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REAL-LIFE VENTILATION FILTER PERFORMANCE IN A CITY ENVIRONMENT

PARTICLE FILTRATION IN ENERGY EFFICIENT HOUSING WITH MVHR

REHVA'S COVID-19 GUIDANCE DOCUMENT

Crises*

THE CORONA CRISIS

Our professionals, responsible for the design, installation, operation and maintenance of our building systems, can contribute to limit the infection risk due to airborne viruses and contaminated surfaces in buildings by using proper ventilation and cleaning strategies. A REHVA taskforce under leadership of **Jarek Kurnitski**, Chair of REHVA Technology and Research Committee, produced a REHVA COVID-19 Guidance Document: *How to operate and use building services in order to prevent the spread of the coronavirus disease (COVID-19) virus (SARS-CoV-2) in workplaces*. See page 55 and the REHVA Website https://www.rehva.eu/activities/covid-19-guidance.

In this Guidance Document, REHVA summarizes advice on the operation and use of building services in areas with a coronavirus disease (COVID-19) outbreak, in order to prevent the spread of COVID-19 depending on HVAC or plumbing systems related factors. Read the advice as an interim guidance; the document may be complemented with new evidence and information when it becomes available. The given guidance is an addition to the general guidance for employers and building owners that is presented in the WHO document 'Getting workplaces ready for COVID-19'. The Guidance Document is primarily intended for HVAC professionals and facility managers, but may be useful for e.g. occupational and public health specialists.

More crises to address: Many people state that there will be a difference between the time before and after this Corona crisis. This can be doubted as we have many other global challenges. Challenges that are for now silenced and impacted by this crisis but will emerge very soon again.

THE CLIMATE CRISIS

European Union leaders have agreed that the bloc's coronavirus economic recovery plan should take heed of its aim to fight climate change. The 27 EU leaders agreed to coordinate a coronavirus economic recovery plan. Although the details of the plan itself still have to be worked out, a statement said they had agreed that it should be consistent with the "green transition", the phrase the EU uses to describe the aim of reducing emissions that heat the planet. The EU's executive commission wants its 27 member states to sign up at a summit in June to plans to make the entire bloc greenhouse gas neutral by 2050.

HVAC&R professionals are interactive at global level

We can learn and benefit from our professional around the globe. In the slipstream of these crises, some anti-global sentiments have been observed. However, threats due to the climate change and infectious diseases are global. They can only be addressed and solved at global level: new insights, vaccines and technical solutions to conquer these threats. As our REHVA Guidance Document reflects; prepared in cooperation with experts active at global level. REHVA's involvement in the IEQ-GA (www.ieq-ga.net) reflects our global involvement. REHVA's close cooperation with its MoU partner organisations around the globe demonstrate our proactive attitude to cooperate at global level where we have to find the solutions for our crises. ■

JAAP HOGELING
Editor-in-Chief
REHVA Journal

* A crisis (from the Greek κρίσις - krisis; plural: "crises"; adjectival form: "critical") is any event that is going (or is expected) to lead to an unstable and dangerous situation affecting an individual, group, community, or whole society. Crises are deemed to be negative changes in the security, economic, political, societal, or environmental affairs, especially when they occur abruptly, with little or no warning. More loosely, it is a term meaning "a testing time" or an "emergency event". [Source: Wikipedia]

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This article is based on a paper presented at the 40th AIVC - 8th TightVent & 6th Venticool Conference "From energy crisis to sustainable indoor climate" 15-16 October 2019, Ghent, Belgium

Real-life ventilation filter performance in a city environment

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Within any building ventilation principle, the outdoor air is considered as a source of fresh, "clean" air, which is however not always the case. Air filters have the potential to improve the quality of the supplied air by mechanical ventilation systems. Nonetheless, little is known about their real-life performance within a large particulate matter size range.

Keywords: Ventilation, Particulate matter, Filter Performance, Indoor Air Quality, Outdoor Air Pollution

Within the ventilation principle of buildings, the outdoor air is considered as a source of fresh, "clean" air. Outdoor air quality monitoring by environmental agencies, academic research projects and a broad range of citizen science projects show that this is not always the case. Although the outdoor air quality in our cities already improved, the concentrations of certain pollutants, including particulate matter, remains problematic. Ventilation systems may play a role in the introduction of these outdoor air pollutants into the indoor environment, with potential adverse effects on the indoor air quality and the health of residents.

The filters that are present in certain mechanical ventilation system types are primarily present to protect the system and its components against fouling but have the potential to improve the quality of the supplied air. The efficiency of these air filters for general ventilation is nowadays measured according to the EN ISO 16890:2016 standard [1] for classification reasons and to allow mutual comparison of their performance. However, as literally stated by the standard, "the performance results obtained in accordance with ISO 16890 cannot be quantitively applied to predict performance in service with regard to efficiency and lifetime". Furthermore, the test conditions used within this standardized procedure differ from real-life conditions (e.g. in terms of air speed, filter size, the use of synthetic particles, …) and the measurement range is limited to 0.3–10 µm particles.

Therefore, within our research project (Out2In) we investigate the real-life efficiency and its evolution in function of time of air filters and precipitators compatible with domestic ventilation systems within a city environment (Brussels, Belgium) looking at particles with a size from 10 nm to 10 µm. This to get a better understanding of the (preventative) role ventilation and its filters play in the penetration of outdoor air pollutants. This paper presents some highlights of obtained results so far.

Materials and methods

Test setup

A test setup was constructed in our Brussels-based laboratory consisting of 12 parallel test lines, which are all connected to a distribution box. At his turn, the distribution box is connected to the outdoor air allowing the measurements to be conducted with the real-life pollutant load of the Brussels outdoor air (see **Figure 1 A & B**). Each test line is composed of one or two filter boxes/devices (inter)connected to the other parts by round metal ductwork (ø160 mm) (see following paragraph for the selected filters/devices) and a constant flow fan set at 150 m³/h.

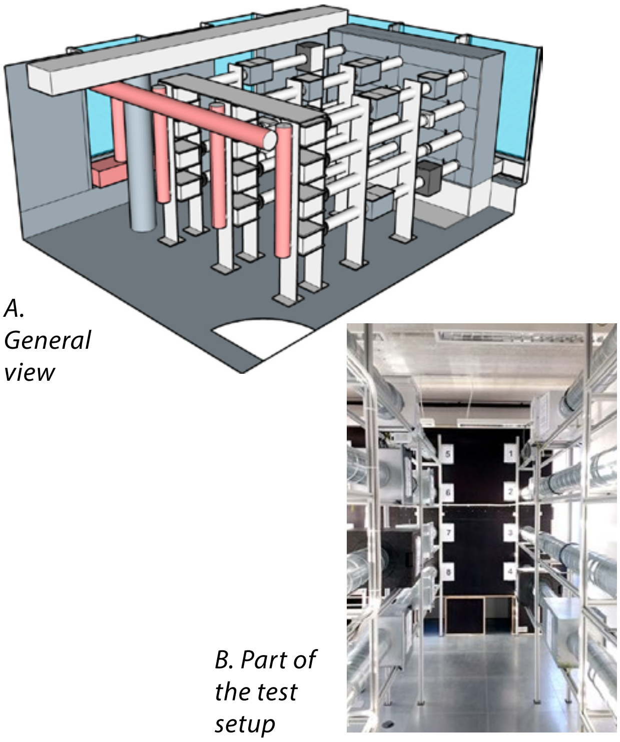


Figure 1. Computer-based design model and picture of the test setup as built.

Selected filters/devices

Classic filters – six test lines are equipped with filters or combinations of them which are nowadays already used in ventilation systems. This includes coarse filters (G3 and G4 class filters according to EN779 [2], see remark in the further research paragraph) and a fine filter (F7 class). From the same classes also different types of filters are included like duct type, wireframe, folded panel and bag type filters.

Intensive filtration – four test lines are equipped with filters which are nowadays rather exceptionally used in domestic ventilation systems including an F9 and H10 filter (= E10, Efficiency Particulate Air filter, EN 1822:2009 [2]). These filters are all of the folded panel type.

Innovative devices – two test lines are equipped with electrostatic precipitators (ESPs). Although, the principle of electrostatic precipitation is known for decades and already used in industrial applications, only recently devices connectable to domestic ventilation systems became available on the market. An electrostatic precipitator in general consists of two parts: the ioniser and the collector. Within the ioniser, the air and its particulate load will get charged (in this case positively) due to the corona discharge principle (high voltage on a small electrode). Within the second part, the ionised particles are then collected on collector plates with an opposite or neutral charge. Both tested systems differ especially in their collector part, one makes us of disposable plastic collector plates (DC), while the other makes use a collector with horizontal cleanable plates (CC).

Measurements

Differential pressure over each filter box or device is measured on a monthly basis using a TSI PVM-620 manometer. Ozone production is verified using a Teledyne T204 gas analyser.

Particulate matter load of air samples is measured in number-based concentrations within the range of 10 nm up to 10 µm using two different devices. Particles within the size range of 10–420 nm are quantified using a Scanning Mobility Particle Sizer (TSI, Nanoscan 3910 SMPS), while those between 0.3–10 µm using an Optical Particle Sizer (TSI, OPS 3330). The measurements are conducted according to a procedure based on the Eurovent 4.10 guideline [4]. This guideline describes a method for in situ determination of fractional efficiency of general ventilation filters.

Results, discussion and conclusions

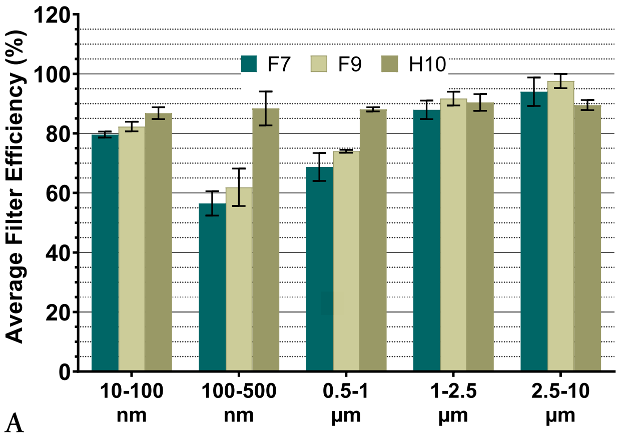
Coarse filters (G3 and G4)

Generally, the efficiency of coarse filters, especially for particles smaller than 1µm, was found to be rather limited (data not shown). Moreover, a large variability in efficiency was observed for different filter types within a same coarse filter class (G3 or G4). Therefore, coarse filters cannot be considered as contributing to an improved air quality in terms of particulate load. The use of coarse filters with a small filter surface should be avoided because of their typical very high initial and sharply increasing pressure drop (see duct type and wireframe in **Table 1**).

Fine filters (F7, F9, H10)

As can be expected, fine filters are in general more efficient than coarse filters. Upon comparison of the tested F7 and F9 filter, the results indicate a slightly, but non-significant, higher efficiency for the F9 filter throughout the complete measurement range (see **Figure 2**). Both filters however show a dip in their efficiency for the particle range 100–500 nm and 0.5–1 µm. As shown by the fractional efficiency profile for the F7 filter (**Figure 2 C**) this dip in efficiency (< 80%) extends from particles with an aerodynamic diameter of 60 to 700 nm (See vertical lines in **Figure 2 C**). The tested H10 filter at new state on the other hand, shows a very high efficiency within the full measuring range (see **Figure 2 A & B**). After two and a half months in continuous use (see **Figure 2 B**), the F7 and F9 filters do not show an obvious difference in efficiency, while for the H10 a decrease for the particles in de size ranges from 100–500 nm and 0.5–1 µm can be observed.

At new state, the pressure drop caused by the fine filters is larger than the ones observed for most coarse filter types (except for the wireframe and duct type filter) (see **Table 1**). During the 2.5 months term, the pressure drop increased gradually and equally for the F7 and F9 filter, while for the H10 filter the increase is higher. The increase in pressure drop for all fine filters is however lower than the one for the G4 folded panel (FP) coarse filter. It must be mentioned that each of the fine filter classes is installed in a test line with the same G4 FP filter as a prefilter. Unprotected fine filters have not been tested. In conclusion, fine filters have the potential to improve the quality of the supplied air by a ventilation system in terms of particulate load with a rather limited increase in pressure drop when protected by a coarse filter.



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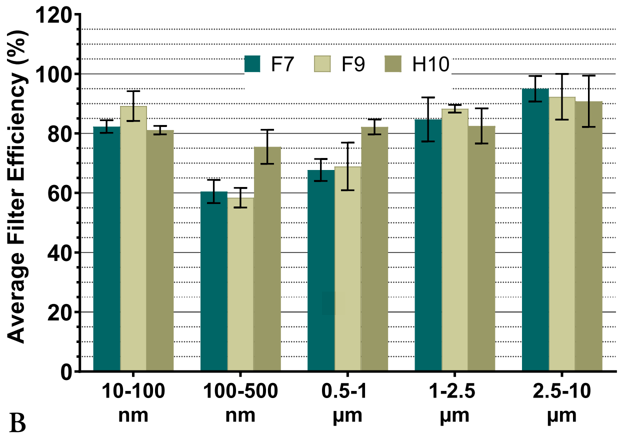

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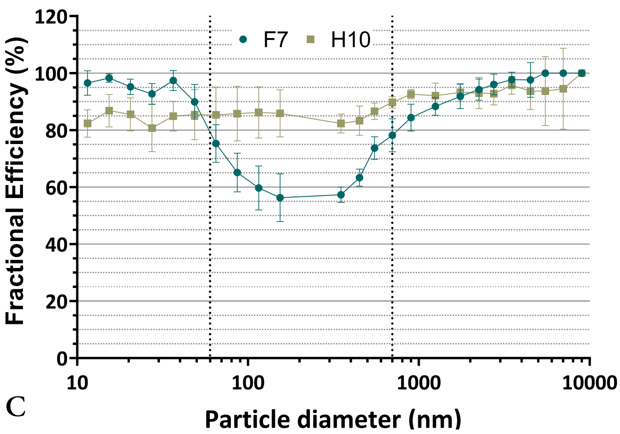

C

Figure 2. Average filter efficiency of fine filter types with indication of the 95% confidence interval at new state (A) and after 2.5 months of continuous use (B). Fractional efficiency profile within the complete measurement range (10 nm–10 µm) for an F7 filter and an H10 after 1 month in continuous use (C).

Table 1. *Pressure drop (Pa) as a function of time for the coarse and fine filters and the electrostatic precipitators (ESP), cc = cleanable collector, dc = disposable collector, FP= folded panel, B=bag, duct-type = round filter with the same diameter as the ductwork, wireframe = metal frame wrapped with a single layer of filter material.*

Time elapsed	Filter class and type									
	G3		G4			F7*	F9*	H10*	ESP	
	Duct type	FP	Wire-frame	FP	B	FP			cc	dc
Initial	98	9	31	11	7	23	23	27	8	16
1 month	200	12	67	18	8	24	21	28	9	16
2.5 months	285	12	125	43	16	32	36	47	10	21

* protected by a G4 FP coarse filter

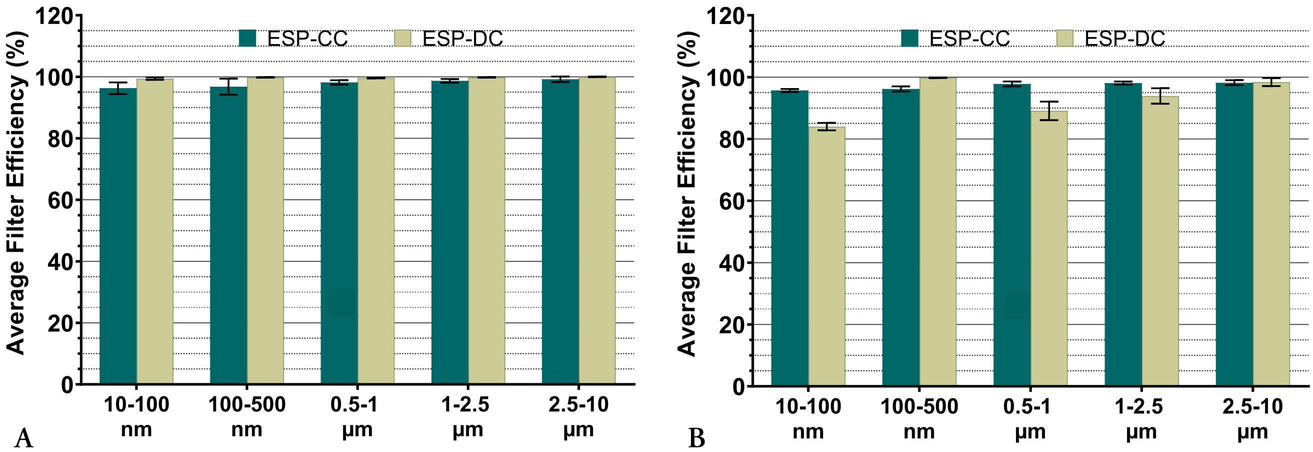

Figure 3. Average filter efficiency of the electrostatic precipitators with indication of the 95% confidence interval at new state (A) and after 2.5 months of continuous use (B). cc = cleanable collector, dc = disposable collector.

Electrostatic precipitators

Both precipitators exhibit a very high efficiency (>96%) within the full measuring range at new state. After 2.5 months in use, the version with the cleanable collector still shows a high efficiency throughout the measuring range, while for the version with the disposable collector the efficiency for some particle ranges, more precisely 10–100 nm and 0.5–1 µm dropped. Visual inspection of the collector plates indicates that a black coloration can be observed at the back of the collector plates, indication that the collector gradually becomes saturated.

The pressure drop over the system with the cleanable collector is lower than that of the version with the disposable collector (see **Table 1**). This is a result of the more open inner structure of the cleanable system. However, for both systems their pressure drop is rather small in comparison to the pressure drop over the tested fine filters and only has a small tendency to increase in function of time. Moreover, the ESPs are not protected by a prefilter as is the case for the fine filters. The ozone production was found to be limited for both systems (cleanable: 9.1±1.5 and disposable:5.9±1.8 ppb). In conclusion, electrostatic precipitation seems a promising technique due to the high efficiency of particle capture within the full range (10 nm–10 µm) and the associated low pressure drop in comparison to fine filters.

Further research

Further follow-up is necessary to get a more complete picture of the evolution of the efficiency of these filters and their pressure drop. For the electrostatic precipitators also the potential effect that ionized air might have on human health should be looked at. Remark: By the time the filters were purchased, the EN 779:2012 standard was still in use. In the meanwhile, is has been replaced by the EN ISO-16890:2016 standard [1] which makes use of a different method and classification of filters. Therefore, there is no one on one relation between the old and new classification. As an indication, the G3 and G4 classes would now correspond to ISO-coarse >80% and >90% (dust arrestance), F7 to ePM_1 50–65% (efficiency) or $ePM_{2.5}$ 65–95% and F9 to ePM_1> 80% or $ePM_{2.5}$>95%. In further research the test setup will be relaunched with a new composition guided by the results of initial one and making use of filters classified according to ISO-16890 standard. ■

Acknowledgments

The results shown are coming from the ongoing research project Out2In at BBRI. The authors wish to thank the Brussels-Capital Region – Innoviris for the financial support of this project.

References

[1] EN ISO 16890-1:2016, *Air filters for general ventilation - Part 1: Technical specifications, requirements and classification system based upon particulate matter efficiency (ePM)*, European Committee for Standardization.

[2] EN779:2012, *Particulate air filters for general ventilation - Determination of the filtration performance*, European Committee for Standardization.

[3] EN 1822-1:2019, *High efficiency air filters (EPA, HEPA and ULPA) - Part 1: Classification, performance testing, marking*, European Committee for Standardization.

[4] Eurovent 4.10:2005, *In situ determination of fractional efficiency of general ventilation filters*, Eurovent/Cecomaf.

This article is based on a paper presented at the 40th AIVC - 8th TightVent & 6th Venticool Conference "From energy crisis to sustainable indoor climate" 15-16 October 2019, Ghent, Belgium

Particle filtration in energy efficient housing with MVHR

Highly energy efficient buildings are very airtight and usually require the installation of a mechanical ventilation with heat recovery (MVHR). But which ambient air filter class is a reasonable choice in terms of indoor air quality and energy use when also considering indoor generation?

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Keywords: MVHR, air filtration, particulate matter, $PM_{2.5}$, Ultrafine PM, particle exposure, indoor originated particles, cooking, cooker hood

Study objectives & methodology

Highly energy efficient buildings have very airtight building envelopes and use mechanical ventilation systems to ensure sufficient air exchange. E.g. the Passive House standard, a certification scheme for very energy efficient buildings, requires the installation of mechanical ventilation with heat recovery (MVHR) (PHI n.d.). When using a MVHR fresh air is supplied into bedrooms (and living rooms). The same amount of air is extracted from the wet rooms, i.e. kitchen, bathroom and toilet, and exhausted to the ambient once it has passed the heat exchanger. In European homes with MVHR, no air is recirculated within the dwelling (in contrast to North American homes). To protect the heat exchanger from fouling, filters are needed. For this purpose, a rather coarse filter class, e.g. G4 or equivalent, is sufficient. To reduce the exposure of the occupants to outdoor-originated particulate matter (PM), many MVHR units foresee the installation of a higher filter class for supply air. E.g. the Passive House standard requires the use of an supply air filter with an efficiency rating of minimum F7 according to EN 779 (EN 2012) or ePM_1>50% according to the more recent ISO 16890. Note, that EN 779 classified filter media by its average filtration efficiency for particles with a diameter of 0.4 µm, while ISO 16890 considers filtration efficiency over the entire particle size spectrum. Typically, the supply air filter is positioned at the ambient air intake, this way it also protects the ventilation system from fouling. Since the potential health effects of fine and ultrafine particle exposure are receiving growing attention, the question arises what filter class should be recommended for highly airtight homes with MVHR. Is the current Passive House requirement reasonable or would it make more sense to recommend a higher or lower filter class? What is the effective filtration performance, i.e. the effective occupant exposure and what are the associated energy costs?

To answer these questions a number of aspects have to be considered: e.g. in-/exfiltration through the building envelope, particle deposition (e.g. gravitational settling, adhesion) and opening of doors and windows by the occupants influence the indoor particle concentration. Additionally, indoor particle sources like cooking (considered the major indoor source) can substantially contribute to occupant exposure.

To estimate exposure depending on outdoor concentration, cooking activity and ventilation concept a computer simulation study was performed using the software CONTAM. A model representing a typical Austrian residential dwelling with two bedrooms was generated incorporating all of the aforementioned aspects (**Figure 1**). Part of the challenge is that particles of different sizes behave very differently, so that the entire relevant particle size spectrum has to be modelled and that the respective model parameters have to be provided size-dependent. The necessary parameters were extracted from reports and publications of other experimental studies (Liu and Nazaroff 2003; Riley et al. 2002; Shi 2012)even though most human exposure to PM of outdoor origin occurs indoors. In this study, we apply a model and empirical data to explore the indoor PM levels of outdoor origin for two major building types:

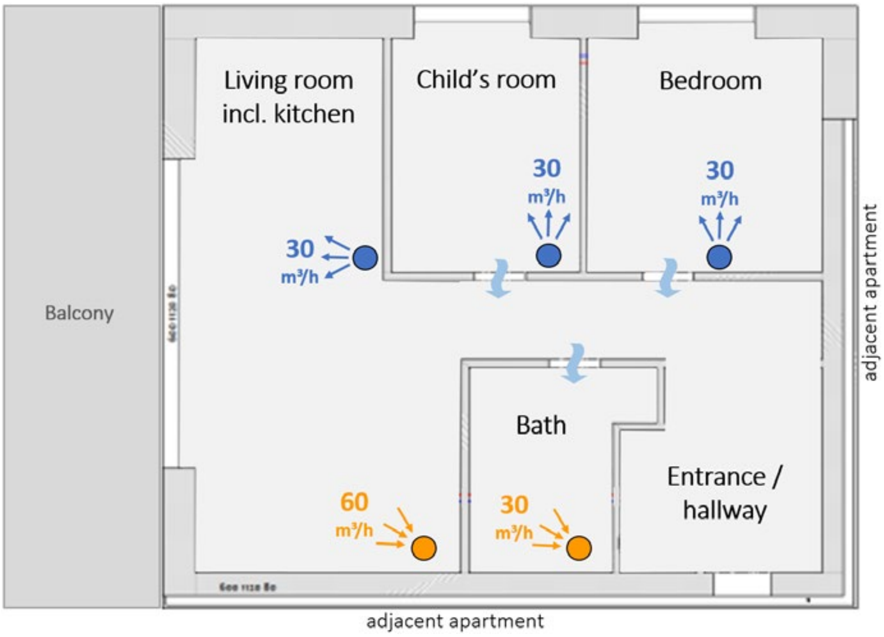

Figure 1. Sketch of the simulated floor plan representing a typical new Austrian residential dwelling.

offices and residences. Typical ventilation rates for each building type are obtained from the literature. Published data are combined with theoretical analyses to develop representative particle penetration coefficients, deposition loss rates, and ventilation-system filter efficiencies for a broad particle size range (i.e., 0.001-10 mum. A sensitivity analysis was performed for relevant model parameters to ensure that a variation on the assumed parameters will not totally change the results and therefore the conclusions, see (Rojas 2019) for more details.

Main results

Figure 2 shows the simulated particle size distribution for four distinct hours of a winter day: (a) night times: only outdoor-originated particles are present;

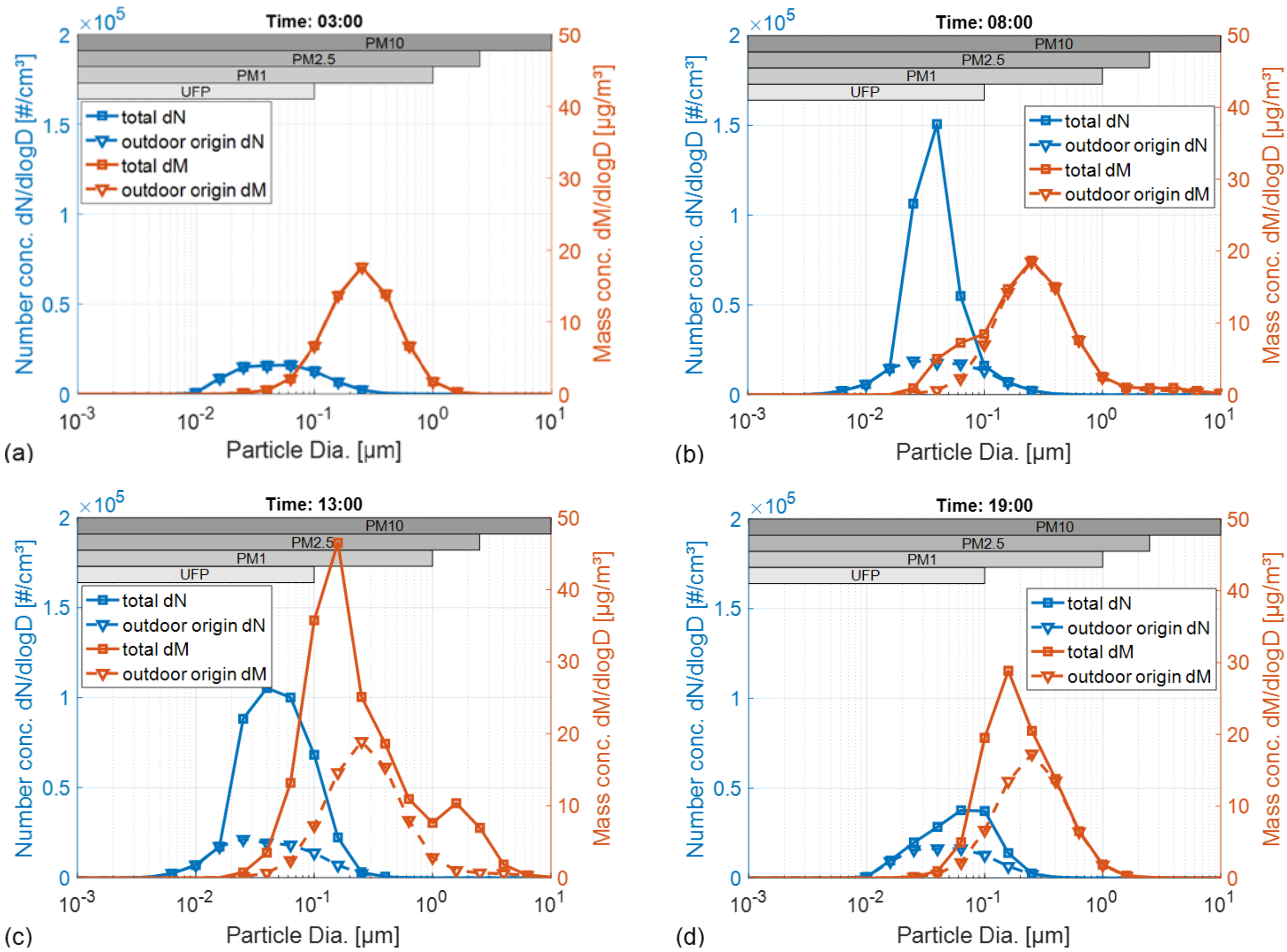

Figure 2. Log-normalized PM size distribution in the living room at four different hours of the day: during the night (a), after breakfast (b), after lunch (c), after dinner (d). The distribution of the outdoor-originated number and mass concentration is also plotted to differentiate between contributions from indoor and outdoor sources.

(b) after breakfast (with bread toasting activity): the number concentration is strongly increased by indoor-originated particles, however the mass concentration is still dominated by outdoor-originated particles (increased by morning airing event); (c) after lunch: the cooking event (frying burger) substantially increases the number and mass concentration; (d) after dinner: the number and mass concentration is notably increased by another cooking activity (heating oil). As one can also see, there is little difference between PM_1, $PM_{2.5}$ and PM_{10} values, i.e. most of the time indoor exposure is mainly dominated by sub-micrometre sized particles.

The results of the variation in air filter class show that a F7 filter (according to EN 779, roughly equivalent to MERV13 according to ASHRAE Standard 55.2 or ePM_1>50% according ISO 16890) reduces the average $PM_{2.5}$ exposure of a person (that is home all day) to outdoor-originated particles by 67% compared to outdoor air. This comes at a relatively low additional electrical energy consumption (the extra fan power needed to overcome the flow resistance created by the filter). In comparison, the use of a lower class filter like a M5 (equivalent to MERV9/10) or a higher class filter like F9 (equivalent to MERV15) would reduce the exposure by 26% or 79%, respectively. See triangles/dashed line in **Figure 3**. Note that the simulated filters were classified according to EN 779, because fractional efficiency curves for filters according to ISO 16890 were not available to the authors yet.

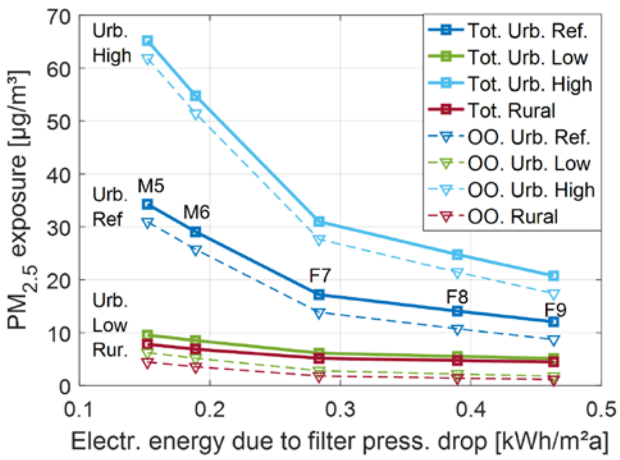

Figure 3. Average $PM_{2.5}$ exposure of a person staying home all day as a function of electric energy consumption of the fan due to the pressure drop of the filter. "Urb. High" represents highly polluted areas with daily means of ~80 µg/m³, "Urb. Ref" moderately polluted areas with means of ~40 µg/m³ and "Urb. Low" low polluted urban areas with a daily mean ~8 µg/m³. The dashed line/triangle show the exposure to outdoor-originate PM.

Depending on the outdoor air PM concentration and the level of cooking activities by the occupants, the exposure to indoor generated particles might become a substantial or even dominant fraction of the total PM exposure. To assess the exposure to cooking related PM, different cooktop ventilation strategies (no cooker hood, a recirculating cooker hood with carbon filter and an extracting cooker hood) were simulated. When operating extracting cooker hoods in airtight buildings the inflow of make-up air has to be provisioned, e.g. by a dedicated make-up air opening or an open window. This is the reason that the use of an extracting device is not necessarily beneficial when the outdoor concentration is high or moderate and the particle generation from cooking is low or moderate. However, for low outdoor air concentrations, the use of an extracting cooker hood will greatly reduce exposure to particles from cooking, in particular for strongly emitting activities like frying.

Conclusions

This is a simulation study and therefore its results are affected by assumed boundary conditions. Nevertheless, this study gives insights and trends for the exposure to PM in highly energy efficient homes, which help the selection of sensible PM filtration systems. The results confirm that the use of a F7 filter (roughly equivalent to ePM_1 50% or MERV13) makes sense as a general precautionary recommendation, since the relation between exposure reduction and associated

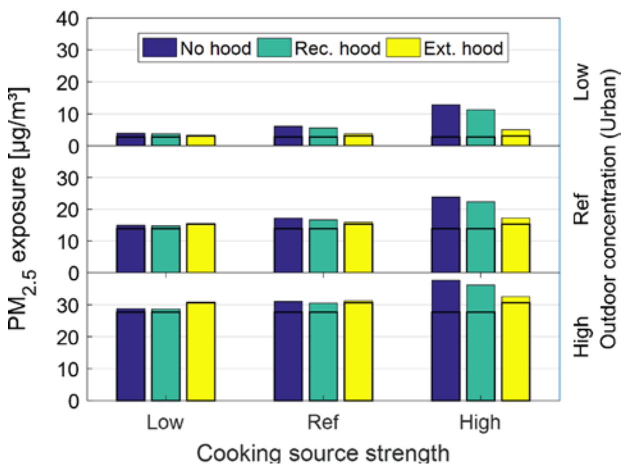

Figure 4. Average $PM_{2.5}$ exposure of a person staying home all day for different outdoor concentrations, different cooking source strength and different cooktop ventilation strategies (no hood, recirculating hood and extract hood). Horizontal lines show exposure to outdoor-originate PM.

energy penalty is good. The results also show that for outdoor air concentrations as typically encountered in urban areas in well developed countries (labelled "low" in this study, see also (WHO 2016)), the total PM exposure may be dominated by indoor sources like cooking (**Figure 4**). Here, effective measures, like the use of extracting cooker hoods, are recommendable for high cooking activities. For locations with moderate or high outdoor PM concentrations, as often encountered in Asian cities, the use of higher filter classes like F9 or equivalent are recommendable. They will further reduce the exposure to outdoor-originated PM. In those cases, the use of extracting cooker hoods may not be advisable due to the introduction of outdoor particles with the make-up air. For conditions with high outdoor PM concentrations and high cooking source strength as often encountered in Asian households, a need for new product developments, such as recirculating cooker hoods or make-up air openings with particle filtration, is identified. ■

References

EN. 2012. "EN 779:2012 Particulate Air Filters for General Ventilation - Determination of the Filtration Performance."

Liu, De Ling and William W. Nazaroff. 2003. "Particle Penetration through Building Cracks." *Aerosol Science and Technology* 37(7):565–73.

PHI. n.d. "About Passive House - What Is a Passive House?" Retrieved September 29, 2018 (https://passiv.de/en/02_informations/01_whatisapassivehouse/01_whatisapassivehouse.htm).

Riley, William J., Thomas E. McKone, Alvin C. K. Lai, and William W. Nazaroff. 2002. "Indoor Particulate Matter of Outdoor Origin: Importance of Size-Dependent Removal Mechanisms." *Environmental Science and Technology* 36(2):200–207.

Rojas, Gabriel. 2019. "Ambient Air Filter Efficiency in Airtight, Highly Energy Efficient Dwellings – A Simulation Study to Evaluate Benefits and Associated Energy Costs." in *AIVC Proceedings 2019*, AIVC.

Shi, Bingbing. 2012. "Removal of Ultrafine Particles by Intermediate Air Filters in Ventilation Systems - Evaluation of Performance and Analysis of Applications Ventilation Systems." Chalmers University of Technology, Göteborg, Sweden.

WHO. 2016. "Concentration of PM2.5 in Nearly 3000 Urban Areas, 2008-2015." Retrieved May 9, 2019 (http://gamapserver.who.int/mapLibrary/Files/Maps/Global_pm25_cities_2008_2015.png).

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Cloud based large-scale performance analysis of a smart residential MEV system

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This study is a first large-scale analysis of the performance of a cloud connected and smart residential mechanical extract ventilation (MEV) system based on field data. About 350 units were analysed over a period of 4 months from December 2018 up to March 2019, corresponding with the main winter period in Belgium. Half of the units were installed as a smartzone system which means additional mechanical extraction from habitable rooms as bedrooms. The air extraction was controlled on different parameters (humidity, CO_2 and VOC) depending on the room type. Indoor climate and IAQ were analysed with respect to design criteria set out in standards as well as fan characteristics and energy consumptions. Since rooms are often unoccupied or occupied at a low level, advanced demand control technology proves to have a high potential to limit total energy consumption, while assuring a good IAQ. These findings should also be reflected within the European ventilation legislation, such as Ecodesign.

Keywords: Smart connected ventilation, demand controlled MEV, large-scale in-situ monitoring, IAQ, energy consumption

Ventilation is a quite complex process whose quality is affected by many parameters related to the manufacturing, design, installation, use and maintenance of the system over its life cycle. Up to now, the design of ventilation is usually descriptive in its approach and the performance is often theoretically analysed under ideal conditions. As a consequence, some of the aforementioned aspects are not taken into account. During recent years, however, several ventilation field studies in the residential sector were carried out due to the availability of affordable and/or plug-and-play monitoring apparatus (see overview by De Maré et al., 2019). Nowadays, IoT devices become also available in the residential ventilation industry, allowing to investigate the real performance of these ventilation units during their lifetime on a large scale. This study is a first global analysis and part of a large research programme to investigate over time the occurring indoor air quality in the main rooms and the overall fan characteristics of a connected demand controlled central mechanical extract ventilation (DC MEV) unit. In the study mainly the performance of units without air extraction in the bedrooms (no-smartzone) and with air extraction in the bedrooms (smartzone) was compared under Belgian winter conditions.

Methodology of the Ventilation system analysis

From 2018 on, commercially available "smart" DC MEV (so-called Healthbox 3.0) systems with cloud connection possibility were installed in Belgian houses and residential buildings (see **Figure 1**). The mechanical extraction took place locally in the wet rooms and in about half of the dwellings also directly from the bedrooms. The system with bedroom extraction is hence forward called "with smartzone", and without extraction from the bedroom "no smartzone", as illustrated in **Figure 1**.

The outdoor air was supplied through passive vents placed on top of the windows in the habitable rooms (**Figure 1**). These passive vents are pressure controlled and can additionally be gradually adjusted by the inhabitants between fully open and closed. By means of valves directly attached to the central unit at the end of the extract duct, the air extraction was locally controlled on different parameters depending on the room type: in bathroom and utility room on absolute and relative humidity (AH and RH); in kitchen and bedroom (if extraction available) on CO_2 and in toilets on volatile organic compounds (VOC). Sensors were located at the valves and not within the rooms, which means that sensor values could -to a certain extent- deviate from the room conditions.

In this study during the typical Belgian heating period from December 2018 up to March 2019 (temperate maritime climate), the performance of a fixed number of about 350 devices divided over no-smartzone and smartzone types was investigated. The ventilation units were installed without extra commissioning afterwards to correct or improve the performance of the system. The large-scale cloud data were not filtered on false values or outliers.

Different characteristics of the climate and the system were analysed: indoor comfort (CO_2, humidity), fan characteristics (average and nominal airflow, time fraction minimal airflow rate, average pressure and power input) and total energy consumption. Design values of RH and CO_2 concentration as especially specified in the standard EN 16798-1 (2019) (replaces the EN 15251 standard) were used as criteria to analyse the indoor comfort. Comfort analysis of bedrooms on a large-scale could only take place when direct mechanical extraction with sensor control was present (with smartzone), since sensors were located at the extract valves. For the data analysis, active ventilation was defined as ventilation at flow rates higher than the minimum control values.

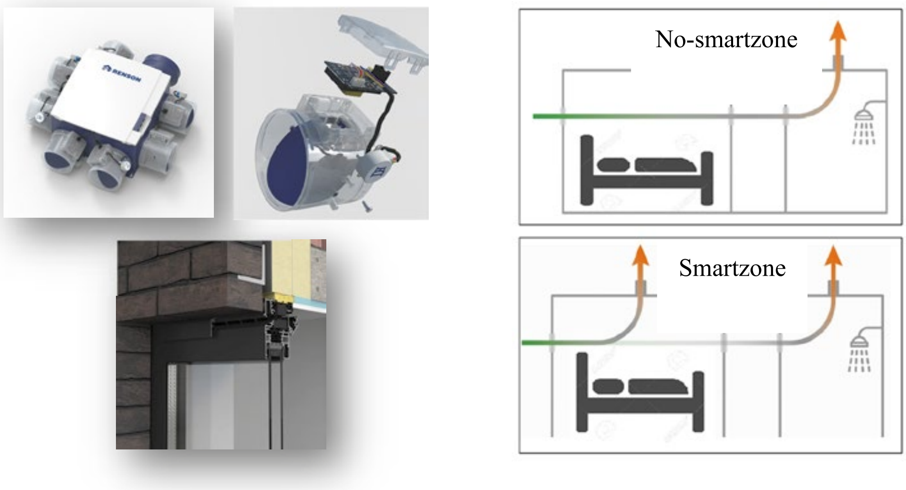

Figure 1. DC MEV system (above-left), passive vents (below-left) and the difference between no-smartzone and smartzone principle (right).

Results

Humidity

Figure 2 illustrates the mean time fraction of RH < 80%, 30% < RH < 70% and 25% < RH < 60% in different rooms (kitchen, bathroom, laundry and bedroom) over the 4 months considered. In the different rooms considered the RH values higher than 80% were very limited. The lowest occurrence was found in the kitchen, the highest in the bathroom where water vapour productions are usually highest. Lower peaks in the kitchen can be due to a quasi-permanent heating, the mostly open connection with the (dry) living room and the standard availability of a separate cooker hood to extract water vapour. For the several rooms considered, the average time fraction with RH values <80% was at least 97.5%, as found in the bathroom.

The mean time fraction of RH between 30 to 70% was close to 90% for the different rooms, with the highest and the lowest time fraction in the kitchen and the bathroom, respectively. This latter logically agrees with the previous findings on RH >80%.

When looking to the average time fraction of RH between 25 and 60% in **Figure 2**, more variation was found between the rooms, with a minimum of 80%. The lowest value was also reported in the bathroom where the highest water vapour productions can be expected. In addition, Lokere (2019) found a negligible risk on mould growth in the different rooms. Newly built houses are well insulated without thermal bridges to prevent condensation.

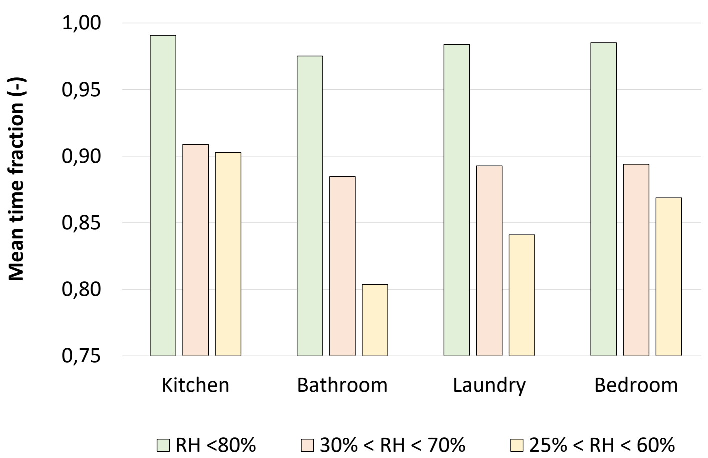

Figure 2. Mean time fraction of RH<80%, 30%<RH<70% and 25%<RH<60% in different rooms.

CO_2 concentration

The IAQ was analysed based on CO_2 categories defined in the EN 16798-1 standard for habitable rooms as (mainly open) kitchen and bedroom, as illustrated in **Figure 3**. Data for the kitchen were derived as an average from systems without and with smartzone, whereas bedroom results concerned only smartzone systems. The data were selected on two different bases: day or night time and during active ventilation (when airflow rate in the room is higher than minimum, corresponding best with the unknown occupancy period). Substantial differences occur between these selections.

In the bedroom, the CO_2 levels belong 80 to 90% of the night-time to category 1 or 2 (< 950 ppm), with a main fraction in category 1 (< 800 ppm). In 90% of the bedrooms with extraction, the CO_2 level was <1,200 ppm during at least 95% of the night-time. When considering only active ventilation (during occupancy) this percentage varied between 70 and 80%, with a dominant group in category 2 and only about 20% in category 1. Comparing the results during night-time and active ventilation points at that approximately half of the night, ventilation is at its minimum flow rate (< 800 ppm) due to no occupancy, low occupancy and deep sleep with CO_2 levels lower than 800 ppm. When considering the total daytime instead of the night-time, the smartzone system also worked on its minimum flow rate during half of the time (see **Figure 4**). For bedrooms, the mean time fraction with CO_2 levels in category 3 (moderate IAQ < 1350 ppm) and 4 (bad IAQ >1350 ppm) were limited to respectively 30% and 5% of the time during active ventilation. This means that the extract capacity of 30 m^3/h in bedrooms can be considered as a minimum design value. Van Holsteijn and Li (2014) reported in the Monicair study similar results with a fraction of at most 1 hr or 10% of the night time that CO_2 concentrations were higher than 1,200 ppm.

The IAQ in the kitchen was analysed during daytime and active ventilation based on the CO_2 categories as illustrated on the right part of **Figure 3**. The IAQ belongs nearly permanently to category 1 and 2 (< 1200 ppm). The difference with the findings in the bedroom can be explained by the shorter occupancy period, the larger room volume of the open kitchen, the presence of a cooker hood and the CO_2 categories according to the EN16798-1 that are less severe in kitchens than in bedrooms. During active ventilation the time percentages with CO_2 levels lower than 800 ppm and between 800-950 ppm were slightly higher than in the bedroom, due to less severe conditions in the kitchen.

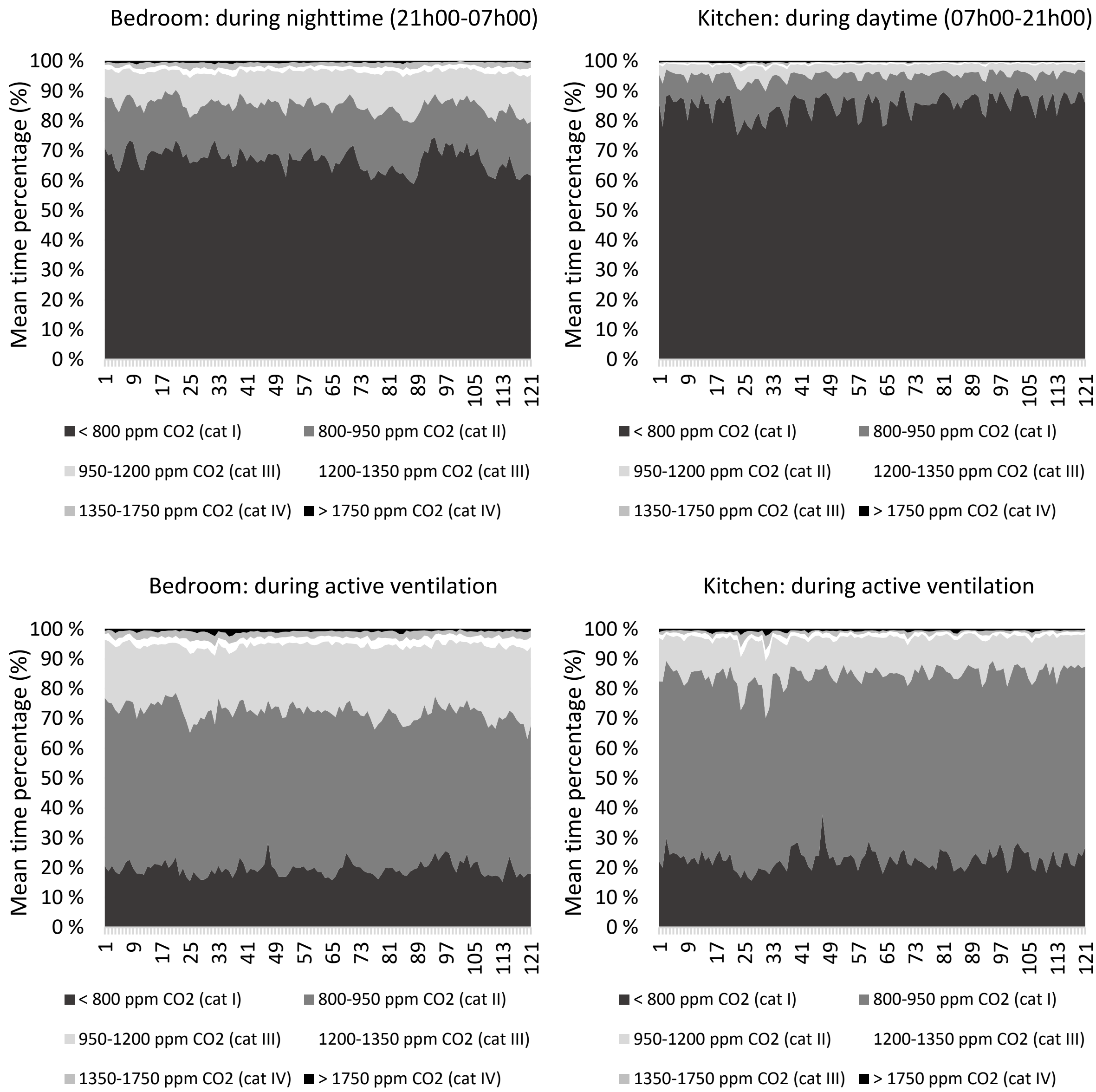

Figure 3. Mean daily time percentage of CO2-categories according to the EN16798-1 standard for bedroom (left) and open kitchen (right) during day or nighttime (above) and during active ventilation (below).

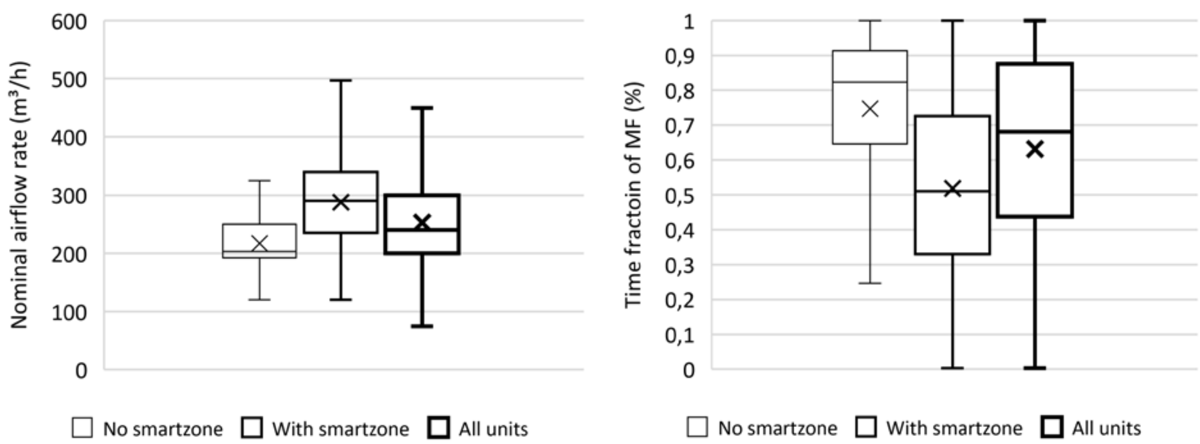

Figure 4. Nominal airflow rate (left) and the average time fraction of minimal ventilation MF (right) of the units.

When looking over the wintertime period a constant trend containing some fluctuations was observed, which can be caused by user behaviour (difference between week and weekend days) and wind conditions.

Furthermore, the exposure to CO_2 expressed as the cumulative CO_2-concentration above 1200 ppm (in ppmh) was calculated, since this is a commonly used parameter in IAQ research. The average daily exposure over the dwellings was 245 ppmh/day which is only 33% of the 733 ppmh/day reported by van Holsteijn and Li (2014). This big difference can be explained by the lower control setpoint of 950 ppm instead of 1200 ppm.

Since large-scale data of the IAQ in bedrooms without direct extraction is not available, some dwellings without smartzone were monitored separately. It was found that many elements have an impact on the IAQ in the bedrooms, such as size of the supply opening, position of the door, occupancy level and wind direction. As a consequence, CO_2 levels can vary between very good (< 1000 ppm) and very bad (>2000 ppm). In general, omitting direct extraction from the bedroom gave rise to maximum CO_2 level in the parent bedroom belonging to category 4 (>1350 ppm).

Fan characteristics and energy consumption

The fan characteristics and the energy consumption were analysed by comparing no-smartzone and smartzone systems. The average values over the 4 months period of several parameters of the connected units were set out as a box plot in **Figure 4 to 6** (daily average in case of time fraction of minimal flow rate MF).

When analysing the time fraction of minimum airflow rate MF over the entire box (= none of the valves is activated), the daily average time fraction is about 75

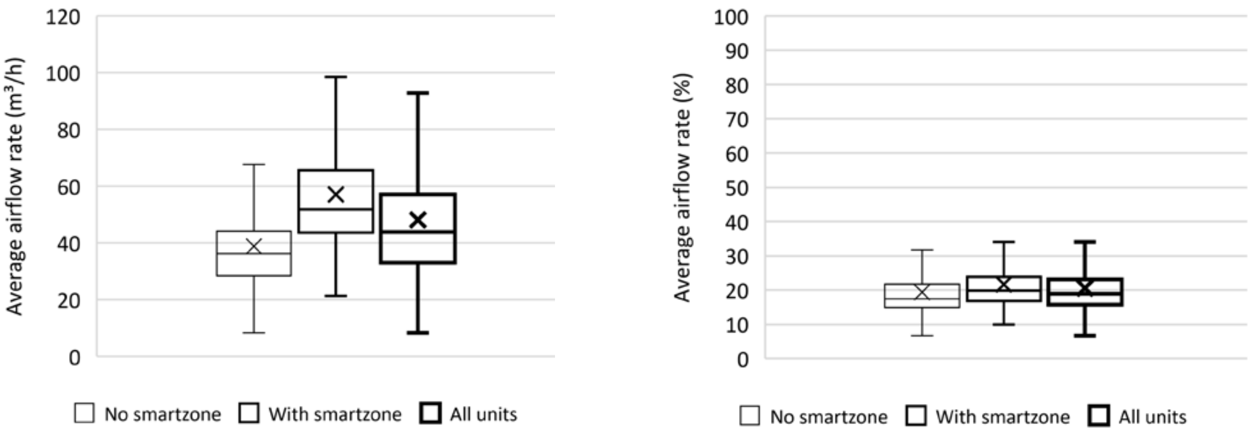

Figure 5. Average airflow rate of the units expressed as "m^3/h" (left) and "%" (right).

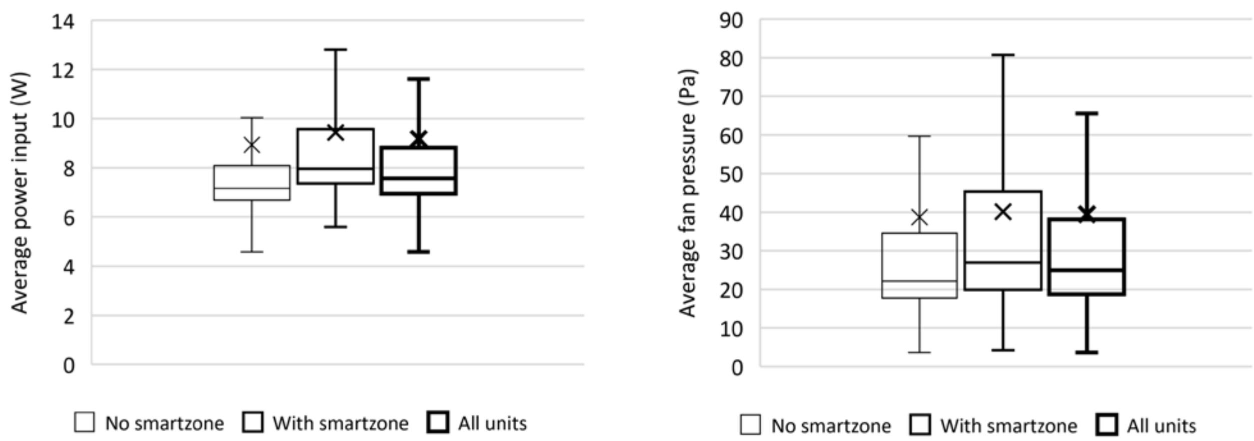

Figure 6. Average power input (left) and average fan pressure of the units (right).

and 50% for the no-smartzone and smartzone system. The high fractions of both systems proved already the huge potential of demand controlled ventilation to save energy. When comparing no-smartzone with smartzone systems, on average 25% of the time or six hours/day, the smartzone system is activated in at least one of the bedrooms to guarantee IAQ. The spread in time fraction is quite large indicating that substantial differences occur over time and between the units. The relation of this MF time fraction with the period of non-occupancy could be further investigated.

The average extract airflow rate of 57.1 m³/h of the smartzone systems was about 50% higher than the value of 38.8 m³/h for no-smartzone systems, however, the IAQ realised with the smartzone system was also better. This was clearly due to the higher installed nominal airflow capacity via the additional extraction points and the higher mean ventilation levels in bedrooms than in wet rooms.

The mean nominal airflow rate (= ventilation capacity) of 288 m³/h of smartzone systems was on average about 32% higher than the value of 218 m³/h of no-smartzone systems.

Compared to the study of van Holsteijn and Li (2014) who found an average extract rate of 76.9 m³/h for a similar ventilation system with smartzone (C4c), the cloud data average extract rate is 26% lower. This is quite remarkable since the MEV system studied controlled the air on a lower setpoint of 950 ppm instead of 1,200 ppm in the habitable rooms. Nominal airflow rates of both ventilation systems were also comparable.

The airflow rate expressed as a fraction of the installed nominal capacity, the so-called reduction or ctrl-factor was about 0.20 in case of smartzone systems. Usually, the ctrl-factor is expressed to the nominal airflow rate of systems with no smartzone. In that case the ctrlfactor of the smartzone systems becomes 0.26, neglecting a small fraction of cross ventilation. In the Belgian (EPB), Dutch (NTA 8800) and European (EN 13142) regulation, the default ctrl-factor for MEV systems with local control and detection in all rooms is substantially higher with values of 0.43, 0.55 and 0.50, respectively. In case of the no-smartzone system, the ctrl-factor cannot be determined since the assumption of equal IAQ is not guaranteed for the bedrooms under the monitored airflow rates.

When looking at all the boxes, the mean operating pressure of the fan was respectively 38.9 and 40.1 Pa for the no-smartzone and smartzone systems (maximum pressure level of the unit is 350 Pa). Median pressure values, however, were substantially lower. Also, the average power input of no-smartzone and smartzone systems was quite similar with values of 9.0 and 9.4 W, respectively, including the power consumption due to electronics and sensors (maximum power input of the unit is 85 W at 400 m³/h and 200 Pa). These average values were about 1.5 W higher than the median values, pointing out that the design or installation of some units was not optimal, giving rise to higher mean electricity consumptions. The small difference between no-smartzone and smartzone systems was realized by means of smart fan and valve control. The required auxiliary energy per unit of airflow rate of the unit, the so-called specific power index SPI as defined in the standard EN 13142, was equal to nearly 0.23 and 0.16 Wh/m³ for the no-smartzone and smartzone respectively.

Extrapolating the average power input to an entire year, resulted in a yearly auxiliary consumption of the extract system of about 79 kWh and 82 kWh for no-smartzone and smartzone systems, corresponding to a total electricity cost of about 20 € in case of an electricity price of 0.25 €/kWh. Van Holsteijn and Li (2014) and Derycke et al. (2018) found an electricity consumption of more than twice that high for similar systems with also extraction from the habitable rooms, i.e. 187 and 186 kWh, respectively. The substantial lower energy consumption in this study is due to a recent optimisation of the MEV system at the hardware- and software-level and probably due to a lower overall occupancy level and a larger dataset.

The C4a system without smartzone and without local control in the wet rooms, as investigated by van Holsteijn and Li (2014) showed a lower yearly auxiliary consumption of 50 kWh and a higher average airflow rate of 95 m³/h compared to the no-smartzone system investigated. The CO_2-exposures in case of C4a, however, were considerably higher.

The average ventilation heat losses could be estimated based on a mean measured indoor air temperature of 21°C, a mean outdoor temperature of 6°C over a six-month heating period from November up to April in Belgium and a 85% efficiency of the heating system, approaching 5350 MJ for a smartzone system. These ventilation heating losses are 32% lower than the value of 7874 MJ reported by van Holsteijn and Li (2014) for a similar heating season. Assuming a gas price of 0.05 €/kWh, the yearly average heating cost for ventilation with the smartzone MEV system is about 75 €. Additional cross ventilation through passive vents can to some extent increase that heating cost. It can be stated that in many cases the total yearly energy cost related to the operation of the smartzone ventilation system (heating and auxiliary energy) will be limited to 100 €.

Within the Ecodesign framework and its requirement to provide consumers with accurate information regarding energy consumption, it is relevant to compare the smartzone MEV-results with a MVHR system. Ecodesign and its labelling scheme must allow consumers to identify how energy efficient a product actually is and to assess a product's potential to reduce energy costs. In order to make this comparison, the following assumptions were made for the balanced MVHR system:

- The real average airflow rate is 125 m³/h which equals half of the mean nominal airflow rate system of 250 m³/h over all the units (cf. **Figure** 4).
- This average airflow rate, which varies between a minimum and a maximum value, is assumed to assure an adequate IAQ in case of no zone controlled systems.
- The overall efficiency of the heat recovery unit in-situ is 60% taking into account real circumstances such as leakages, defrosting, unbalance, pollution, usability of recovered heat, … This lower recovery efficiency in practice compared with laboratory measurements is justified by studies as Merzkirch et al. (2015), Faes et al. (2017) and Knoll et al. (2018).

Under these assumptions the ventilation heat losses are about 4,700 MJ or nearly 12% lower than the MEV system with smartzone. The similar heat losses of both the MVHR and the smartzone system are comprehensible since the mean ctrl-factor of 0.26 of the MEV system corresponds with a virtual heat saving efficiency of 74%. Besides, the real electricity consumption of a MVHR system will be at least four times higher due to the presence of two fans and the much higher pressure losses in the unit caused by filtering and heat recovery (Derycke et al., 2018). As a consequence, since electricity is at least three to four times more expensive than gas, the mean yearly energy cost of a MVHR system will not be lower than that of the MEV with smartzone.

Conclusions

Cloud connected ventilation systems combined with data analysis allows to investigate their performance on a large-scale. Due to technological and digital evolutions MEV systems with smartzone combined with natural supply are able to guarantee IAQ in every room and perform energetically equally or better than MVHR systems in countries with a mean winter temperature not lower than freezing point. These real performance data should also be reflected in the Ecodesign calculation and labelling to limit the gap between what is promised and the final reality. ■

References

De Maré, B., Germonpré, S., Laverge, J., Losfeld, F., Pollet, I. & Vandekerckhove, S. (2019). Large-scale performance analysis of a smart residential MEV system based on cloud data. Proceedings of the 40th AIVC conference, 15-16 October, Gent.

Derycke, E., Bracke, W., Laverge, J. and Janssens, A. (2018). Energy performance of demand controlled mechanical extract ventilation systems vs mechanical ventilation systems with heat recovery in operational conditions: Results of 12 months in situ-measurements at Kortrijk ECO-Life community. Proceedings 39th AIVC Conference, Antibes (France), 18-19 September 2018, 838-847.

Faes, W., Monteyne, H., Depaepe, M. and Laverge, J. (2017). A 'use factor' for HRV in intermittently heated dwellings. Proceedings 38th AIVC conference, Nottingham (UK), 13-14 September 2017, 337-341.

Knoll, B., Borsboom, W. and Jacobs, P. (2018). Improving the usability and performance of heat recovery ventilation systems in practice. Proceedings 39th AIVC Conference, Antibes (France), 18-19 September 2018, 833-837.

Lokere, L. (2019). Big data in demand controlled ventilation: comparison of measured data with literature. Master dissertation, 120 p.

Merzkirch, A., Maas, S., Scholzen, F. and Waldmann, D. (2015). Primary energy used in centralized and decentralized ventilation systems measured in field tests in residential buildings. Proceedings 36th AIVC Conference, Madrid, 23-24 September 2015, 197-203.

Valk, H., van Holsteijn, R. and Hofman, M. (2019). Indicatieve beoordelingsmethode systeemprestatie ventilatie voor individuele woningen IBVP. Toelichting, onderbouwing en validatie bij Ontw. NEN1087:2019, 33 p.

van Holsteijn, R. and Li, W. (2014). Monicair: MONItoring & Control of Air quality in Individual Rooms. Eindrapport WP1a, 98 p.

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Assessment of mid-term and long-term building airtightness durability

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The increasing weight of building leakages energy impact on the overall performance of low-energy buildings led to a better understanding and characterization of the actual airtightness performance of buildings. Several European countries have already included mandatory requirements in their Energy Performance regulation (EP-regulation) regarding the building airtightness. In France, the EP-regulation requires a limit airtightness level for residential buildings that must be justified by measurement. However, low expertise is available today on the durability of building airtightness and its evolution in mid- and long-term scales.

The French research project "Durabilit'air" (2016–2019) was conducted in order to improve our knowledge on the variation of buildings airtightness through onsite measurement campaigns and accelerated ageing in laboratory controlled conditions.

This paper is issued from the second task of the "Durabilit'air" project. This task deals with the quantification and qualification of the durability of building airtightness of single detached houses. It is done through field measurement campaigns at mid-term and long-term scales. This paper presents the results of both MT and LT measurements.

Methodology

The MT campaign aims at characterising the yearly evolution of building airtightness of new dwellings over a 3-year period. A sample of 30 new single-detached low-energy houses (**Figure 1**), measured upon completion (reference measurement n_0), has been selected nationwide. The airtightness of each building was measured once per year over the 3-year period (measurements n_1, n_2 and n_3). Besides, five buildings of this sample were measured twice per year in order to investigate the impact of seasonal variations.

The LT campaign aims at characterising the evolution of building airtightness of existing dwellings over a longer period from 3 to 10 years. A second sample of 31 existing single-detached dwellings (**Figure 1**), measured upon completion (reference measurement n_0), has been selected. The dwellings have been constructed during the last 10 years. The airtightness of each dwelling was measured once (measurement n_x).

The measurement protocol was defined after a detailed literature review (Leprince, 2017). The protocol is mainly based on the standard ISO 9972 (ISO 9972, 2015) and its French implementation guide (FD P50-784, 2016) for the measurement method with additional requirements for the measurement conditions in order to reduce uncertainties due to measurement procedure (measurements under the same conditions as the first measurement upon completion, detailed qualitative leakage detection, questionnaires for regarding the modifications of the building envelope).

Evolution of envelope air permeability

For the MT sample, **Figure 2** shows a significant increase in the mean air leakage rates at 50 Pa (q_{50}) between the measurements n_0 and n_1 by 58.9 $m^3.h^{-1}$, i.e. +18% (p-value = 0.037 < 0.05), than a stabilization of q_{50} at n_2 and n_3. For the LT sample, we observe similar results as MT sample with a significant increase in the mean q_{50} between n_0 and n_x by 67.7 m^3/h, i.e. +20% (p-value = 0.002 < 0.05).

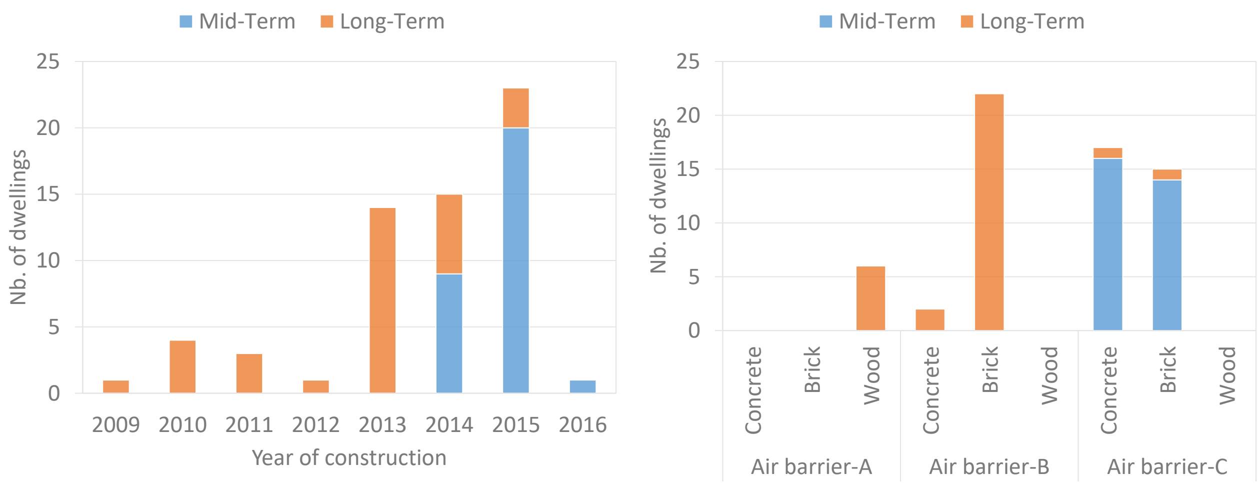

Figure 1. Distribution of buildings depending on the year of construction (left) and buildings main material and type of air barrier (right); Air barrier-A when the air barrier is ensured by vapour barrier, Air barrier-B by coating on the masonry, and Air barrier C by plasterboards and mastics at the inside facing of the walls.

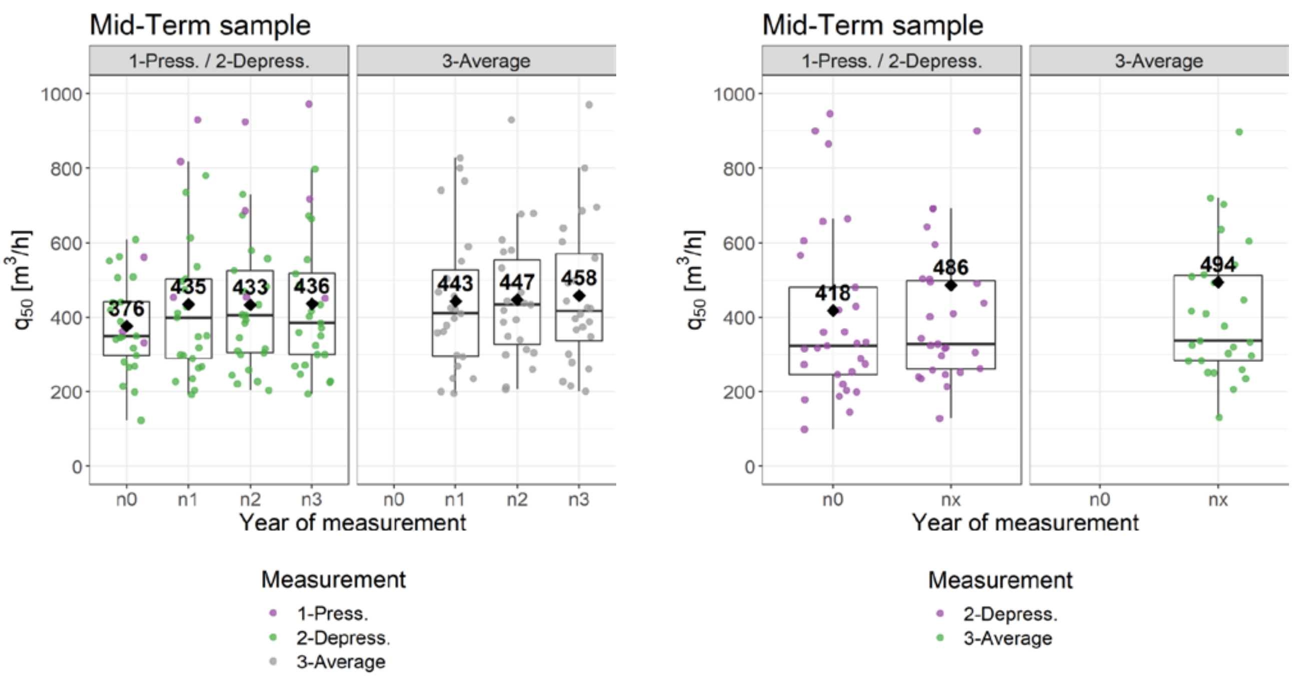

Figure 2. Boxplot of the measured air leakage rates at 50 Pa q_{50} for the measurements n_0, n_1, n_2 and n_3 of the MT sample, and the measurements n_0 and n_x of the LT sample.

In order to analyse the correlation between the evolution of the air permeability and the age of the houses, we have performed a linear regression of the evolution in q_{50} on the timespan between the measurements at completion and the other measurements. It has shown a lack of correlation between the evolution in q_{50} and the age of the houses for both MT and LT samples. Therefore, the air permeability does not seem to change with the age of the building; it varies mainly during the first two years of the building, and then stabilizes, as observed in the state of the art done by (Leprince, 2017). Variations during the first two years may have several origins, including actions by the occupants when they move in the building (e.g. installing furniture, picture frames, downlight…), the first heating of the building or the structural movement due to foundation settlement.

Analysis of explanatory factors

In order to go further in the understanding of the variation of buildings airtightness, we have examined the evolution of air leakage rate q_{50} regarding the houses main characteristics (constructor, number of levels, type of air-barrier, type of material, type of floor, type of roof, type of heating, specific HVAC equipment) and the modifications by the occupants (modification on windows, modification on walls).

Figure 3 and **Figure 4** show the relative gap in q_{50} and the evolution in q_{50} between different measurements for all houses of the MT sample depending on the number of levels and the type of roof respectively.

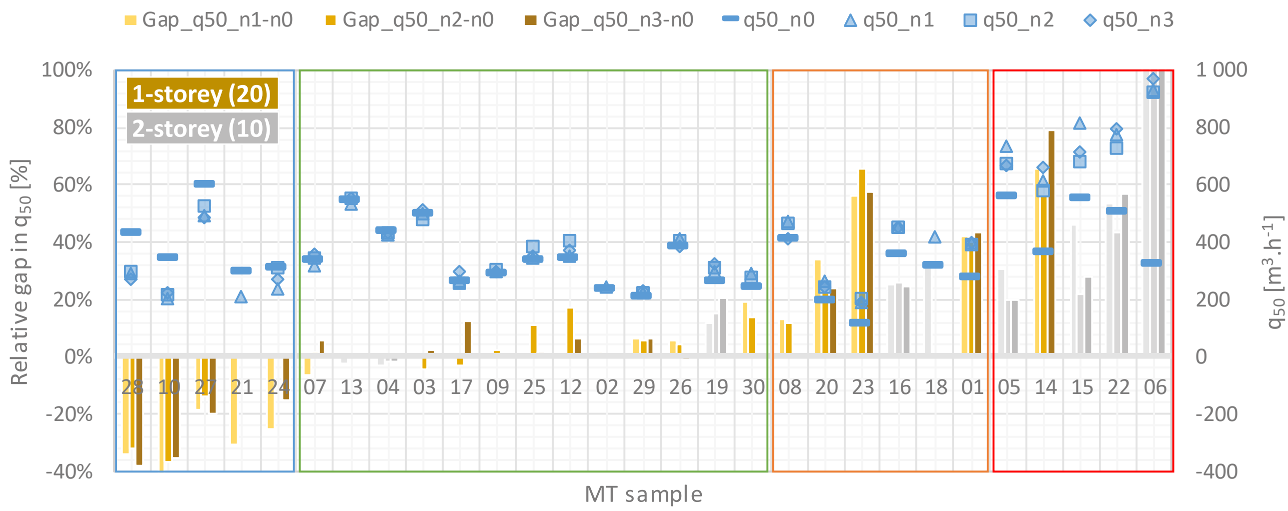

Figure 3. The relative gap in q50 (left y-axis) and the evolution in q50 between different measurements (right y-axis) for all houses of the MT sample depending on the number of levels.

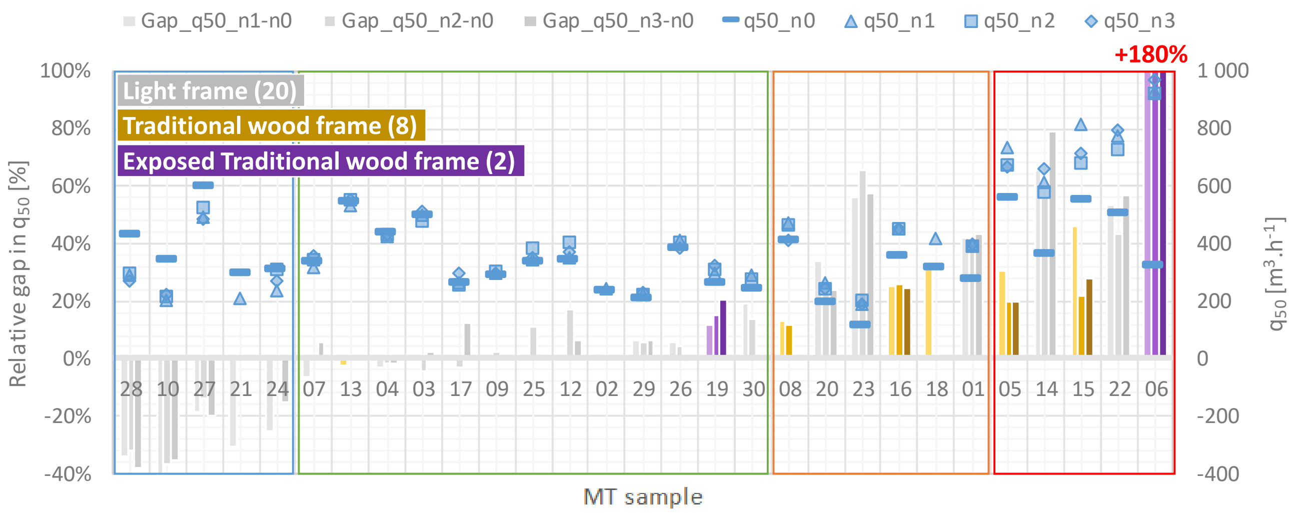

Figure 4. The relative gap in q_{50} (left y-axis) and the evolution in q_{50} between different measurements (right y-axis) for all houses of the MT sample depending on the type of roof.

The houses on the x-axis are sorted in ascending order of the evolution in q_{50}. They are classified into 4 categories:

- significant decrease in q_{50} (< –50 $m^3.h^{-1}$): 5 houses for the MT and LT samples each;
- no or little variations in q_{50} (–50 to +50 $m^3.h^{-1}$): 13 houses for MT sample and 8 houses for LT sample;
- moderate increase in q_{50} (+50 to +150 $m^3.h^{-1}$): 6 houses for MT sample and 10 houses for LT sample;
- strong increase in q_{50} (> +150 $m^3.h^{-1}$): 5 houses for MT sample and 7 houses for LT sample.

It is difficult to make statistical analysis to identify the impact of different factors on the evolution in q_{50} due to the small size of the samples regarding the factors.

For the MT sample, we are generally observing an upward trend of q_{50} for 2-storey detached houses (**Figure 3**) with traditional wood frame (**Figure 4**). For the two houses with exposed wood frame of this sample (MT06 & MT19), MT06 has become much leakier (q_{50} at n_1 almost 4 times higher than n_0), mainly because of leakages appearing at the junction between the wood and the plasterboard (shrinkage of mastic). While the airtightness level of MT19 has remained almost stable between n_0 and n_1. Knowing that both houses are tighten with the same method, the conditions of implementation of the air-barrier seem to have an impact on the durability of the airtightness. Unfortunately, it was not possible for us in this study to collect information on the conditions of implementation; our knowledge was limited to the type of treatment of the airtightness from the technical plans, without having information about the products and their implementations. Therefore, it would be interesting to investigate this factor in future studies.

The same analysis was performed for the LT sample. The airtightness of wooden houses (6 houses) has generally remained stable and even improved for 2 houses. It is interesting to notice that laboratory testing has come to the same conclusion on wood structure (Litvak, 2019) and it may be due to the expansion of wood with the humidity that may expand the wood and therefore reduce leakages.

Regarding the modifications of walls, all houses were generally modified by the occupants (drilling the walls for installing furniture, decoration, hood, downlight led...) whatever the evolution of the airtightness. Therefore, it is difficult to draw general conclusions from these observations about the impact of the modifications by occupants on the evolution of the airtightness.

Evolution of leakages

We have analysed the evolution in the number of leakages for both samples. The results have shown an increase in the number of leakages for doors and windows, electrical components, penetrations through envelope and junctions between walls and doors/windows. However, multiple linear regression has been performed and has shown that the evolution in q_{50} is not correlated with the evolution in the number of leakages. Therefore, a thorough leakage location detection is not useful as long as it does not quantify leakages for the analysis of the onsite durability. Thus, new methods are needed to detect and to quantify leakages.

Conclusions

The durability of building airtightness of low energy single-detached houses was assessed through two field measurement campaigns at mid-term (MT) and long-term (LT) scales.

The results have shown that the airtightness of houses can deteriorate mainly during the first two years and then it seems to stabilise as:

- For MT sample, the mean and median values of the air leakage rates q_{50} in years n_1, n_2 and n_3 are equivalent;
- MT and LT samples show the same mean evolution of the air leakage rate q_{50} (respectively +18% and +20%).

However, as for other studies (Leprince, 2017), we have observed that the building airtightness deteriorated significantly in some houses while in others it stabilised or even improved. With this study, it has not been possible to identify "where and why" new leakages are appearing. However, it has led us to the following useful conclusions:

- One of the two houses with exposed wood-frame has become much leakier, mainly because of leakages appearing at the junction between the wood and the plasterboard (shrinkage of mastic). While the airtightness of the other house has remained almost stable. Therefore, the conditions of implementation of the air-barrier seem to have an impact on the durability of the airtightness.

- It has not been possible to determine the location of the new leakages causing the deterioration of the airtightness. New methods are needed not only to locate but also to quantify more precisely leakages. A thorough leakage detection is not useful as long as it does not quantify leakages for the analysis of the onsite durability.
- Observed variations of the air permeability are not due to seasonal variations and given the strict protocol applied in this study, they are probably not due to measurement uncertainty (Moujalled, 2019).
- The evolution of the airtightness does not appear to be correlated in this study with the following parameters: constructor, type of air-barrier, type of floor, type of heating, specific HVAC equipment.

The following three parameters seem to be correlated with the evolution of the airtightness:

- The material: it seems that the airtightness of wood houses tends to stabilise or even improve over years, maybe due to the expansion of wood with humidity.
- The number of levels: 2-storey houses seems to deteriorate more than 1-storey ones, which is maybe due to more important foundation settlement.
- The type of roof: houses with traditional wood frame seem to deteriorate more than houses with light frame because of the multiple junctions between the wood and the plasterboard.

Regarding the houses where the airtightness has improved (10 houses for both samples), this improvement is maybe due to the building material (2 wooden houses), the maintenance of windows (2 houses), or the sealing of leaks by occupants (2 houses). However, for the other four houses, we have not been able to explain it.

Therefore, the results of this study do not stress the need to perform long-term study on the durability of airtightness, but on the contrary to better understand where and why leakages appear during the first year, which causes the deterioration of the building airtightness (very short-term ageing). Other parameters need to be considered, such as the environmental conditions (hygrothermal, dustiness) during the implementation of the air barrier or the evolution of the temperature and humidity inside the building during the first year. In addition, modifications made by occupants need to be known more closely. More frequent airtightness measurements (e.g. monthly measurements) could be performed on a small sample of houses over the period from the implementation of the air barrier until one year after building completion, by recording at each measurement the aforementioned parameters. ■

Acknowledgments

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References

FD P50-784. (2016). Performance thermique des bâtiments - Guide d'application de la norme NF EN ISO 9972. France: AFNOR.

ISO 9972. (2015). Thermal performance of buildings - Determination of air permeability of buildings - Fan presurization method. France: AFNOR.

Leprince, V., Moujalled, B., & Litvak, A. (2017). Durability of building airtightness, review and analysis of existing studies. 38th AIVC Conference "Ventilating healthy low-energy buildings". Nottingham, UK, 13-14 September 2017.

Litvak, A., Allègre, F., Moujalled, B., & Leprince, V. (2019). Assessment of the durability of airtightness products in laboratory controlled conditions: developement and presentation of the experimental protocol. 40th AIVC - 8th TightVent & 6th venticool Conference. Ghent, Belgium, 15-16 October 2019.

Moujalled, B., Berthaullt, S., Litvak, A., Leprince, V., & Frances, G. (2019). Assessment of long-term and mid-term building airtightness durability: field study of 61 French low energy single-family dwellings. 40th AIVC - 8th TightVent & 6th venticool Conference. Ghent, Belgium, 15-16 October 2019.

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New findings on measurements of very airtight buildings

The trend in European countries is that the airtightness of buildings (Passive houses, certain large buildings, apartments) is getting better and better. This leads to new challenges when performing airtightness tests: Much more time than usual and patience is needed. This work shows the modified measurement procedure and gives recommendations how to achieve reliable test results.

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Keywords: airtightness, blower door test, very airtight buildings, apartments, pressure build-up time, test procedure, very low air change rate, n_{50}-value

Over the last decades, airtightness has become a necessary and important characteristic of the building envelope. Many years of experience as well as growing know-how in the production of good air barriers frequently lead to building airtightness of excellent quality [Leprince]. Large buildings with specific airtightness requirements, for example oxygen reduction in warehouses for chemicals or food items, show air change rates (n_{50}-value) as low as 0.03 h^{-1}. Passive houses and apartments in some instances achieve n_{50}-values significantly below 0.6 h^{-1}.

It can be observed that the common measurement of these extremely airtight objects is reaching its limits. This leads to new challenges for measurement technology and measurement teams.

This article will look at the measuring procedure in such cases and give recommendations on how to achieve reliable and repeatable airtightness test results.

Description of the problem

There is little experience about how long it takes to build-up a stable and constant pressure difference in a building or apartment during an airtightness test with the BlowerDoor. When testing buildings with very low air change rates (n_{50}-values $\ll$ 0.6 h^{-1}) the normal automated test does not seem to work properly. One indication of this is when the readings fluctuate strongly around the target pressure and the measurement is interrupted after some time. If the individual measuring points are widely scattered around the line of best fit (the correlation coefficient in this case is significantly lower than 0.98), this is further indication.

Based on experience from measurements and calculations, the following sections will show which pressure build-up times can be expected in buildings with very low air change rates (n_{50}-values).

Testing very airtight objects

Real-time display and recording of all readings from an airtightness test

To investigate the reasons for the different measurement behaviour, we recorded the measurements of different buildings with low and extremely low air change rates with a data logger program (TECLOG from The Energy Conservatory). This program shows and records the building pressure difference and the readings of the BlowerDoor fan (airflow and fan pressure) over time in real time.

The characteristics of the measurement curves with sampling intervals of one second make it possible to trace the build-up of the building pressure [Brennan et al.]. This enables the measurement team to react appropriately to special measurement situations.

Example of a very slow pressure build-up

The following object shows an example of how the building pressure of one measuring point is built up in a very airtight building. **Figure 1** shows a warehouse with an interior volume of V = 46,600 m³. The impressively low air change rate n_{50} is 0.03 h^{-1}, in order to be able to keep the input of nitrogen into the hall, which is necessary for food technology reasons, as low as possible. This allows the system to be used for oxygen reduction can be held small and the power consumption minimized.

How the building pressure is built-up after turning on the measuring fan can be seen in the following diagram (**Figure 2**). The horizontal timeline runs the time during the measurement, and the y-axis shows the pressure difference in Pascal. The green curve shows the progression of the building pressure difference and the red curve the fan pressure at the measuring fan, resulting in the airflow depending on the fan configuration (ring).

Slightly before 9:51 a.m., the red curve for the fan pressure strongly declines from 0 Pa to ca. –350 Pa, indicating that the measuring fan (Minneapolis BlowerDoor Model 4, B Ring) has been turned on. The green curve for the building pressure increases comparatively slowly from the 0 Pa starting pressure to the target pressure of approx. 50 Pa. The closer the curve comes to the 50 Pa, the flatter it becomes (asymptotic progression).

At 9:56 a.m., **after** about **5 minutes** (**300 seconds**), both **measurement curves** run **parallel to** the **time axis**. This is the **sign** that the **target pressure has been reached** with sufficient accuracy and that no further serious changes are to be expected. Only from this point on we can assume stable and constant conditions.

Now, over at least 30 seconds, readings for this pressure stage can be recorded and averaged. This average value is one single test point of at least five measuring points (ISO 9972 / EN 13829) from which the leakage curve for this building is calculated.

Figure 1. Warehouse for herbs with an air change rate n_{50} = 0.03 h^{-1}, internal Volume V = 46,400 m³ and airflow at 50 Pa V_{50} = 1.620 m³/h.

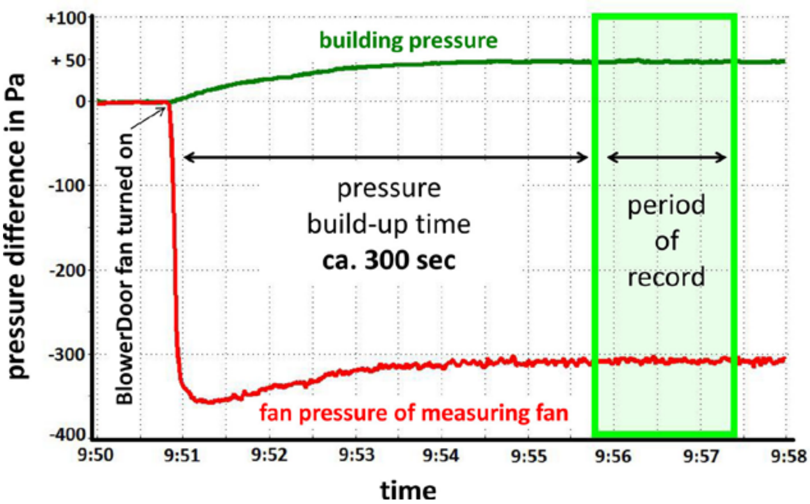

Figure 2. Approx. 300 seconds build-up time from 0 Pa starting pressure to 50 Pa building pressure (green curve from approx. 9:51 to 9:56).

Calculation of the pressure build-up time

In order to control the measurement optimally, it is necessary to know the pressure build-up times for very airtight objects. Calculations by [Zeller] show that the **pressure build-up time is inversely proportional to the air change rate at 50 Pa (n_{50}-value).** Basis of his calculations are the ideal gas equation, the equation for the leakage curve of a building, and assuming a constant airflow (independent of the building pressure). **Figure 3** shows the pressure build-up times for different air change rates when the building pressure is controlled from 50 Pa starting pressure to 40 Pa target pressure. An air flow exponent of 0.67 is assumed for this calculation.

The diagram clearly shows that with decreasing air change rates the pressure build-up times increase until a constant building pressure is achieved. The 40 Pa building pressure is built-up within a few seconds if the n_{50}-value is 3 h^{-1}. The build-up time is around 15 seconds at an n_{50} of 0.6 h^{-1} (green curve, Passive House requirement) and much more than approx. 300 seconds if the n_{50} is 0.03 h^{-1} (grey curve).

For the measuring practice, the following equation [Zeller] helps to estimate the minimum pressure build-up time for each single test point of a multipoint airtightness test that must be planned for achieving repeatable and reliable tests results.

$$t(\mathrm{s}) = \frac{9(\mathrm{s/h})}{n_{50}(\mathrm{h}^{-1})}$$

Where

t = pressure build-up time in seconds

n_{50} = air-change rate in h^{-1}

Boundary conditions:

- Pressure stages in increments of approximately 10 Pa
- Airflow exponent around 0.67
- Target pressure is reached with a tolerance of ±0.5 Pa.

Example:

The desired air change rate at 50 Pa: $n_{50} \leq 0.1\ h^{-1}$.

$$t(\mathrm{s}) = \frac{9(\mathrm{s/h})}{n_{50}(\mathrm{h}^{-1})} = \frac{9(\mathrm{s/h})}{0.1\ (\mathrm{h}^{-1})} = \mathbf{90\ s}$$

The pressure build-up time for this example is ca. 90 seconds per pressure stage.

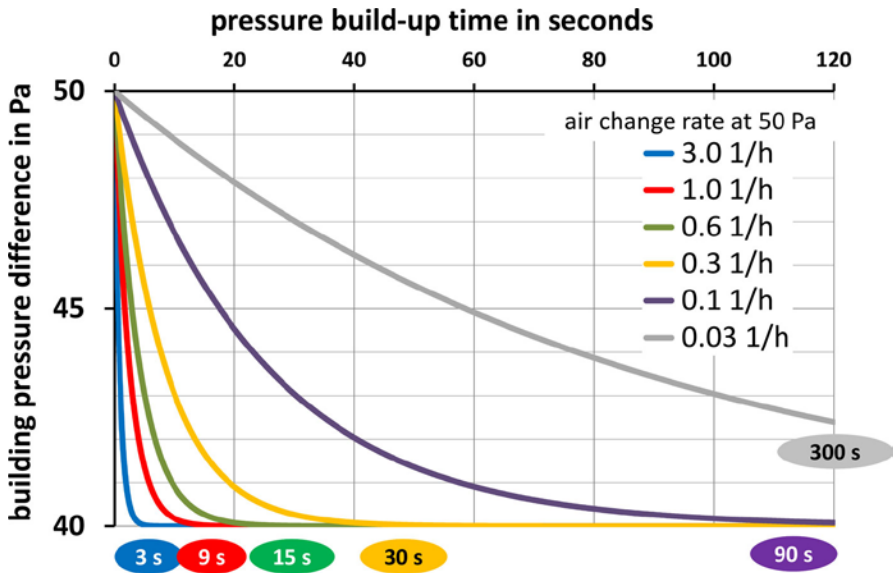

Figure 3. Pressure build-up times for different air change rates at 50 Pa (n_{50}-value). The starting pressure is 50 Pa and the target pressure 40 Pa. The airflow exponent n of the leakage curve is 0.67 [Zeller].

The calculated build-up times may deviate from a real test. The following factors affect the pressure build-up time, among others:

- The build-up time is decreased if the increment between the measuring points is reduced from 10 Pa (70 Pa, 60 Pa, 50 Pa, etc.) to 5 Pa (70 Pa, 65 Pa, 60 Pa, etc.).
- A higher airflow exponent of the leakage curve will reduce the build-up time.

Comparing the calculations with the real-test example

For comparisons, the pressure build-up time for the building presented before is calculated. The air change rate is 0.03 h^{-1} and the airflow exponent of the leakage curve n is 1. The diagram in **Figure 4** shows the calculated pressure build-up time from 0 Pa starting pressure to a target pressure of 50 Pa.

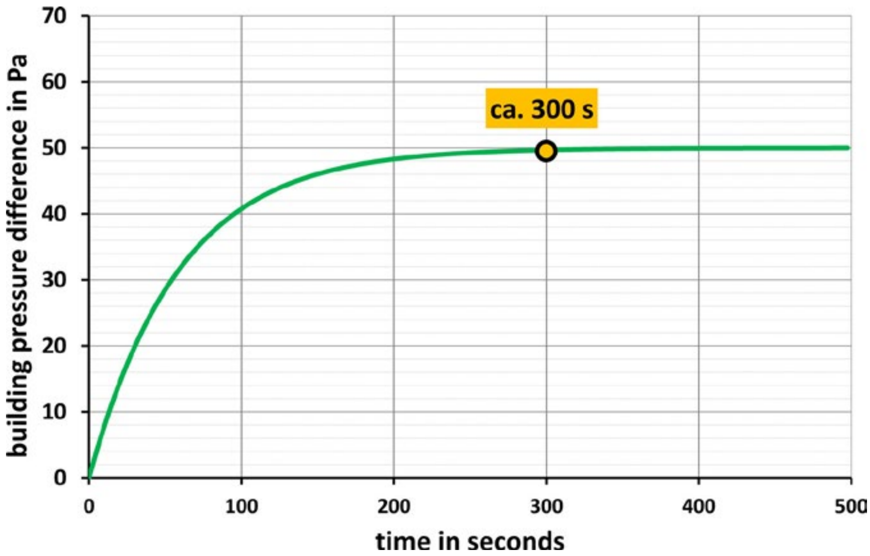

Figure 4. Calculated pressure build-up time for a building with n_{50} = 0.03 h^{-1}, airflow exponent n = 1 and increasing the building pressure from 0 Pa to ca. 49.5 Pa.

The calculation shows that 49.5 Pa building pressure is reached after approx. 300 seconds. During the real airtightness measurement, the target pressure had been built up sufficiently after about 300 seconds (see Figure 2).

This means that the calculations correspond very well to the experience in real life.

Conclusions

Measurement experiences show, that airtightness tests of very airtight buildings such as warehouses with air change rates at 50 Pa of 0.03 h^{-1} (e.g. due to oxygen reduction), passive houses or apartments with n_{50}-values lower or much lower than 0.6 h^{-1} take longer than tests in buildings with common air change rates.

This is due to the fact that the **pressure build-up time** for one building pressure difference during a depressurization or pressurization test **is inversely proportional to the air change rate at 50 Pa** (n_{50}-value) of the building [Zeller]. The smaller the n_{50}-value, the longer it takes for the required target pressure to build up (e. g. the build-up time for an n_{50} of 3 h^{-1} is approx. 3 seconds, for 0.3 h^{-1} approx. 30 seconds or for 0.03 h^{-1} approx. 300 seconds).

The comparison between the pressure build-up times actually achieved and the theoretical calculations result in a very good agreement.

With the help of the formula for estimating the pressure build-up time [Zeller] and the use of data logger software with display of the building pressure differences and the airflow of the test equipment in real time, traceable and reliable measurement results can be achieved even in very airtight buildings. ■

References

Brennan, T., Clarkin, M. Nelson, G., Olson, C., Morin, P. (2014): Beyond single family residential. The Energy Conservatory, Minneapolis US.

Leprince, V. (2018): Mesure d'étanchéité à l'air à petit débit.

Zeller, J. (2019): unpublished study on temporal progress of pressure build-up (in German language).

EN 13829 (2001): Thermal performance of buildings – Determination of air permeability of buildings – Fan pressurization method (ISO9972:1996, modified)

ISO 9972 (2015): Thermal performance of buildings — Determination of air permeability of buildings – Fan pressurization method (ISO 9972:2015).

Reference Guide BlowerDoor Standard and Reference Guide BlowerDoor MiniFan (2018) as well as Reference Guide BlowerDoor MultipleFan (2018).

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Influence of horizontal mounted flue gas exhaust systems on indoor air quality

Horizontal mounted flue gas exhaust systems are used to reduce the installation costs of combustion appliances. The position of the exhaust terminal must be carefully chosen to prevent smoke from entering the ventilation system of nearby buildings. In this paper, a method based on computational fluid dynamics is used to determine the suitable zones for the mounting of the exhaust terminal with respect to the ventilation air supply openings.

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Keywords: indoor air quality, ventilation, horizontal mounted flue gas exhaust, smoke exhaust, pollutants dispersion around buildings

Context

Combustion appliances are used in many buildings to provide space heating and domestic hot water. These appliances emit smoke that mostly contains carbon dioxide and water vapour, but also, depending on the type of fuel and the quality of the combustion, unburned hydrocarbons such as carbon monoxide, soot, tars and particulate matter. These products must be kept away from the ventilation air supply openings to limit their impact on the indoor air quality (IAQ).

An efficient way to prevent the flue gas from entering the building is to place the exhaust terminal above the top of the roof (see **Figure 1**), as far as possible from the ventilation air supply openings. The wind velocity, combined with the buoyancy of the smoke, will move the plume away from the building and dilute it into the atmosphere.

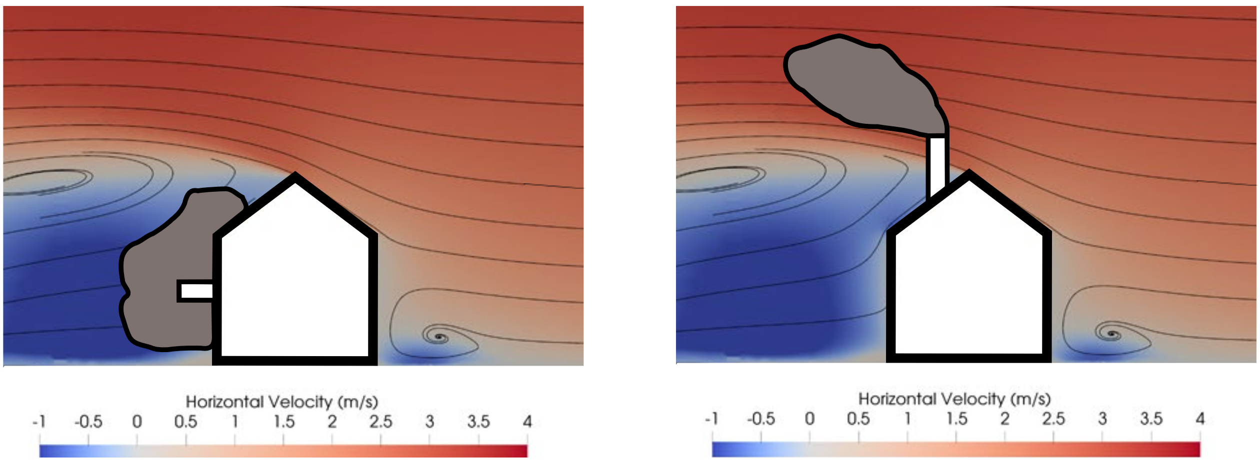


Figure 1. Streamlines of the wind flow around a building from a CFD simulation, with a superimposed qualitative representation of the smoke plume.

To reduce the installation costs of modern appliances, the chimney is often as short as possible and the exhaust terminal is mounted on a vertical wall, right next to the appliance. In that case, the plume might be partially trapped in a recirculation zone and remains close to the building with less dilution, increasing the risk of contamination. A minimal distance between the exhaust terminal and the ventilation air supply openings must be determined in order to avoid the recirculation of the pollutants inside the building.

Specific methods can be found in European and Belgian standards. A comparative example is given in **Table 1**. It highlights the discrepancies between the existing methods and the need for a tool to select the most appropriate one, or to develop a more widely accepted one.

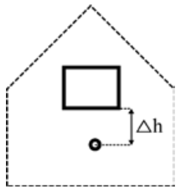
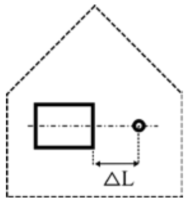
The minimal distance between the horizontal mounted flue gas exhaust system and the ventilation air supply openings depends on many parameters, including the heating power of the appliance, the temperature of the flue gas, the pressure of the exhaust and many others. But the most important parameter is the wind flow pattern around the building, that depends on the shape of the building and on the direction of the wind. Depending on the flow pattern and on the position of the exhaust terminal, the flue gas plume can be driven away from the building by the wind, or be taken back against it.

A relevant method to study the wind flow pattern and the flue gas dispersion around buildings is to perform computational fluid dynamics (CFD) simulations.

CFD and Numerical model

The complex physics of the problem is described by a set of equations (the Navier-Stokes equations) that are solved by a CFD tool. The concentration field of the pollutants around the building is determined from the solution of the equations. For industrial (non-academic) research, an alternate version of the Navier-Stokes equations (RANS equations: Reynolds-Averaged Navier-Stokes equations) and a turbulence model ($k - \omega\ SST$) are used, as it has been proven appropriate in other studies dealing with flow around buildings (Ramponi R, 2012). The numerical simulations are carried out on a four facades isolated building located on a flat ground. By adjusting the geometrical parameters of the numerical model, the geometry can be extended to that of multi-storey buildings and terraced houses, as represented in **Figure 2** on the following page. The exhaust flow, temperature, and position as well as the

Table 1. *Discrepancies between the different standard methods.*

Geometrical configuration	Standard reference	Recommended distance
	NBN EN 15287-2(2008) NBN B 61-002(2006) NBN D 51-003(2014)	Δh = 30 cm Δh = 320 cm Δh = 500 cm
	NBN EN 15287-2(2008) NBN B 61-002(2006) NBN D 51-003(2014)	ΔL = 30 cm ΔL = 340 cm ΔL = 100 cm

wind velocity and direction are also adjustable parameters. For each set of parameters, a steady-state solution is computed.

Pollutant field on a façade

To visualize the computed pollutant field near the facades of building, an iso-contour at a dilution of 100 is shown in **Figure 3** on the following page. This specific iso-contour represents the locations in space where the concentration of the pollutant is 100 times lower than that at the exhaust terminal. A dilution of 100, for gas-fired appliances, is considered to be representative of a sufficient air quality to be used for building ventilation

Figure 3 also shows that the smoke plume goes backward against the wind and along the façade as the exhaust terminal is located in a recirculation zone. The iso-contour representing a dilution of 100 is not connected to the exhaust terminal, as either the initial velocity of the flue-gas or the wind pattern initially moves it away from the building before pulling it back against the façade.

Yearly analysis and similarities

The result presented in **Figure 3** is an instant picture of a specific set of operating parameters, but it does not reflect the risk encountered in real life, as the many parameters are dependent on the environmental conditions, including the wind velocity, the wind direction and the outside temperature, that are variable in essence. If a yearly overall effect is to be accounted for, a statistical approach using all the relevant environmental parameters needs to be used. However, this approach implies that many different numerical simulations need to be done

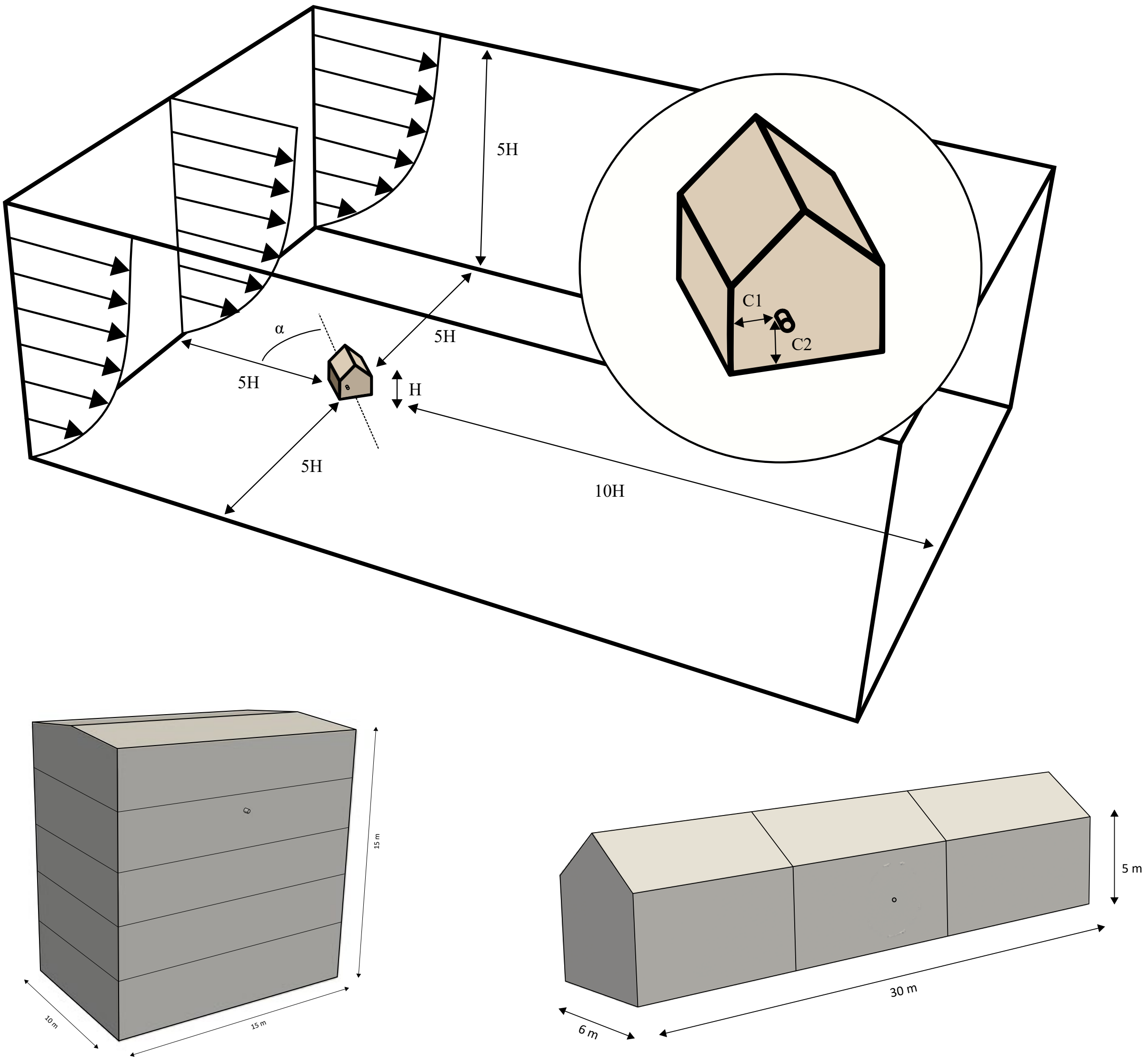


Figure 2. The numerical domain (above) and examples of geometries (below) derived from a four facades building.

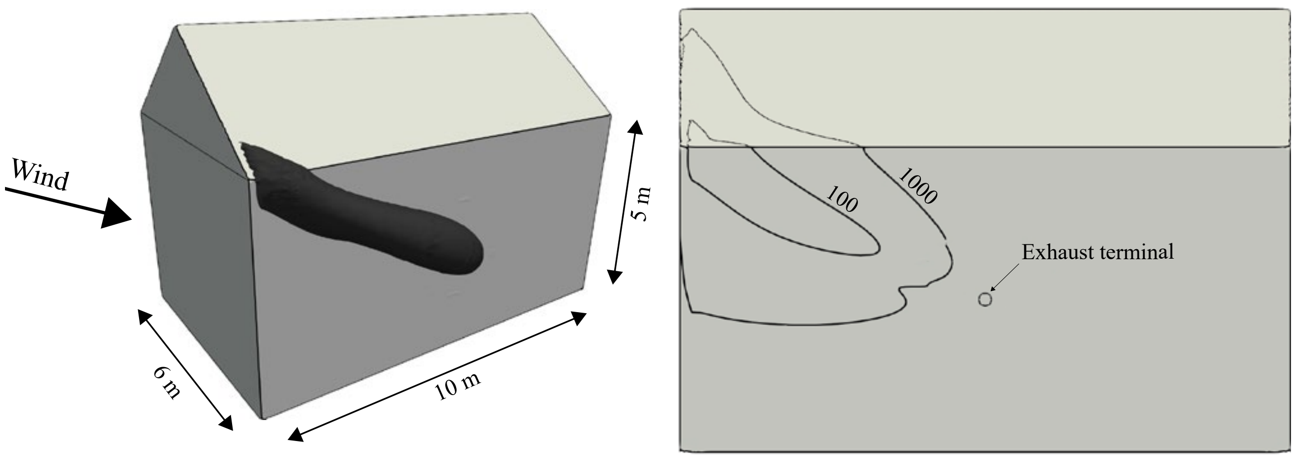


Figure 3. Representation of the iso-contours of concentration of the flue gas around a detached house.

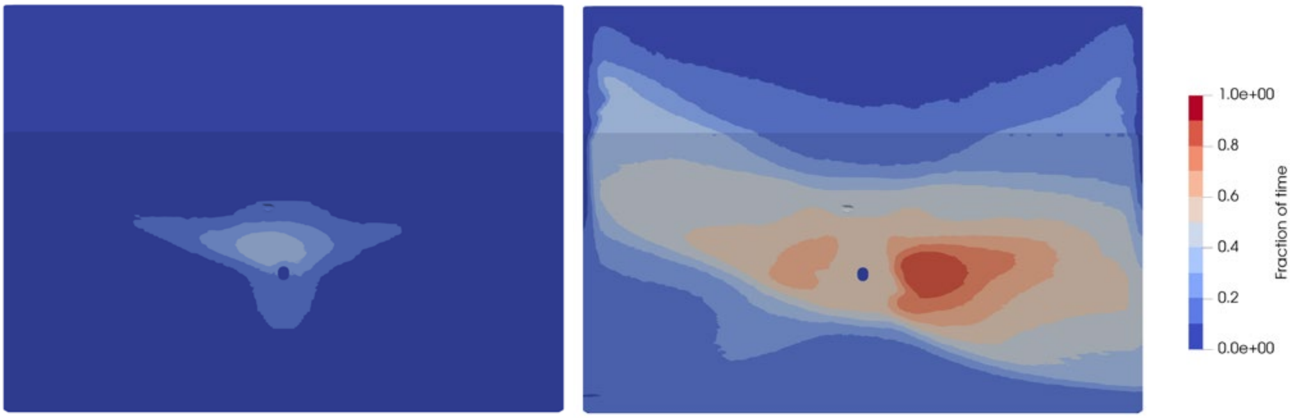


Figure 4. Probability that the dilution of a pollutant is below a threshold of 100 or 1000 on a yearly basis.

in order to get all the relevant results. Fortunately, many similarities can be identified, and the results of several numerical simulations can be used to complement other similar cases, using an appropriate scaling. For instance, the flow pattern around the building remains the same for any wind velocities above 2 m/s, which reduces the need to perform new numerical simulations for different wind velocities. However, the wind velocity is accounted for in the scaling as it increases the dilution of the smoke plume.

Assuming that the heating appliance is operating at nominal power, only height numerical simulations (one per main wind direction) are needed to determine the impact of the smoke on the façades of buildings. Knowing the wind velocity and wind direction for each hour of the year, these height numerical simulations and the scaling procedure are used to compute the pollutant field for each hour, which in turn is used to compute the probability that a concentration threshold is reached or exceeded on the façades of the building. Such probability is shown in **Figure 4** for a dilution of 100 (left-hand side of the figure) and 1000 (right-hand side of the figure).

Future work

The next steps of this project are to further validate the method and to develop a tool, based on these numerical results, that could be used by the heating specialist to determine the suitable locations for the exhaust terminal for many environmental parameters and building geometries. ■

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References

Carlo Gualtieri, A. A. (2017). On the Values for the Turbulent Schmidt Number in Environmental Flows. *Fluids*.

Fougairolle, P. (2009). Caractérisation expérimentale thermo-aéraulique d'un jet transverse impactant ou non, en turbulence de conduite.

Gousseau P, B. B. (2010). CFD simulation of near-field pollutant dispersion on a high-resolution grid: a case study by LES and RANS for a building group in downtown Montreal. . *Atmospheric Environment 45*, 428-438.

Kiyoshi Uehara, S. W. (2003). Studies On Critical Reynolds Number Indices Forwind-Tunnel Experiments On Flow Within Urban Areas. *Boundary-Layer Meteorology 107*, 353-370.

Ramponi R, B. B. (2012). CFD simulation of cross-ventilation for a generic isolated building: impact of computational parameters. *Building and Environment 53*, 34-48.

Tominaga, Y. M. (2008). AIJ guidelines for practical applications of CFD to pedestrian wind environment around buildings. *Journal of wind engineering and industrial aerodynamics*, 1749-1761.

Understanding the indoor environment and its effects

– Part 1: Field study of 21 primary schools

This article presents the survey performed in 21 schools based on the integrated analysis approach, to collect information on ‘Stressors and effects’, ‘Preferences and needs’ and ‘Interactions at environment level’, for different situations.

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Keywords: indoor environmental quality, primary school children, integrated analysis, stressors and effects, interactions, preferences and needs

It is well-known that the environmental conditions in a classroom can affect health, comfort and performance of children [1]. Problems occur even though the guidelines are met, most likely due to the fact that these guidelines are based on criteria that are originally set up for adults, on top of the focus on single factors, which do not consider interactions between them. To gain more insights into the current and potential role of indoor environmental factors on health, comfort and performance of children, an investigation was performed based on a recent introduced research model (**Figure 1**) [2], comprising of a field study and a series of laboratory studies. Part 1 reported here, describes the field studies performed in 54 classrooms of 21 primary schools in the Netherlands, to collect information on ‘Stressors and effects’, ‘Preferences and needs’ and ‘Interactions at environment level’, for different situations, by asking children themselves what they experience and need in classrooms to feel and perform well [3]. The SenseLab studies are reported in Part 2 [4].

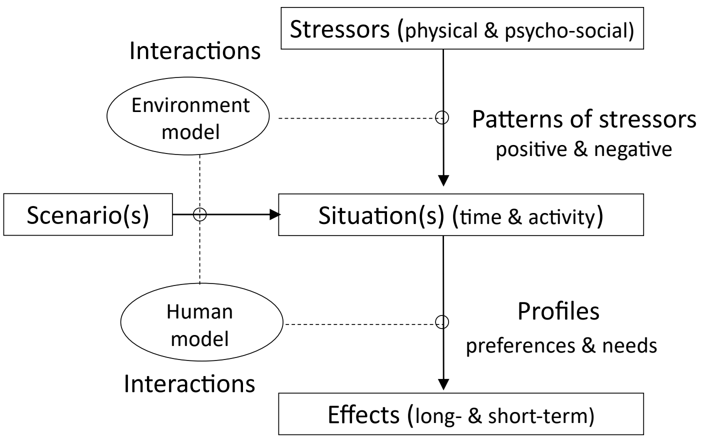

Figure 1. Model for the integrated analysis approach [2].

Study design

In the spring of 2017, a survey on the health and comfort of school children of group 6 and 7 in 54 classrooms of 21 schools in the Netherlands was performed [3]. From the 54 classrooms studied, 45 classrooms studied had a traditional educational system, and 9 classrooms had a non-traditional educational system (following the educational theory of Jena, Montessori or Dalton).

The survey of the schools comprised of a questionnaire for the children about their health and comfort, preferences and needs; a questionnaire for the teacher about activities they perform to improve IEQ; an inspection of the school and its installations, and the classrooms surveyed using checklists. 1,145 completed questionnaires were collected. It took the children about 30 minutes to complete the questionnaire.

Characteristics children studied

In general, boys and girls were equally distributed. The average age of the children studied was 10 years and about one fifth wore glasses or lenses, about one third of the children had someone who smokes at home, and around 52% had a dog, a cat, or a rodent as pet.

At the moment of filling in the questionnaire, 87% claimed to feel good. Most reported diseases (in the last 12 months) were allergy (26%), rhinitis (17%), hay fever (16%) and eczema (16%). The most prevalent school-related health symptoms were headache (17%), sneezing (15%) and itchy eyes (14%) (**Table 1**). Boys reported these symptoms slightly more than girls.

87% of the children was bothered by noise (mainly caused by children themselves), 63% was bothered by smells (mainly caused by children themselves), 42% by sunlight when shining, 37% by garbage on the floor, 35% (did not like the temperature in the classroom (too cold or too warm) and 34% (experienced temperature changes (**Table 2**). Girls were in general more bothered than boys.

Two situations: Traditional vs. non-traditional schools

Classroom-related comfort complaints and Classroom-related health symptoms were evaluated for both the traditional and the non-traditional school children by respectively the Personal Comfort Index (PCI) based on 7 complaints: thermal discomfort, temperature changes, wind/ draught, smells, noise, sunlight and artificial light; and the Personal Symptom Index (PSI) based on nine symptoms: dry eyes, itching or watery eyes, blocked or stuffy nose, running nose, sneezing, dry throat, difficulty breathing, dry, irritated or itching skin, and headache. So, for each child it was calculated for how many of the complaints and symptoms they were bothered with. The average PCI-7 for all school children, for school children from traditional schools and for school children of non-traditional schools, was respectively 2.76, 2.87 and 2.24 (**Figure 2a**). The average PSI-9 for all school children was 3.97, for the children going to non-traditional schools 3.69 and for school children of the traditional schools 4.02 (**Figure 2b**). The differences between the traditional and non-traditional schools were statistical relevant, indicating that children of non-traditional schools had on average less symptoms and less complaints than children from traditional schools.

Table 1. *Symptoms at least once every 2-3 weeks (related to indoor environment).*

Symptom	All [%]	Girls [%]	Boys [%]
Dry eyes	6.7	5.7	7.6
Itching or watery eyes	14.1	12.8	15.4
Stuffy nose	10.4	9.9	10.9
Running nose	9.3	11.7	7.1
Sneezing	15.3	15.0	15.6
Dry throat	11.6	12.9	10.3
Dry, itchy skin	7.4	8.0	6.8
Headaches	17.0	15.9	18.0

Table 2. *Complaints about the indoor environment.*

Complaints	All %	Girls %	Boys %
I do not like the classroom	15.9	16.4	15.3
Thermal discomfort at this moment (too warm/cold)	34.9	34.7	35.1
Bothered by temperature changes	34.0	31.4	36.6
Bothered by wind/draught	7.3	7.8	6.9
Bothered by smells	**62.7**	**67.0**	**58.6**
Bothered by noise	**86.6**	**91.0**	**82.2**
Bothered by sunlight when shining	41.8	43.2	40.4
Bothered by artificial light when on	11.3	11.3	11.3

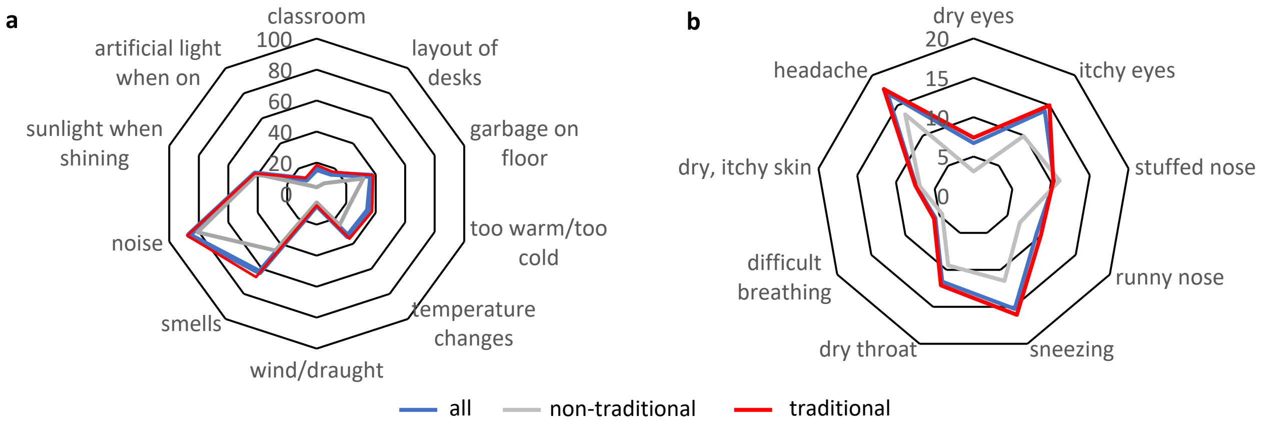

Figure 2. Percentage of children a) with complaints about classroom conditions and b) with symptoms every day or sometimes at school, that went away when not at school.

Multivariate analysis for traditional classrooms to find patterns

Multivariate analysis was performed for the 949 children of the 17 traditional schools, to find patterns of stressors: associations of building-related indicators with occupant-related indicators [3]. The analysis showed that a child at a school in the suburbs had fewer symptoms than a child at a school in a village (in a rural area). A child in a classroom with radiators below windows had more symptoms than in a classroom with floor heating, or in a classroom with air heating as an important way of heating the classroom. Both findings can indicate the presence of air pollution, either caused by inefficient cleaning or inefficient maintenance of the components of the building services. The presence of a solar shading device that hampers ventilation/opening window also increased the number of symptoms, which might indicate inefficient ventilation when required. Furthermore, it was seen that a child in a classroom with mechanical assisted ventilation (no mechanical supply) had more comfort complaints than in a classroom with natural ventilation. A classroom with a dark coloured window frame caused more complaints than a light coloured one, as did laminated flooring vs. synthetic smooth flooring material. Also, vacuuming the classroom floor less than once a week vs. more than once a week increased the PCI.

Actions of teachers to improve IEQ

The frequency of teachers' actions to improve IEQ in classrooms (such as turning on/off lights; lift/lower shades; close/open windows; etc.) was studied to get more insight into the impact of teachers' actions [5]. The percentage of teachers who performed the actions to improve the IEQ in classrooms at least once per day (**Figure 3**) was related to primary school children's comfort perceptions in classrooms. From the comparison was concluded that those actions hardly had an effect on how the children felt. The teachers could not fulfil every child's needs, even though teachers' actions did relate to the child's requests. Two reasons can be put forward: **1.** Not all children have the same needs; which makes it is impossible for a teacher to satisfy each child. **2.** A certain action can improve the conditions for one child, while for the other child the same action can cause a problem.

Clustering school children to identify profiles

Using two-step cluster analysis, six clusters (profiles) of children based on their comfort perceptions and the importance of environmental factors were identified [6] (**Table 3**). The children were asked to rate the importance of 10 indoor environmental factors to their school performance (including feet temperature, air temperature, chair temperature, scent, fresh air, light on desk, light on board, hearing teacher, outdoor sound, indoor sound) on a scale from 0 to 10 (10: very important; 0: not important at all) (**Figure 4a**). Children thought that 'Hearing teacher' had the most important impact on their school performance (8.6). The second and third most important factors were 'Fresh air' (8.0) and 'Air temperature' (7.4).

Table 3. *Six profiles of children (adapted from [6]).*

Profile	Most bothered by	Important
Sound	Noise	Noise indoors and outdoors
All	All	All
Smell and sound	Noise and smell	Understand teacher and fresh air
Thermal and draught	Draught and temperature	Draught and temperature
Light	Artificial and sunlight	Light at desk and (smart)board
Nothing	Hardly anything	Nothing

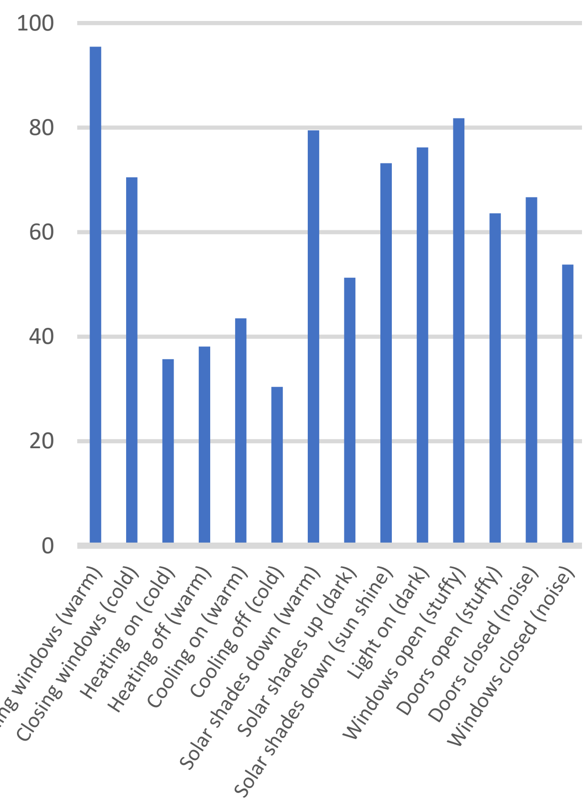

Figure 3. Percentage of teachers who performed the actions asked by children to improve the IEQ in classrooms at least once per day. The reasons for the actions are given in the parenthesis (Adapted from [5]).

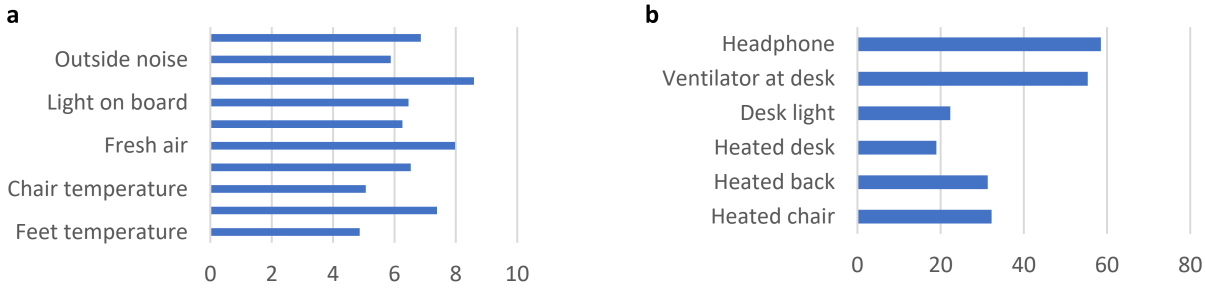

Figure 4. a) Importance index of indoor environmental factors; and b) Preference for six ICDs (%) of children from traditional schools (adapted from [6]).

The children were also asked to give their preference for an ICD (individual control device), including a heated chair, a heated desk, a heated back, a desk lamp, a personal ventilator and a headphone (**Figure 4b**). The most preferred device, according to the children' answers, was 'headphone'. Almost 60% of the children in a classroom indicated that they wanted to have a headphone, followed by the 'ventilator at desk' indicated by 53% of the children [6]. The 'headphone' complied with the 'hearing teacher' importance index, while the 'ventilator at desk' corresponded to the second and the third highest importance index of 'Fresh air' and 'Air temperature'.

Main Findings

The field study of the 21 primary schools, resulted in the following main findings:

- Boys in general reported more symptoms, while girls reported more complaints.
- Main complaints were related to noise and smell (produced by children themselves).
- Different situations (traditional vs. non-traditional schools) resulted in statistically different health and comfort effects: children from traditional schools had more complaints/symptoms than children from non-traditional schools.
- Patterns of stressors (ventilation type, solar devices hampering opening windows, heating system, window frame colour, floor material and vacuum cleaning frequency) were associated with health and/or comfort by applying multivariate analysis.
- Children differed in needs and preferences and were clustered in clusters with different profiles using 2-step cluster analysis.
- Teachers could not fulfil each child's needs in a classroom with the possibilities that were available to change/adapt the indoor environmental conditions.

Conclusion

The outcome of the field study confirmed the need for the newly introduced model [2] (**Figure 1**) and the need for more studies with primary school children on their preferences, needs and responses to single components (sound, thermal, light and air) and interactions of different environmental configurations as reported in Part 2 [4]. ■

Acknowledgment

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References

1. Bluyssen PM (2017) Health, comfort and performance of children in classrooms – new directions for research. *Indoor Built Environ.* **26**(8) 1040-50.
2. Bluyssen PM (2019) Towards an integrated analysis of the indoor environmental factors and its effects on occupants *Intell. Build. Int.* doi.org/1080/17508975.2019.1599318.
3. Bluyssen PM, Zhang D, Kurvers S, Overtoom M, Ortiz M (2018) Self-reported health and comfort of school children in 54 classrooms of 21 Dutch school buildings *Build. Environ.* **138** 106-23.
4. Bluyssen PM (2020) Understanding the indoor environment and its effects, Part 2: SenseLab studies with 335 primary school children, *REVHA Journal issue 2020-03.*
5. Zhang D and Bluyssen PM (2019) Actions of primary school teachers to improve the indoor environmental quality of classrooms in the Netherlands, Intelligent Buildings International, DOI: 10.1080/17508975.2019.1617100.
6. Zhang D, Ortiz M, Bluyssen PM (2019) Clustering of Dutch school children based on their preferences and needs of the IEQ in classrooms *Build. Environ.* **147** 258-66.

Sneeze and cough pathogens migration inside aircraft cabins

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Transmission of respiratory infectious airborne diseases, such as influenza, H1N1, Severe Acute Respiratory Syndrome (SARS) and COVID-19 inside any closed environment like the aircraft cabins has always been a topic to be studied, because the respiratory droplets produced when a passenger with a certain infections talks coughs or sneezes have harmful effects on other occupants. They have the ability to take flight and hang in the surrounding air or land on passengers or surfaces in short time. This work presents the results of a study of airflow behavior of coughing and sneezing droplets that are produced from a moving passenger in wide-body aircraft cabin section at different velocity rates. In addition, it compared between transmission of different flow rates and velocities in order to show how can these diseases transported from a moving and standing passenger to other passengers. This numerical simulation used computational fluid dynamic (CFD) modeling simulation. The results showed that the airflow of coughing and sneezing droplets produced from the moving passengers could reach seated passengers; however, sneezed droplets had more harmful impacts than coughed droplets, also both travelled for a long distance inside the cabin. In addition, when comparing the droplets spread range resulting from the moving passenger and stand-still one, it was found that the quicker the passenger moves, the further the droplets spread.

Influenza, H1N1, Severe Acute Respiratory Syndrome (SARS) and coronavirus disease 2019 pandemic (COVID-19) are infectious diseases that may infect humans either through droplets or airborne particles carrying these diseases [1]. The droplets or particles are produced from an infected person during coughing, sneezing or talking. Moreover, these droplets are transmitted from one person to another person through inhalation [2]. Computational Fluid Dynamics (CFD) numerical simulations as well as practical experiments are used to study the effects of transmission of the droplets inside closed environments. **Table 1** summarizes the studies of the transmission of the airborne particles or droplets and their behaviors.

Regarding respiratory infectious diseases, there are three ways to spread; direct and indirect contacts besides airborne transmission [9]. This happens inside aircraft cabins. In direct contact, the droplets that are coming from the passenger's mouth and nose during coughing, sneezing and talking and containing viruses need only a close contact to transport [4]. Moreover, in indirect contact droplets transmitted from the surfaces like cabin's chair or windows to the passengers [11]. There are many parameters that should be taken into consideration in order to simulate the dispersion and deposition of the expiratory droplets using computational fluid dynamics (CFD). These parameters are [8]:

- Coughing or sneezing flow rate
- Coughing or sneezing direction
- Mouth area
- Temperature of coughed or sneezed droplets
- Size of coughed or sneezed droplets

Concerning the impacts of transmission of diseases due to the movement of passenger, Poussou et al. [12] and Mazumdar et al. [13] studied the impact of moving a passenger or cabin crew through the exhaled droplets that are generated from a seated passenger. In addition, Khalil and Kotb [14] simulated the spreading of coughed particles induced from a moving passenger inside the aircraft cabin. This investigation attempted to use computational fluid dynamic (CFD) simulation, dynamic mesh analyses technique, and Lagrangian equations model to compare between the behaviors of cough and sneeze particles induced from a passenger while moving and standing under different velocities and flow rates.

Mathematical Modeling

The Governing Equations

In this investigation, ANSYS FLUENT V18.1 CFD commercial software was used to solve mass, momentum, and energy equations that are required to simulate the case.

Continuity Equation:

$$\frac{\partial \rho}{\partial t}+\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}+\frac{\partial w}{\partial z}=0 \qquad (1)$$

Momentum Equation:

$$\frac{\partial(\rho u)}{\partial t}+\nabla(\rho u\vec{V})=-\frac{\partial P}{\partial x}+\nabla(\mu grad\ u)+S_x \qquad (2)$$

$$\frac{\partial(\rho v)}{\partial t}+\nabla(\rho v\vec{V})=-\frac{\partial P}{\partial y}+\nabla(\mu grad\ v)+S_y \qquad (3)$$

$$\frac{\partial(\rho w)}{\partial t}+\nabla(\rho w\vec{V})=-\frac{\partial P}{\partial z}+\nabla(\mu grad\ w)+S_z \qquad (4)$$

Energy Equation:

$$\frac{\partial(\rho T)}{\partial t}+\nabla(\rho T\vec{V})=\nabla+\nabla\left(\frac{\lambda}{c_P} grad\ T\right)+S_T \qquad (5)$$

Table 1. *A brief summary the studies of the transmission of the airborne particles or droplets and their behaviors.*

Author	Method	Results
Afshari et al. [3]	Experimental investigation	Illustrated the characteristic differences between the airflow produced during coughing of a healthy person and an infected person.
Zhao et al. [1]	Numerical investigation	Showed that the airborne particles that are generated from a person inside a closed room during normal talking can be transmitted to a short distance, while coughed and sneezed particles can travel to a distance longer than 3 meters.
Leder, and Newman [4]	Theoretical investigation	Concluded that the spread of airborne pathogen transport can happen inside an aircraft cabin due to the infectious air exhaled by an infected passenger and inhaled by another passenger.
Gao and Niu [5]	Numerical investigation	Reported that the possibility of spreading and transmission of respiratory droplets that are produced from a human during a normal breathing process inside a room with a displacement ventilation system is low, nevertheless if two persons face each other, infection may be occurred due to the contaminated air.
Yan et al. [6]	Experimental and numerical investigation	Revealed that the airborne particles can be controlled by the airflow of the ventilation system. Moreover, the location of the infected passenger affects the airborne pathogens transport inside the aircraft cabins.
Gupta et al. [7]	Experimental investigation	Proposed new boundary conditions that can be used to simulate the behavior of coughed droplets using computational fluid dynamics (CFD).
Gupta et al. [8]	Experimental investigation	Clearfield that breathing and talking processes have a great effect on infections transmission, because they have higher event frequency than coughing process.
Han et al. [9]	Experimental investigation	Analyzed and measured the sneezed droplets and their sizes in order to be used as CFD boundary conditions. Moreover proposed a geometric mean of sneezed droplets.
Yan et al. [10]	Numerical investigation	Reported that the droplets mass fraction and the distributions of local air velocity strongly affected by the human body heats.

Moreover, a dynamic mesh analysis in ANSYS program was used in ANSYS FLUENT in order to present the passenger movement inside the aircrafts cabin. Due to moving of the passenger an integral form of conservation equation is used [15]:

$$\frac{\mathrm{d}}{\mathrm{dt}}\int_{\mathrm{V}} \rho\phi \mathrm{dV} + \int_{\partial\mathrm{V}} \rho\phi(\vec{\mathrm{U}} - \vec{\mathrm{U}_{\mathrm{g}}}).\mathrm{d}\vec{\mathrm{A}}$$

$$= \int_{\mathrm{V}} S_{\phi} dV + \int_{\partial V} \Gamma\nabla\phi . d\vec{A} \qquad (6)$$

The model that was used during the simulation to calculate the airflow of the particles and the ventilated cabin is the realizable $K - \varepsilon$ model, as the performance of this model is better than the standard $K - \varepsilon$ model [16], and it is more accurate than RNG $K - \varepsilon$ model [16]. The transport Equations for the Realizable $K - \varepsilon$ Model are as follows [16]:

$$\frac{\partial}{\partial t}(\rho K) + \frac{\partial}{\partial x_j}(\rho K u_j)$$

$$= \frac{\partial}{\partial x_j}\left[(\mu + \frac{\mu_x}{\sigma_K})\frac{\partial K}{\partial x_j}\right] + G_K + G_b - \rho_\epsilon - Y_M + S_K \qquad (7)$$

$$\frac{\partial}{\partial t}(\rho \in) + \frac{\partial}{\partial x_j}(\rho \in u_j)$$

$$= \frac{\partial}{\partial x_j}\left[(\mu + \frac{\mu_t}{\sigma_\in})\frac{\partial \in}{\partial x_j}\right] + \rho C_1 S_\epsilon - \rho C_2 \frac{\epsilon^2}{K + \sqrt{\nu\epsilon}} - C_{1\epsilon}\frac{\epsilon}{K} C_{3\epsilon} G_B - S_E \qquad (8)$$

Where, $\vec{V}$ is the velocity vector, P is the pressure, u, v, w are flow velocity in the directions of x, y and z axis, t is the time, V is the control volume, ϕ is a general scalar, ρ is the fluid density, $\vec{\mathrm{U}}$ and $\vec{\mathrm{U}_{\mathrm{g}}}$ are flow velocity vector and mesh velocity of the moving mesh, respectively, Γ is the diffusion coefficient, S_ϕ is the source term of ϕ, G_K is the turbulence kinetic energy, G_b is the turbulence kinetic energy that is generated due to buoyancy, Y_M is the contribution of the fluctuating dilatation in compressible turbulence to the overall dissipation rate, σ_K and σ_ε are the turbulent Prandtl numbers, S_K and S_E are terms that can be defined by the user, C_1 and C_2 are constants.

Calculations of Cough and Sneeze Droplets

To investigate the behaviors of the cough and sneeze droplets induced from the moving passenger, the discrete phase model was used in ANSYS FLUENT in order to predict the trajectory of the droplets; this can be done by integrating the force balance on the droplets [15].

Droplets Force Balance Equation

The forces balance of the droplet equals the droplet inertia with all forces that affect the droplet, it can be written (for the *x*-direction, as an example) as [15]:

$$\frac{du_d}{dt} = F_D(U - U_d) + g_X\frac{(\rho_d - \rho)}{\rho_d} + F_X \qquad (9)$$

Where, $F_D(U - U_d)$ is the drag force per unit droplet mass, U_d is the velocity of the droplet, ρ_d is the density of the droplet, g_X is the force of gravity on the droplet in *x*-direction, μ is the molecular viscosity and F_X is an additional force.

Model validation

In order to validate this study, ANSYS FLUENT v18.1 CFD commercial program was used. Validation process is to test the reliability and accuracy of the ANSYS Fluent CFD program that was used to simulate a numerical case. This can be done by comparing the generated CFD results with experimental data. During this investigation, the experimental data were selected from Kühn et al. [17] study that was focused on analyzing and measuring the forced and mixed convection heat transfer inside AIRBUS 380 upper-deck cross section cabin mockup. The cross section of this aircraft has a length of 6 meters, a width of 5.1 meters, and a depth of 2.2 meters. Moreover, 20 dummies were added inside the cabin to simulate the passengers. Inner heaters surrounded these manikins in order to simulate their thermal load reflection and four electrical panels were added on the top of each side of the cabin to simulate the heat input of the light. ANSYS design modeler (DM) was used to draw the cabin, as shown in **Figure 1**. A half of a cross-section of the cabin was created in order to speed up the CFD progress. Consequently, we used the same boundary conditions that were used during the experiment. **Table 2**. shows the validation boundary conditions.

ANSYS design modeler (DM) was used to create the 3D model of the cabin. The dimensions of the upper deck cross section cabin are 5.1×2.2×6 meters. **Figure 1** shows the 3D model of the upper deck cabin; nevertheless, a half of the cross-section cabin was used during the simulation in order to perform the simulation in short time.

Table 2. *The validation boundary conditions.*

Temperature of the incoming air	21 C
Temperature of the manikin bodies	33.5°C
The total power of the four electrical heating panels	1.8 kW
The number of air inlets that worked together	24
The total air volume flow rate	300 dm³/s
The total volume flow rate at inner ceiling A inlets	150 dm³/s
The total volume flow rate at lateral air inlets	150 dm³/s
Heat flux of each manikin	55 W

Moreover, by using ANSYS, about 6835652 tetrahedral mesh cells and 8628058 nodes were generated. In addition, we used the realizable $K-\varepsilon$ model. Kühn et al. [15] illustrated the results of the velocity magnitude profile of A50/50 air inlets configuration at x = 1190 mm. also used an equation to illustrate the temperature magnitude at x = 1120, as shown in **Figure 2.** The temperature equation is:

$$\Delta T_{loc} = (T - T_{in})\frac{(\Delta T)}{\Delta T} \tag{10}$$

Where, ΔT_{loc}, $(T - T_{in})$, (ΔT) and ΔT are the corrected and actual measured local temperature difference to the incoming air temperature.

From the comparison of the experimental velocity and temperature data and the CFD results in **Figure 2**, it was found that the argument between them is good and can be accepted.

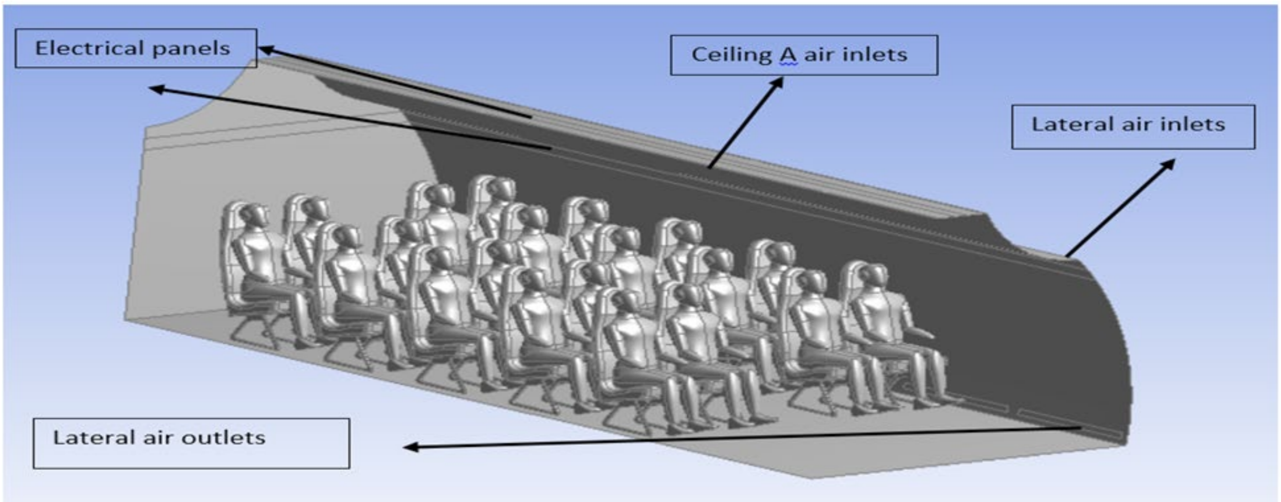


Figure 1. 3D model of the A380 upper-deck cabin.

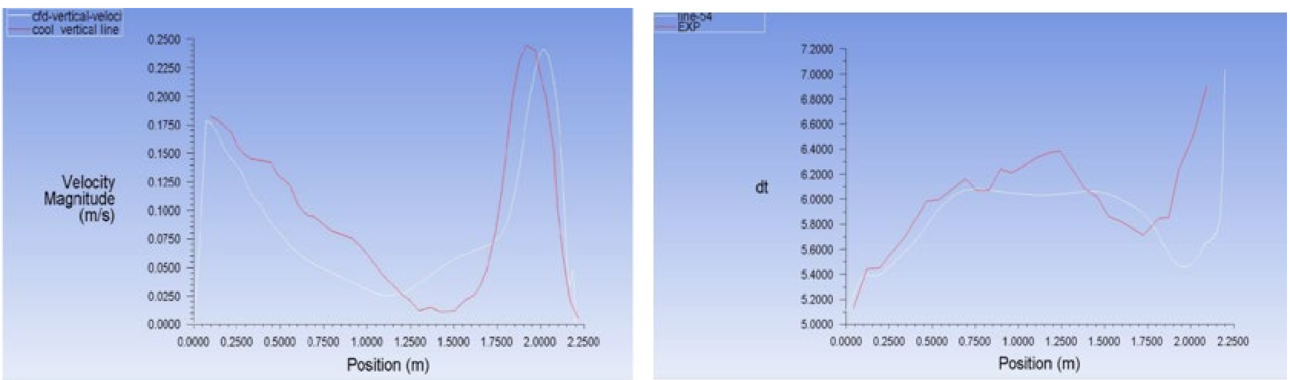


Figure 2. A comparison between the experimental velocity and temperature magnitude and the CFD results.

Numerical model

Proposed model

The dimensions of the geometric model are also based on the model used by Kühn et al. [15]. **Table 3** shows the simulation boundary conditions of the case study. We selected this aircraft cabin, because the probability of diseases transmission inside its cabin is higher than any other aircrafts due to including large number of passengers during long flights. Moreover, a dummy was installed in the middle of the cabin's aisle in order to simulate the exhalation of the coughed and sneezed droplets during the movement. This dummy has a length of 1.67 m and a width of 0.45 m besides its mouth area is 4 cm^2, as recommended by Gupta et al. [7]. **Figure 3** shows the 3D model of the moving passenger inside the cabin. Throughout our CFD simulation, the realizable $K-\varepsilon$ model and coupled pressure-velocity coupling were used.

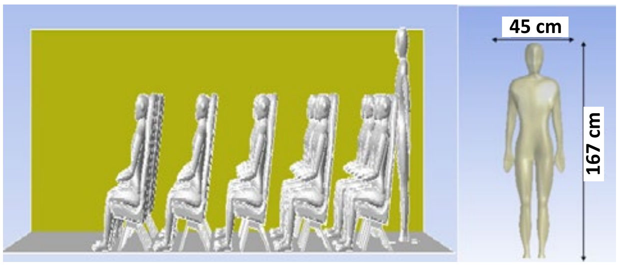


Figure 3. 3D model of the cabin and moving passenger.

Table 3. *The simulation boundary conditions.*

CFD software	ANSYS FLUENT V18.1
Turbulence model	The realizable $K-\varepsilon$ model
Moving passenger's height	1.67 m
Moving passenger's width	0.44 m
The total air volume flow rate	300 dm^3/s
The total volume flow rate at inner ceiling A inlets	150 dm^3/s
The total volume flow rate at lateral air inlets	150 dm^3/s
Temperature of supply air flow	18°C
Temperature of ceilings	22°C
Temperature of electrical lights	27°C
Temperature of the moving passenger	36°C
Temperature of the seated manikins	34.5°C
Back wall temperature	22°C
Floor temperature	24°C
Mass flow rate of the moisture from the mouths of the passengers	0.05 kg/s
Speed of the moving passenger	0.6 m/s

Design Case Setup

Economy class in the A380 aircraft cabin was selected because of the higher density of passengers inside it, which may cause a risk of pathogen diseases transmission. This study focused on transmission of coughed and sneezed droplets or particles that are produced by a passenger in case of moving with a constant speed between passengers and without any movement. To perform an accurate CFD investigation, coughed and sneezed droplets properties were used, as illustrated in **Table 4.**

Concerning modeling turbulent dispersion of droplets, stochastic discrete- particle model that enables us to predict the behavior of the droplets through integrating the trajectory equations for the individual droplets or particles using instant fluid velocity along the droplet path during the integration [15].

Design Case Studies

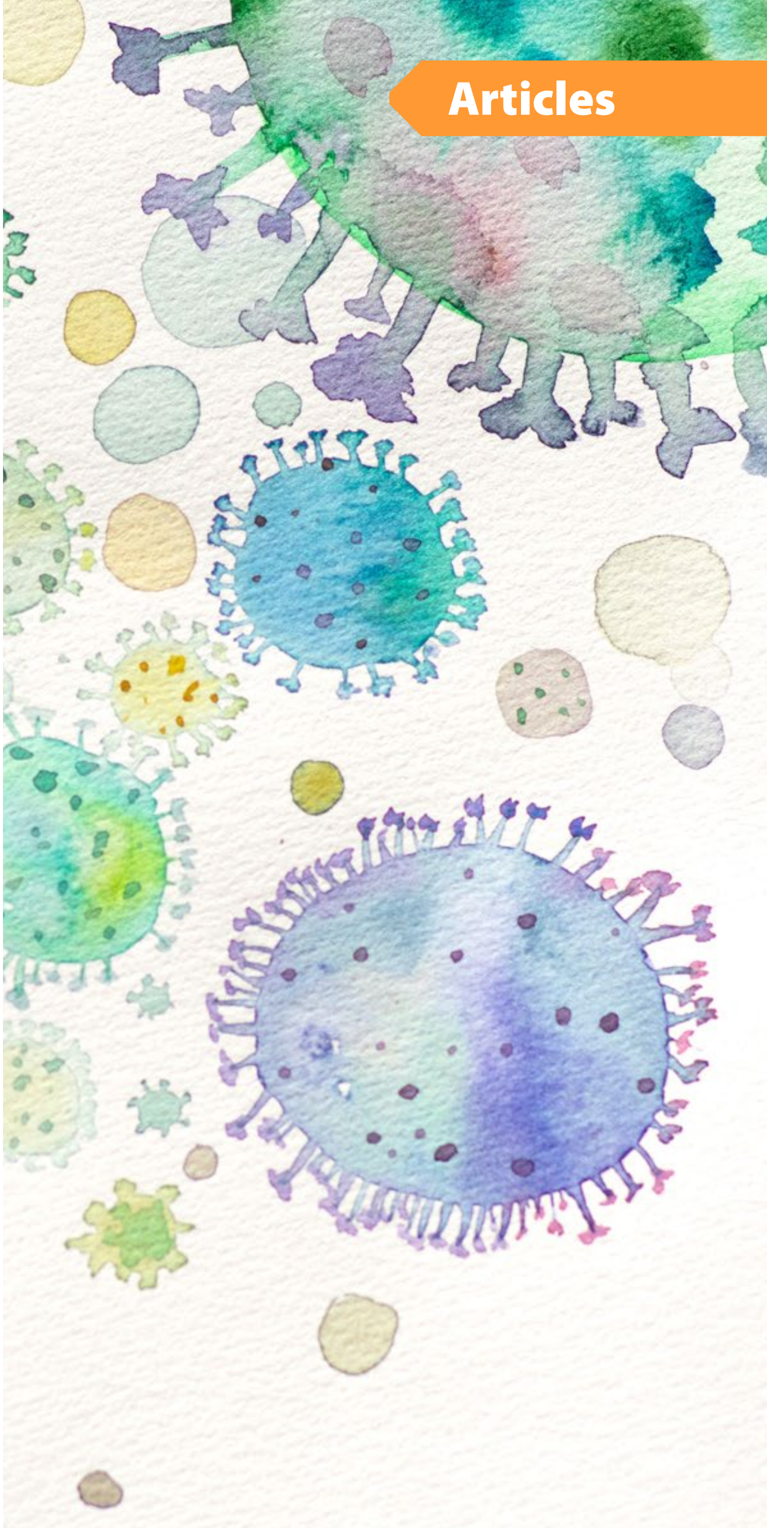
Two cases were simulated during this investigation each case has two scenarios. They can be described as follows: In cases one and two, transmission behaviors of sneezed and coughed droplets or particles produced from a passenger or cabin crew member were investigated during standing without any movement and moving with a constant speed up to 0.6 m/s. In long flight that may extend up to 7 hours, too many passengers leave their seats to do different activities; therefore, these scenarios can be happened. During this investigations, different coughing and sneezing flow rates were used, moreover, different velocities, as illustrated in **Table 5.**

Table 4. *Properties of coughed and sneezed droplets.*

Zhao et al. [1]	Coughing velocity	20 – 100 m/s
Zhu et al. [18]	Coughing velocity	6 – 22 m/s
Zhu et al. [18]	The total cough volume	0.8 – 2.2 dm^3
Mahajan et al. [19]	The total cough volume	5 dm^3
Gupta et al. [7]	• Mouth area for men • Mouth area for women • Cough flow rates for men • Cough flow rates for women • Coughing period • The cough jet direction	4 cm^2 3.370 cm^2 3 – 8.5 dm^3 1.5 – 6 dm^3 0.3 sec 40°
Jennison [20] Duguid [21] Buckland & Tyrrell [22]	Coughing and sneezing droplets size	• 7-100 µm • 1-2000 µm • 50-850 µm

Table 5. *Coughed and sneezed droplets characteristics.*

Parameters	Sneezing	Coughing
Temperature of the droplets	35	35
Exhaled period	1 sec	0.3 sec
Exhalation velocity	30 m/s	11.5 m/s
Max droplet diameter	500 µm	500 µm
Min droplet diameter	50 µm	50 µm



Results and their Discussions

This CFD study investigated the behavior of coughed and sneezed droplets and their transmission in the aircraft cabin during the flights using ANSYS FLUENT software.

Case One

Sneezing during Standing

Figures 4 & 5 show the transmission of the sneezed droplets that were produced from the passenger mouth for one second during his/her standing. These droplets' spread in *x*, *y*, and *z* positions were analyzed for 4 seconds during the CFD investigation, as shown in **Figure 5** where *x* and *y* represent width and height of the cabin. From the results, after exhaling the sneezed droplets with a speed of 30 m/s and their sizes are ranged from 50 – 500 µm. **Figure 5** shows that the droplets transported to more than 1.7 meters in *x*-direction and 1.8 meters in *y*-direction at the end of the simulation process. Moreover, these droplets traveled from the first to the second row.

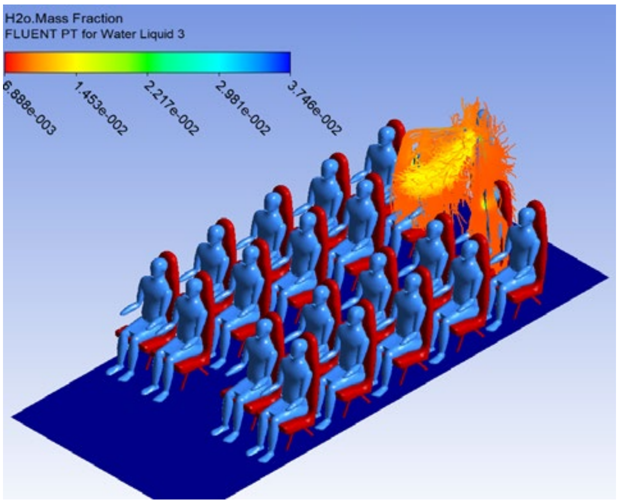


Figure 4. Transmission of the sneezed droplets during standing still.

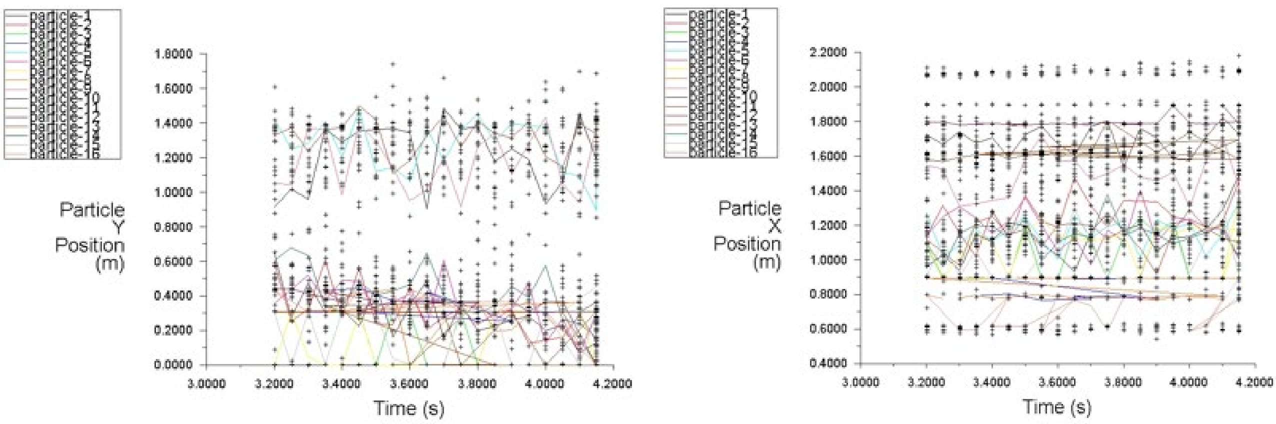


Figure 5. Transmission of the sneezed droplets in x- and y-directions during standing still.

Coughing during Standing

Moreover, **Figures 6 – 7** show the spread of the coughed droplets that were produced from the passenger mouth for one second during his/her standing with a speed of 11.5 m/s [18]. These droplets' transmission was simulated for 3 seconds during the CFD investigation, as shown in **Figure 6** after exhaling the coughed droplets their sizes are ranged from 50 – 500 µm. **Figure** 7 shows that the droplets traveled to more than 1.1 meters in *x*- and *y*-direction at the end of the simulation process. Moreover, these droplets traveled from the first to the second row.

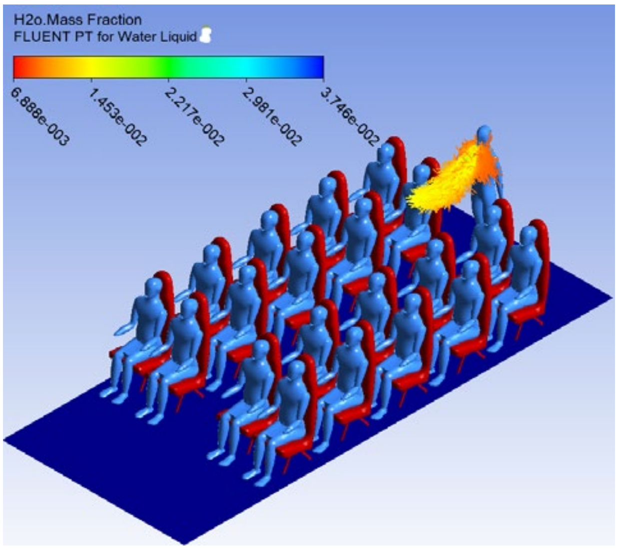


Figure 6. Transmission of the sneezed droplets ▶ during standing.

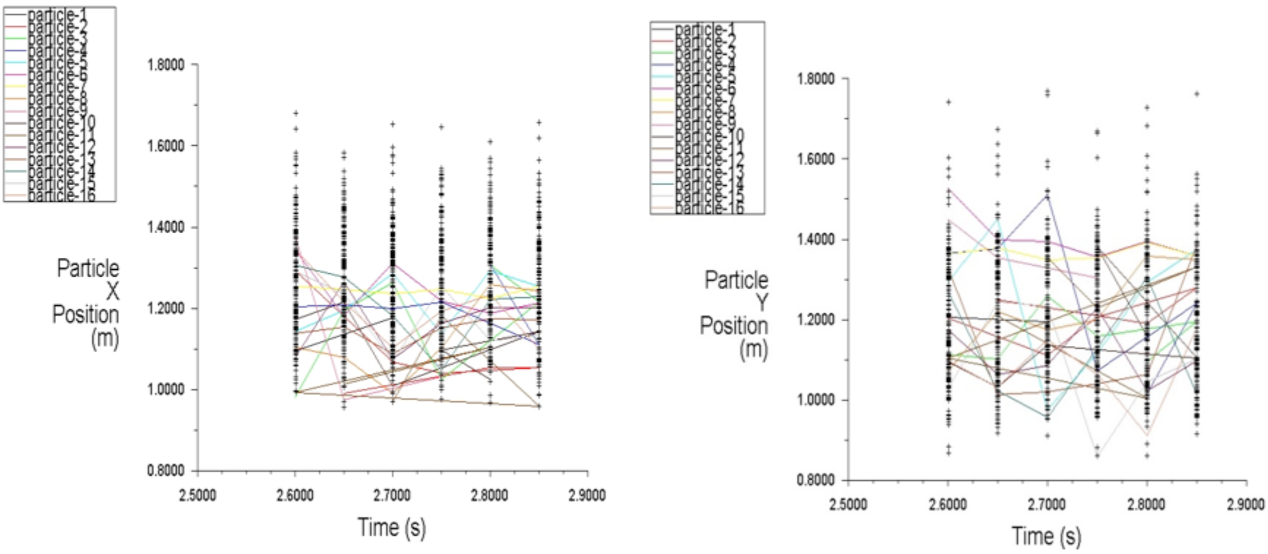


Figure 7. Transmission of the coughed droplets in x- and y-directions during standing.

Photo by Elizaveta Galitckaia / Shutterstock

Case two

Sneezing during Motion

Regarding sneeze during passenger's movement, the moving passenger started to sneeze for 1 second with a velocity of 30 m/s during the CFD simulation as shown in **Figures 8 – 9.** The sneeze droplets were able to take a flight, reach the surrounding passengers directly, and still had the ability to reach other passengers as they were still in the air. Moreover, these droplets spread to 2 m in *x*-direction and 1.5 m in *y*-direction at the end of the simulation process that extended for six seconds.

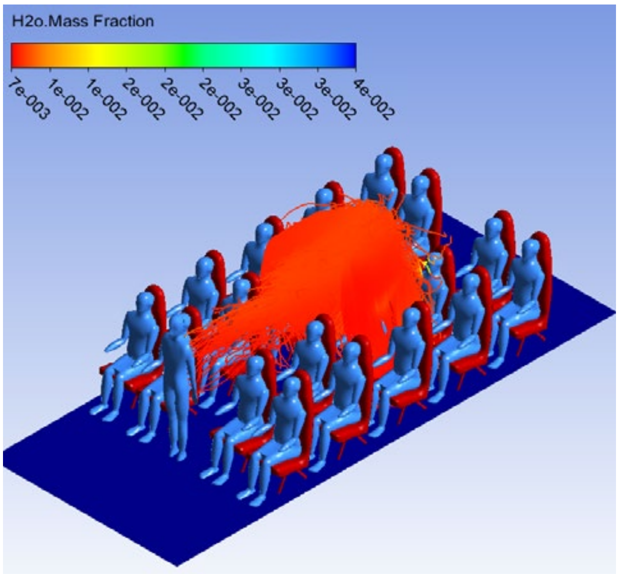


Figure 8. Transmission of the sneezed droplets during motion.

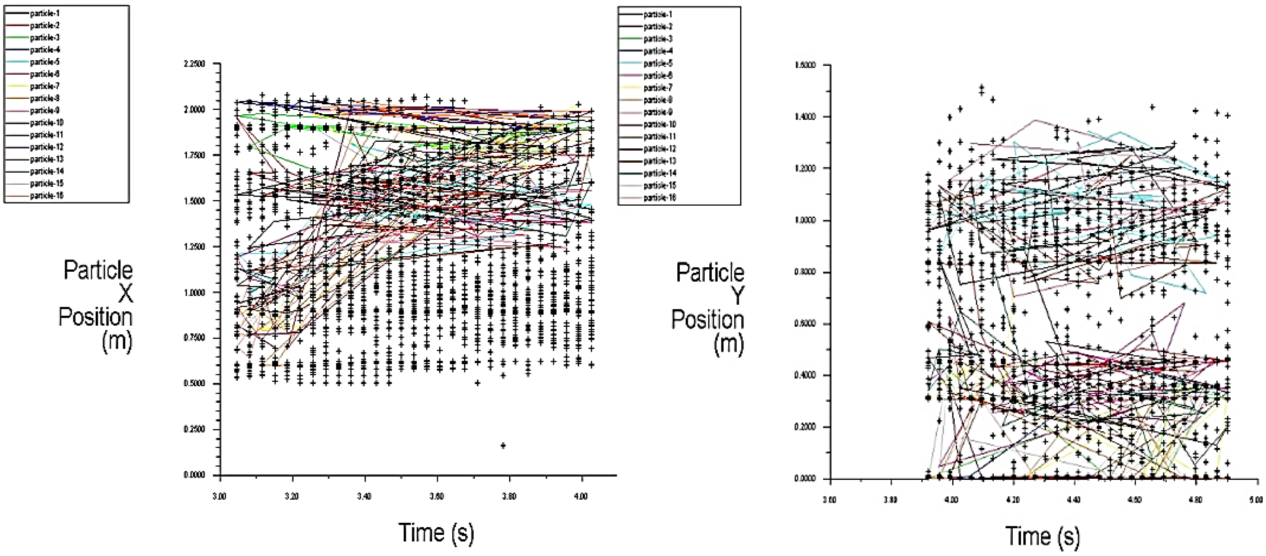


Figure 9. Transmission of the sneezed droplets in x- and y-directions during moving.

Coughing during motion

The moving passenger started to cough after 3.4 seconds of moving up to 3.4 seconds, and the exhalation velocity was 11.5 m/s. **Figures 10-11** shows the same droplets after 6 seconds of the passenger's movement. Moreover, at the end of the injection period that extended for 0.3 seconds, these ranges rose to 1.75 m in *x*-direction and 1.4 m in *y*-direction.

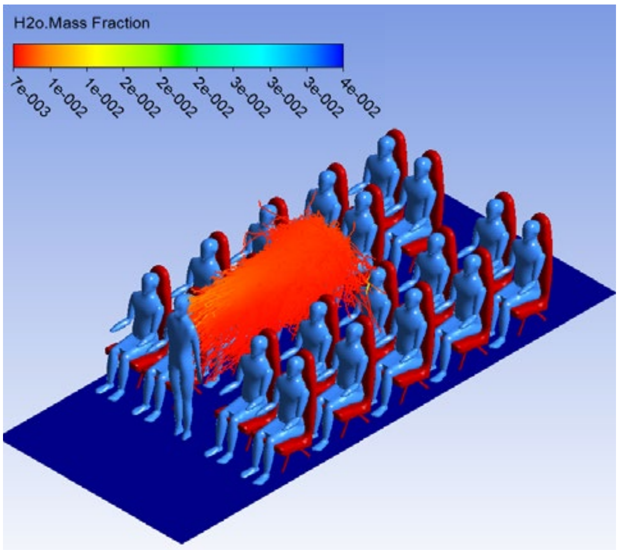


Figure 10. Transmission of the coughed droplets during motion.

Conclusions

Based on the present CFD simulation for the behaviors of the sneezed and coughed droplets that produced from a moving passenger inside the aircraft cabin, the relevant conclusions are as follows:

1. The transmission of the sneezed droplets that were exhaled from the standing passenger could reach the seated passengers in the first and second rows and still have the ability to travel and reach more passengers, while the coughed droplets could travel up to 1.1 meters without any movement from the passenger.

2. During the movement of the passenger with a constant speed, the droplets spread widely inside the aircraft cabin and managed to attacked many passengers inside it.

3. The impacts of the sneezed droplets on the seated passengers were much stronger than the coughed droplets. ■

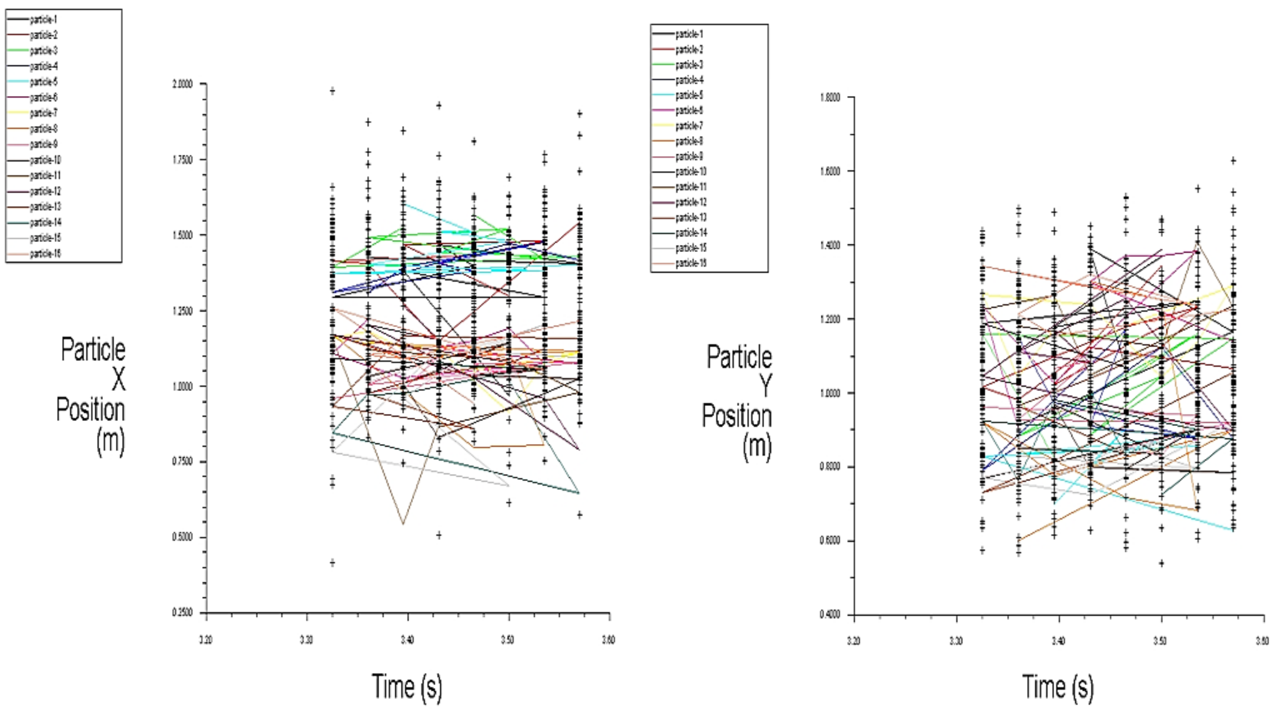


Figure 11. Transmission of the coughed droplets in x- and y-directions during moving

References

[1] Zhao, Bin, Zhao Zhang, and Xianting Li. "Numerical study of the transport of droplets or particles generated by respiratory system indoors." *Building and Environment* 40, no. 8 (2005): 1032-1039.

[2] Deacon, J. "The Microbial World—Airborne microorganisms." (2001).

[3] Afshari, A., S. Azadi, T. Ebeling, A. Badeau, W. T. Goldsmith, K. C. Weber, and D. G. Frazer. "Evaluation of cough using Digital Particle Image velocimetry." In Proceedings of the Second Joint 24th Annual Conference and the Annual Fall Meeting of the Biomedical Engineering Society [Engineering in Medicine and Biology, vol. 2, pp. 975-976. IEEE, 2002].

[4] Leder, K., and David Newman. "Respiratory infections during air travel." Internal medicine journal 35, no. 1 (2005): 50-55.

[5] Gao, Naiping, and Jianlei Niu. "Transient CFD simulation of the respiration process and inter-person exposure assessment." Building and Environment 41, no. 9 (2006): 1214-1222.

[6] Yan, Wei, Yuanhui Zhang, Yigang Sun, and Dongning Li. "Experimental and CFD study of unsteady airborne pollutant transport within an aircraft cabin mock-up." Building and Environment 44, no. 1 (2009): 34-43.

[7] Gupta, J. K., C-H. Lin, and Q. Chen. "Flow dynamics and characterization of a cough." Indoor air 19, no. 6 (2009): 517-525.

[8] Gupta, Jitendra K., Chao-Hsin Lin, and Qingyan Chen. "Characterizing exhaled airflow from breathing and talking." Indoor air 20, no. 1 (2010): 31-39.

[9] Han, Z. Y., W. G. Weng, and Q. Y. Huang. "Characterizations of particle size distribution of the droplets exhaled by sneeze." Journal of The Royal Society Interface 10, no. 88 (2013): 20130560.

[10] Yan, Yihuan, Xiangdong Li, and Jiyuan Tu. "Thermal effect of human body on cough droplets evaporation and dispersion in an enclosed space." Building and Environment 148 (2019): 96-106.

[11] Labarrere, Carlos A., J. R. Woods, J. W. Hardin, G. L. Campana, M. A. Ortiz, B. R. Jaeger, B. Reichart et al. "Early prediction of cardiac allograft vasculopathy and heart transplant failure." American Journal of Transplantation 11, no. 3 (2011): 528-535.

[12] Poussou, Stephane B., Sagnik Mazumdar, Michael W. Plesniak, Paul E. Sojka, and Qingyan Chen. "Flow and contaminant transport in an airliner cabin induced by a moving body: Model experiments and CFD.

[13] Mazumdar, Sagnik, Stephane B. Poussou, Chao-Hsin Lin, Sastry S. Isukapalli, Michael W. Plesniak, and Qingyan Chen. "Impact of scaling and body movement on contaminant transport in airliner cabins." Atmospheric Environment 45, no. 33 (2011): 6019-6028.

[14] Khalil, Essam E., and Hassan Kotb. "Numerical simulation of airflow and airborne pathogen transport in aircraft cabins: Dynamic Mesh Analyses." In AIAA SciTech 2020 Forum, p. 1934. 2020.

[15] Ansys, I. "ANSYS Fluent Theory Guide, Ansys." *Inc., Canonsburg* (2012).

[16] Shih, Tsan-Hsing, William W. Liou, Aamir Shabbir, Zhigang Yang, and Jiang Zhu. "A new k-ε eddy viscosity model for high reynolds number turbulent flows." Computers & Fluids 24, no. 3 (1995): 227-238.

[17] Kühn, M., Johannes B., and Claus W. "Experimental parametric study of forced and mixed convection in a passenger aircraft cabin mock-up." Building and Environment 44, no. 5 (2009): 961-970.

[18] Zhu, Shengwei, Shinsuke Kato, and Jeong-Hoon Yang. "Study on transport characteristics of saliva droplets produced by coughing in a calm indoor environment." Building and environment 41, no. 12 (2006): 1691-1702.

[19] Mahajan, R. P., P. Singh, G. E. Murty, and A. R. Aitkenhead. "Relationship between expired lung volume, peak flow rate and peak velocity time during a voluntary cough maneuver." British Journal of Anesthesia 72, no. 3 (1994): 298-301.

[20] Jennison, M. W. Atomizing of mouth and nose secretions into the air as revealed by high-speed photography. 1941.

[21] Duguid, J. P. "The numbers and the sites of origin of the droplets expelled during expiratory activities." Edinburgh Medical Journal 52, no. 11 (1945): 385.

[22] Buckland, F. E., and D. A. J. Tyrrell. "Experiments on the spread of colds: 1. Laboratory studies on the dispersal of nasal secretion." Epidemiology & Infection 62, no. 3 (1964): 365-377.

Renovation of a heating system

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General overview of the structure and functioning of a heating system in apartment buildings renovation

Central heating, particularly hot-water heating where the heat emitters used are radiators and convectors, is the most common type of heating system in all places where, during the cold seasons of the year, continuous heating is needed. In Europe alone, it is estimated that there are one billion radiators/convectors in use.

There is a reason for their popularity: Properly designed and properly constructed radiator heating systems work reliably, last a long time, and deliver an excellent thermal comfort. Their reliability is enhanced by decades of user experience of the functioning of both the components and the assembled whole. Indeed, radiator systems have revealed to be one of the least problematic of buildings' different technical systems.

In terms of the structure of their piping, radiator networks are of two basic types: one-pipe systems and two-pipe systems (**Figure 1**). Two-pipe systems are by far the most popular apartment buildings. The use of vertical one-pipe systems in apartment buildings was widespread in Eastern Europe. To some extent, horizontal one-pipe systems are used mainly in small buildings. Because of their deficient in cooling and the resultingly weak energy efficiency, it is advisable to shift from one-pipe systems to the two-pipe option.

This presentation focuses on radiator networks in apartment buildings that are renovated. It is also of key importance to be able to renovate the heating systems while the residents are on site. If it is possible to move the residents to temporary housing for the duration of the renovation, this would offer opportunities for other types of technical solutions.

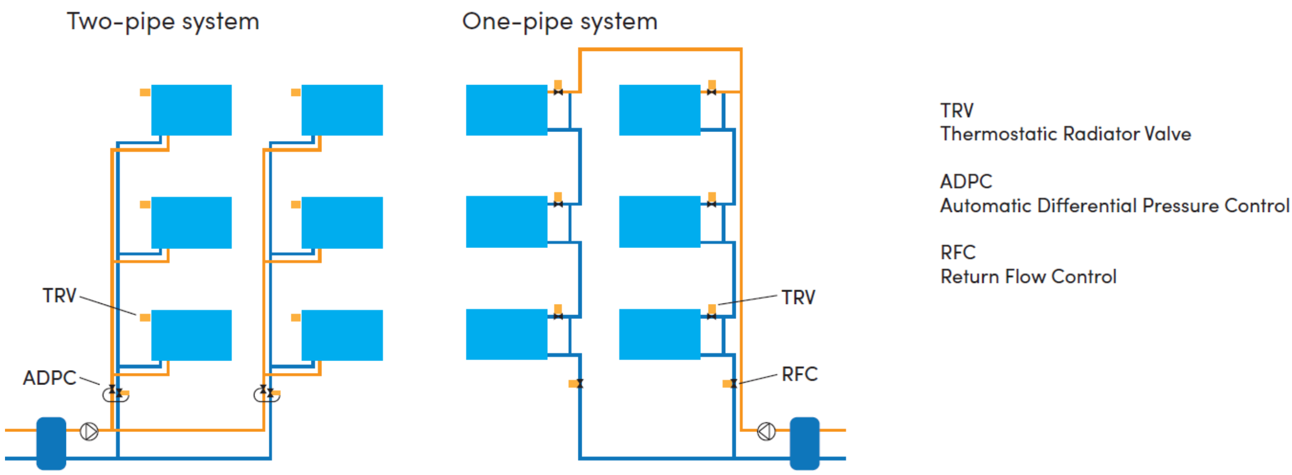

Figure 1. Structure of a radiator network: a two-pipe system (left) and a one-pipe system (right).

Actions to be performed on a heating network during the renovation.

Because renovation of building stock are guided by the statutorily defined objective (EU EPBD requirements) for improving buildings' energy efficiency to the level of a nearly zero-energy building (nZEB), the renovation actions shall ensure that the target energy efficiency is achieved, and that the repairs help to create the conditions for making the buildings carbon neutral.

In old buildings, the key energy renovation focus is to reduce heat losses from the building envelope, such as the replacement of windows and outer doors, and the improvement of the heating insulation. Actions aimed at increasing active energy efficiency include, e.g., shifting to carbon neutral systems for heat generation, installation of heat recovery equipment, reduction of electrical devices' consumption, arrangements to reduce the consumption of tap water (particularly domestic hot water), and implementing measurement of water and energy consumption. Buildings' own electricity generation systems are being installed in ever-increasing numbers. Reduction of cooling needs and the setup of more energy-efficient cooling systems are also an important part of renovation construction.

In addition to these measures, one of the most energy-efficient and cost-effective actions that can be taken is the enhancement of radiator networks and turning them into low-temperature heating systems. Heating systems and their functioning are of decisive importance to thermal comfort, energy efficiency and energy costs.

To improve the energy efficiency of heat generation in areas such as heat pumps and district heating, the heating network's temperatures need to be brought to a considerably lower level than before (**Figure 2**). The aim is to improve the efficiency of heat generation and at the same time lower the costs of generating heat energy.

Energy remodeling of a building changes certain building features. The heating needs of the rooms change, as do the ratios of heating needs between the different rooms. This means the heating network needs to be redesigned with dimensions adapted to the new conditions and requirements. Generally, what should be retained from the older system are the heating network's transmission lines and risers. It is practical

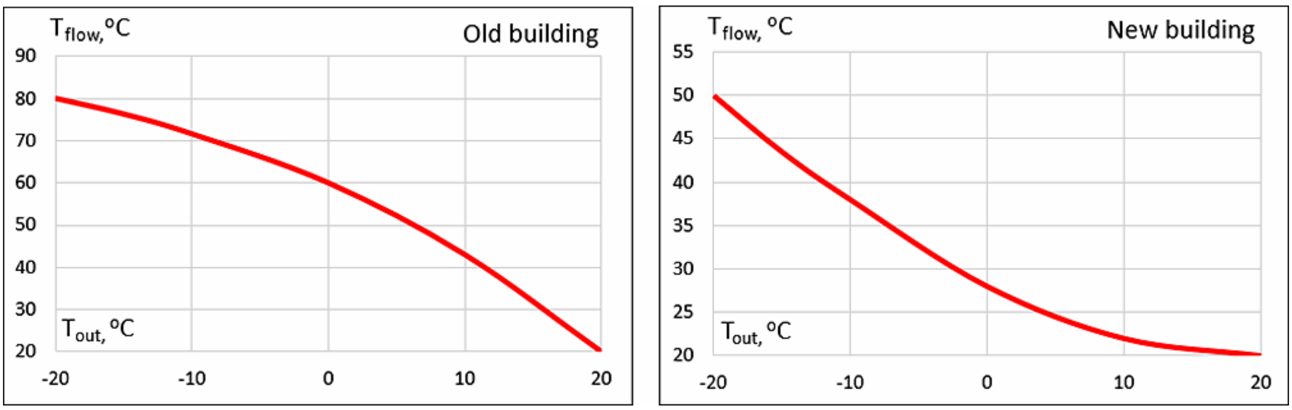

Figure 2. Examples: The old building (left) has high flow water temperatures and a convex heating curve. The new and deep-renovated old buildings (right) have low flow water temperatures due to the low heat demand and a concave heating curve due to the high influence of solar and internal heat gains.

to replace the radiator connection pipes with new ones when possible (**Figure 3**).

New radiators should be dimensioned to the right size for a low-temperature system, while ensuring that their heat-radiating surface is as large as possible, taking into account the space available for installation. Radiator valves should be replaced with precisely preset thermostat valves. The existing risers should be equipped with automatic differential pressure control valves. The heating network should be balanced using calculated values. It is also advisable to update the temperature controller and the water circulation pump.

In an energy-efficient building, up to 60–80% of heating needs during a heating period can be covered by heat gains from residents and electrical devices, and the direct radiation of the sun. The radiator and thermostat, working together, make it possible to utilize free quantities of heat.

In practice, achieving a balanced heating network is straightforward because in the new operating situation, the old supply risers are looser and are no longer a source of friction losses: If one chooses a pressure difference level of, e.g., 10 kPa, this pressure difference will be precisely preserved, even with radiator valves. The settings values of radiator valves can therefore be determined almost entirely on the basis of the design heat demand. A low pressure difference ensures that a radiator valve functions precisely, without making noises, and also ensures good cooling of water.

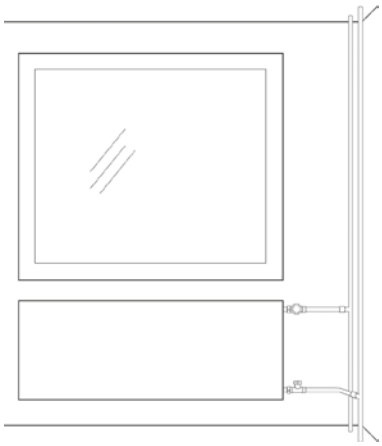

Figure 3. A properly dimensioned radiator will have a large heat-radiating surface. A new radiator and its valves are easiest to install when the radiator connection pipes from risers to radiator valves are replaced.

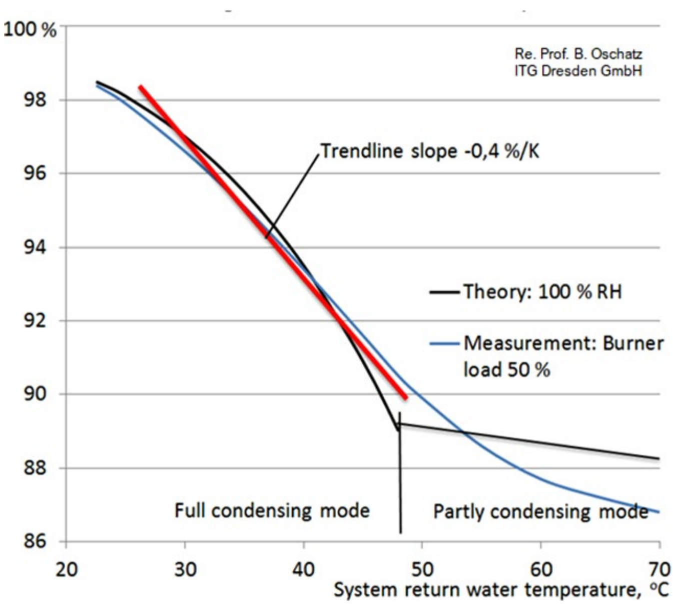

Figure 4. The condensation of output gases is significantly enhanced when the temperature of the return water falls to under 50°C, in which case boiler efficiency can improve by up to 10%.

Dimensioning and energy efficiency of radiators at district heating and heat pump sites

District heating

With a district heating connection, a functional level for the dimensioning temperature is 60/30/21°C (flow temperature/return temp/room temp). Heavy cooling, i.e., low temperature of return water – improves the energy efficiency of district heating: The network's ground losses are smaller, lower levels of flow and pumping power are made possible, the boiler operating efficiency improves when the temperatures of flue gasses decrease, and increased condensation enhances the functioning of the flue gas scrubbers reducing the particle emissions (**Figure 4**). Thanks to these benefits, many district heating providers have also been able to reduce consumer tariffs. In energy prices, it is typical to have a €2/MWh deduction for each degree the temperature of the return water is reduced; for example, the monthly average of return water temperature compared to a reference temperature of 50°C. Some district heating providers also issue fines when the temperature of return water exceeds the reference temperature.

Efficient condensation of flue gases, and the boiler efficiency that such condensation affords, pertains to all types of heating boilers, such as bio-mass, gas and oil boilers.

Heat pump system

It is important to a heat pump's efficiency to keep the heating system's temperatures low. When the heating need is low, radiators can also be dimensioned for very low temperatures.

The operating efficiency of a heat pump is described with the coefficient of performance (COP), which is the ratio of the heat generated by the heat pump system (Q) to the work done by the electrical energy of the compressor (W).

$$COP = \frac{Q}{W}$$

where

- Q is the useful heat supplied or removed by the considered system
- W is the work required by the considered system

The expression COPa is also used for the annual coefficient of performance.

In practice, the temperature of the supply water is of decisive importance because a heat pump's coefficient of performance (COP) is about 2/3 dependent on the supply water's temperature, and 1/3 on the temperature of the return water (**Figure 5**). For this reason, in the dimensioning of a heat pump, a temperature of, e.g., 50/40°C (flow/return temperature) is better than 60/30°C, the latter of which is suitable for district heating. For a guideline value, one can assume that a decrease of 10°C degrees in supply water temperature will improve COP by about 30%, which, at an annual level, means that the heat coefficient COPa rises by 12-15%, with focus on the space heating.

Production of domestic hot water (above 55°C) solely with geothermal heat pumps and outdoor air heat pumps is often not economic. For most heat pumps, 50°C can be regarded as a reasonable temperature lift. The larger the temperature lift, the lower the COP becomes (**Figure 6**). The optimal temperature increase level depends on the COP corresponding to the threshold temperature level in question, and the prevailing price ratio between electricity and other forms of energy.

For their heat source, exhaust air heat pumps use ventilation exhaust air, which has a high temperature (in the range of 22°C year-round). With a high initial temperature, an exhaust air heat pump can produce warm supply water and domestic hot water energy efficiently. But be aware that given the limited extract airflow of a mechanical ventilation system the capacity of heat pumps using the exhaust air as their heat source is limited.

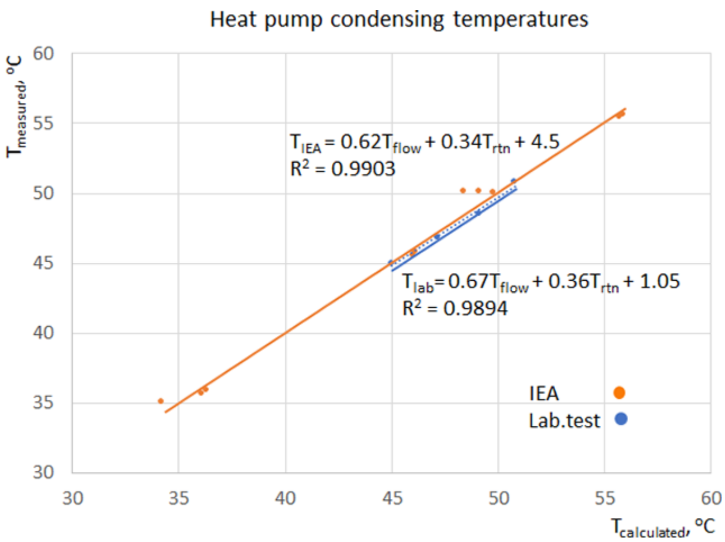

Figure 5. A heating network's supply water temperature has about a 2/3 impact on a heat pump's COP, and return water has an impact of about 1/3 – compare the coefficients of the regression equations.

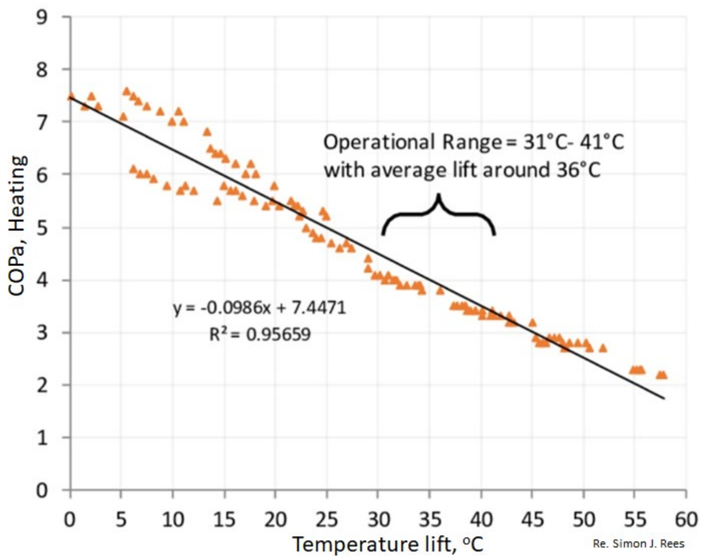

Figure 6. Typical COPa values gathered from different sources.

Generally speaking, it is recommended to use a heat pump in parallel with district heating or a heating boiler if the capacity of the heat pump is insufficient on its own to achieve economic heating of domestic hot water or peak efficiency of the heating system.

However, one should remember that such hybrid systems always require high-quality control and connection systems to ensure optimal functioning. ■

Finnish Society of Indoor Air Quality and Climate (Sisäilmayhdistys) 30 years

The 30-year-old Finnish Society of Indoor Air Quality and Climate emphasises research and cooperation

Finnish Society of Indoor Air Quality and Climate celebrates its 30th anniversary in 2020. The anniversary year started off with the annual Indoor Climate Conference and a special anniversary gala night. The conference was participated by 1,300 indoor air professionals, while the gala brought together a large number of distinguished people and long-term partners who have played key roles over the years.

The association was established in the autumn of 1990 with the task of organizing the International Indoor Air 1993 Conference in Helsinki. Since the successful event, the association has been a trailblazer in the industry – its list of achievements ranges from indoor climate ratings to material emission classifications and cleanliness taxonomies. The material emission classification was recognised already in 2007 in EN standard.

Characteristically, the association always involves a group of experts from many organisations to maintain impartiality in the work.

FINNISH SOCIETY OF INDOOR AIR QUALITY AND CLIMATE

World largest conference on indoor air quality and climate

Key programme in this year's Indoor Climate Conference included more than sixty keynotes and presentations. The topics varied from microbe research and chemical impurities to indoor air quality verification and risk assessment as well as ventilation solutions and development. Exhibition consisting of 80 companies also gives tools to everyday work of many indoor environment specialists participating the conference.

If we pick one among the dozens of interesting speakers, Professor **Juha Pekkanen** talked to a tight-packed room about indoor air risk assessment. His message was clear: "Instead of only underlining the risks, we should help people understand and proportion risks related to indoor air."

The conference has been organised annually in Finland since 1987 and, from the very beginning, it has brought together a wide array of experts – scientists, technology companies, designers and authorities. "The concept has been the same from the start – we invite professionals from different backgrounds to meet, discuss and share their ideas. This way, year after year, the conference is building an ecosystem of indoor air visionaries," says **Mervi Ahola**, Executive Director of the Finnish Indoor Air Association.

This year, the conference hosted a record audience even though the looming coronavirus caused a couple of hundred cancellations.

Research and cooperation across the board

In his speech, **Risto Kosonen**, Chairman of the association, emphasized the multidisciplinary nature of indoor air work and the importance of cooperation within the industry. "Our operations have always been based on impartiality, researched knowledge and multidisciplinary approach. The association has become an internationally unique social innovation. We have built links between researchers, authorities, educational institutions as well as companies to discuss, influence and develop things together," Risto Kosonen stated.

Risto Kosonen also emphasized the importance of research funding. "To operate in the international community requires our own cutting-edge research and adequate funding."

In his turn, Professor emeritus **Olli Seppänen** described the history of the association and the development of indoor air research in Finland in its speech. He also called for attention to the large number of distinguished researchers who have worked on indoor air issues in Finland over the decades. Olli Seppänen was the first president of the Finnish association, and the second president of ISIAQ.

ISIAQ, the international organization for indoor air organisations, appreciates the Finnish Indoor Air Association's pioneering role in the field. "We particularly appreciate the contribution of the association in publishing guidelines on indoor air, in classifying building materials and indoor air quality, and in the systematic dissemination of information through conferences and workshops," says **Marzenna Dudzinska**, President of ISIAQ.

Finnish Society of Indoor Air Quality and Climate is a one of the four professional member associations of FINVAC, representing more than 6,000 professionals in Finland. FINVAC has been an active member of international organisations like REHVA and SCANVAC.

The conference and the anniversary gala night was held 10th of March 2020 in Helsinki. ■

For more information, please contact Mervi Ahola
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Want to ride the building renovation wave? *Renovate heating and cooling!*

A climate-neutral building stock by 2050 is crucial to achieve carbon-neutrality for the whole European economy. Therefore, the Renovation Wave for Buildings should accelerate the replacement of the tens of millions of old, inefficient heating and cooling systems installed in Europe's buildings with new, highly efficient and renewable-based ones.

The good news is that these new, highly efficient and renewable technologies already exist. In heating: from condensing boilers already working with biomethane to electric and gas heat pumps, from hybrids to solar thermal, from micro-combined heat and power to fuel cells, from thermal energy storage to digital energy managements systems. And other technologies are in the making, to integrate new renewable sources of energy. Also, in cooling, constant innovation brings efficiency gains and ever-increasing performance to new appliances. Depending on the building, climate conditions and preferences of consumers, different heating and cooling technologies can be used for renovation projects.

"Heat pumps are an efficient and well-proven technology that can provide both, heating and cooling. This will be more and more important for healthy and comfortable indoor conditions, considering increasing temperatures coming with a greater need for cooling throughout Europe," says **Andrea Voigt**, Director General of EPEE.

But the replacement of old appliances is not proceeding fast enough. How to accelerate it? First, financing upfront investments in heating and cooling technologies for renovation will be essential, for example with national scrapping schemes or green mortgages. Indeed, while these investments pay back over time, there are still important upfront costs.

"Renovation packages that include financial incentives and make the heater replacement easy and stress free for the end consumer are important tools that should be pushed for by the European Commission and the member states in the upcoming renovation strategy. Similarly, new players that build their business on modern business models, i.e. using the economic value of demand side flexibility, reduce the end-user cost for the investment. From a technical perspective, the latest generation of heat pumps is feasible to replace fossil fuel heating systems. It is mostly economic barriers that need to be overcome", says **Thomas Nowak**, Secretary General of the European Heat Pump Association.

And crucially focus on consumers and installers: "There can be no renovation wave of heating in buildings without people: they should be in charge to choose the most suitable heating system for their building. This means being aware of the efficiency gains achievable with new heating systems; having the means to afford the upfront replacement costs and easily finding skilled installers to bring efficient technologies to your home", says **Federica Sabbati**, Secretary General of EHI.

For more information, please contact the respective associations (please see the following page).

ehi
association of the
European Heating Industry

The association of the European Heating Industry (EHI), represents 90% of the European market for heat and hot water generation, heating controls and heat emitters, 75% of the hydronic heat pump market, 80% of the biomass central heating market (pellets, wood) and 70% of the solar thermal market. EHI Members produce advanced technologies for heating in buildings, including: heating systems, burners, boilers, heat pumps, components and system integrators, radiators, surface heating & cooling and renewable energy systems. In doing so, we employ directly more than 125.000 people in Europe and invest over 1 billion euros a year in energy efficiency.

For further information, please contact **Paolo Basso**, Policy Director, paolo.basso@ehi.eu or visit www.ehi.eu

ehpa
european
heat pump association

The Brussels based European Heat Pump Association aisbl (EHPA) represents the majority of the European heat pump industry. It has currently 130 members from all parts of the industry's value chain: heat pump and component manufacturers, research institutes, universities, testing labs and energy agencies.

Its key goal is to promote awareness and proper deployment of heat pump technology in the European marketplace for residential, commercial and industrial applications. EHPA coordinates the European Quality label for heat pumps and the CEN Heat pump KEYMARK. It compiles the annual sales statistics and market outlook (stats.ehpa.org) and organises several events, among them the EU heat pump forum (www.hp-forum.eu).

For further information, please contact
Oliver Jung, EU Affairs manager, oliver.jung@ehpa.org;
Eirini Litina, Senior Communication manager, +32 (2) 400 10 17, eirini.litina@ehpa.org or visit www.ehpa.org.

EPEE
European Partnership for Energy and the Environment

The European Partnership for Energy and the Environment (EPEE) represents the refrigeration, air-conditioning and heat pump industry in Europe. Founded in the year 2000, EPEE's membership is composed of over 50 member companies as well as national and international associations from three continents (Europe, North America, Asia).

With manufacturing sites and research and development facilities across the EU, which innovate for the global market, EPEE member companies realize a turnover of over 30 billion Euros, employ more than 200,000 people in Europe and also create indirect employment through a vast network of small and medium-sized enterprises such as contractors who install, service and maintain equipment. As an expert association, EPEE is supporting safe, environmentally and economically viable technologies with the objective of promoting a better understanding of the sector in the EU and contributing to the development of effective European policies. Please see our website (http://www.epeeglobal.org) for further information.

As part of the activities EPEE and its members are undertaking to raise awareness on sustainable cooling, EPEE will launch a broader #CountOnCooling campaign. The EPEE White Paper "Count on Cooling: A five-step approach to deliver sustainable cooling" examines the crucial role of cooling in the 21st century.

For further information, please contact the EPEE Secretariat (secretariat@epeeglobal.org) and visit our website at www.epeeglobal.org.

City of Helsinki launched one-million-euro open competition for energy experts

A global one-million-euro challenge competition was launched on March 27th at Helsinki City Hall to answer the question: How can we decarbonise the heating of Helsinki, using as little biomass as possible?

The climate crisis is the most crucial challenge of our time, and cities have a key role in driving the shift to a low-carbon economy. Finnish government has out ruled the use of coal as heating fuel by 2029. Helsinki is one of the leading cities in the transition towards a sustainable future, with the goal of becoming totally carbon-neutral by 2035. But there is an issue to overcome. Currently, more than half of the city's heating energy is produced with coal. In order to achieve carbon-neutrality, Helsinki needs radically new solutions to meet city´s heat demand. And we are not alone. To fight climate change, sustainable heating solutions are needed in cities all over the world. Heating not just beyond coal, but also beyond burning biomass. That is why the Helsinki Energy Challenge is launched. City of Helsinki has allocated one million euro for the awards of the competition.

Deadline for applications for the competition is 31th of May, 2020 16:00 EET.

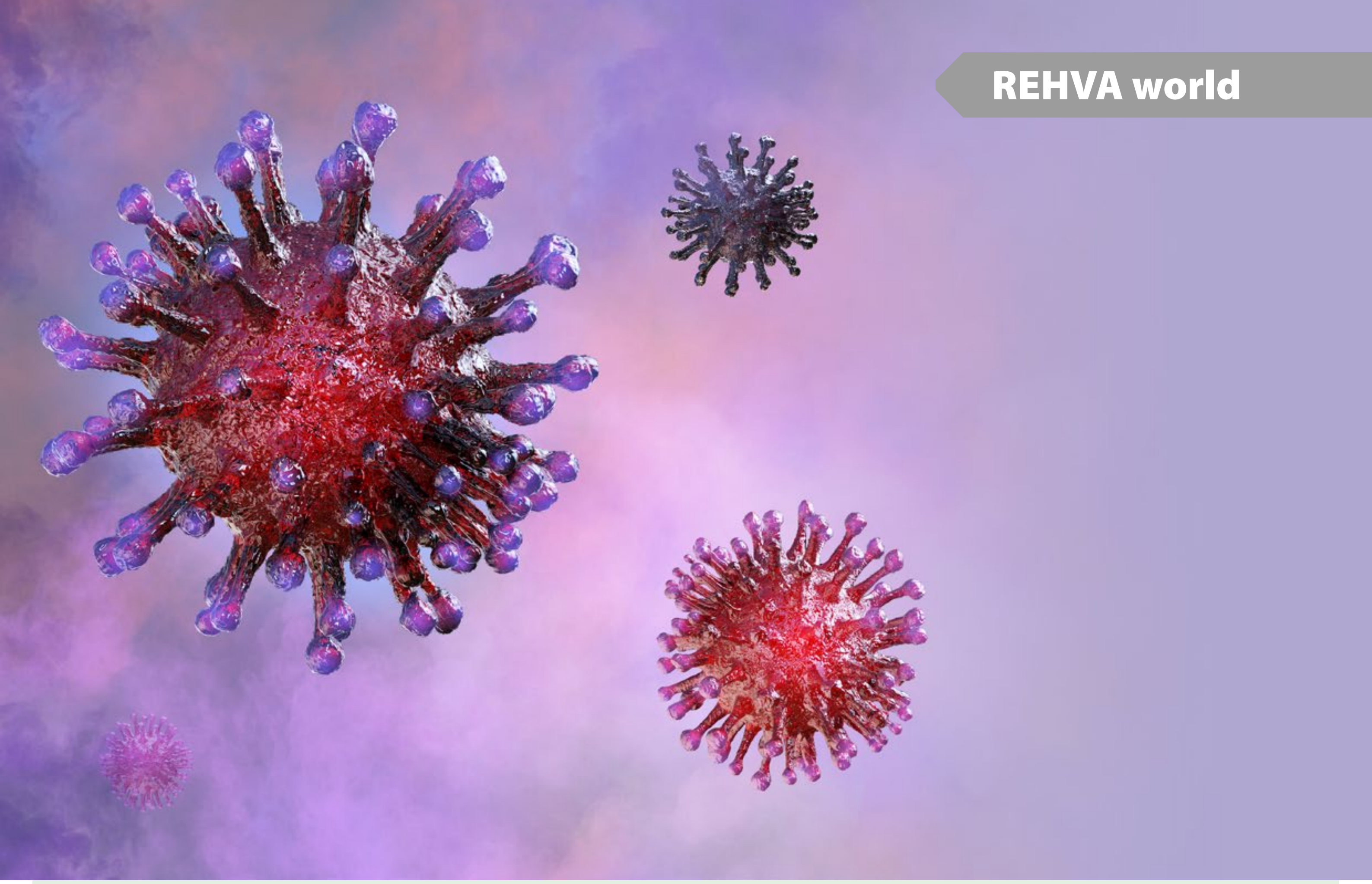
The final entries are due by end of September 2020. They will be evaluated by an international jury. The winner(s) will be announced in October 2020. ■

More information at https://energychallenge.hel.fi/

Major of the City of Helsinki announced the Helsinki Energy Challenge Competition on February 27th.

> *"Climate change is a global crisis that will not be solved through quick fixes. With the Helsinki Energy Challenge we are seeking new innovative solutions, even if it would mean significant changes to our existing system. We invite innovators from all around the world to use Helsinki as a testbed for truly sustainable solutions for urban heating. Taking this next step might lead to a revolutionary breakthrough in our fight for a more sustainable city life."*
>
> – Mayor of Helsinki, Mr. Jan Vapaavuori

Buildings in Helsinki are mainly heated by coal fired district heating power plants. City will abandon the coal fired plants by 2029, and is looking new solutions with the open competition.



REHVA COVID-19 Guidance Document

As response to the coronavirus (SARS-CoV-2) COVID-19 pandemic, REHVA experts produced a REHVA COVID-19 Guidance Document, on how to operate and use building services in areas with a coronavirus outbreak to prevent the spread of coronavirus depending on HVAC or plumbing systems related factors.

REHVA COVID-19 Guidance Document considers the best available evidence and knowledge to date, utilizing an ongoing Dutch literature review elaborated by dr. **Francesco Franchimon**, complemented by international REHVA experts as a joint effort under leadership of **Jarek Kurnitski**, Chair of REHVA Technology and Research Committee.

Due to the ever-changing information about the disease, the document will be updated and complemented with new evidence when it becomes available. REHVA thanks the co-authors of this document for their much-appreciated contribution.

Read the full Guidance Document on the following pages or at https://www.rehva.eu/activities/covid-19-guidance.

Version April 3, 2020. This document is an update to the March 17 version. Updates will follow as necessary. See for later updates: https://www.rehva.eu/activities/covid-19-guidance

REHVA COVID-19 Guidance Document

How to operate and use building services in order to prevent the spread of the coronavirus disease (COVID-19) virus (SARS-CoV-2) in workplaces

Disclaimer: This REHVA document is based on best available evidence and knowledge, but in many aspects' corona virus (SARS-CoV-2) information is so limited or not existing that previous SARS-CoV-1 evidence* has been utilized for best practice recommendations. REHVA excludes any liability for any direct, indirect, incidental damages or any other damages that would result from, or be connected with the use of the information presented in this document.

Introduction

In this document REHVA summarizes advice on the operation and use of building services in areas with a coronavirus disease (COVID-19) outbreak, in order to prevent the spread of COVID-19 depending on HVAC or plumbing systems related factors. Please read the advice below 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 is presented in the WHO document 'Getting workplaces ready for COVID-19'**. The text below is intended primarily for HVAC professionals and facility managers, but may be useful for e.g. occupational and public health specialists.

In the following the building related precautions are covered and some common overreactions are explained. The scope is limited to commercial and public buildings (e.g. offices, schools, shopping areas, sport premises etc) where only occasional occupancy of infected persons is expected; hospital and healthcare facilities (usually with a larger concentration of infected people) are excluded.

The guidance is focused to temporary, easy-to-organize measures that can be implemented in existing buildings which are still in use with normal occupancy rates. The advice is meant for a short period depending on how long local outbreaks last.

Transmission routes

Important for every epidemic are the transmission routes of the infectious agent. In relation to COVID-19 the standard assumption is that the following two transmission routes are dominant: **1) via large droplets** (droplets/particles emitted when sneezing or coughing or talking) and **2) via surface** (fomite) **contact** (hand-hand, hand-surface etc.). A third transmission route that is gaining more attention from the scientific community is the **faecal-oral** route.

The faecal-oral transmission route for SARS-CoV-2 infections is implicitly recognized by WHO, see their latest technical briefing of March 2, 2020[i]. In this document they propose as precautionary measure to flush toilets with closed lid. Additionally, they suggest avoiding dried-out drains in floors and other sanitary devices by regularly adding water (every 3 weeks depending on climate) so that the water seal works properly. This is in line with an observation 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)[ii]. It is known that flushing toilets are creating plumes containing droplets and droplet residue when toilets are flushed with open lids. And we know that SARS-CoV-2 viruses have been detected in stool samples (reported in recent scientific papers and by the Chinese authorities)[iii,iv,v]. In addition, a comparable incident was recently reported in an apartment complex (Mei House). Therefore, the conclusion is that the faecal-oral transmission routes can't be excluded as transmission route.

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* In the last two decades we are 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). In the present document our focus is on the last aspect of SARS-CoV-2 transmission. When it is referred to the SARS outbreak in 2002–2003 we will use the name of SARS-CoV-1 virus at that time.

** https://www.who.int/docs/default-source/coronaviruse/getting-workplace-ready-for-covid-19.pdf?sfvrsn=359a81e7_6

Via air, there are two exposure mechanisms[vi,vii]**:**

1. **Close contact transmission** through large droplets (> 10 microns), which are released and fall to surfaces not further than about 1–2 m from the infected person. Droplets are formed from coughing and sneezing (sneezing forms many more particles typically). Most of these large droplets fall on nearby surfaces and objects – such as desks and tables. People could catch the infection by touching those contaminated surfaces or objects; and then touching their eyes, nose or mouth. If people are standing within 1–2 meter of an infected person, they can catch it directly by breathing in droplets sneezed or coughed out or exhaled by them.
2. **Airborne transmission** through small particles (< 5 microns), which may stay airborne for hours and can be transported long distances. These are also generated by coughing and sneezing and talking. Small particles (droplet nuclei or residue) form from droplets which evaporate (10 microns droplets evaporate in 0.2 s) and desiccate. The size of a coronavirus particle is 80-160 nanometre***,[viii] and it remains active for many hours or couple of days (unless there is specific cleaning)[ix,x,xi]. SARS-CoV-2 remains active up to 3 hours in indoor air and 2–3 days on room surfaces at common indoor conditions[xii]. Such small virus particles stay airborne and can travel long distances carried by airflows in the rooms or in the extract air ducts of ventilation systems. Airborne transmission has caused infections of SARS-CoV-1 in the past[xiii,xiv]. For Corona disease (COVID-19) it is likely but not yet documented. There is also no reported data or studies to rule out the possibility of the airborne-particle route. One indication for this: Corona virus SARS-CoV-2 has been isolated from swabs taken from exhaust vents in rooms occupied by infected patients. This mechanism implies that keeping 1–2 m distance from infected persons might not be enough and increasing the ventilation is useful because of removal of more particles****.

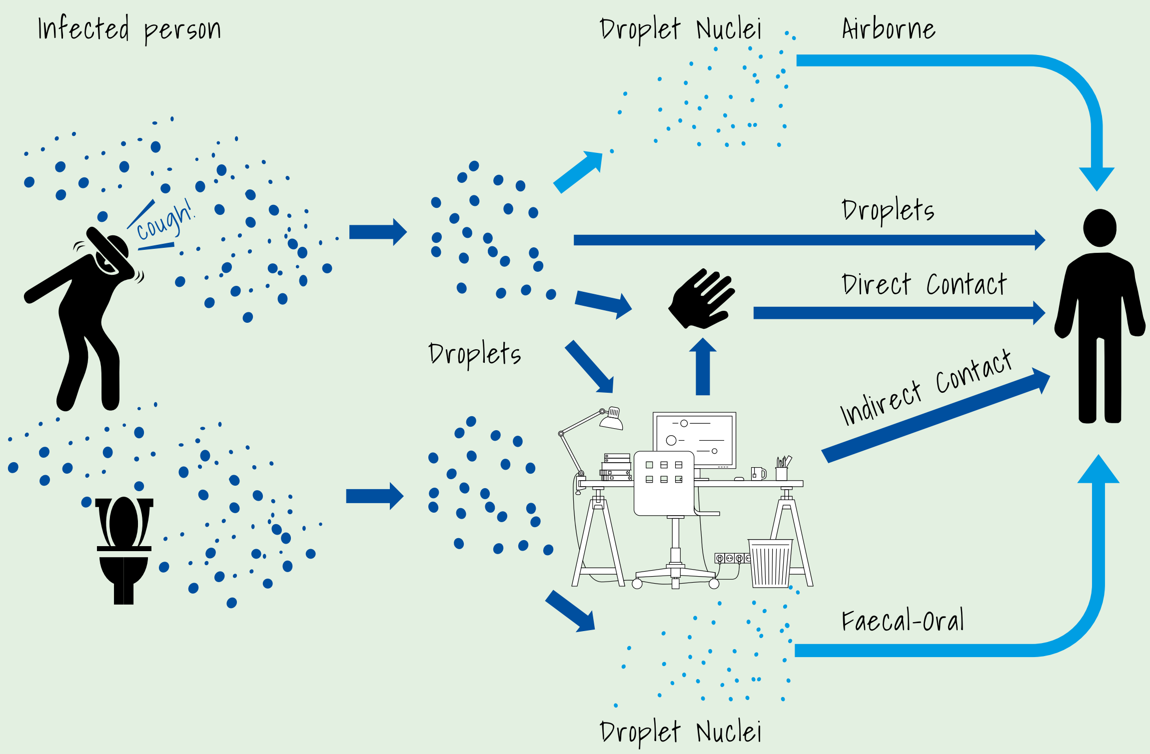


Figure 1. WHO reported exposure mechanisms of COVID-19 SARS-CoV-2 droplets (dark blue colour). Light blue colour: airborne mechanism that is known from SARS-CoV-1 and other flu, currently there is no reported evidence specifically for SARS-CoV-2. [Adapted from figure by Francesco Franchimon]

*** 1 nanometer = 0.001 micron

**** Personal respiratory protection measures such as respirators and solid visors are out of the scope of this document.

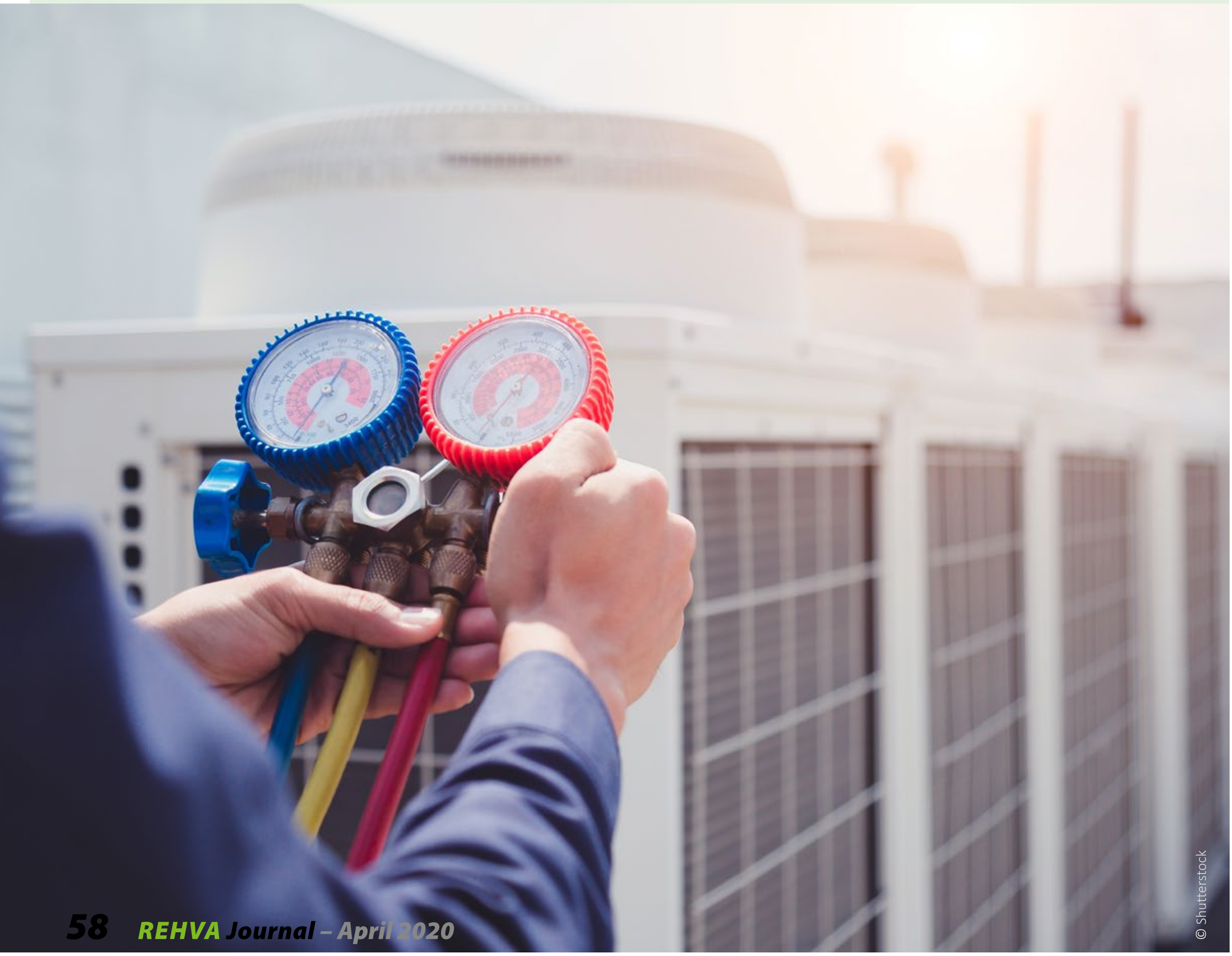
Version April 3, 2020. This document is an update to the March 17 version. Updates will follow as necessary. See for later updates: https://www.rehva.eu/activities/covid-19-guidance

With SARS-CoV-2 the airborne route – infection through exposure to droplet nuclei particles – has currently acknowledged by WHO for hospital procedures and indirectly through the guidance to increase ventilation[xv]. It may exist when certain conditions are met (i.e. opportunistic airborne) according to China national Health Commission (unpublished result). Airborne transmission can be possible according to Japanese authority under certain circumstances, such as when talking to many people at a short distance in an enclosed space, there is a risk of spreading the infection even without coughing or sneezing[xvi]. Latest study[xvii] concluded that aerosol transmission is plausible, as the virus can remain viable in aerosols for multiple hours. Another recent study[xviii] that analysed superspreading events showed that closed environments with minimal ventilation strongly contributed to a characteristically high number of secondary infections. The manuscript draft discussing airborne transmission concludes that evidence is emerging indicating that SARS-CoV-2 is also transmitted via airborne particles[xix].

Conclusion in relation to the airborne transmission route:
At this date we need all efforts to manage this pandemic from all fronts. Therefore REHVA proposes, especially in 'hot spot' areas to use the ALARA principle (As Low As Reasonably Achievable) and to take a set of measures that help to also control the airborne route in buildings (apart from standard hygiene measures as recommended by WHO, see the 'Getting workplaces ready for COVID-19' document).

Practical recommendations for building services operation

Increase air supply and exhaust ventilation
In buildings with mechanical ventilation systems extended operation times are recommended. Change the clock times of system timers to start ventilation at nominal speed at least 2 hours before the building usage time and switch to lower speed 2 hours after the building usage time. In demand- controlled ventilation



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systems change CO_2 setpoint to lower, 400 ppm value, in order to assure the operation at nominal speed. Keep the ventilation on 24/7, with lowered (but not switched off) ventilation rates when people are absent. 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. Considering a springtime with small heating and cooling needs, the recommendations above have limited energy penalties, while they help to remove virus particles out of the building and to remove released virus particles from surfaces.

The general advice is to supply as much outside air as reasonably possible. The key aspect is the amount of fresh air supplied per person. If, due to smart working utilization, the number of employees is reduced, do not concentrate the remaining employees in smaller areas but maintain or enlarge the social distancing (min physical distance 2–3 m between persons) among them in order to foster the ventilation cleaning effect.

Exhaust ventilation systems of toilets should always be kept on 24/7, and make sure that under-pressure is created, especially to avoid the faecal-oral transmission.

Use more window airing

General recommendation is to stay away from crowded and poorly ventilated spaces. In buildings without mechanical ventilation systems it is recommended to actively use operable windows (much more than normally, even when this causes some thermal discomfort). Window airing then is the only way to boost air exchange rates. One could open windows for 15 min or so when entering the room (especially when the room was occupied by others beforehand). Also, in buildings with mechanical ventilation, window airing can be used to further boost ventilation.

Open windows in toilets with passive stack or mechanical exhaust systems may cause a contaminated airflow from the toilet to other rooms, implying that ventilation begins to work in reverse direction. Open

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toilet windows then should be avoided. If there is no adequate exhaust ventilation from toilets and window airing in toilets cannot be avoided, it is important to keep windows open also in other spaces in order to achieve cross flows throughout the building.

Humidification and air-conditioning have no practical effect

Relative humidity (RH) and temperature contribute to virus transmission indoors affecting virus viability, droplet nuclei forming and susceptibility of occupants' mucous membranes. Transmission of some viruses in buildings can be limited by changing air temperatures and humidity levels. In the case of COVID-19 this is unfortunately not an option as coronaviruses are quite resistant to environmental changes and are susceptible only for a very high relative humidity above 80% and a temperature above 30°C [ix,x,xi], which are not attainable and acceptable in buildings for other reasons (e.g. thermal comfort and microbial growth). SARS-CoV-2 has been found highly stable for 14 days at 4°C 37°C for one day and 56°C for 30 minutes were needed to inactivate the virus[xx].

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

Small droplets under interest (0.5 – 10 micron) will evaporate fast under any relative humidity (RH) level[xxii]. Nasal systems and mucous membranes are more sensitive to infections at very low RH of 10–20%[xxiii,xxiv], and this is the reason for which some humidification in winter is sometimes suggested (to levels of 20–30%). This indirect need for humidification in winter in the

COVID-19 case is not relevant however given the incoming climatic conditions (from March onwards we expect indoor RH higher than 30% in all European climates without humidification).

Thus, in buildings equipped with centralized humidification, there is no need to change humidification systems' setpoints (usually 25 or 30%[xxv]). Considering the springtime that is about to start, these systems should not be in operation anyhow.

Heating and cooling systems can be operated normally as there are no direct implications on COVID-19 spread. Usually, any adjustment of setpoints for heating or cooling systems is not needed.

Safe use of heat recovery sections

Under certain conditions virus particles in extract air can re-enter the building. Heat recovery devices may carry over virus attached to particles from the exhaust air side to the supply air side via leaks.

Rotary air to air heat exchangers (i.e. rotors, called also enthalpy wheels) may be sensitive for considerable leaks 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 about the same as that of plate heat exchangers being in the range of 1–2%. For existing systems, the leakage should be below 5%, and has to be compensated with increase of 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 that higher pressure on the exhaust air side is created. This will cause leakage from 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%[xxvi], that is not acceptable.

It is 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), but the transfer is limited to gaseous pollutants such as tobacco smoke and other smells[xxvii]. Thus, there is no evidence that virus-bearing particles starting from 0.1 micron would be an object of carry over leakage. Because the leakage rate does not depend on the rotation speed of rotor, it is not needed to switch rotors off. Normal operation of rotors makes it easier to keep ventilation rates higher. It is known that the carry-over leakage is highest at low airflow, thus higher ventilation rates are recommended.

If leaks are suspected in the heat recovery sections, pressure adjustment or bypassing (some systems may be equipped with bypass) can be an option in order to avoid a situation where higher pressure on extract side will cause air leakages to supply side. Pressure differences can be corrected by dampers or by other reasonable arrangements. In conclusion, we recommend to inspect the heat recovery equipment including the pressure difference measurement. To be on the safe side, the maintenance personnel should follow standard safety procedures of dusty work, including wearing gloves and respiratory protection.

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

No use of recirculation

Virus particles in return ducts can also re-enter a building when centralized air handling units are equipped with recirculation sectors. It is recommended to avoid central recirculation during SARS-CoV-2 episodes: close the recirculation dampers (via the Building Management System or manually). In case this leads to problems with cooling or heating capacity, this has to be accepted because it is more important to prevent contamination and protect public health than to guarantee thermal comfort.

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 particles with viruses effectively since they have standard efficiencies (G4/M5 or ISO coarse/ePM_{10} filter class)[xxix] and not HEPA efficiencies.

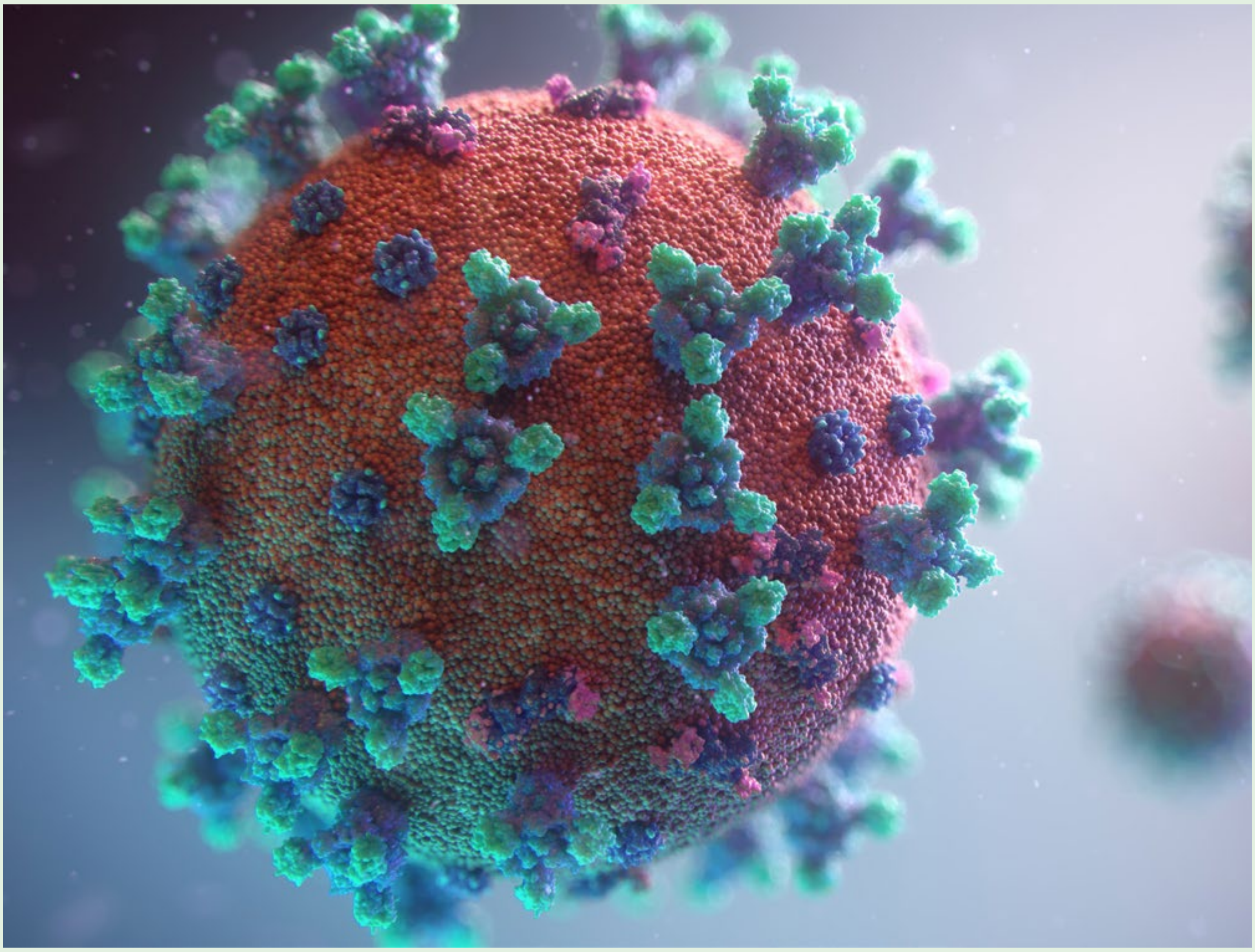

Photo by Fusion Medical Animation on Unsplash

Some systems (fan coil and induction units) work with local (room level) circulation. If possible (no significant cooling need) these units are recommended to be turned off to avoid resuspension of virus particles at room level (esp. when rooms are used normally by more than one occupant). Fan coil units have coarse filters which practically do not filter small particles but still might collect particles.

On the fan coil heat exchanger surface, it is possible to inactivate the virus by heating up fan coils to 60°C during one hour or 40°C during one day when the fan coil unit has a heating function.

If fan coils cannot be switched off, because of intensive use for heating or cooling purposes, it is recommended that their fans are operated continuously because the virus can sediment in filters and resuspension boost can follow when the fan is turned on. In continuous circulation operation virus particles will be removed with exhaust ventilation or by window airing in older buildings.

Duct cleaning has no practical effect

There have been overreactive statements recommending to clean ventilation ducts in order 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 above guidance about heat recovery and recirculation is followed. Viruses attached to small particles will not deposit easily in ventilation ducts and normally will be carried out by the air flow anyhow[xxx]. Therefore, no changes are needed to normal duct cleaning and maintenance procedures. Much more important is to increase fresh air supply, avoid recirculation of air according to the recommendations above.

Change of outdoor air filters is not necessary

In COVID-19 context, it has been asked should the filters to be replaced and what is the protection effect in very rare occasions 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***** or ISO $ePM_{2.5}$ or ePM_1) which filtrate well particulate matter from

***** An outdated filter classification of EN 779:2012 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. The size of a naked coronavirus particle of 80–160 nm[xxxi] ($PM_{0.1}$) is smaller than the capture area of F8 filters (capture efficiency 65–90% for PM_1), but many of such small particles will settle on fibres of the filter by diffusion mechanism. SARS-CoV-2 particles also aggregate with larger particles which are already within the capture area of filters. This implies that in rare cases of virus contaminated outdoor air, standard fine outdoor air filters provide a reasonable protection for a low concentration and occasionally spread viruses in outdoor air.

Heat recovery and recirculation sections are equipped with less effective extract air filters (G4/M5 or ISO coarse/ePM_{10} filter class) which aim is to protect equipment from dust. These filters do not have to filter out small particles as virus particles will be ventilated out by exhaust air (see also the recommendation not to use recirculation under 'no use of recirculation').

From the filter replacement perspective, normal maintenance procedures can be used. Clogged filters are not a contamination source in this context, but they reduce supply airflow which has a negative effect on indoor contaminations itself. Thus, filters must be replaced according to normal procedure when pressure or time limits are exceeded, or according to scheduled maintenance. In conclusion, we do not recommend changing existing outdoor air filters and replace them with other type of filters nor do we recommend changing them sooner than normal.

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

Room air cleaners can be useful in specific situations

Room air cleaners remove effectively particles from air which provides a similar effect compared to ventilation. To be effective, air cleaners need to have at least HEPA filter efficiency. Unfortunately, most of attractively priced room air cleaners are not effective enough. Devices that use electrostatic filtration principles (not the same as room ionizers!) often work quite well too. Because the airflow through air cleaners is limited, the floor area they can effectively serve is normally quite small, typically less than 10 m². If one decides to use an air cleaner (again: increasing regular ventilation often is much more efficient) it is recommended to locate the device close to the breathing zone. Special UV cleaning equipment to be installed for the supply air or room air treatment is also effective as killing bacteria and viruses but this is normally only a suitable solution for the equipment for health care facilities.

Toilet lid use instructions

If toilet seats are equipped with lids it is recommended to flush the toilets with closed lids in order to minimize the release of droplets and droplet residues from plumes in the air[xxxi,i]. It is important that water seals work all time[ii]. Therefore, organise that building occupants are instructed to use the lids.

Summary of practical measures for building services operation

1. Secure ventilation of spaces with outdoor air
2. Switch ventilation to nominal speed at least 2 hours before the building usage time and switch to lower speed 2 hours after the building usage time
3. At nights and weekends, do not switch ventilation off, but keep systems running at lower speed
4. Ensure regular airing with windows (even in mechanically ventilated buildings)
5. Keep toilet ventilation 24/7 in operation
6. Avoid open windows in toilets to assure the right direction of ventilation
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. Switch fan coils either off or operate so that fans are continuously on
11. Do not change heating, cooling and possible humidification setpoints
12. Do not plan duct cleaning for this period
13. Replace central outdoor air and extract air filters as usually, according to maintenance schedule
14. Regular filter replacement and maintenance works shall be performed with common protective measures including respiratory protection ■

Acknowledgements

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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.

Literature

This document is partly based on a literature survey. The scientific papers and other documents that were used can be found in this document: https://www.rehva.eu/activities/covid-19-guidance

References

i WHO, 2020b
ii Hung, 2003
iii WHO, 2020a
iv Zhang et al, 2020
v Guan W-J et al, 2020
vi Luongo et la, 2016
vii Li et al, 2007
viii Monto, 1974
ix Doremalen et al, 2013
x Ijaz et al, 1985
xi Casanova et al, 2010
xii Doremalen et al, 2020
xiii Li et al, 2005a
xiv Li et al, 2005b
xv WHO, COVID-19 technical guidance: Guidance for schools, workplaces & institutions
xvi Japanese Ministry of Health, Labour and Welfare
xvii Doremalen et al, 2020
xviii Nishiura et al, 2020
xix Allen and Marr, 2020
xx Chin et al, 2020
xxi Doremalen et al, 2020
xxii Morawska, 2006
xxiii Salah et al, 1988
xxiv Kudo et al, 2019
xxv ISO 17772-1:2017 and EN 16798-1:2019
xxvi Carlsson et al, 1995
xxvii Ruud, 1993
xxviii Han et al, 2005
xxix Fisk et al, 2002
xxx Sipolla MR, Nazaroff WW, 2003. Modelling particle loss in ventilation ducts. Atmospheric Environment. 37(39-40): 5597-5609.
xxxi Best et al, 2012

Sensor maintenance for optimal energy savings in HVAC

LARS STORMBOM
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Advanced control regimes such as Demand Controlled Ventilation (DCV) and free cooling are gaining popularity as the pressure to reduce energy consumption in HVAC is mounting. However, no amount of intelligence in the building automation system will help you if the sensor measuring the actual conditions have drifted. It is also not enough that accuracy requirements are met out of the box, the requirements should be maintained during the lifetime of the building.

Indoor air conditions are considered benign for sensors. On the other hand, sensors used in building automation are rarely calibrated or serviced once the system has been commissioned. Miss-wired or faulty sensors are common, so at least one comparison measurement should be done during the system commissioning. It is advisable to check the installed sensors after a couple of years against a reliable handheld instrument.

Some measurements demand extra care.

Outdoor humidity measurement

Economizers can save energy in some climates by using free cooling from outdoor air. In humid climates the most important factor is the amount of humidity in the outdoor air, not the temperature. At 30°C the enthalpy changes from 30 kJ/kg to 96 kJ/kg when the relative humidity changes from dry to 95%RH. According to ASHRAE standard 90.1, differential enthalpy control or fixed enthalpy control is recommended in economizers for hot and humid climates. The RH accuracy for control sensors should be < ±5%RH. While most sensors are specified to ±5%RH or better, this specification is out of the box. The ±5%RH should be maintained over lifetime of the system.

Outdoor humidity measurements are more demanding. The sensors are subjected to high humidity, high winds, solar heating and pollution. It makes sense to use one properly maintained, high-quality outdoor humidity sensor instead of multiple low-quality sensors.

Maintenance includes, in addition to periodic checking of the measurement, also regular cleaning of the radiation shield. Failure to do so may lead to temperature readings several °C higher and relative humidity values more than 10%RH lower than actual values.

The most important consideration is to use a sensor designed for outdoor use. Some sensors that look good on the data sheet can drift so much in outdoor conditions as to be unusable after a few months. In **Figure 1**, you can see the test results for three Vaisala HUMICAP® sensors used outdoors for more than 12 years at the Vaisala outdoor test site in Vantaa, Finland. Even with these impressive results, we still recommend periodic checking against a reliable handheld instrument at least every second year as conditions outdoors vary dramatically.

CO_2 sensors

CO_2 sensors are central in reducing energy consumption using DCV. As the measurement directly controls the amount of fresh air used accuracy measurement accuracy requirements are tightening. The Californian regulation CEC-400-2008-001-CMF requires a ±75ppm accuracy at 600 ppm and 1000 ppm including 5 years stability. ASHRAE standard 90.1 for green buildings requires a ±50 ppm accuracy at 1000 ppm. This kind of accuracy will not be achieved with simple instruments relying on 400 ppm background concentration compensation algorithms. The 1000 ppm control CO_2 concentration is too far from the supposed 400 ppm background CO_2 concentration as sensitivity drift is also likely to build up over time. Especially the ±50 ppm requirement can be achieved only with dual beam or single beam-dual wavelength instruments (like the Vaisala CARBOCAP®) that are regularly calibrated using calibration gases. A calibration interval of 2 years is probably enough depending on the instrument type.

For slightly lower requirements a five-year service or replacement regime may be enough as demonstrated in **Figure 2**, which shows the stability of 23 tested Vaisala CARBOCAP® GM10 measurement modules.

Where outdoor CO_2 sensors are used in order to control for a 600 ppm difference between indoor and outdoor CO_2 concentrations, this single sensor becomes one of the most important sensors in the whole building. Drift in this sensor will affect all the independent zones in the building. Outdoor sensors are subjected to high humidity and temperature variations that may cause drift in devices designed for indoor use.

In conclusion: Many HVAC instruments are used in order to save energy. To achieve projected energy savings, the measurements have to perform properly during their whole lifetime. If something is worth measuring, it is worth to measure right! ■

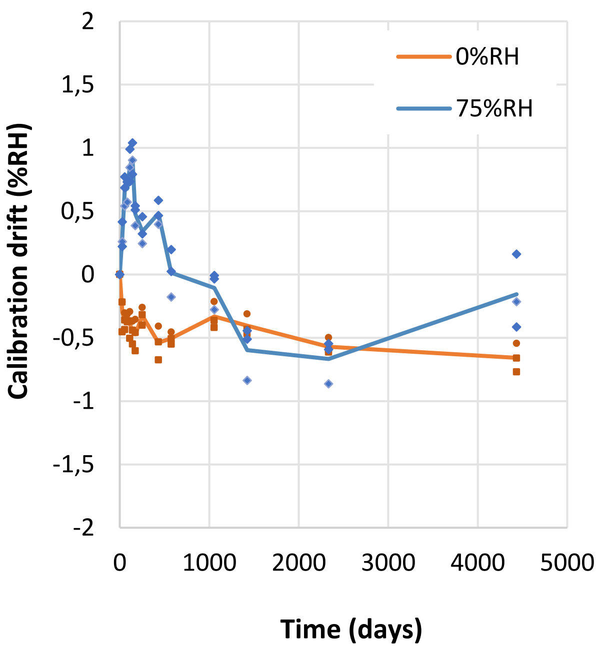


Figure 1. Vaisala HUMICAP® sensors' outdoor stability test data.

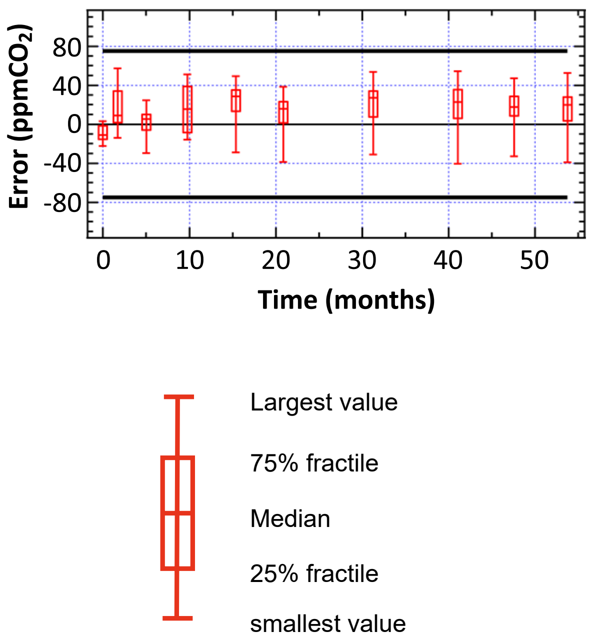


Figure 2. Indoors stability test results for 23 GM10 CO_2 modules at 1000 ppm. Black lines represent California standard CEC-400-2008-001-CMF requirements.

Room units from Belimo

Belimo Sensors – the foundation of comfort

Belimo is expanding their sensor range with a new product line of room units that will be launched over the next few years. This is the first time Belimo will be breaking into the visible area in buildings with such an extensive product range. The first products of the new line include active and passive sensors as well as passive room operating units.

The new Belimo room units are the perfect addition to the existing sensor range

The new Belimo room units react quickly and can be connected to existing third-party control systems. The construction and integrated technology offer the architect an aesthetic and timeless design, the installer a quick installation, the system integrator an easy commissioning and the end customer a comfortable room climate.

To facilitate installation, spring-loaded terminal blocks have been installed in the units, which ensure reliable electrical contact at all times.

The passive units are available with the most common temperature elements. Various analogue volt outputs or a MP-Bus interface are available for the active devices. These output signals enable versatile integration into the building management system.

The Belimo Assistant App enables simple commissioning of the active room sensors and their diagnosis with a smartphone via NFC. The sensors can be parameterised in power-off state.

The new room units were developed at the headquarters of Belimo Automation AG in Hinwil, Switzerland. They are maintenance-free and ensure optimal room comfort over the entire product life cycle. The entire range of room units is guaranteed for 5 years.

For more information, see www.belimo.eu ■

Active and passive room sensors

Passive room operating units

Belimo Assistant App

Send information of your event to Ms Giulia Marenghi gm@rehva.eu

Exhibitions, Conferences and Seminars in 2020 & 2021

Exhibitions 2020

1-4 Sep	SHK Essen	Essen, Germany	https://www.shkessen.de/branchentreff/
8-11 Sep	MCE - Mostra Convegno Expocomfort	Milan, Italy	https://www.mcexpocomfort.it/
27 Sep - 2 Oct	Light+Building 2020	Frankfurt, Germany	https://light-building.messefrankfurt.com/frankfurt/en.html

Conferences and seminars 2020

15-18 May	REHVA Annual Meeting	Online	https://www.rehva.eu/events/details/rehva-annual-meeting
1-3 June	14th TTMD Symposium	Istanbul, Turkey	http://www.ttmd.org.tr/en/activities/international-symposium-on-installation-in-construction
1 Sep	Danvak Dagen 2020	Copenhagen, Denmark	https://danvak.dk/produkt/danvakdagen2020/
6-9 Sep	NSB 2020 Building Physics Conference	Tallinn, Estonia	www.nsb2020.org/
14-15 Sep	CIBSE Symposium	Glasgow, UK	https://www.cibse.org/technical-symposium-2020
14-16 Sep	AIVC Conference	Athens, Greece	https://www.aivc.org/event/14-16-Sep-2020-conference-athens-41st-aivc-conference
21-24 Sep	13th IEA Heat Pump Conference	Jeju, Korea	http://hpc2020.org/
13-14 Oct	BuildSim Nordic 2020	Oslo, Norway	https://buildsimnordic2020.ibpsa-nordic.org/our-travels/
13-15 Oct	Chillventa 2020	Nurnberg, Germany	https://www.chillventa.de/en
29-31 Oct	Refcold	Delhi, India	https://www.refcoldindia.com/home
1-5 Nov	Indoor Air 2020	Seoul, Korea	www.indoorair2020.org
4-6 Nov	Brussels Summit	Brussels, Belgium	https://www.rehva.eu/events/details/rehva-brussels-summit-2020

Conferences and seminars 2021

10-12 Jan	Climamed	Lisbon, Portugal	http://www.climamed.org/en/
Jan/Feb	Roomvent 2020	Torino, Italy	http://roomvent2020.org/
17-21 Apr	Cold Climate	Tallin, Estonia	https://www.scanvac.eu/events.html
29 Sep –2 Oct	ISK Sodex 2021	Istanbul, Turkey	http://www.sodex.com.tr/

! **Due to the COVID19 circumstances, the dates of events might change.**

Please follow the event's official website.

The International Ventilation Congress AirVent

On February 12, 2020 the International Ventilation Congress AirVent ran successfully already in the third time within the Aquatherm Moscow exhibition. The event brought together designers and business professionals, engineers and architects on the one platform, which allowed to exchange technical information, new ideas and discuss the latest achievements in the field of engineering equipment of buildings of the future.

The Congress was supported by the largest professional associations and organisations: Federation of European Heating, Ventilation and Air Conditioning Associations (REHVA), Europe's Industry Association for Indoor Climate, Process Cooling, and Food Cold Chain Technologies (EUROVENT), Federation of German Heating Industry (BDH), Industry Association of German manufacturers of equipment for air conditioning and ventilation (FGK), China Heating , Ventilation and Air conditioning Association (CCHVAC), Moscow Architectural Institute (State Academy).

Congress relevance

Distinctive feature of the Congress is the investigation of global issues such as climate change, engineering technologies for solving environmental problems, energy shortages and sustainable development, jointly with practical solutions, increasing comfort and preserving people's health - indoor air quality, modern technologies for HVAC systems for residential and public buildings, energy efficiency of engineering systems.

The microclimate quality, discussed within the Congress, is one of the most important themes nowadays. According to the research of the Institute of Health IHME (Institute for Health Metrics and Evaluation), poor air quality is always among the main negative factors that increase mortality and disability all over the world. It was already proven that polluted air increases the risk of the development of cardiac and chronic respiratory diseases, asthma, lung infections and cancer. For instance, according to IHME data, in 2017 bad air quality was determined as the fifth by magnitude risk factor for mortality in the world and caused about 4.9 million deaths.

REHVA at AirVent

Frank Hovorka, President of REHVA gave the speech "*Improving the reliability of buildings' sustainability data and their integration in financial risk analysis and decision-making*". Real estate is crucial for the successful transition to a low-carbon economy as it represents 40% of global energy consumption and emits about the same amount of greenhouse gas emissions. Under various scenarios, energy demand from the sector is expected to double by 2050 and direct and indirect CO_2 emissions to increase in the range of 50–150% without additional mitigation efforts. In order to stay on the path below 2°C, buildings-related emissions need to decrease by nearly 80% from 2015 (Paris agreement) levels by 2050. This can only be achieved by consistently integrating the environmental externalities ("risks") into financial decision making.

Evidence on the positive links between buildings' sustainability (like energy performance and GHG emissions) and financial performance 2,3, is increasingly compelling and much work has gone into developing frameworks and tools for the industry, including on sustainability metrics, to support practitioners with the integration of ESG(environmental, social and governance) and climate related aspects into their financial decision making. Yet, as of today, energy/environmental data remain insufficiently considered in risk assessments and resulting investment decisions. A crucial reason for this is that existing data on sustainability performance is often not considered as a reliable and accurate enough proxy for the translation into financial performance. Increasing the reliability of information on the energy/environmental performance of buildings is a fundamental brick in the broader global effort to demonstrate and integrate the correlation between their environmental and financial performance into decision making. It is particularly important to ensure that risk departments are associated to this effort to include sustainability considerations in risk assessment, and therefore systematically encourage sustainability in real estate. Building industry needs to translate information and target all main financial industry groups (banks, investors and insurers) who deal with real assets and here in particular the ESG and risk management departments.

Frank Hovorka, President of REHVA.

While both regulatory and voluntary standards, labels and third-party verification already exist, they represent primarily compliance-based methods and procedures and give no indication about the reliability of the underlying information. The resulting uncertainty of the currently available data (voluntary disclosure and certification as well as mandatory labels) cannot create the chain of trust that is indispensable for investments, loans and securities to be directed to the sustainable and energy efficiency buildings sector and projects. By analysing and verifying how the sustainability data was produced (perimeter and method of calculation or measurement), the proposed process would allow to assess and disclose the level of quality and certainty of the data. Importantly, we need to provide a qualitative assessment on the extent to which the data captures the actual performance of the building. Improvements in technology (e.g. the development of numerical tools applied to buildings like BIM) have made physical data, tracking actual energy/environmental performance of buildings, increasingly accessible at a lower cost. Comparing calculated available data to the actual physical data would allow to better understand the reliability of calculated data from different sources. This data analytics process would enhance trust in the data and facilitate its integration in valuation, risk analysis and financing decision across the banking, investors and insurance industries. Ultimately it would allow to scale up financial flows towards sustainable properties. ■

REHVA and ISHRAE delegation meeting at ACREX 2020 in Delhi.

REHVA highlights from ACREX 2020

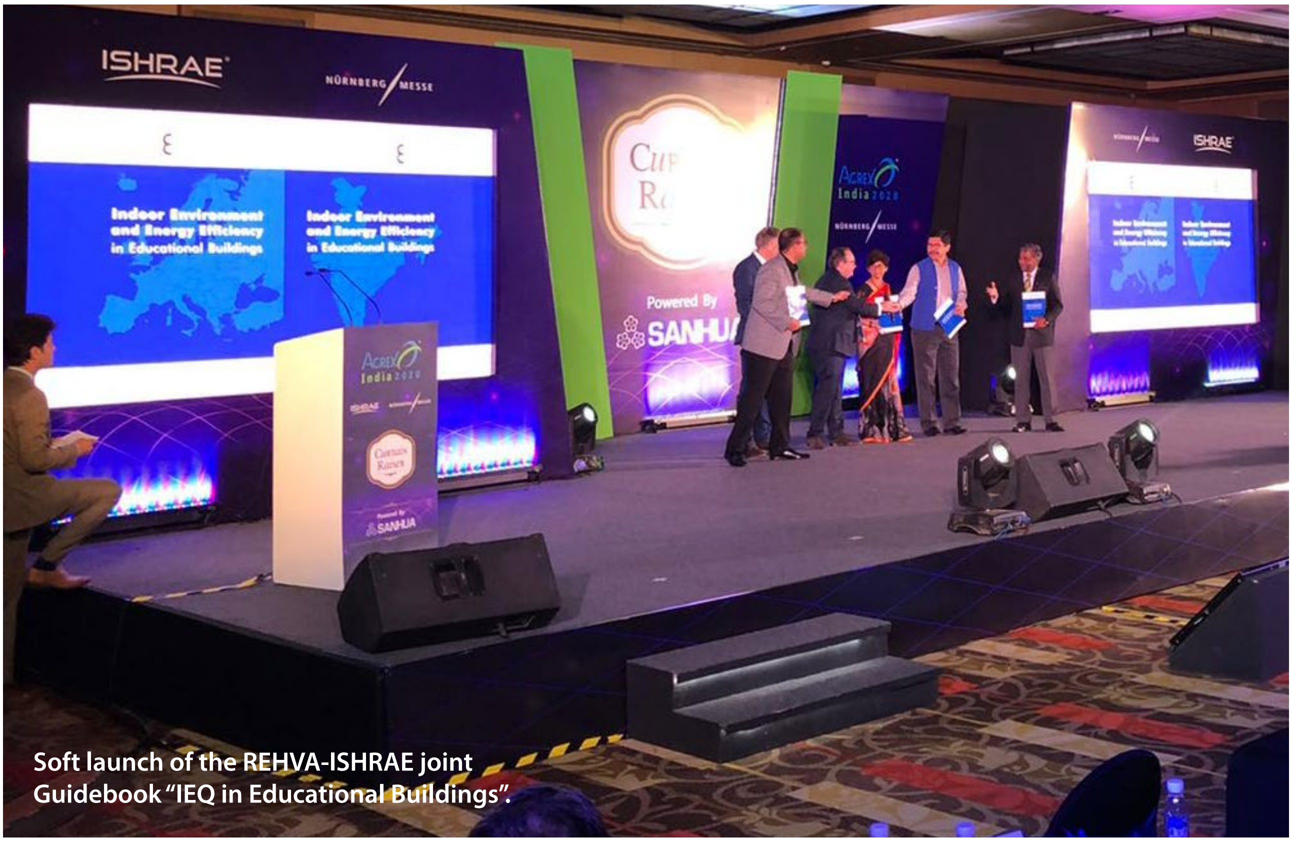
GIULIA MARENGHI
REHVA Project Communication Officer

ACREX is the largest South-Eastern Asia show in the HVAC and intelligent buildings sector. Organized by ISHRAE, Indian Society of Heating, Refrigerating and Air Conditioning Engineers, and Nurnberg Messe, the show took place in New Delhi from the **27th February till the 1st of March** and brought together exhibitors from more than 40 countries.

With an expected size of 5.9 billions USD by 2024, the HVAC market in India is expanding constantly. Many European, North American and Chinese manufacturers have attended the event, that has now scored its 21st edition.

ACREX was also the occasion to showcase and enhance the ongoing technical collaboration between REHVA and ISHRAE experts. On 28th February, the two associations co-organized the seminar "*Low Energy Cooling and Occupants Health*". REHVA representatives were also involved in several institutional meetings with ISHRAE, aiming to foster and to further strengthen the exchange of knowledge between Europe and India, by the set-up of new REHVA-ISHRAE initiatives and by the enhancement of the existing ones.

Many joint activities are previewed in the next months: from the organization of the HVAC World Student Competition, taking place on 30th October 2020 at Refcold Show in New Delhi, till the launch of a joint REHVA-ISHRAE Guidebook on Indoor Environmental Quality in Educational Buildings.



Soft launch of the REHVA-ISHRAE joint Guidebook "IEQ in Educational Buildings".

REHVA-ISHRAE Seminar "Low Energy Cooling and Occupants Health"

Efficient cooling technologies are essential to guarantee, at the same time, high performances in energy use and building occupants well-being. However, balancing the two aspects can represent a challenge.

Chaired by REHVA Treasurer Ms. **Nivedita Jadhav**, the ACREX 2020 REHVA-ISHRAE Seminar "*Low Energy Cooling & Occupants Health*" elaborated further on the topic, widening the focus on the issue: from positive links between buildings' sustainability and its financial performance, to efficient passive cooling technologies with low energy requirements, till the application of radiant cooling in Indian conditions and application of air purifiers and filtration technologies in residences. The seminar shed light on **different aspects of low energy cooling technologies**, including passive cooling, radiant cooling and filtration technologies for health and well-being, presenting both design principles and applicative examples from the design and operational perspective.

A rich panel of Indian and international experts from various professional and academic backgrounds have shared with the ACREX 2020 audience the latest findings on the topic.

***Frank Hovorka**, REHVA President, "Sustainability Data and Building Performance: Value Trigger"*

Frank Hovorka, REHVA President and Director of Technology and innovation of the French Federation of Real Estate Developers (FPI) has underlined the

link of buildings sustainability and their market value. Paris Agreement has highlighted since 2015 that buildings are part of the solution for what concerns CO_2 emissions cut and the fight against climate change. However, to trigger investments in sustainable buildings it is necessary to make it understandable and attractive for investors to aim for buildings sustainability. The true challenge is to move the talks on sustainability "from the boiler room to the board room". Hovorka presented some free access tools representing a valuable asset to assess the liaison between sustainability and financial performance. First of all, the logbook developed by REHVA fellow **Maja Virta,** allowing to estimate the building energy performance in the medium term (up to 50 years). Hovorka also introduced to the audience the ALDREN project – of which REHVA is part of – results, translating buildings energy rating into economic value.

***Jaap Hogeling**, REHVA External Relation Committee Chair, "Low energy cooling technology – Radiant & ventilation"*

Jaap Hogeling, who is also heading the EPB Center, presented different type of cooling technologies, including ventilative and radiant, with reference to their capacities and to ISO standards. Hogeling proposed different evaluative criteria to consider the most appropriate technology for specific environments. He mentioned two REHVA Guidebooks, the nr. 7 "*Low Temperature Heating and High Temperature Cooling*" and nr. 21 "*Active and Passive Beam Application Design Guide*", as point of reference for those willing to further explore the topic.

***Madhusudhan Rapole**, M.D., Oorja Energy Engineering, "Case study on radiant cooling – Indian application"*

Madhusudhan Rapole is founder of Oorja Energy Engineering Services, consulting focuses on Renewable and Energy Efficient Cooling & Heating solutions for industrial and commercial requirements, with hands-on expertise in renewables and energy efficiency based solutions for large industrial, commercial and military requirements. He presented the performances of different cooling installation across India: the vast territory of the country includes a variety of climates that imply different cooling solutions. From Vijayawada, through Hyerabad till Chennai, Rapole showcased successful examples on cooling technologies applications.

***Richie Mittal**, ISHRAE President Elect, "Low energy cooling technology: multi-stage evaporative cooling"*

Richie Mittal, ISHRAE National President Elect (2019-2020) and Managing Director of OVERDRIVE ENGINEERING PVT. LTD, has been working in the air conditioning industry for 34 years and he is guest Lecturer in Prominent Engineering Colleges including IIT, Delhi. Hi presentation focused on a specific cooling technology, the multi stage cooling system, that can lower the amount of energy needed while assuring occupants comfort. They're more efficient than single stage systems because they can use the lowest level of cooling needed or can use higher levels on very cold or hot days. The technology includes three stages of cooling process: indirect evaporative cooling, direct evaporative cooling and direct/indirect evaporative cooling.

***Bjarne Olesen**, Prof., DTU, "Filters and purifiers for good health in residential applications"*

Bjarne Olesen is full time professor in Indoor Environment & Energy at the Technical University of Denmark and Director of the International Center for Indoor Environment and Energy, Technical University of Denmark. His presentation focused on occupant's health, its sources, how to assure it and assess it. Prof. Olesen highlighted how indoor air quality represents a key factor not only for occupant's health but also for their comfort and productivity. Filtration and air cleaning are proven to be highly impact on health: the challenge is particularly important in regions where outside pollution bans the natural ventilation option. However, there are potential limits to air filtration for occupant's wellbeing, as "too filtered" air may damage IAQ.

***Yashkumar Shukla**, CEPT, University of Ahmedabad, "Project Lecavir: low energy cooling & ventilation in Indian residences"*

Yashkumar Shukla, who is Technical Director at Centre for Advanced Research in Building Science and Energy (CARBSE), CEPT University, presented the results of Lecavir project. The project inquires the exponential increase of energy use for cooling in India. The main output of this project is a design guidebook aiming to provide design directions to architects and professionals on how to apply mixed ventilation techniques (mechanical and natural). This method, especially in residential ventilation, can trigger significative energy savings. ■

Ventilation 2021: 13th International Industrial Ventilation Conference for Contaminant Control

August 15-18, 2021 Toronto, Canada

Ventilation 2021 Conference takes place Aug. 15-18, 2021 at the Sheraton City Centre in downtown Toronto. Inaugurated in 1985, the "Industrial Ventilation Conference" takes place every three years allowing time to develop new research and technology applications and to document the findings. The conference has rotated locations and organizers between Europe, North America and Southeast Asia. The 2021 conference will be hosted by ASHRAE.

The proposed conference theme is "leading edge industrial ventilation technologies for a low-carbon environment." The program will include and call for papers and separate call for presentations. More information to come regarding the Call for Papers and other important deadlines.

The goal of the conference is for international engineers, practitioners, researchers, scientists, and regulatory personnel working in the specialized industrial ventilation field to share recent advancements from a global perspective in the field of ventilation and contaminant control.

ashrae.org/ventilation2021

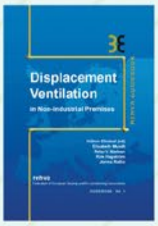
Key issues to be covered:

- Occupational health, environmental emissions and safety considerations in industrial process ventilation system design and applications
- Innovations in ventilation system (Equipment, Innovative sensors measurements, energy efficiency, productivity, sustainability, etc.)
- Thermal Hydraulic Modelling, measurement and test & balancing techniques, AI applications, optimization models, data mining, etc.
- Industrial HVAC Systems- Innovation & Best Practices (Equipment, Controls, Risk Management, Energy Efficiency, Productivity, Sustainability, etc.)
- Best practices and risk evaluations and management in industrial ventilation and air conditioning systems application (advanced manufacturing, health care/operating theatres, professional kitchens, clean spaces/nanotechnology, tunnel and mine ventilation, power plants etc.)
- Modelling Advances (New techniques, automation, scripting, etc.)
- Best practices in data centre and ventilation and air conditioning system design and applications.
- Filtration Systems for Contaminant Control
- Lesson learned in industrial ventilation and air conditioning systems design and applications.

REHVA

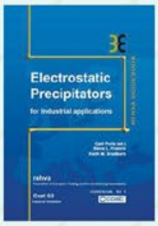
Federation of European Heating, Ventilation and Air Conditioning Associations

EUROPEAN GUIDEBOOKS



No.01: DISPLACEMENT VENTILATION IN NON-INDUSTRIAL PREMISES

No.02: VENTILATION EFFECTIVENESS



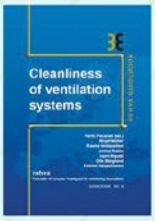
No.03: ELECTROSTATIC PRECIPITATORS FOR INDUSTRIAL APPLICATIONS

No.04: VENTILATION AND SMOKING

No.05: CHILLED BEAM APPLICATION GUIDEBOOK

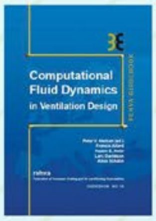
No.06: INDOOR CLIMATE AND PRODUCTIVITY IN OFFICES

No.07: LOW TEMPERATURE HEATING AND HIGH TEMPERATURE COOLING

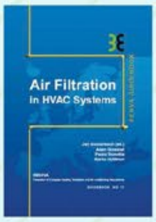


No.08: CLEANLINESS OF VENTILATION SYSTEM

No.09: HYGIENE REQUIREMENTS FOR VENTILATION AND AIR-CONDITIONING SYSTEMS



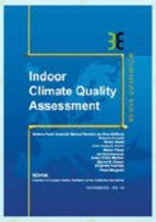
No.10: COMPUTATIONAL FLUID DYNAMICS IN VENTILATION DESIGN



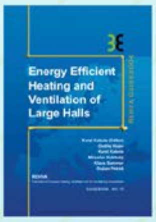
No.11: AIR FILTRATION IN HVAC SYSTEMS

No.12: SOLAR SHADING

No.13: INDOOR ENVIRONMENT AND ENERGY EFFICIENCY IN SCHOOLS - PART 1

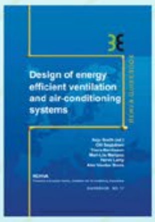


No.14: INDOOR CLIMATE QUALITY ASSESSMENT

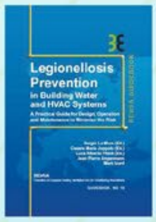


No.15: ENERGY EFFICIENT HEATING AND VENTILATION OF LARGE HALLS

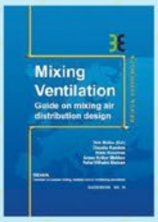
No.16: HVAC IN SUSTAINABLE OFFICE BUILDINGS



No.17: DESIGN OF ENERGY EFFICIENT VENTILATION AND AIR-CONDITIONING SYSTEMS



No.18: LEGIONELLOSIS PREVENTION IN BUILDING WATER AND HVAC SYSTEMS



No.19: MIXING VENTILATION

No.20: ADVANCED SYSTEM DESIGN AND OPERATION OF GEOTABS BUILDINGS

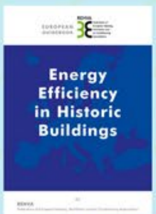
No.21: ACTIVE AND PASSIVE BEAM APPLICATION DESIGN GUIDE

No.22: INTRODUCTION TO BUILDING AUTOMATION, CONTROLS AND TECHNICAL BUILDING MANAGEMENT

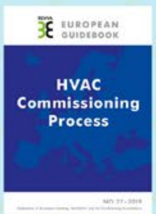
No.23: DISPLACEMENT VENTILATION

No.24: FIRE SAFETY IN BUILDINGS

No.25: RESIDENTIAL HEAT RECOVERY VENTILATION



No.26: ENERGY EFFICIENCY IN HISTORIC BUILDINGS



No.27: HVAC COMMISSIONING PROCESS (REHVA-ISHRAE)

No.28: NZEB DESIGN STRATEGIES FOR RESIDENTIAL BUILDINGS IN MEDITERRANEAN REGIONS

No.29: QUALITY MANAGEMENT FOR BUILDINGS