# Infection risk-based ventilation design method

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## SUMMARY

There is large amount of research on COVID-19 infections including the spread and removal mechanisms of the virus in indoor spaces. Ventilation, air cleaning and air disinfection are the main engineering measures to control the virus spread in buildings. Wells Riley model allows to calculate the infection risk probability for any airborne virus aerosol-based transmission, but this calculation is overcomplicated in the ventilation design because of large amount of input data needed that is not easy to understand to ventilation designers. In this paper, an explicit equation derived for ventilation rate in the steady state at given infection risk probability is applied and further simplified to be suitable for practical design purposes. Application of the default input data for quanta emission rates, breathing rates and removal mechanisms by decay and deposition makes it possible to propose outdoor air ventilation rate equations which only parameters are the number of occupants and room volume. These equations for common indoor spaces make it possible to design pandemic ready buildings with ventilation and air cleaning solutions.

## KEYWORDS

Infection risk, COVID-19, quanta emission, event reproduction number, ventilation design.

## 1 INTRODUCTION

EN 16798-1:2019 specifies indoor air quality (ventilation rates) design methods so that the method based on perceived air quality is the first method (6.3.2.2 Method 1 based on perceived air quality). Respiratory infection risk-based design method introduced in this paper is intended to complement this method so that the highest ventilation rate given by these methods shall be used.

According to the standard, in non-residential buildings, ventilation rates are calculated from perceived air quality by the visitors (unadapted persons) depending on the emissions from humans and building materials. Outdoor air flow rate:

$$q_{tot} = Nq_p + A_R q_B \tag{1}$$

where
$q_{tot}$ = total ventilation rate for the breathing zone, L/s
$N$ = design value for the number of the persons in the room,
$q_p$ = ventilation rate for occupancy per person, L/(s person)

$A_R$ = room floor area, $m^2$
$q_B$ = ventilation rate for emissions from building, L/(s $m^2$)

For low polluting materials, outdoor air ventilation rates are according to Equation 1 (1 L/s = 3.6 $m^3$/h):

- 10 L/s per person + 1 L/s per floor area in Category I;
- 7 L/s per person + 0.7 L/s per floor area in Category II (default, representing a normal level of expectation);
- 4 L/s per person + 0.4 L/s per floor area in Category III.

These ventilation rates should be compared with infection risk-based ventilation rates $Q$ and the higher value shall be used.

## 2 INFECTION RISK-BASED VENTILATION RATES

Kurnitski et al. (2021) have used Wells Riley model to derive an explicit equation for ventilation rate in the steady state at given infection risk probability, fully mixing air distribution and one infectious person in the room:

$$Q = \frac{q Q_b \mathrm{D}}{\ln\left(\frac{1}{1-p}\right)} - \left(\lambda_{dep} + k\right)V \tag{2}$$

where

| | |
|---|---|
| $Q$ | outdoor air ventilation rate ($m^3$/h) |
| $p$ | probability of infection for susceptible person (-) |
| $q$ | quanta emission rate per infectious person (quanta/(h pers)) |
| $Q_b$ | volumetric breathing rate of an occupant ($m^3$/h), see Table 1 |
| $D$ | duration of the occupancy (h) |
| $\lambda_{dep}$ | deposition onto surfaces (1/h) |
| $k$ | virus decay (1/h) |
| $V$ | volume of the room ($m^3$) |

The main parameters affecting the required ventilation rate are the quanta emission rate (=emission source intensity), occupancy duration, accepted level of probability of infection and room volume. This equation allows to include other removal mechanisms in addition to outdoor air ventilation, such as air cleaners or facial masks:

$$Q = \frac{(1-\eta_i) I q Q_b (1-\eta_s) \mathrm{D}}{\ln\left(\frac{1}{1-p}\right)} - \left(\lambda_{dep} + k + k_f\right)V \tag{3}$$

where

| | |
|---|---|
| $I$ | number of infectious persons (-), default value $I = 1$ |
| $\eta_s$ | facial mask efficiency for susceptible person (-) |
| $\eta_i$ | facial mask efficiency for infected person (-) |
| $k_f$ | filtration by portable air cleaner (1/h) |

For a portable air cleaner, the filtration removal rate ($k_f$) is calculated with the rate of airflow through the filter ($Q_f$), the removal efficiency of the filter ($\eta_f$) and room volume $V$:

$$k_f = \frac{Q_f \eta_f}{V} \tag{4}$$

For portable cleaners with a high-efficiency particle air (HEPA) filter, the clean air delivery rate (CADR, $m^3/h$) can be used to calculate the filtration removal rate as $k_f = CADR/V$. The removal efficiency of filters and the CADR are particle-size dependent. These parameters are to be estimated based on the size range of 0.3-0.5 µm (REHVA 2022).

To derive simple ventilation rate equations which can used in the ventilation design, the following default values have been applied for input data of mask efficiency, other removal mechanisms, quanta emission rates and breathing rates:

- facial cloth mask efficiency (Ueki et al. 2021) for susceptible person $\eta_s = 0.3$
- facial cloth mask efficiency for infected person $\eta_i = 0.5$
- surface deposition loss rate (Buonanno et al. 2020) $\lambda_{dep} = 0.24$ 1/h
- virus decay (Van Doremalen et al. 2020) $k = 0.63$ 1/h
- quanta emission rate for common respiratory viruses, long term (> 2h) occupancy $q = 10$ quanta/(h pers)
- quanta emission rate for common respiratory viruses, short term (≤ 2h) occupancy with active oral communication $q = 20$ quanta/(h pers)
- number of infectious persons in the room $I = 1$ pers
- breathing rate in offices and classrooms $Q_b = 0.60$ $m^3/h$
- breathing rate in meeting rooms and restaurants $Q_b = 0.76$ $m^3/h$
- occupancy duration $D$ = 2, 5 and 8 hours in meeting rooms, classrooms and offices respectively

An acceptable individual probability $p$ for a specific room can be calculated from the event reproduction number $R$:

$$p = \frac{RI}{N_s} \tag{5}$$

where

$R$ event reproduction number (-), default value $R = 0.5$

$N_s$ the number of susceptible persons in the room $N_s = N - I$

At low number of susceptible persons in the room, Equation 5 gives high values of the probability which have been limited to $p \leq 0.1$.

It is possible to simplify equations 2 and 3 by using the Taylor approximation of an exponential $e^n \cong 1 + n$ at low doses, that allows to rewrite Wells-Riley equation $p = 1 - e^{-n}$ as follows:

$$n \cong \frac{1}{1-p} - 1 \tag{6}$$

where
$n$ quanta inhaled by occupant (quanta)

Taylor approximation provides reasonable accuracy at low $p$ values, for instance 2.4% at $p$ = 0.05 and 4.7% at $p$ = 0.1. By using another approximation $1/(1-p) \cong 1+p$ that applies if $|p| \ll 1$ equation 3 can be rearranged:

$$Q = \frac{(1-\eta_i) q Q_b (1-\eta_s) \mathrm{D} N_s}{R} - \left(\lambda_{dep} + k + k_f\right) V \tag{7}$$

This equation allows to calculate infection risk-based ventilation rates in simple fashion when substituting default values of quanta emission rate, breathing rate and occupancy duration.

## 3 INFECTION RISK-BASED VENTILATION RATES FOR COMMON SPACES

By applying Equation 7 and default values specified in Section 2, infection risk-based outdoor air ventilation rate equations for common spaces can be derived as shown in Table 1. These airflow rates apply for situation with no facial masks, no portable air cleaners and fully mixing air distribution.

Table 1. Outdoor air ventilation rates Q (L/s) calculated from the number of persons in the room N (-) and volume of the room V (m3).

| | **N ≥ 6** | **1 < N < 6** |
|---|---|---|
| Office | Q = 26.7(N-1) – 0.242V | Q = 133 – 0.242V |
| Classroom | Q = 16.7(N-1) – 0.242V | Q = 83.3 – 0.242V |
| Meeting room, restaurant | Q = 16.9(N-1) – 0.242V | Q = 84.4 – 0.242V |
| Gym | Q = 73.3(N-1) – 0.242V | Q = 367 – 0.242V |

Outdoor air ventilation rates calculated with equations in Table 1 apply at full mixing air distribution. For other air distribution solutions the required supply airflow rate can be calculated with ventilation effectiveness defined in EN 16978-3:2017:

$$Q_s = \frac{Q}{\varepsilon_v} \tag{8}$$

where
$Q_s$ required supply airflow rate at actual air distribution solution (L/s)
$\varepsilon_v$ ventilation effectiveness (-)

Ventilation effectiveness can be calculated from measured tracer gas concentrations:

$$\varepsilon_v = \frac{C_e - C_o}{C_i - C_o} \tag{9}$$

where

$C_e$ concentration in the extract air duct;

$C_i$ concentration in the breathing zone at studied location in the room;

$C_0$ concentration in the supply air.

In the case of large rooms or rooms with partitions, the volume in equations in Table 1 should represent the volume of the zone where infectious quanta emission is expected to be spread and removed by extract air. Ventilation effectiveness values depend on the source location and the values representing a worst case or typical locations should be used.

Portable air cleaners may compensate a considerable part of infection risk-based outdoor air ventilation rate. Portable air cleaners shall be located so that a fully mixing air distribution is achieved in the room or zone with volume $V$. For a portable air cleaner, the filtration removal rate $k_f$ (1/h) is calculated with the rate of airflow through the filter $Q_f$ ($m^3$/h), the removal efficiency of the filter $\eta_f$ (-) and room volume $V$ ($m^3$):

$$k_f = \frac{Q_f \eta_f}{V} \tag{10}$$

For portable cleaners with a high-efficiency particle air (HEPA) filter, the clean air delivery rate (CADR, $m^3$/h) can be used to calculate the filtration removal rate as $k_f = CADR/V$. Outdoor air ventilation rates with portable air cleaners for common spaces can be calculated with equations shown in Table 2.

Table 2. Outdoor air ventilation rates Q (L/s) with portable air cleaners calculated from the number of persons in the room N (-) and volume of the room V (m3).

| | **N ≥ 6** | **1 < N < 6** |
|---|---|---|
| Office | $Q = 26.7(N-1) - (0.87+k_f)V/3.6$ | $Q = 133 - (0.87+k_f)V/3.6$ |
| Classroom | $Q = 16.7(N-1) - (0.87+k_f)V/3.6$ | $Q = 83.3 - (0.87+k_f)V/3.6$ |
| Meeting room, restaurant | $Q = 16.9(N-1) - (0.87+k_f)V/3.6$ | $Q = 84.4 - (0.87+k_f)V/3.6$ |
| Gym | $Q = 73.3(N-1) - (0.87+k_f)V/3.6$ | $Q = 367 - (0.87+k_f)V/3.6$ |

For high-capacity portable air cleaners it is possible that outdoor air ventilation rate $Q$ becomes negative, indicating that air cleaners and deposition and decay removal mechanisms are sufficient to remove the virus.

## 4 CALCULATION EXAMPLE

Consider an open plan office of 6 persons, 50 $m^2$ floor area and room height of 2.6 m. Impinging jet ventilation with ventilation effectiveness $\varepsilon_v$=1.2 is used.

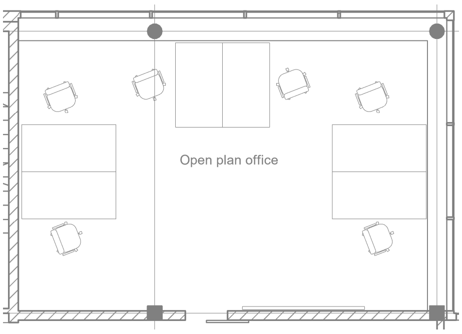

Figure 1. Layout of an open plan office of 50 m$^2$.

The following input data is used in the calculation of required ventilation rate:

- event reproduction number $R = 0.5$
- surface deposition loss rate $\lambda_{dep} = 0.24$ 1/h
- virus decay $k = 0.63$ 1/h
- quanta emission rate $q = 10$ quanta/(h pers)
- number of infectious persons in the room $I = 1$ pers
- breathing rate in offices and classrooms $Q_b = 0.60$ m$^3$/h
- occupancy duration $D = 8$ hours

An acceptable individual probability $p$ for is calculated with equation 5:

$$p = \frac{RI}{N_s} = \frac{0.5\times 1}{6-1} = 0.1$$

Ventilation rate for fully mixing air distribution is calculated with equation 2:

$$Q = \frac{qQ_b\mathrm{D}}{\ln\left(\frac{1}{1-p}\right)} - \left(\lambda_{dep} + k\right)V = \frac{10\times 0.60\times 8}{ln\left(\frac{1}{1-0.1}\right)} - (0.24 + 0.63)130 = 342.5\frac{m^3}{h} = 95.1\frac{L}{s}$$

The same value calculated with simplified equation in Table 1 is slightly higher showing the highest possible deviation of 7% at maximum individual probability value of 0.1:

$$Q = 26.7(6-1) - 0.242 \times 130 = 102.0\frac{L}{s}$$

Ventilation rate 95.1 L/s corresponds to 1.9 L/(s m$^2$) that is in between Category I and II ventilation rates with low polluting materials of 2.2 and 1.5 L/(s m$^2$) calculated with Equation 1. Fully mixing ventilation airflow rate is recalculated to impinging jet ventilation with higher ventilation effectiveness with equation 8:

$$Q_s = \frac{Q}{\varepsilon_v} = \frac{95.1}{1.2} = 79.3\frac{L}{s}$$

Ventilation rate 79.3 L/s corresponds to 13.2 L/s per person or 1.6 L/(s m$^2$).

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## 6 REFERENCES

Kurnitski, J.; Kiil, M.; Wargocki, P.; Boerstra, A.; Seppänen, O.; Olesen, B.; Morawska, L. Respiratory infection risk-based ventilation design method. Building and Environment, 206, 2021 https://doi.org/10.1016/j.buildenv.2021.108387

REHVA 2022, Criteria for room air cleaners for particulate matter https://www.rehva.eu/fileadmin/content/documents/Downloadable_documents/REHVA_COVID-19_Recommendation_Criteria_for_room_air_cleaners_for_particulate_matter.pdf

H. Ueki *et al.*, "Effectiveness of face masks in preventing airborne transmission of SARS-CoV-2," *MSphere*, vol. 5, no. 5, 2020.

G. Buonanno, L. Morawska, and L. Stabile, "Quantitative assessment of the risk of airborne transmission of SARS-CoV-2 infection: prospective and retrospective applications," *Environ. Int.*, vol. 145, p. 106112, 2020. https://doi.org/10.1016/j.envint.2020.106112

N. Van Doremalen *et al.*, "Aerosol and surface stability of SARS-CoV-2 as compared with SARS-CoV-1," *N. Engl. J. Med.*, vol. 382, no. 16, pp. 1564–1567, 2020.