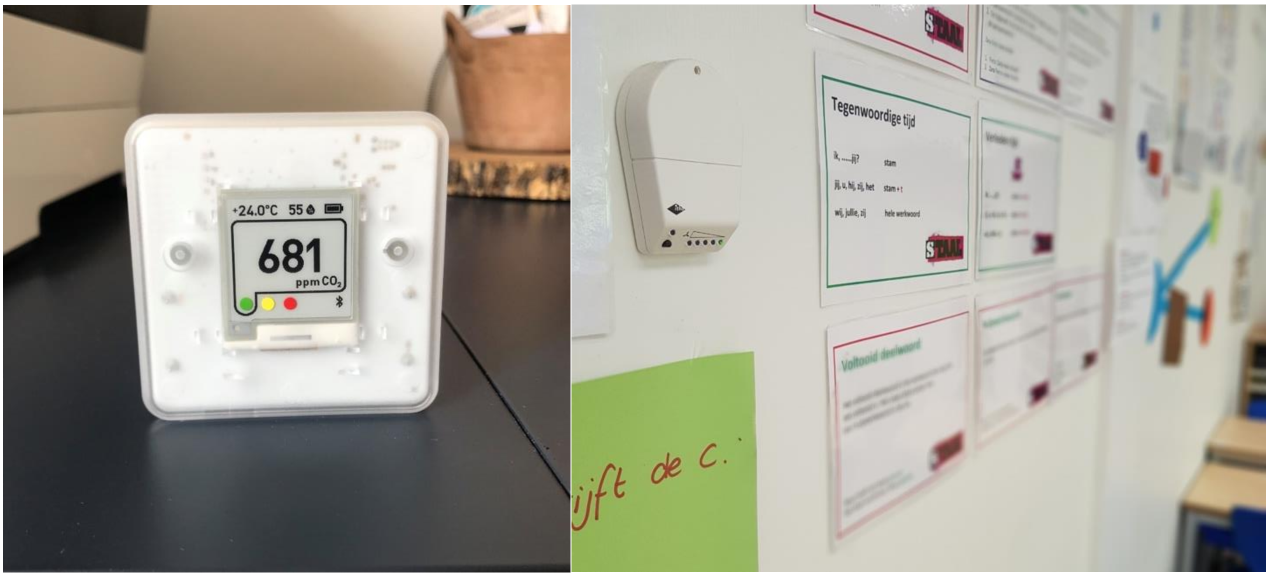


Figure 17. Examples of CO_2 monitors with traffic light indicator showing the indoor air quality.

- Check operating hours of mechanical ventilation systems. Switch ventilation to nominal speed at least 2 hours before the school starts and switch off or to lower speed 2 hours after occupancy. Keep toilet ventilation in the nominal speed in similar fashion as the main ventilation system.[14]
- Switch air handling units with central recirculation to 100% outdoor air.
- Adjust the setpoints of CO_2 controlled ventilation systems (if present). With these systems, the amount of air exchange is automatically reduced with lower occupancy to save energy. In order to reduce the risk of transmission of infectious diseases full ventilation is needed, even if only part of the students is present. Ask your maintenance company if CO_2 controlled ventilation is present in your building. Generally, they are also the ones to adjust the setpoints.
- Give teachers instructions on how to use the ventilation facilities:
    - ✓ Open windows and ventilations' grilles as much as possible during school hours. Opening windows just underneath the ceiling reduces the draught risk. In rooms with mechanical

[14] More detailed ventilation operation guidance is provided in Section 4.1.

air supply and exhaust this is usually not necessary, but extra ventilation is positive and does not disrupt the ventilation system.

- ✓ Ensure regular airing with windows during breaks (also in mechanically ventilated buildings).
- ✓ Make sure that ventilation facilities are not obstructed or blocked by curtains or furniture.
- ✓ Keep an eye on any installed CO_2 monitors (ask pupils to assist). Be aware that more aerosols are released during activities such as singing or sport.
- ✓ Use local cooling systems, like fan coils or split units, as you usually do[15]. Though, make sure that there is ***always*** supply of fresh outdoor air by mechanical ventilation systems or operable windows.

Figure 18. Open windows as much as possible during school hours and ensure airing during breaks.

In the long-term it obviously makes sense to structurally improve the ventilation, since poor indoor air quality leads to, among others, headache, fatigue and reduced learning performance.

Some contractors and maintenance companies are now offering to replace filters, but this is NOT necessary to reduce infection risks. Only replace filters when necessary or already planned. In addition, one talks about cooling and humidification of air. Adjusting the setpoints of the climate system to lower values is NOT necessary and useless in schools. The same goes for placing humidifiers, because there is NO evidence that this is effective. Focus on things that really matter, such as proper ventilation.

Sanitary

[15] More detailed guidance on fan coils and split units is provided in Section 4.6.

Points of attention for the sanitary facilities (taps, toilets, sewers):

- Flush all toilets, water taps and showers before the school reopens. If water taps haven't been used for several weeks, the water that is still in the pipes may be of poor quality.
- Check if water taps in all toilets are in operating condition (with soap dispensers and paper towels) or provide other facilities to disinfect hands after using the toilet.
- Replace frequently used water taps with taps with a sensor, so that they can be used without touching them.
- Make sure that floor drains do not run dry to avoid an open connection to the sewer. Fill the drains regularly with water. Add some oil to prevent the water seal from evaporating quickly.
- Give the instructions to flush toilets with closed lid and wash hands after toilet use.

More information

https://www.rehva.eu/activities/covid-19-guidance

https://www.who.int/emergencies/diseases/novel-coronavirus-2019/advice-for-public

https://www.who.int/emergencies/diseases/novel-coronavirus-2019/technical-guidance/guidance-for-schools-workplaces-institutions

https://www.unicef.org/media/66216/file/Key%20Messages%20and%20Actions%20for%20COVID-19%20Prevention%20and%20Control%20in%20Schools_March%202020.pdf?sfvrsn=baf81d52_4

Feedback

If you are specialist in the issues addressed in this document and you have remarks or suggestions for improvements, feel free to contact us via info@rehva.eu. Please mention 'COVID-19 interim document' as subject when you email us.

Colophon
This document was prepared by the COVID-19 Task Force of REHVA's Technology and Research Committee, based on the first version of the guidance developed in the period between March 6-15th 2020 by REHVA volunteers.

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