Effectiveness of personalized ventilation in reducing airborne infection risk for long-term care facilities

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ABSTRACT

Throughout history, the human population has experienced major outbreaks of infectious diseases. In December 2019 the previously unknown SARS-CoV-2 virus emerged, which had a huge impact globally. Residents of long-term care facilities (LTCFs) showed to be highly susceptible to infection due to their frailty. Respiratory infectious diseases, such as COVID-19, can spread among others via the airborne transmission route. This is caused by sharing the same indoor environment. To reduce the risk of infection via the airborne route, it is important to consider ventilation and other building services system measures, including personalized ventilation (PV). PV has the potential of being a suitable solution for LTCFs, as it could still allow interaction between residents and visitors in the common rooms. Something which is regarded very important from a mental health perspective. To identify the potential of PV in the context of infection risk, a laboratory experiment was conducted to investigate its effectiveness on the infection risk reduction.
The research was performed in a controlled climate chamber. In the experiment a person was mimicked and positioned close to a PV system that provided filtered recirculated air. A particle source maintained a constant particle concentration in the room. The performance of the PV system was measured through the particle concentration near the breathing zone as compared to the room concentration. Several design parameters were investigated. Translating the outcomes to a fictive (equivalent) ventilation rate, the Wells-Riley equation was applied to determine the infection risk. The outcomes indicated that, in this laboratory setting, the PV system can reduce the risk of an infection up to 50%. The performance is affected by the distance of the supply head to the breathing zone, the angle of the supply head, airflows in the room and the location of the particle source.
To further optimize the system and allow its application in LTCFs, several aspects still need further attention, such as mobility/placing the person, the breathing pattern of the user and factors influencing the comfort and use.

KEYWORDS

Ventilation, Infection prevention, Experimental study, Wells-Riley

1 INTRODUCTION

The COVID-19 pandemic showed to have a large impact on the residents of Long-Term Care Facilities (LTCFs). LTCFs can be described as nonacute residential and nursing facilities that are the home of people that need some form of long-term care. All over the world massive outbreaks with high case fatality rates were reported in LTCFs. This did not only affect the residents, but also the care workers and visitors (Comas-Herrera, et al., 2020) (Thompson, et al., 2020). The European Centre for Disease Prevention and Control (ECDC, 2020) presented data that shows that a majority of the clusters and outbreaks were in health- and social care setting, especially in LTCFs. In the Netherlands, LTCFs were indicated as a setting where most COVID-19 infections occurred (RIVM, 2020). The high fatality rates in LTCFs are related to the, generally, frail health situation of its residents (van der Wal, 2006) and the delayed implementation of protection of care professionals and residents. Age-related decline in immunity may affect the response to immunizations and increase their susceptibility (Siegel, Rhinehart, Jackson, & Chiarello, 2007). As a result, infections can have severe consequences for residents of LTCFs including debilitation, hospital admission and death (Koch, Eriksen, Elstrøm, Aavitsland, & Harthug, 2009).

Within LTCFs, residents live close together and can interact freely with each other. This can contribute to the spread of infectious diseases. It is hard to apply restrictions to these interactions, because of the psychosocial risks associated (Siegel, Rhinehart, Jackson, & Chiarello, 2007). Nevertheless, during the COVID-19 pandemic at several points in time contacts between residents and with visitors from outside, including family members, were prohibited. This affected the (mental) health of the residents of LTCFs and increased loneliness, which has always been a major issue. Loneliness can increase the risk of depression, alcoholism, suicidal thoughts, aggressive behaviours, anxiety and impulsivity (Simard & Volicer, 2020). Another issue to take into account is the group of older adults who suffer from dementia. They have an altered sensitivity to indoor environmental conditions and therefore careful attention to the indoor environment in LTCFs is desirable, because the physical environment can directly influence their health and wellbeing (Kort, 2012).

The spread of infectious agents can occur in various ways including physical contact, contaminated food, body fluids, objects, airborne inhalation or through vector organisms (Kumar, Damodar, Ravikanth, & Vijayakumar, 2012). This research focuses on the airborne transmission via aerosols. Airborne transmission can be described as: “the transmission of diseases caused by dissemination of droplet nuclei that remain infectious when suspended in air over long distance and time” (Atkinson, et al., 2009). A distinction can be made in long-range, as defined by Atkinson et al. (2009), and short-range exposure. The latter refers to the exposure to aerosols at a distance <1.5 m from an infected person (Liu et al. 2017).

For the spread of infections of diseases in general, the design of proper ventilation systems can play an important role. Paying more attention to ventilation requirements could lead to significant infection control benefits (Atkinson, et al., 2009). Research demonstrated that engineering controls, including sufficient and effective ventilation, targeting airborne transmission should be considered in the overall strategy to limit infection risks indoor (Morawska, et al., 2020). These measures address the long-range transmission.

This research focuses on a ventilation related improvement for application in LTCFs to reduce the airborne transmission of infectious agents. The reduction of the long-range transmission is the main focus of this research, but, similar to Xu et al. (2020), the effectivity on the reduction of short-range transmission is investigated as well. The objective of the work therefore is to determine the potential of a personalized ventilation (PV) solution. The potential is defined as the reduction in infection risk, as that is assumed to be the aim of ventilation, not the amount of clean air provided by the system. The potential is investigated for different situations. The goal is to arrive at a ventilation solution, in terms of sufficient reduction of the risk of infection, that would enable the contact between residents of an LTCF and their guests, also in times of potential exposure to infectious diseases. This would improve their quality of life.

2 METHOD

In this work the effectiveness of a simplified concept of a personalized ventilation (PV) system, shown in Figure 1, is investigated. The air is supplied by the PV system at a certain angle. The air supplied is recirculated from the room and filtered with a HEPA-filter in the supply duct at 0.1 m from the supply opening. The amount of PM2.5 at the supply, as compared to the concentration in the room, is on average 0.6% (supply and room concentration were measured with two Portable Aerosol Spectrometers MODEL 11-D GRIMM). The supply has an area of 48.5 cm^2 and the supply flow rate was determined at 65 m^3/h.

The measurements were performed in a controlled climate chamber (Schellen et al. 2010). The ventilation flow rate of the chamber was set to 180-190 m^3/h, which resulted in 3.7 air changes per hour (ACH). The human body was simplified to a heated carbon box as shown in Figure 1. The dimensions of the box are 0.41 × 0.41 m and 0.60 m high, and a heat source in the box produced 100 W. No effort was made to arrive at a closer resemblance of the human body, as we first were interested whether the concept would work at all. The breathing zone was assumed at 1.1 m height directly in front of the box. Exposure measurements were performed at 0.09 m and 0.27 m from the 'mouth'. Besides the carbon box, the picture in Figure 1 zooms in on the desk and the PV-system on the left. The supply of the PV-system was positioned targeting at the breathing zone of the heated box.

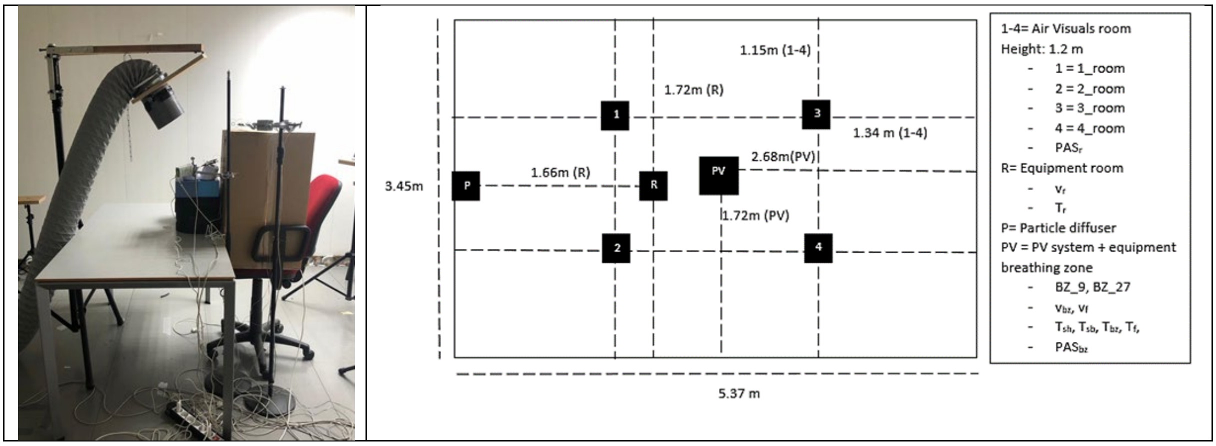

Figure 1. Simplified PV system concept (left), location measurement devices (right; PAS refers to GRIMM PM sensors, 'r' is Room and 'bz' is breathing zone, 'BZ_x' refers to the low cost sensors positioned in the breathing zone.

Table 1. Equipment information as applied in the experiments.

	Coding	Type sensor	Range	Accuracy
Particle concentration	1_room, 2_room, 3_room, 4_room, BZ_9, BZ_27, particlediff	IQAir AirVisual (PM2.5) [low cost sensor]	0 to 1798 $\mu g/m^3$	±10%
	PAS_{BZ}, PAS_R	Portable Aerosol Spectrometer MODEL 11-D GRIMM [research grade instrument]	0 $\mu g/m^3$ to 100 mg/m^3	<3% (ISO 21501-4)
Air velocity	v_r, v_{bz}, v_f	SensoAnemo 5150NSF	0.05 to 5 m/s	0.02 m/s ± 1.5% of reading
Temperature	T_{sh}, T_{sb}, T_{bz} T_r, T_f	Interchangeable NTC thermistor 2154	-55 to 80 °C	±0.05 °C

Two research grade instruments (GRIMM) and seven low cost PM sensors (Air Visual) were used to measure the PM concentrations in the room and in the breathing zone. Figure 1 provides information on the location of the sensors in the room. This also includes information on the position of the particle generator and equipment to measure temperature and velocity. Details on the equipment applied (and coding for Figure 1) are summarized in Table 1. The research grade instruments were calibrated. The low cost sensors were compared with the research grade instruments.

A particle diffuser (U7145 -Ultrasonic Humidifier U7147 BONECO) was used to mimic the droplet generation of an infected person. To make the diffused particles comparable to saliva, they were generated from a mixture of water and oil (1:40, oil:water). The particle diffuser was located in the middle of the wall where the inlet grill of the room ventilation is located (see Figure 1). The diffuser diffused particles with a velocity between 1.7 to 2.2 m/s. A fan was located near the particle diffuser to spread the particles more equally over the climate chamber. The size of the particles diffused was between 1 and 10 μm, with a peak at 5 μm.

The particle concentrations measured at the different locations in the room were averaged to identify the room concentration. As complete mixing was not fully obtained a reference situation was used to compare the performance of the PV-system. The reference situation assumed a case where the PV-system was not active. For this situation the PM-concentration in the breathing zone was compared to the PM-concentration in the room (at 0.09m from 'mouth': 0.98 (SD 0.03); at 0.27m from 'mouth': 1.24 (SD 0.09). These ratios from the reference case were used to assess the results when the PV-system was functioning ($ratio_{ref}$).

Infection risk was calculated applying the Wells-Riley equation (Noakes and Sleigh, 2009). For that, the breathing rate was assumed at 0.5 m^3/h. Three scenarios were defined to assess the infection risk: (1) 52.5 quanta/h, one infector talking slowly 75% of the time for one hour and the receiver is in a rest position; (2) 52.5 quanta/h, one infector talking slowly 75% of the time for three hours and the receiver is in a rest position; (3) 337.5 quanta/h, one infector in the room and sings 75% of the time for one hour and the receiver is in a rest position (Buonanno, Stabile, & Morawska, 2020). The scenarios were defined with the exposure in a LTCF in mind.

The fictive (equivalent) ventilation rate (Q_{case}) in the breathing zone was determined from the measured ratio of the PM concentration at the breathing zone versus the average concentration in the room for the case: $Q_{case}=(ratio_{ref} \times Q_{ref})/ratio_{case}$; $ratio_{case}$ is determined per situation by dividing the average particle concentration in the breathing zone by the average particle concentration in the room. In all cases the ACH in the climate chamber was kept the same. Q_{case} then was used to calculate the potential infection risk.

Four cases with the PV system were investigated (in bold the reference situation is indicated):

- *Distance of PV-system to 'mouth'* (0.38, **0.48**, 0.58m; height to table [0.9m]: 0.57, **0.67**, 0.77m; horizontal distance to 'mouth': 0.32, **0.39**, 0.41m).
- *Angle of the supply head* (**30°**, 40°, 50° from vertical)
- *Dynamic situation with a table fan* positioned in three different positions (Figure 2 [left]) and two fan settings (low [1]: 2.8-3.2 m/s; high [2]: 3.5-4.0 m/s). The following combinations were investigated: position 1 setting 2, position 2 setting 1, position 2 setting 2 and position 3 setting 1. The reference situation for the PV-system was applied.
- *Short range exposure* to assess the PV performance in case particles are produced close to the person. Two cases were investigated (see Figure 2 [right]). The ratio was

determined based on the PV-system being active and not active. The reference situation for the PV-system was applied. The ratio is determined by dividing the average particle concentration with PV system by the average particle concentration without the PV system.

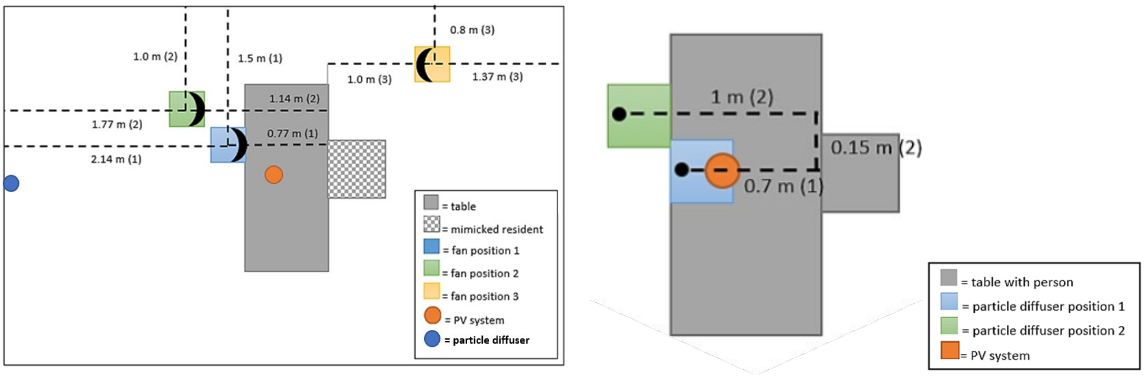

Figure 2. Position of *fan* for dynamic situation (left). Position of *particle diffuser* for short-range route (right).

All measurements were performed twice. Statistical analysis was performed using IBM SPSS Statistics. A paired sample T-test was conducted to assess whether a significant difference existed between the two measurements per case. A one sample T-test was conducted for the ratio determined per case, compared to the reference case. In all cases the p-value was assumed at <0.05, with a confidence interval of 95%.

Besides the PM-concentration also comfort was assessed, specifically draught (according to ISO 7730). However, in this paper these outcomes will not be discussed.

3 RESULTS

In Figure 3 two pictures of smoke visualizations are presented to show the performance of the PV-system. The visualizations show that the smoke is induced in the clean air flow as supplied via the PV-system. Therefore, the breathing zone receives a mixture of clean and room air.

Figure 3 Visualization of the air stream caused by the PV system. Left: smoke supplied from the front, Right: smoke supplied from the back. Orange cross: breathing zone.

Table 2 provides a summary of all results obtained from the different cases described. It provides information on the ratios of the particle concentration as determined and the infection risk for the different scenarios as could be calculated from that information.

Table 2. Overview of measurement results.

Measurement			Ratio	SD (ratio)	Infection risk		
		Distance from breathing zone [cm]			Scenario 1	Scenario 2	Scenario 3
			[-]	[-]	[%]	[%]	[%]
Reference		9	1	0.03	13.2	34.7	59.8
		27	1	0.09	13.2	34.7	59.8
Distance	Dist_0.38	9	0.38*#	0.02	5.2	14.9	29.3
		27	0.50*#	0.03	6.8	19.2	36.6
	Dist_0.48	9	0.54*#	0.03	7.6	20.5	38.9
		27	0.64*#	0.04	8.7	23.8	44.2
	Dist_0.58	9	0.68*#	0.04	9.2	25.1	46.2
		27	0.87*	0.07	11.6	30.9	54.8
Angle	Angle_30	9	0.54*#	0.02	7.6	21.2	40.0
		27	0.64*#	0.04	8.7	23.8	44.2
	Angle_40	9	0.57*#	0.03	7.8	21.5	40.5
		27	0.83*	0.06	11.1	29.8	53.1
	Angle_50	9	0.89*#	0.05	11.9	31.5	55.6
		27	0.79*#	0.08	10.6	28.6	51.4
Dynamic	Dynamic_p1-s2	9	0.93*#	0.03	12.4	32.7	57.2
		27	0.81*#	0.04	10.9	29.2	52.2
	Dynamic_p2-s2	9	0.71*#	0.10	9.6	26.1	47.7
		27	0.72*	0.04	9.7	26.4	48.1
	Dynamic_p2-s1	9	0.66*#	0.12	8.9	24.5	45.2
		27	0.72*#	0.03	9.7	26.4	48.1
	Dynamic_p3-s1	9	0.71*#	0.08	9.6	26.1	47.7
		27	0.75*#	0.03	10.1	27.3	49.5
Short range	Short_0.7	9	1.20#	0.32	15.7	40.0	66.5
		27	4.73#	0.58	48.9	86.6	98.7
	Short_1	9	0.35#	0.04	4.8	13.8	27.3
		27	0.35#	0.04	4.8	13.8	27.3

*significant difference between the ratio and the reference situation
significant difference between the two measurements of the same situation

The effect of induction of air, as shown in Figure 3, increases when the PV-system is located further away from the breathing zone. This results in an increased risk of infection as compared to a case with the PV-system closer to the breathing zone. The ratio and the risk of an infection decreases when the angle of the supply head decreases, which indicates that a more horizontal angle of the supply head leads to better performance of the PV system.

The ratios of the dynamic situation are significantly closer to the room situation as compared to the ratios of Dist_0.48, which is the case with the same setting of the PV system. The disturbing air flow has a negative effect on the performance of the PV system.

Considering the influence of the location of the particle source, it was observed that the first location of the particle diffuser (0.7 m from the mimicked resident) in the short-range exposure situation leads to high ratios. The second location of the particle diffuser (1 m from the mimicked resident) shows better performances of the PV system, even better than for the situation where aerosols are generated in the room further away.

4 DISCUSSION

In this research the infection risk was calculated, based on the measured particle concentration, with and without a PV system as an indication for the equivalent ventilation. Without a PV-system, the maximum infection risk (Scenario 3, with 337.5 quanta/h, one infector in the room and sings 75% of the time for one hour and the receiver is in a rest position) was determined at 60%. With the PV system, the maximum risk could be reduced up to a factor two (29%). However, for many of the investigated situations the reduction in the maximum risk, when the PV-system was applied, was in the order of 20%, compared to the maximum risk for the reference case. These results show that the PV-system applied, is able to improve the exposure conditions, but that it is not able to bring it down by, e.g. an order of magnitude. The induction of the air, as visualized in Figure 3, is regarded the main cause for that. This is also reflected in the increased risk as function of the distance of the supply opening to the breathing zone (case *Distance*). The angle (case *Angle*) has less influence on the risk as in all cases the distance to the breathing zone was kept the same. The interaction of the thermal plume from the heated box with the flow could explain the differences found.

The study of Xu, et al (2020) investigated the role of a PV system in protecting against airborne disease transmission in close proximity (<1 m). In the study of Xu, et al. (2020) the infection risk without PV system was measured at 85% and with the PV system between 28% and 85%. The effect of the PV-system as determined in this study aligns with the order of magnitude improvement as found by Xu, et al (2020). It should, however, be noted that in the study of Xu, et al (2020) aerosols were generated at 0.86m from the receiver. A comparison with the Short-range case therefore is also possible. For that case exposure was measured when locating the particle diffuser close to the mimicked resident. Two locations were tested, 0.7m and 1m. The smaller distance resulted in a ratio higher than 1. This would indicate that the particle concentration in the breathing zone is higher than the amount mixed in the room. The assumption is that this is caused by the fact that the contaminant airflow from the particle diffuser intersected with the clean airflow of the PV system before it reached the breathing zone. The particles are supplied with a velocity between 1.7 to 2.2 m/s, while the average supply velocity from the PV-system is in the order of 1 m/s. As a result, the clean air is already contaminated. This effect is not expected to occur in such extent in a real setting as the source, a human breathing, will not be that constant in direction. For the second location of the particle diffuser (at 1 m from the breathing zone) the above did not occur, and again aligned to the order of magnitude as found by Xu et al. (2020).

The disturbance of the flow field (case *Dynamic*) reduces the effectiveness of the PV-system. However, still an improvement in the order of 20% was achieved if the disturbance assumes more realistic conditions (a bit further from the breathing zone, lower velocities). It is important that the supply flow from the PV-system is not disturbed by the airflow surrounding the PV-system.

The research presented was a pilot study and had some limitations. The setup as applied showed not to result in a complete mixing of the particles in the room, including the breathing zone, when the PV system was turned off. Significant differences were observed between the particle concentration at different locations. We therefore measured the concentration at several positions in the room to determine the average room concentration. Due to the limited number of sensors, we assumed the positions applied were representative, also for the cases where the

PV-system was turned on. Based on the outcomes we excluded one low-cost sensor from the analysis (nr.2) as the concentration measured showed to be affected by its close position to the particle diffuser. The measured deviations for the other locations differed between 0% to 30% from the average.

Every measurement was done twice to analyse the repeatability of the experiment. The mean ratios of these two different measurements were compared to each other, which revealed a maximum difference of 6%.

The visualization using smoke (Figure 3) shows that the PV system is able to create a straight air flow. This means that the position of the person with respect to the PV system is an important parameter to take into account when developing a PV system. To increase the robustness of the system it would be interesting to investigate the performance in a wider area that would better represent the location where air will be breathed from.

The performance of the PV-system is a function of several parameters, as shown. In the design these parameters should be taken into account. If the induction of room air into the air supplied by the PV-system can be minimized, that would be beneficial. However, though a significant reduction in the infection risk is possible when a PV-system is applied, other design aspects come into play as well when application in LTCFs is foreseen. Apart from the mobility issue discussed above, comfort is another point of attention. Though not discussed in the results, draught was investigated in the research as well. For the design applied, only in case of a short distance of the PV-system to the breathing zone (*Distance* Dist_0.38), draught could be considered an issue of concern (did not meet the class B criteria of ISO 7730, draught rate >20%). However, at higher flow rates and/or different design solutions, draught may become more problematic. Other design issues would refer to acoustics, light, safety, aesthetics etc.

The PV system as investigated can be regarded an air cleaning device. As it filters out aerosols, the system will reduce the concentration of aerosols in the room. As a result, a Clean Air Delivery Rate may be determined. Though the CADR may not be representative for its effectiveness as the main advantage of the system is that it takes advantage of its location in the room and departs from a mixed assumption for the ventilation and focuses on a higher ventilation effectiveness.

5 CONCLUSIONS

A Personalized Ventilation (PV) system was investigated within the context of reducing the risk of infection. Application of such a system in a Long-Term Care Facility (LTCF) was the point-of-departure for the research. The study reveals that the investigated PV system (concept) is able to reduce the risk up to a factor two. However, the performance is influenced by several design and use parameters. Nevertheless, PV-systems appear to provide an additional means to reduce the infection risk. Moreover, in general, frail older people in LCTF's stay located for several hours at one position. Therefore, PV systems will contribute to having interactions with visitors / family. As a result, they may be part of a solution to allow the continuation of the necessary social contacts in LTCFs to take place, also in times of an (airborne) infectious disease being present.

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