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Potential of ventilation measures for reducing the risk of infection

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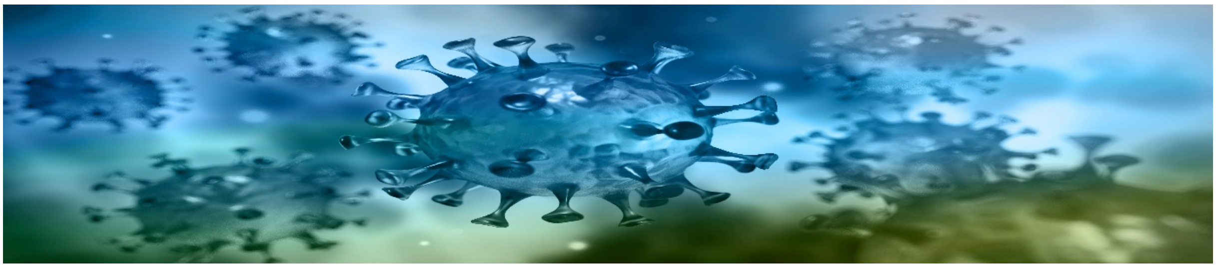

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Abstract

It was not possible to stop the global spread of the COVID-19 pandemic in spite of considerable efforts and restrictions. One reason on which the experts are largely agreed is the virus ability to travel through the air from the host to the newly infected person. The multitude of viruses travelling with airborne particles follows the air flow almost inertia-free.
Therefore, the simply formulated requirement for protection against infections in places of public assembly is:

- *suppression of the flow from the infected person to other room users*

This publication analyses the potential of ventilation technologies for reducing the risk of infection in places of public assembly, for example in classrooms.
In addition to the analysis of the extent to which ventilation solutions are able to influence the air flow in the room, the risk of infection will, on the basis of the current state of knowledge, be identified by a transient calculation for the beginning and the subsequent hours of room use and the ventilation solutions will be compared in this way.

The results show that the transient examination of the first few hours of room use shows a much lower risk of infection than the stationary assessment of the steady state. As expected, the risk of infection in rooms that are poorly ventilated or not ventilated at all increases quickly. An increasing room size and an increasing air exchange help to reduce the risk. Only properly operated and controlled displacement or layered ventilation systems can virtually eliminate the risk of infection. Whilst displacement ventilation makes retrofitting an unattractive prospect due to the necessary technological effort and the volumetric air flows, retrofittable layered ventilation systems are conceivable. Unlike with displacement ventilation, the protective effect of layered ventilation systems in the occupied area sets in completely in adequately occupied rooms, but only after approx. 6 mins.
Mixing ventilation systems and circulating air purifiers can help to reduce the risk of infection. A supplementary cyclical free intermittent and cross ventilation is nevertheless also advisable to supplement these. The circulating air purifiers in particular can only have a limited influence on the room air flow. As the volumetric air flow of the circulating air purifiers increase, the general risk of infection falls and the risk of infection for the infected persons neighbours increases significantly. The reason for this is turbulence-induced flow streaks, which so often carry high virus concentrations straight to the infected person's neighbour. Close to the ceiling can be regarded as the best position for operation, especially in the case of circulating air purifiers with a low volumetric flow.

In conclusion, mixing ventilation systems, installed in millions of rooms as the state of the art, are insufficient to eliminate a risk of infection. A rethinking of the ventilation solutions to be applied during already pending energy-focused renovations allows rooms to be designed in such a way in the future that their room air poses no risk of infection.

Introduction

Long before the emergence of COVID-19, institutions such as the World Health Organisation (WHO) and the World Economic Forum (WHO) listed the greatest current global risks, including the risk of a pandemic, in their annually published overviews.[i] For more than a year now, the international community has been helpless in the face of the spread of COVID-19, in spite of considerable efforts. Several million people have died of or with COVID-19. A mortality rate higher than it is now hardly bears thinking about. Especially in view of the large number of cases and the associated possibility of people picking up new mutating strains of the virus, doubts about the risk potential should have become rarer.

How the virus spreads

Despite numerous containment measures, the virus has been able to spread throughout the world. Virologists and health authorities had to ask themselves how the virus spreads. Contrary to a sometimes controversial view amongst experts, the most recent analyses of scientific treatises and the results derived from these[ii] show that airborne transmission indoors is an important factor.
Particular significance is attached to aerosols in this context. They arise when breathing and speaking and in particular high numbers when we sing. As it can be assumed that symptomatic people stay in quarantine, coughing will not be further considered here as a route of transmission.

Whilst the heavy liquid droplets and large aerosols fall and sprinkle surfaces in a person's immediate vicinity, the accumulation of fine aerosols with a diameter of around 1 µm evaporates within milliseconds. The largest of the particles still approximately following the air flow, which have a diameter of approximately 10 µm, evaporate within a second[iii/ iv/ v]. Lighter particles, possibly loaded with infectious agents and perfectly following the air flow, survive. In conjunction with the ability of a large proportion of the COVID-19 viruses to live for at least 3 h in the room air,[vi] it is clear that the key issue associated with the objective of lowering the risk of infection inside is the safe continued use of the virus-contaminated air. Therefore, the flow control urgently needs to be addressed.

- *The key issue for reducing the risk of infection in rooms is that of an appropriate flow control*

So far, most scientific studies have assumed an isotropic mixing indoors. This room air flow corresponds to the ideal mixing ventilation. The mixing ventilation flow type is the most common flow type indoors and the least favourable room air flow from the perspective of the risk of infection.

The greater the heat influx into a room, e.g. through the room users or radiators, the greater the flow-determining influence of thermals. In this context, the introduction of a parameter κ to characterise the statistical correlation of heat and momentum-based flow directions makes it easier to understand and assess the risk of infection. In the ideal mixing ventilation system, all flow directions occur equally. This limiting case shall be defined by κ = 0. If the vectors of kinetic and thermal flow energy are perfectly aligned, κ = 1. If the vectors of kinetic and thermal flow energy are perfectly opposed, κ = -1.

- Thermals in opposite direction to flow direction κ = -1
- Ideal mixing ventilation, isotropic flow κ = 0
- Thermals in same direction as flow direction κ = 1

In real room air flows, κ will be adjusted between 0 < κ < 1.

The requirement for the suppression of the flow path from the infected person to the person in need of protection is trivial to the reduction of the risk of infection. It is already apparent that mixing in the room (κ → 0) is *not* able to satisfy this trivial requirement. If the thermal and the kinetic flow counteract one another, this leads to increased turbulence in the first place and thus to commingling. In this case (κ → -1), the requirement for protection can only be satisfied by a strong displacement flow characterised by kinetic energy.

In addition to the direction of the forces shaping the flow, their size is of critical importance for the assessment and/or shaping of the room air flow. In ventilation technology, the dimensionless *Archimedes* number[vii] is used in this context to describe the relationship between these influences.

Formula 1

$$\textit{Archimedes}-\textit{number}\ \mathrm{Ar} = \frac{\text{Gravity}}{\text{Inertial force}} \equiv \frac{\text{free convection}}{\textit{forced}\ \text{convection}} = \left(\frac{v_{\text{buoyancy}}}{v_{\text{mechanical}}}\right)^2$$

It is usual to adjust the definition of the Archimedes number to the task to be assessed, for example for the assessment of a displacement flow or the flow of round or flat air jets, such as those produced by circulating air purifiers. In the present case, the velocities relate to the floor area A_R.

The Archimedes number can be adjusted by a correction factor $(1-\varepsilon)^2$ with ε as the ratio of the reduction in the area caused by furniture or people to the total area.

$$Ar = \frac{2 \cdot g \cdot H \cdot \Delta T}{\left(\frac{\dot{V}_e}{A_R}\right)^2 \cdot T_R} \cdot (1-\varepsilon)^2$$

with

g : Gravity $\left[\mathrm{m}/\mathrm{s}^2\right]$

H : Room height $[\mathrm{m}]$

ΔT : Temperature difference exhaust air - supply air $[\mathrm{K}]$

$\dot{V}_e$: mechanically moved volume flow $\left[\frac{m}{s}\right]$

A_R : Room area $[m^2]$

T_R : Temperature exhaust air $[\mathrm{K}]$

ε : Ratio of area reduction to total area

Formula 2

The above definition of the Archimedes number shall be used to assess the influence of various common flow measures – displacement flow, the mixing ventilation-based use of circulating air purifiers, and layered ventilation – on the room air flow and thus on the risk of infection.

Ventilation systems

Displacement flow

The safe continuation of infectious agents without putting the neighbours at risk is only possible through vertical evacuation. The direction against (κ = -1) or with (κ = 1) the thermal is decisive for the stability of the displacement flow.

According to Regenscheit from a paper by Linke, stable conditions are obtained with the following Archimedes numbers when the room is heated[viii]:

- Displacement flow with gravity against the thermal $Ar < 92$
- Displacement flow against gravity with the thermal $Ar < 720$

The essential heating load and the approximate difference in temperature to be applied for the thermal buoyancy ΔT depend, for example in occupied classrooms, on the number of people and the air exchange, i.e. on the person-specific volumetric air flow. The lower the specific volumetric flow – transmission losses are marginal with newer building standards – the greater the temperature increase between the supply air and the extracted air.

An occupied classroom with seated activity shall be used as an example. The heat output for this level of activity is[ix] approximately 95 W for sensible heat and 25 W for latent heat. The person-related temperature increase, taking into consideration the increase in air humidity at an estimated 160 m³/h/person, is approximately $\Delta \mathrm{T}(160\mathrm{m}^3/\mathrm{h}/\mathrm{person}) \approx 1{,}8\mathrm{K}$. The room has a height of 3 m and the temperature is set at 22 °C. The reduction in area caused by people and tables is not taken into consideration, as there are hardly any obstructions to the flow acting around the emission source of the head ($\varepsilon=0$).

The representative room air velocity or the necessary room air exchange of the flow case can be calculated by rewriting Formula 2. Below, the required air exchange is determined for the flow directed with and against the thermal as an example.

Flow with the thermal (κ = 1)

$$v_e = \sqrt{\frac{2\cdot \mathrm{g}\cdot \mathrm{H}\cdot \Delta\mathrm{T}}{Ar\cdot T_R}} = \sqrt{\frac{2\cdot 9.81\cdot 3\cdot 1.8}{2\cdot 360\cdot (22+273.15)}\left[\frac{m\cdot m\cdot K}{s^2\cdot K}\right]} = 0.022\,m/s$$

Necessary air exchange: $$n = \frac{v_e}{H}\cdot 3600 = \frac{0.022m/s}{3m}\cdot 3600s/h = 26.4\frac{1}{h}$$

Flow against the thermal (κ = -1)

$$v_e = \sqrt{\frac{2\cdot \mathrm{g}\cdot \mathrm{H}\cdot \Delta\mathrm{T}}{Ar\cdot T_R}} = \sqrt{\frac{2\cdot 9.81\cdot 3\cdot 1.8}{2\cdot 46\cdot (22+273.15)}\left[\frac{m\cdot m\cdot K}{s^2\cdot K}\right]} = 0.062m/s$$

Necessary air exchange: $$n = \frac{v_e}{H}\cdot 3600 = \frac{0.062m/s}{3m}\cdot 3600s/h = 74.4\frac{1}{h}$$

Conclusion for displacement flow

The conclusion from the examination of the displacement flow is that the flow control directed against the thermal can be ruled out as impracticable. The horizontal displacement flow is also not ideal. In the latter case, the neighbours of an infected person are exposed to a risk; in the former case, the necessary volumetric air flow is disproportionately high. The displacement flow in superposition with the thermal, on the other hand, requires a much lower air exchange than a displacement flow against the thermal. Practicable air exchanges can be achieved with an optimisation of the ratio of the thermal and inertial forces of the ascending displacement.

Circulating air purifiers

A frequently promoted practice for reducing the risk of infection is the use of circulating air purifiers. These suck in the room air, remove or kill, depending on the procedure used, at best almost all infectious agents and then blow the contamination-free air back into the room. For simplification, this publication assumes that the appliances purify the air completely (100

%). It must be noted that circulating air purifiers are based on the principle of mixing ventilation. The more ideal the mixing ventilation (κ →0), the less critical the spatial positioning and the expulsion vector of the appliances. However, as the heat influx increases, e.g. due to a higher occupancy of the room or the operation of radiators with high transmission losses, the influence of the thermal becomes dominant. In this case, the room air flow deviates from the ideal mixing ventilation and a thermal stratification with supply air vectors running with or counter to the thermal (-1 < κ < 1) arises.

The Archimedes number introduced above, applied to the mechanical room ventilation on the one hand and to the circulating air purifiers on the other hand, helps to assess the influences of flow kinetics and thermals, for example caused by people in the room, of the forced convection of the mechanical ventilation, and of the circulating air purifiers on the room air flow. High Archimedes numbers indicate a dominance of the thermal-based lift.

Air purifiers can be found in a very wide range of volumetric air flows.
As an example, a high air purifier volumetric flow of 2,200 m³/h shall be used to calculate the Archimedes number. The spatial situation is assumed to correspond to the defined lift situation. A complete room occupancy and thus thermal coupling is assumed. The room is assumed to have a gross floor area of 60 m². The minimal permissible hygienic air exchange is 20 m³/h/person. The building is assumed to satisfy a modern energy standard; transmission losses are therefore ignored. The temperature increase of the hygienic air exchange from the supply air to the extracted air is approximately ΔT= 14K, applying the energy and mass balance under these outlined constraints.
The Archimedes number can be applied twice in this assessment. Firstly for the assessment of the flow-shaping influence of the air flow purifier, and secondly for the influence of the ventilation technology to ensure a hygienic air exchange.

Air purifiers:

$$Ar = \frac{2 \cdot \mathrm{g} \cdot \mathrm{H} \cdot \Delta \mathrm{T}}{\left(\frac{\dot{V}_e}{A_R}\right)^2 \cdot T_R} = \frac{2 \cdot 9.81 \cdot 3 \cdot 14}{\left(\frac{2200}{3600 \cdot 60}\right)^2 \cdot 295.15} \left[\frac{\frac{m}{s^2} \cdot m \cdot K \cdot s^2}{\left(\frac{m^3}{s} \Big/ m^2\right)^2 \cdot K}\right]$$

$$Ar \approx 26{,}913$$

The resulting high Archimedes number of Ar= 26,913 for the air purifier indicates that the circulating air purifiers can only have a limited influence on the room air flow in the described flow situation. In the case of smaller circulating air flows, the influence of the purifiers on the room air flow is consequently even lower.

The second influence of mechanical or natural ventilation on the room air flow, the room ventilation with an Archimedes number of 11,306, also submits to the dominance of the thermal.

The result is supported by the experiment presented below, in which, in spite of a high air exchange and thus a low ΔT, the circulating air flow of the air purifiers is able to reduce, but not dispel the thermal stratification (see the left-hand temperature profiles in Fig. 1). At the right-hand side of the diagram, the profiles of the arising thermal stratification without a specific air circulation can be seen.

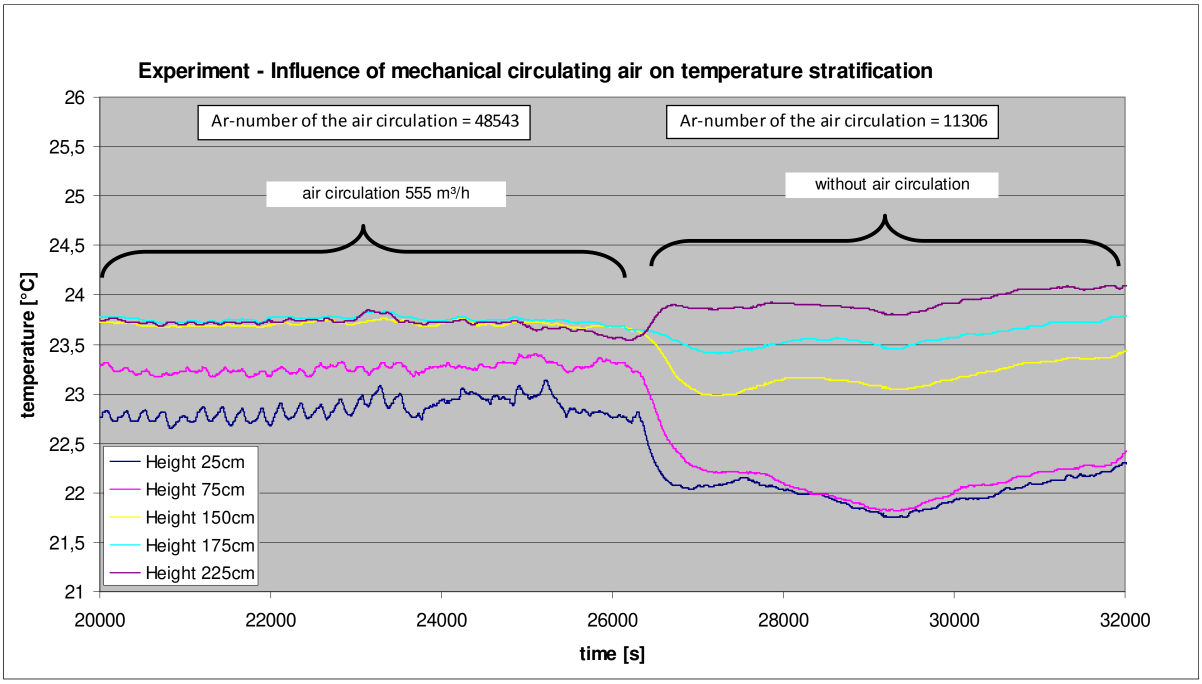

Fig. 1: Influence of the air circulation momentum, for example of an air purifier, on the thermal stratification

Constraints: air exchange 115 m³/h/person dummy, room size 44 m², height 3 m, 10 dummies, sensible heat influx 120 W/dummy, temperature difference between supply air and extracted air (3 K) taking transmission losses into consideration, mean room air temperature 296.3 K. Installation close to the ground

In parallel to the local temperatures in the described experiment to assess the influence of the circulating air purifiers, the substance exposure levels and indirectly the local risk of infection were measured. The substance exposure levels were determined by measuring the N_2O as a foreign tracer gas. This tracer gas, which follows the air, found its release at the emitter.

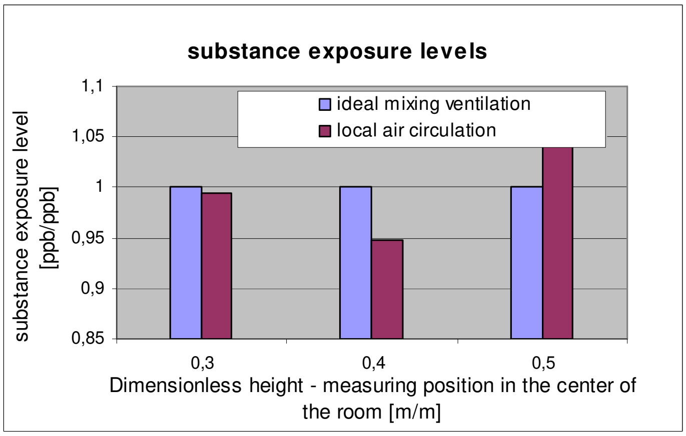

Fig. 2: averaged substance exposure levels, room height 3 m, during the selective air circulation (for example circulating air purifiers), see Fig. 1

With a local air circulation in line with that of the circulating air purifiers, the risk of infection of the neighbour to the emitter increased in the experiment at head height (1.5 m) in comparison with the ideal mixing ventilation (κ = 1). Towards the floor, on the other hand, the substance exposure levels fell to 0.9 m and 1.2 m, see Fig. 1. The result supports the statement that intermittent flows from the emitter to the neighbour can cause increased substance exposure levels and thus an increased risk of infection.

The substance exposure level referred to above φ is defined as the number concentration of foreign substances following the air in an inertia-free manner in the investigated case $\Psi_{\text{measurement}}$ in relation to the concentration that would result with the ideal mixing ventilation $\Psi_{\text{mixing ventilation}}$ (κ = 0).

$$\varphi = \frac{\Psi_{measurement}}{\Psi_{\text{mixing ventilation}}}$$

Conclusion for circulating air purifiers

Circulating air purifiers cannot prevent thermal stratification and thus the concentration of viruses in the upper layers when the room is partially or fully occupied. In this context, the effectiveness of inefficient circulating air purifier in particular is largely dependent on their position in the room. In the event of high Archimedes numbers, an installation aimed at an effective operation must be near to the ceiling in the area of the highest virus concentrations. Due to the conservation of mass close to the ground at the foot of the lift column, air draughts that return the air to the occupied area are created with or without the assistance of circulating air purifiers.

As the following examinations of the risk of infection show, circulating air purifiers in conjunction with mixed air flows (-1 < κ < 1) do not produce virus-free air. Virus concentrations and thus the risk of infection is very likely to be lowered. Depending on the circulating air flow, the achievable physical substance exposure levels or, for example, the virus concentrations are informative about the performance limits of circulating air purifiers.

Mixing ventilation systems

Mixing ventilation systems with 100 % fresh air or decontaminated circulating air are roughly comparable with the action of the circulating air purifiers. Virus-free air cannot be attained with this form of flow due to the physically unavoidable accumulation until a steady state is achieved. The air pollution is very likely to be reduced when the air circulation increases.
The assessment of the room air-shaping influence in comparison with the thermal is carried out in line with procedure described for circulating air purifiers. Equally, the achievement of

the isotropic flow (κ →0) is also essentially dependent on the air exchange when mixing ventilation systems are used.

We will not go into mixing ventilation systems with a proportion of non-decontaminated circulating air to increase the flow kinetics and thus reduce the thermal influence, as such systems verifiably contribute to the occurrence of infections.

Layered ventilation

A special form of room air flow is layered ventilation. Due to the near-the-ground supply of uncontaminated air, layered ventilation supports thermals and, when properly controlled, prevents the formation of air draughts and thus the return of contaminated air from the upper thermal layers. The flow control is aligned with the thermal (κ →1) in a similar way to the upwards-directed displacement flow, with the difference that the layered ventilation close to the ground must be introduced selectively and not over a wide area and the necessary air exchange must primarily be sufficient not for displacement but for compensation for the lifting volumetric flows. Whilst the flow control of layered ventilation is much more flexible than that of displacement ventilation, the adjustment of the necessary compensation volumetric flow, which in turn has an influence on the rise in temperature caused by the air exchange, is much more complex in terms of the air purification in the occupied area and the restriction of the required volumetric flow and is also dependent on the use of the room.
If the control is successful, much lower substance exposure levels and therefore much lower risks of infection in the occupied area can be achieved than with mixing ventilation. In comparison with displacement flow, layered ventilation generally requires much lower volumetric flows. Lower volumetric flows and the more flexible flow control allow layered ventilation to be retrofitted much more easily than displacement flow.

The following Fig. 3 shows substance exposure levels in room air flow experiment for mixing and layered ventilation. The experiment set-up corresponds to the set-up underlying Fig. 1 and Fig. 2, with the difference of a full room occupancy and deviating volumetric air flows.
The gradient of the substance exposure level with mixing ventilation is, as expected, approx. 1. Due to the proximity of the measuring point (neighbour position, 0.8 m from the infected person) to the emitter, the flow turbulences of mixing ventilation cause streaks that periodically make the neighbour’s exposure at his head height much worse and thus lead to a substance exposure level at head height of significantly above 1 on average. Therefore, the neighbour is exposed to a considerably higher risk than room users who are further away. Layered ventilation achieves 10-times lower exposure levels than mixing ventilation and therefore a 10-times lower risk of infection, especially in the occupied area.

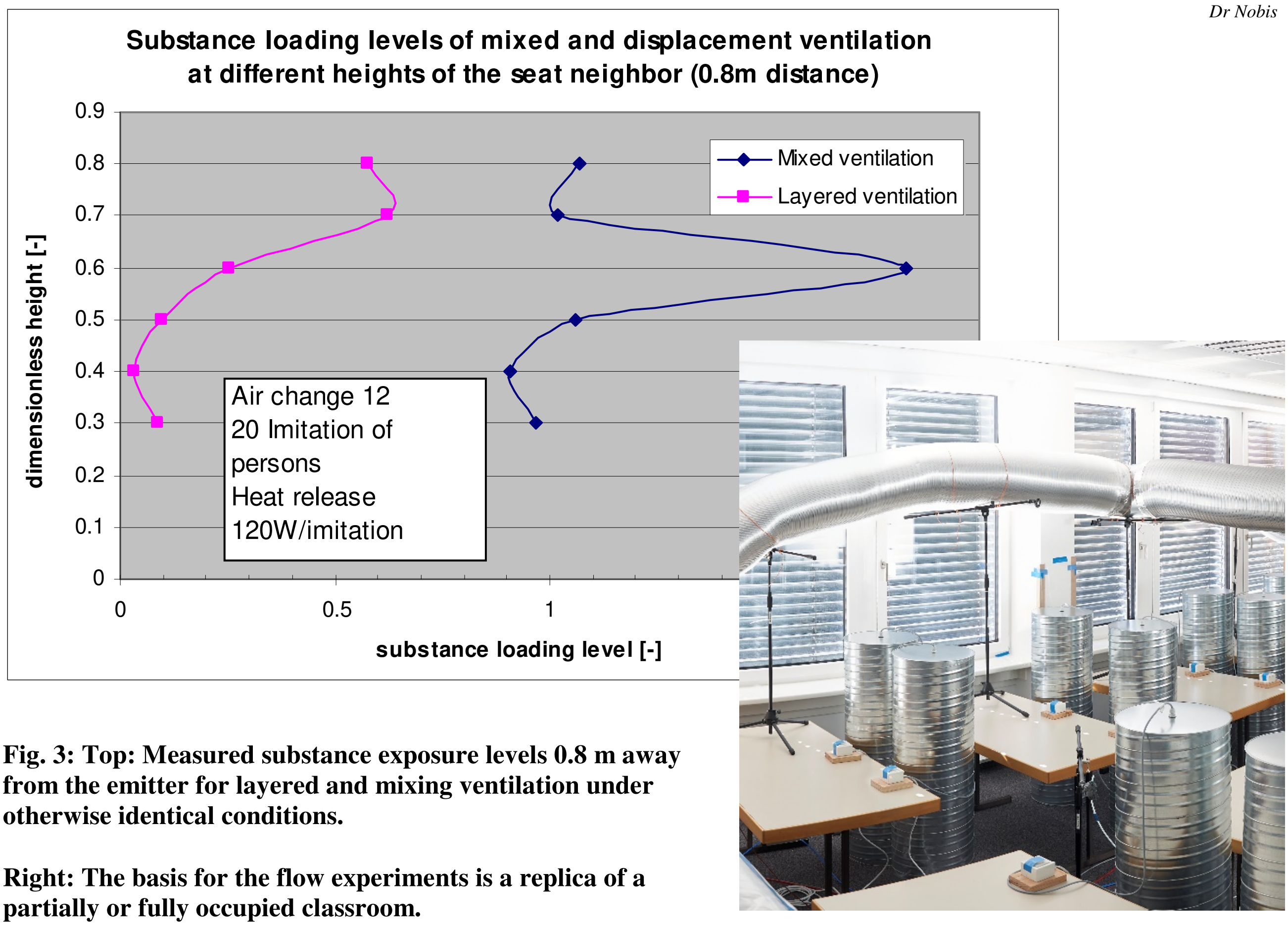

Fig. 3: Top: Measured substance exposure levels 0.8 m away from the emitter for layered and mixing ventilation under otherwise identical conditions.

Right: The basis for the flow experiments is a replica of a partially or fully occupied classroom.

Conclusion for layered ventilation

The properly controlled layered ventilation significantly lowers the risk of infection in the occupied area and also requires a smaller air exchange than the displacement flow. The reduced substance exposure levels in comparison with the mixing ventilation can be measured even for the emitter's neighbour. Due to the more flexible air flow, layered ventilation is open to retrofitting.

Risk of infection

Above, the risk of infection and the substance exposure level were related to one another. A series of authors[1] has set out to estimate the risk of infection of the ideal mixing ventilation. The estimates made are based on a variety of publications and observations and can still be regarded as an aid to understanding due to the incomplete state of knowledge about the

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[1] Model Calculations of Aerosol Transmission and Infection Risk of COVID-19 in Indoor Environments International Journal of Environmental Research and Public Health 17(21), published: Rep. 2020, 11, 03.

infection path of COVID-19. The quoted publication examines the case of the stationary steady state, both in relation to the enrichment of the room air and regarding the dying of the viruses. However, at the start of the room use, the specific virus exposure is low and it only increases as the saturation of the room increases when a mixing ventilation system is used. The larger the room and the lower the air exchange, the greater the influence of the virus mortality. The exponential approach to the calculation of the virus lifespan over the emission time is integrated into the transient examination employed here and a time-dependent survival rate of the viruses is applied to the concentration in the room. Particular attention must be paid to the fact that a continuous replenishment of the viruses in the room, and thus a constant survival rate, is assumed when the air exchange period is achieved.

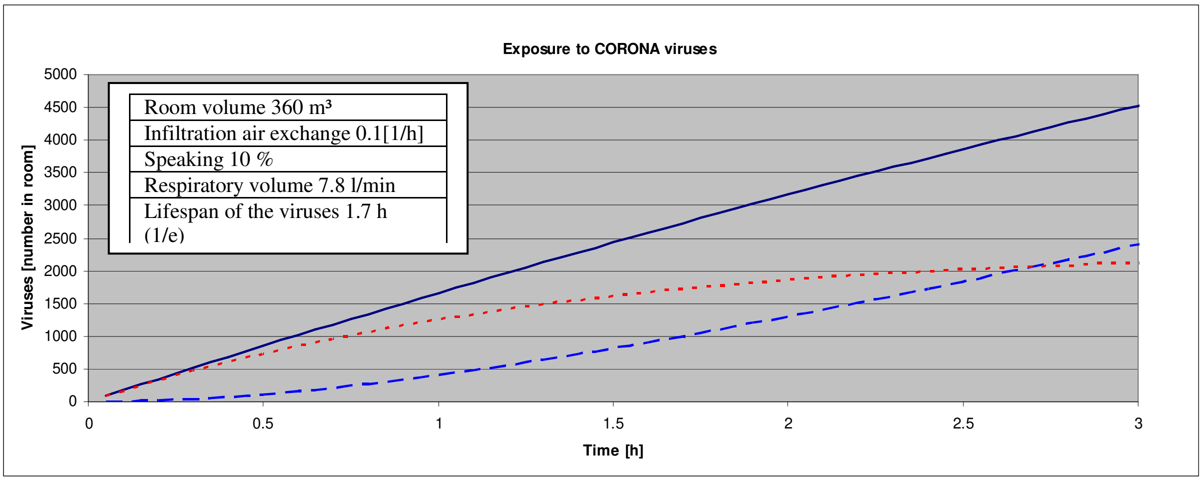
As an example, the following table shows a comparison between the risks in the case of the stationary calculation with those from the transient calculation employed by the authors for a 6 h period of room use. The shorter the period of room use examined, the greater the difference in the number of viruses that can be observed between the stationary calculation and the temporally discrete calculation. Therefore, the deviation in the risk of infection between the calculation methods is greater for short periods than for longer periods.

Room volume 360 m³, 24 room users over 6 [h], normally infectious (no super spreader), Proportion of speaking 10 [%], respiratory volume 7.8 [l/min], ***air exchange 0.35[1/h]***		
	Stationary examination	Transient examination
Risk of one person from the group falling ill	53.4 [%]	27.2 [%]
Deviation	96.3 %	

Room volume 360 m³, 24 room users over 6 [h], normally infectious (no super spreader), Proportion of speaking 10 [%], respiratory volume 7.8 [l/min], ***air exchange 2[1/h]***		
	Stationary examination	Transient examination
Risk of one person from the group falling ill	24.2 [%]	13.4 [%]
Deviation	*80.6 %*	

Table 1: Infection risk of two air exchange rates assuming inertia (stationary approach) in comparison with the time-dependent examination of a recently used room

The following figures show the transient loading of the room air with COVID-19 viruses in the presence of an infected person and the exponential dying-off of the viruses, taking into account the room volume, the air exchange and the flow control. The assumptions made by the calculations employed correspond to those made by the quoted publication, except for the conservative assumption of the respiratory minute volume flow in the order of 7.8 l/min for the emitter and non-infected persons.



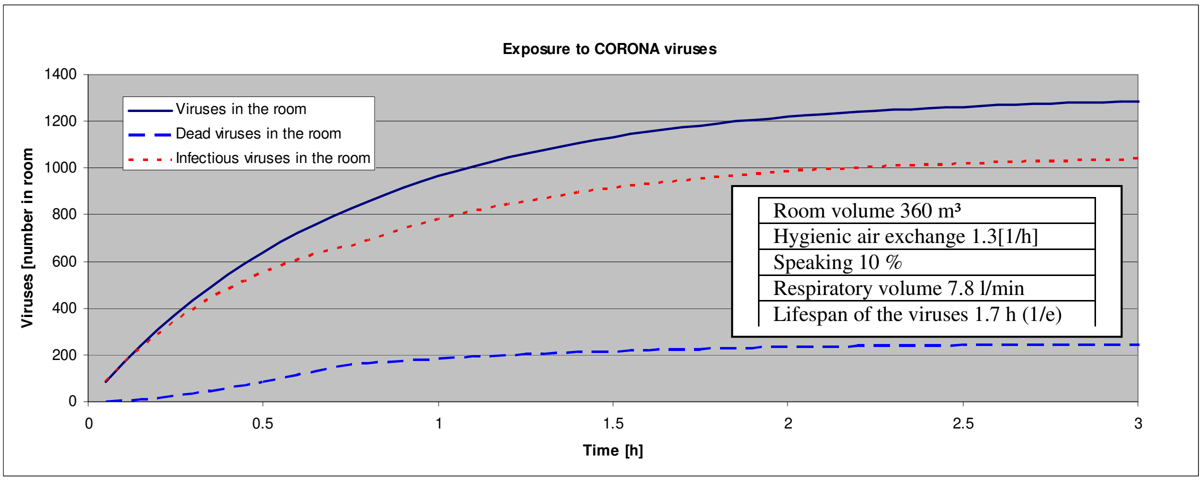


Fig. 4: Example progressions of the number of viruses in the room plotted over time in the event of continuous emission from a normal infected person (no super spreader), subdivided into the absolute number of viruses in the room, the viruses that have died off and the living viruses. This form of flow corresponds to the ideal mixing ventilation system. The top graph represents the closed room, only ventilated by infiltration (air exchange 0.1[1h]) over 20 minutes, as per the corresponding ventilation recommendation of the Federal Environment Agency, for example. The bottom figure corresponds to the state of the art of ventilation technology and thus most of all mechanical ventilation systems, in which the necessary hygienic air exchange is ensured via mixed air systems.

The higher of the two diagrams shows the almost unventilated room, as frequently encountered at schools during the winter. The virus concentration shows an almost linear increase. The sum of the viruses that have died off follows the linear increase with a delay, whilst the remaining infectious viruses achieve the maximum limit value of a steady state after several hours.

The bottom diagram, on the other hand, shows a state-of-the-art mixing ventilation system. In this room too, the number of viruses in the room increases over time but achieves a steady state earlier and at a lower level. Equally, the level of the number of infectious viruses is much lower than in a room without a mechanical ventilation system.

The integration of the breathed-in viruses, taking the probability of deposits into consideration, including the collection efficiency of the protective masks, gives the exposure dose and thus the risk of infection, which rises as the time for which the room is used (see Fig. 2). The following examinations focus on the risk of infection, especially at the start of the use of the room and the subsequent hours of room use. Especially these hours are the most important time for the infection, as the concentrations in the room can be brought back almost to zero with regular breaks and intermittent or cross ventilation.

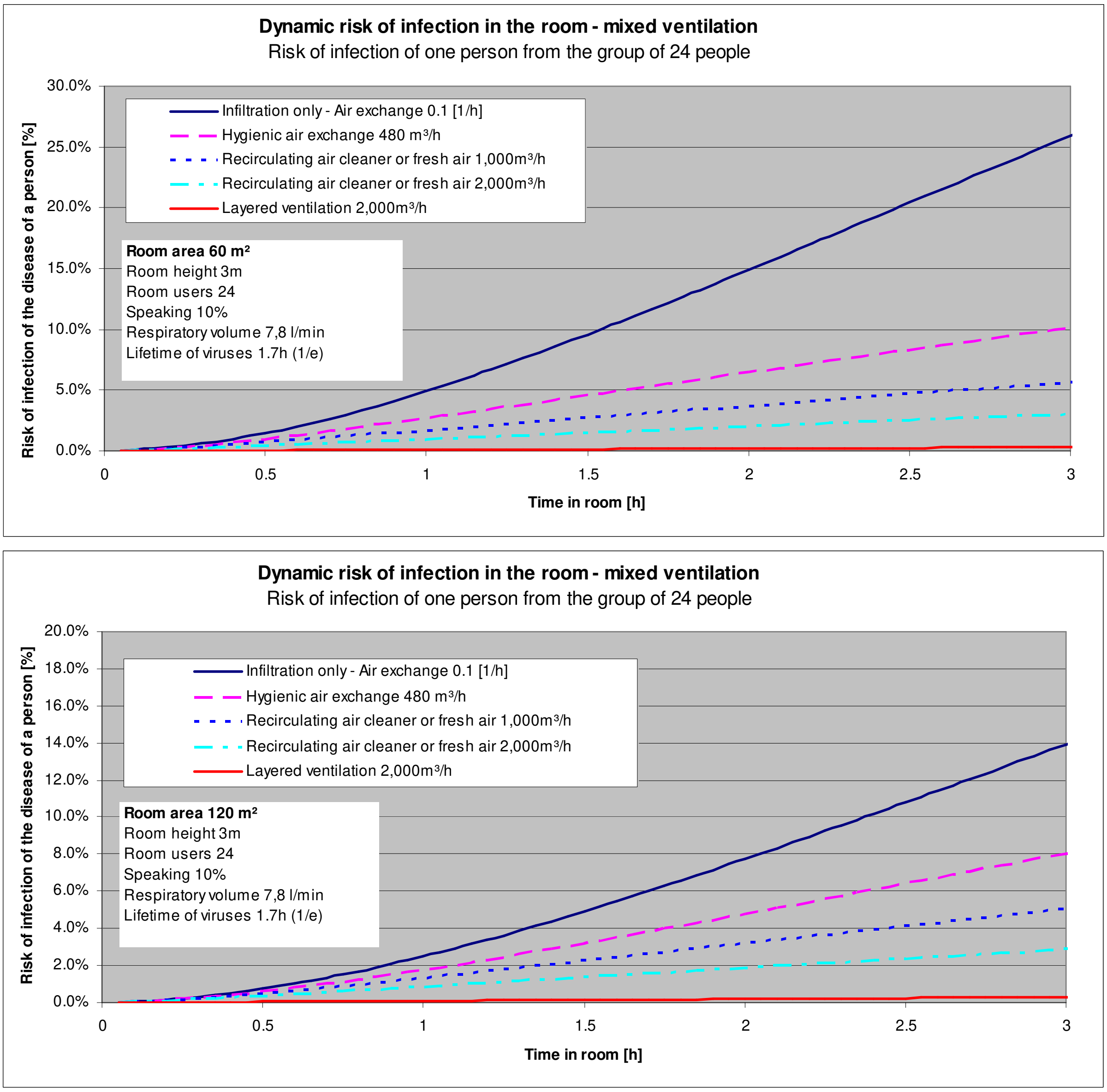


Fig. 5: Progression of the risk of infection for a person from the group to fall ill, plotted over the time spent in the room for different ventilation systems and rooms

The upper diagrams Fig. 5 include the risk of infection within rooms with a floor area of 60 and 120 m², occupied by 24 people, calculated during the composition of this paper. They examine the ventilation situations “free ventilation”, circulating air purifiers or fresh mixed air systems at 1,000 or 2,000 m³/h, and a layered ventilation also at 2,000 m³/h. The risk of infection is shown at the time until which the user stayed in the room under the indicated conditions.

With closed windows and without any ventilation measures (only infiltration), the strong increase (blue lines) of the risk of infection is striking. After 20 minutes, the recommendation of the Federal Environment Agency of Germany, the risk of infection for the small room reaches 0.76 % and for the large room 0.4 %. The importance of the very regular intermittent or cross ventilation is underlined by these results. All the ventilation measures, whether they are based on fresh air or purified air, reduce the risk of infection significantly. Greater air exchanges are favourable. Only layered ventilation achieves risks of infections in the per mil range in the presented period of 3 h in the occupied area for seated persons, at 0.3 %.

With all the ventilation options, apart from displacement and layered ventilation, regular intermittent or cross ventilation in the breaks is recommended.

Whilst the mixing ventilation systems, with the assistance of ventilators, exert a more or less significant influence on the room air flow ($-1 < \kappa < 1$), the buoyancy drives the formation of the thermal stratification when layered ventilation is used. Therefore, whilst the formative room air flow can also be detected in the absence of room users when mixing ventilation systems are used, the thermal stratification of layered ventilation only arises when room users, and thus the heat sources, are present. Therefore, the question is how long does the air flow take to form the protective thermal stratification when the room is occupied?

Information about the time taken to form an effective layered ventilation is provided by the following diagram, which was generated from the flow experiment in the context of this paper. After 6 minutes, air exposure levels and thus the infection risk of a neighbour seated 0.8 m away are reduced to a tenth.

In times of active infection protection, Fig. 6 shows that, when a correctly controlled layered ventilation system is used, the removal of particle protection masks can only be recommended after 6 minutes of room occupancy by at least 50 % capacity.

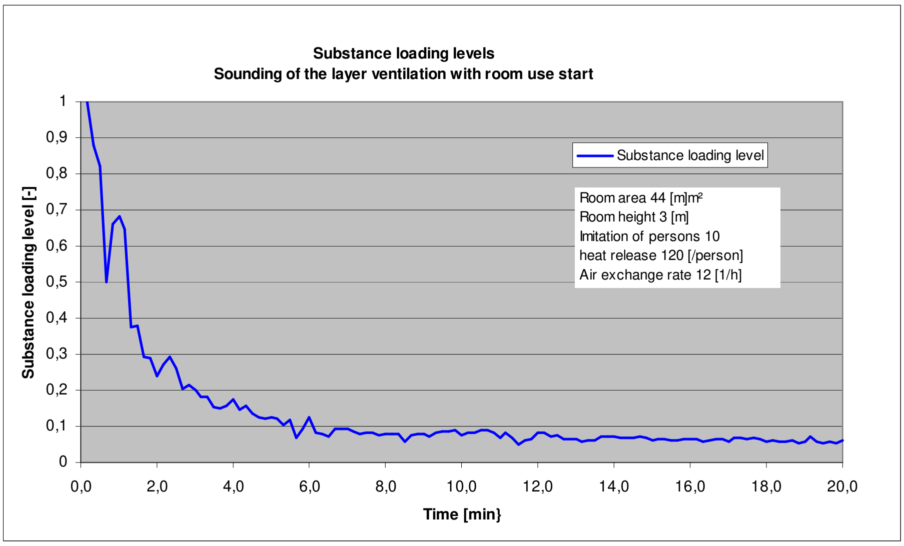


Fig. 6: Decrease in the substance exposure levels when the room users are present and formation of the thermal stratification. After approx. 6 minutes, air exposure levels and thus the infection risk for seated people are reduced to a tenth.

Outlook

This publication it appears to be worth investigating the correlation of the Archimedes number with the mixing or layered ventilation quality (κ). This investigation can, for example, provide information about the size and positioning of the circulating air purifiers and provide quantitative support for the planning of such solutions by the application of the Archimedes number.

Layered ventilation systems utilise the aligned flow vectors (κ→1) of thermals and mechanical ventilation, and the low-momentum air supply feed. To assess room air flows and influences on the risk of infection, the introduction of an adapted Archimedes number according to Formula 2, which considers the orientation of the forces to one another as well as the relationship between them.

Formula 3

$$Ar_{\text{Layered ventilation}} = \frac{2 \cdot \mathrm{g} \cdot \mathrm{H} \cdot \Delta\mathrm{T} + \kappa \cdot v^2{}_e}{v^2{}_e \cdot T_R}$$

With flow in the same direction (κ→1), the lift effect is enhanced. With an opposing flow, the modified Archimedes number falls. Based on this, future investigations can demonstrate correlating statements about stratification stabilities and achievable substance exposure levels of various operational configurations and thus help to optimise ventilation systems with the aim of air pollution control.

Literature

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