REHVA
Federation of European Heating, Ventilation and Air Conditioning Associations

REHVA COVID-19 Ventilation Calculator

November 2020

1 Introduction

This guide 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 guide 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 of the main Guidance document, 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 in the main Guidance document.

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 main Guidance document - 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]:

$$p = 1 - e^{-n} \quad (1)$$

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):

$$n = C_{avg} Q_b \mathrm{D} \quad (2)$$

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:

$$\frac{dC}{dt} = \frac{E}{V} - \lambda C \quad (3)$$

where

E quanta emission rate (quanta/h);

V volume of the room (m^3);

λ first-order loss rate coefficient[i] 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[ii] and Diapouli[iii]. For virus decay Fears[iv] 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}):

$$k_{filtration} = \frac{Q_{filter}\eta_{filter}}{V} \quad (4)$$

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 $k_{filtration} = CADR/V$. 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[v] and quanta generation rates for SARS-CoV-2[vi]. 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 activitiesvii.

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 ratesviiiix.

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 1 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 1. 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.

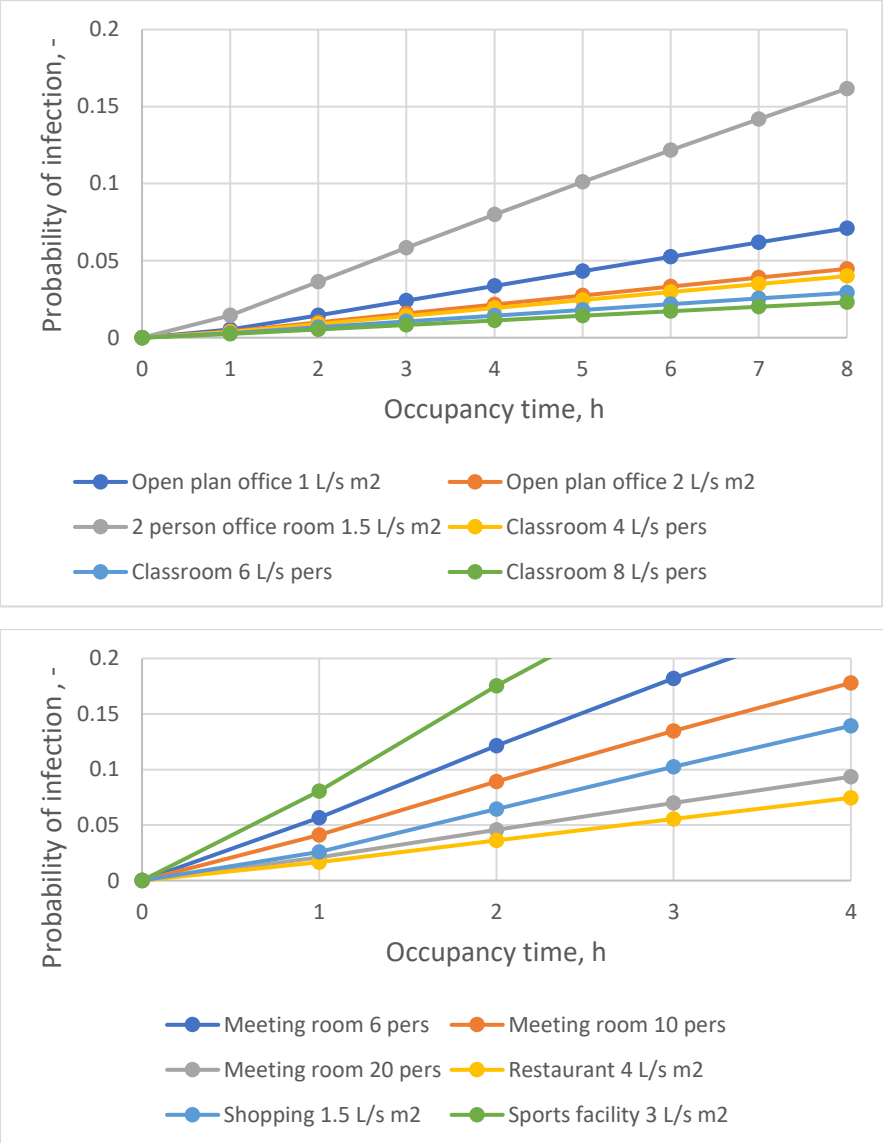

Figure 1. Infection risk assessment for some common non-residential rooms and ventilation rates calculated with the REHVA COVID-19 ventilation calculator. 1.5 L/s per m2 ventilation rate is used in 2 person office room of 16 m2, and 4 L/s per m2 in meeting rooms. Detailed input data is reported in Table 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 1.

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 2 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 2 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%.

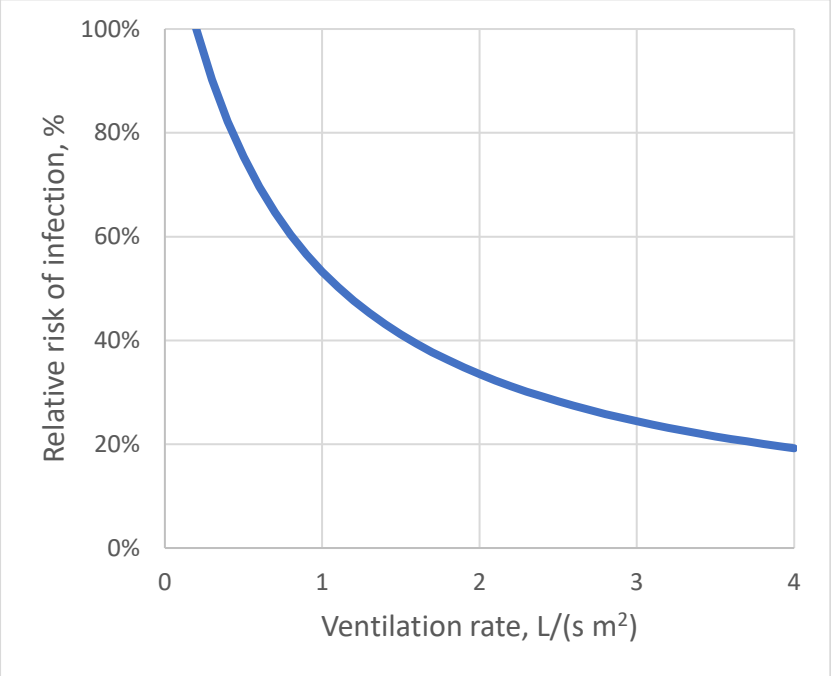

Figure 2. Relative risk in open plan office of 50 m2 where 2 L/s per person (0.2 L/s per m2) ventilation rate is considered as a reference level for a superspreading event with 100% relative risk.

Finally, Figure 2 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 in the main Guidance document. 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 3 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.

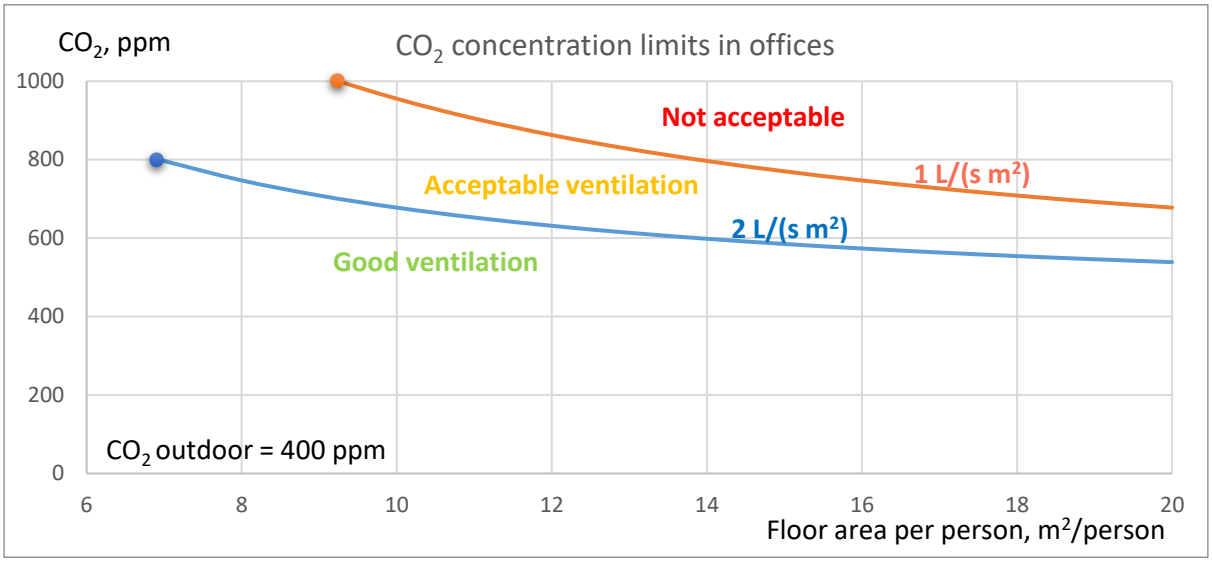

Figure 3. CO_2 concentration (absolute values that include outdoor concentration) dependency on ventilation rate and occupancy in offices.

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 4. The ECDC addresses this possibility (see main Guidance document - 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.

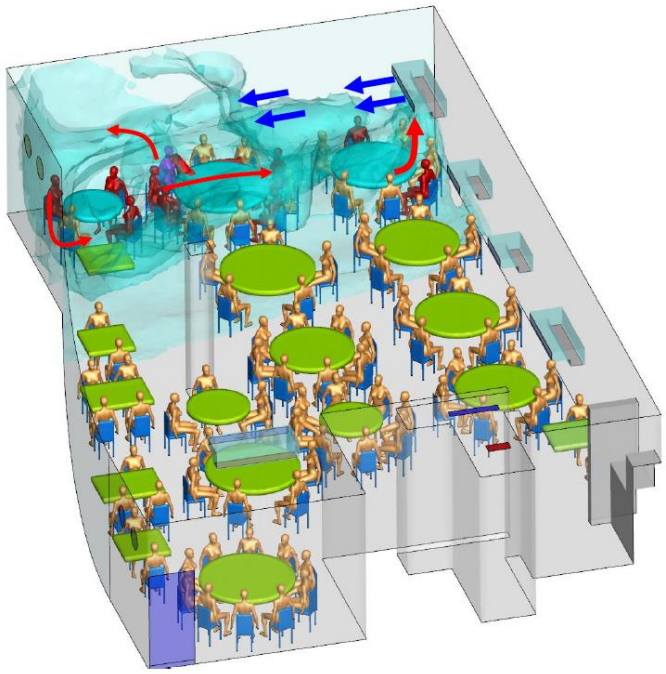

Figure 4. CFD simulated air distribution by split unit in Guangzhou restaurantxvii. The index person is shown with magenta-blue and nine infected persons with red. (Figure: courtesy Yuguo Li

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[xxi].

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 the main Guidance document - 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.

Download the COVID-19 ventilation calculator at REHVA's website:
https://www.rehva.eu/covid19-ventilation-calculator

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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