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Innovative Ventilation System for Public Spaces: Economic Study, IAQ Performance and Airborne Infection Risk Evaluation in various settings

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ABSTRACT

During the COVID-19 pandemic, public spaces have been identified as major sites for airborne transmission, especially in densely occupied and poorly ventilated spaces. In Belgium, many public spaces are still insufficiently ventilated and need to be equipped with a ventilation system. However, economic factors and technical constraints hinder the implementation of ventilation systems in practice. There is thus a need for practical and cost-efficient solutions that are easier to integrate in existing buildings and retrofit projects.

The aim of this study was to identify innovative ventilation systems and strategies that address economic and technical constraints, while taking into account the specific needs of public spaces and health aspects.

An economic study was conducted with specialized engineering offices for different settings (restaurant, concert venue,…) to evaluate the cost-effectiveness of these solutions compared to standard ventilation systems. Additionally, Computational Fluid Dynamic (CFD) simulations were used to assess IAQ performance, including airborne transmission in the presence of a contagious occupant.

The results indicate that several innovative ventilation solutions are relevant alternatives for existing buildings. For example some systems are based on alternative ventilation strategies with mechanical exhaust in occupied spaces rather than supply. Others are based on the combination of a basis system and a boost system for temporarily higher capacity. In this paper, one of these solutions is presented. Depending on the context and performance requirements, these solutions are cost-effective and easier to implement in existing buildings while ensuring sufficient IAQ. Therefore, these innovative solutions show substantial potential to support the deployment of ventilation systems in existing public spaces, improving IAQ in alignment with the objectives of Belgium's recent regulation.

INTRODUCTION

Public indoor spaces (restaurants, theatres, etc.) have been identified as major sites for airborne transmission during the Covid-19 pandemic, especially in densely occupied and poorly ventilated spaces. Recent evidence of airborne transmission of pathogens such as Sars-CoV-2 emphasized the crucial role of ventilation for safe indoor environments (Wang et al. 2021).

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The supply of clean air contributes to the dilution of pollutant concentrations in room air, including viral aerosols. Additionally, air distribution plays an important role in the spatial distribution of viral material, possibly reducing or increasing concentrations locally. Ideally, pollutants emitted by an infected person should be removed before they are completely mixed with room air. Since the covid outbreak, there has been extensive research on optimal ventilation strategies to protect against airborne transmission of infectious diseases in indoor environments (Izadyar and Miller 2022; Al-Rikabi et al. 2024).

In Belgium, many public spaces are still insufficiently ventilated and need to be equipped with a ventilation system. However, in existing buildings, standard balanced mechanical systems are hardly feasible due to their large size, and it might not always be possible to distribute supply and exhaust openings in the whole room because of many technical constraints: reduced space for the fan and ductwork, presence of other existing techniques (e.g. lighting), attic rooms, etc. Moreover, post-covid economic context makes it difficult for owners or operators to invest in ventilation systems, since stringent restrictions (closures, limited occupancy, etc.) during the pandemic affected their business and financial condition. There is thus a need for practical and cost-efficient ventilation solutions for public spaces, that are easier to integrate in existing buildings while ensuring occupants comfort and health.

In this research, several innovative solutions that address economic and technical constraints of existing small to middle-sized public spaces were identified. This paper presents one of these innovative solutions, named “MEV Hall” system. To verify the economic relevance of this alternative solution, an economic study was conducted with specialized engineering offices to evaluate its cost-effectiveness compared to standard ventilation systems for 3 different settings: a restaurant, a concert venue and small classes. Additionally, air distribution and contaminants spatial distribution were studied under different exhaust layouts for two occupancy settings using Computational Fluid Dynamic (CFD) simulations. The impact of a limited number of supply and exhaust openings on the air distribution and long-range airborne infection risk was evaluated and compared to typical mixing and displacement ventilation.

INNOVATIVE VENTILATION SOLUTION

The innovative ventilation solution “MEV Hall” presented in this study relies on mechanical exhaust ventilation (MEV) principle with outdoor air supply in an unoccupied space (typically a corridor or a hall) and mechanical exhaust in the occupied space(s). Outdoor air is supplied through a single large opening whose capacity is sized for the total supply airflow rate. Air in the hall is transferred to the occupied space through the open door or through dedicated transfer openings. Mechanical exhaust in occupied spaces ensures that the required airflow rate is provided in those spaces, regardless of the airtightness of the envelope. To ensure occupants thermal comfort, additional heating can be foreseen in the hall to preheat the air before being transferred in the occupied room.

Different technical implementations of this principle are possible depending on the configuration of the building. Outdoor air supply can be implemented in an existing entrance door, as a replacement for the glazing of an existing window or in a façade of the building. Exhaust can be implemented by one or several decentralised fans or distributed in space through a ductwork.

The main advantage of mechanical exhaust systems compared to balanced mechanical systems is their reduced size (fan and ductwork), which is of great interest for existing buildings. But the proposed innovative system has several additional advantages compared to standard mechanical exhaust systems, mainly thanks to the supply of outdoor air in an unoccupied space. First, this principle allows to preheat the fresh air before it reaches the occupants, which reduces risk of thermal discomfort during winter season. Then, sensitivity to outdoor noise is reduced which is particularly important in urban areas. Finally, the limited number of supply openings reduces the impact on the building envelope, especially when replacement of window frames is not foreseen.

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ECONOMIC STUDY

Method

The economic study was conducted with four specialized engineering offices to evaluate the cost-effectiveness of the MEV Hall system compared to standard MEV and balanced ventilation systems. Three case studies were selected from a sample of mid-sized public spaces located in Belgium to cover typical encountered settings: a restaurant, a concert venue and a set of 7 small rooms. The engineer offices realised the design of the ventilation systems based on the building plans and according to a 25 $m^3/(h \cdot pers)$ (15 cfm/pers) ventilation rate requirement. The main characteristics of the case studies and ventilation rates are provided in Table 1. For a given case study, the mechanical part of standard MEV system and MEV Hall are identical, only the natural part differs. Note that the cost of window frame or glazing replacement in the case of standard MEV were not included in the study.

Table 1. Case Studies Description for the Economic Study

	Surface	Occupancy	Ventilation rate
Restaurant	80 m^2 (860 ft^2)	40 people	1000 m^3/h (590 cfm)
Concert venue	103 m^2 (1110 ft^2)	80 people	2000 m^3/h (1200 cfm)
Set of small rooms	7 x 23 m^2 (250 ft^2)	6 people per room total : 42 people	150 m^3/h (88 cfm) per room total : 1050 m^3/h (618 cfm)

Results and discussion

The results of the economic study are illustrated in Figure 1. The graph represents the average cost of the ventilation systems for each case study. From this graph, it is observed that the average cost of the MEV Hall system is close to the standard MEV and significantly lower than the balanced ventilation (BV) system. This result indicates that the MEV Hall system is a viable alternative to the standard MEV system. While both MEV systems have same similar cost, the MEV Hall system has several advantages compared to the standard MEV as stated above. Finally, MEV Hall has a lower cost than balanced ventilation, but the latter allows for heat recovery. Therefore, future work should also include operational cost estimation.

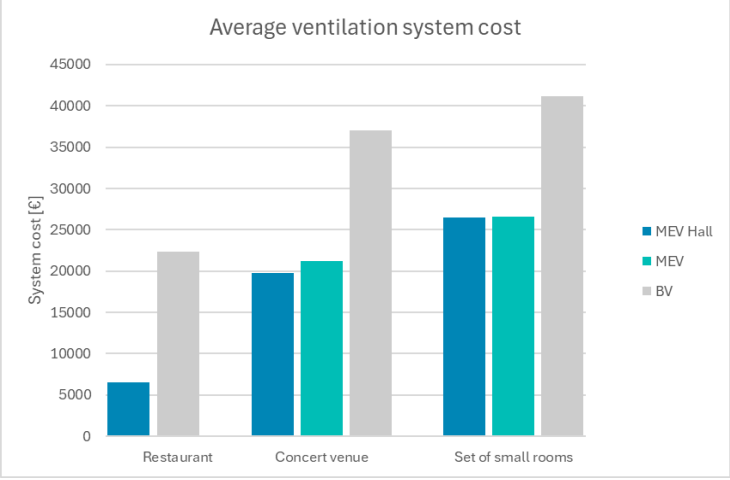

Figure 1 Economic study - Average cost of MEV Hall, standard MEV and balanced ventilation (BV) systems for the restaurant, concert venue and set of small rooms.

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IAQ PERFORMANCE EVALUATION

Method

Steady-state airflow path and contaminants spatial distribution were studied in a reference room under different ventilation strategies using CFD simulations. The reference room is a generic mid-sized rectangular room of 72 m^2 (775 ft^2) with dimensions 12 x 6 x 2.7 m (39 x 20 x 8.9 ft) as depicted in Figure 2. Two different occupancy settings were defined to represent typical configurations of a restaurant and of a small theatre, although it could also apply to other types of room as well (concert venue, conference rooms, etc). Occupants are arranged in 10 tables of 4 people for the restaurant (total: 40 occupants) and in 10 rows of 6 people for the theatre (total: 60 occupants). Occupants are modelled as simplified manikins similar to (Yan, Li, and Tu 2017). Concerning furniture, only the tables of the restaurant are included and modelled as planar surface of dimensions 0.7 x 1.2 m (28 x 47 in) without legs.

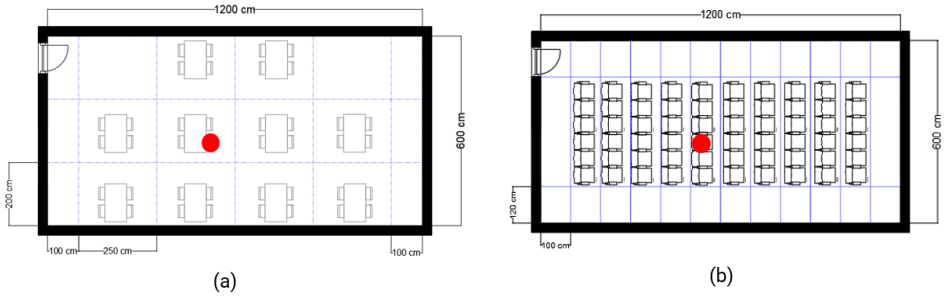

Figure 2 Reference room for the CFD simulations. (a) Restaurant occupancy setting (b) Theatre occupancy setting. The infected occupant's location is indicated by the red dot.

The room is always at full occupancy. Each occupant is a heat source of 36 W according to (Yan, Li, and Tu 2017). Occupants carbon dioxide (CO_2) production is 20 L/h. A single occupant is infected and source of virus. Its location is indicated by the red dot in Figure 2 for each occupancy setting. A quantum emission rate of 42 quanta/h has been considered, corresponding to Sars-CoV-2 90^{th} percentile value considering light activity and speaking (Kurnitski et al. 2021). Due to uncertainties on quantum emission rate, resulting virus aerosol concentration are only used to compare different ventilation strategies relatively (no absolute quantification). Since the analysis is focused on the impact of ventilation on the infection risk at long range, the viral contaminant is considered purely gaseous. As a conservative hypothesis, deposition and degradation in time are neglected. Furthermore, it is considered that pollutants don't have any impact on the airflow in the simulations.

The airflow rate for each occupancy configuration is calculated based on a requirement of 25 $m^3/(h \cdot pers)$ (15 cfm/pers) to align with Belgian regulation (6 November 2022 law), resulting in 1000 m^3/h (590 cfm) for the restaurant and 1500 m^3/h (880 cfm) for the theatre. The airflow rate is provided continuously. Pollutants concentration in supply air is null (room air CO_2 concentration to be interpreted relatively). The air is supplied at a temperature of 18°C. The temperature of the walls is 20°C. The building envelope is considered airtight. Wind, solar gains and other internal gains (excepting occupants) were not included.

It is assumed that individual infection probability is a function of the number of quanta inhaled. The latter is directly proportional to the viral contaminant concentration, for a given breathing rate and occupancy duration. Therefore, long-range virus concentrations were used to compare the performance of different ventilation strategies for a given setting.

The four ventilation systems under study are:

- Mixing ventilation (MV) with swirl diffusers

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- Displacement ventilation (DV)
- "MEV Hall" with distributed exhaust
- "MEV Hall" with limited exhaust distribution (central duct)

Supply and exhaust layouts for each ventilation strategy are depicted in Figure 3. The same layout is used for both occupancy settings.

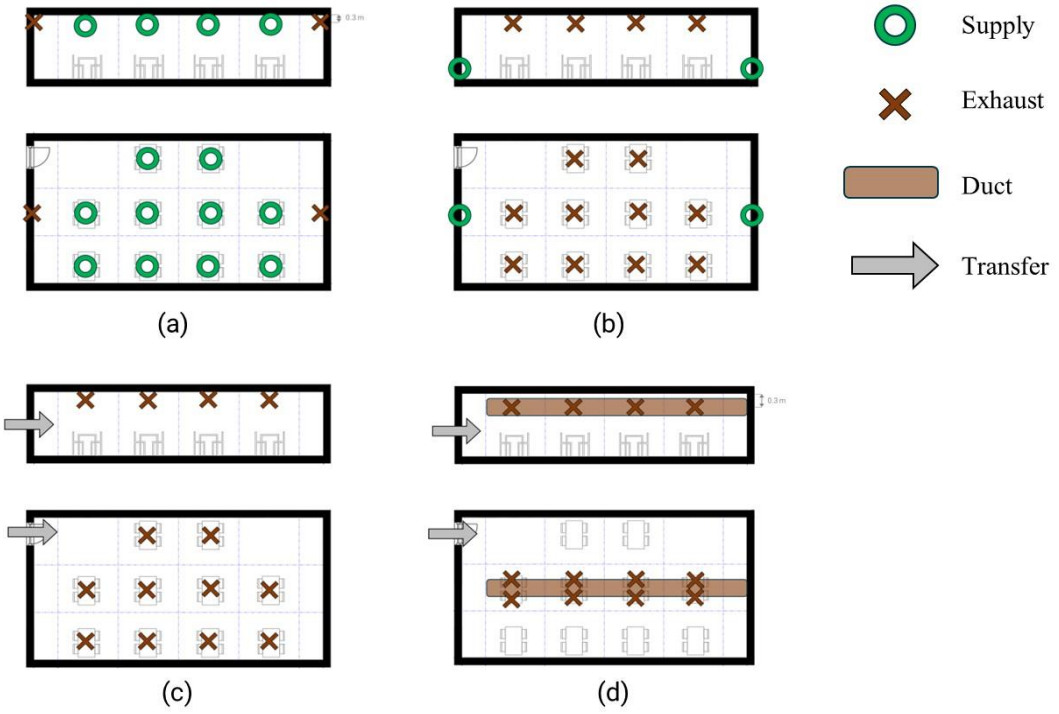

Figure 3 Supply and exhaust layouts for (a) Mixing ventilation (b) Displacement ventilation (c) MEV Hall with distributed exhaust (d) MEV Hall with limited exhaust distribution.

Supply and exhaust characteristics are summarized in Table 2. Ventilation openings are modelled as rectangular plain surfaces, except for swirl diffusers for which geometry is modelled in detail according to TDF-SilentAIR 400 product design. Displacement diffusers are placed on the floor. Wall openings and duct grilles are located 0.3 m (1 ft) away from the ceiling. The duct diameter of "MEV Hall with limited exhaust" is 450 mm (17.7 in).

For "MEV Hall" systems, an additional region before the door is included in the calculation domain to model the natural free flow of supply air through the open door.

Table 2. Supply and Exhaust Characteristics of Ventilation Systems under Study

	Mixing ventilation (MV)	Displacement ventilation (DV)	"MEV Hall" with distributed exhaust	"MEV Hall" with limited exhaust
Supply	10 swirl diffusers	2 displacement diffusers 800 x 1000 mm (30 x 40 in)	Open door 1000 x 2000 mm (40 x 80 in)	Open door 1000 x 2000 mm (40 x 80 in)
Exhaust	2 wall openings 800 x 200 mm (30 x 8 in)	10 ceiling openings 300 x 300 mm (12 x 12 in)	10 ceiling openings 300 x 300 mm (12 x 12 in)	8 duct grilles 300 x 100 mm (12 x 4 in)

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Results and discussion

Air distribution and CO_2 levels are analysed on horizontal and vertical cross-sections of the reference room. The color scale for CO_2 concentration is saturated above 1000 ppm. Note that resulting CO_2 concentrations are to be interpreted in relative value. Figure 4 shows CO_2 concentration on a vertical cross-section for mixing ventilation (MV), displacement ventilation (DV) and "MEV Hall" strategies for each occupancy setting. It is observed that the "MEV Hall" strategies exhibit behaviour similar to displacement ventilation. The air supplied through the door tends to spread at the floor level and rises upon contact with occupants, resulting in a vertical concentration gradient. In contrast, CO_2 concentrations for mixing ventilation follow a more homogeneous distribution in space, indicating effective mixing of supply air with room air.

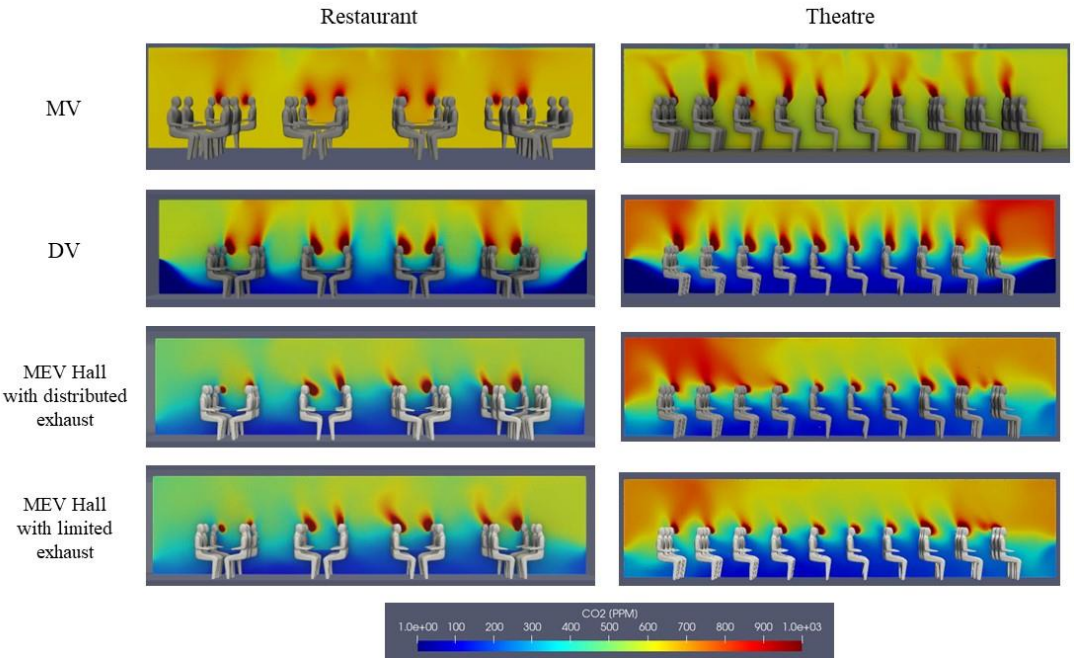

Figure 4 CO_2 concentrations on a vertical cross-section for mixing ventilation (MV), displacement ventilation (DV), "MEV Hall with distributed exhaust" and "MEV Hall with limited exhaust" for the restaurant (left) and theatre (right) occupancy settings.

Figure 5 shows CO_2 concentration on a horizontal cross-section at breathing level, i.e. 1.3 m (4.3 ft) from the floor, for mixing ventilation and MEV Hall strategies, for each occupancy setting. Despite single supply opening (open door), MEV Hall strategies result in lower CO_2 concentration at breathing level compared to mixing ventilation. Then, by comparing MEV Hall strategies with each other, it appears that spatial distribution of CO_2 concentration is not significantly different. It means that, for this case study, extracting room air with a central duct is equally performant as exhaust openings distributed over the whole ceiling. This is an encouraging result for existing buildings where technical constraints often prevent from widely distributing supply and exhaust openings.

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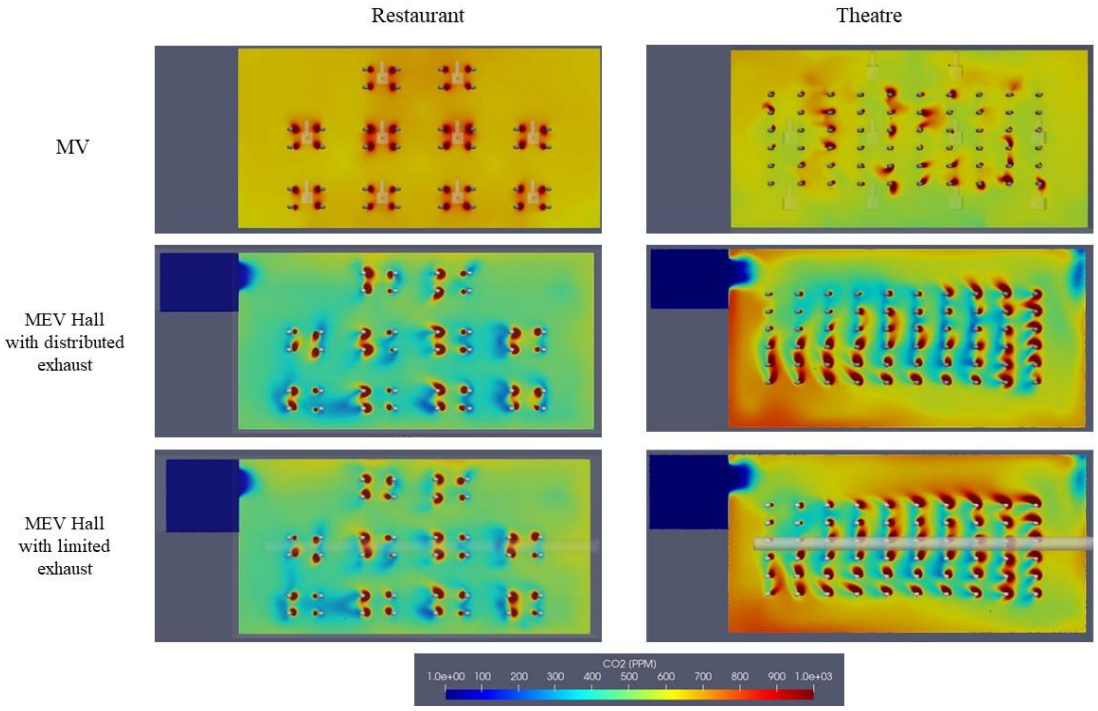

Figure 5 CO_2 concentrations on a horizontal cross-section at breathing level for mixing ventilation (MV), "MEV Hall with distributed exhaust" and "MEV Hall with limited exhaust" for the restaurant (left) and theatre (right) occupancy settings.

Finally, viral contaminant levels are analysed on horizontal and vertical cross-sections of the reference room. The color scale for the graphs is limited to 0.10 quanta/m^3 (0.003 quanta/ft^3). This choice is intended to better distinguish long-range concentrations. Since occupancy duration and breathing rate are fixed for a given setting (restaurant/theatre), local long-range virus concentrations are used as an indicator of the individual infection probability to compare the performance of different ventilation strategies in a given setting.

Figure 6 shows virus concentration for mixing ventilation (MV) and "MEV Hall strategy with limited exhaust" (central duct), for each occupancy setting. It is observed for mixing ventilation that virus particles tend to spread in the room, quite far away from the virus source. For "MEV Hall", long-range virus concentrations are very low compared to mixing ventilation. This result indicates that virus particles tend to be rapidly extracted before being completely mixed with room air, leading to lower concentrations at long range. This points out that "MEV Hall" is more performant to prevent airborne transmission than standard mixing ventilation in this case. Since only one position of the infected occupant was studied, further work should include several other locations of the infected occupant.

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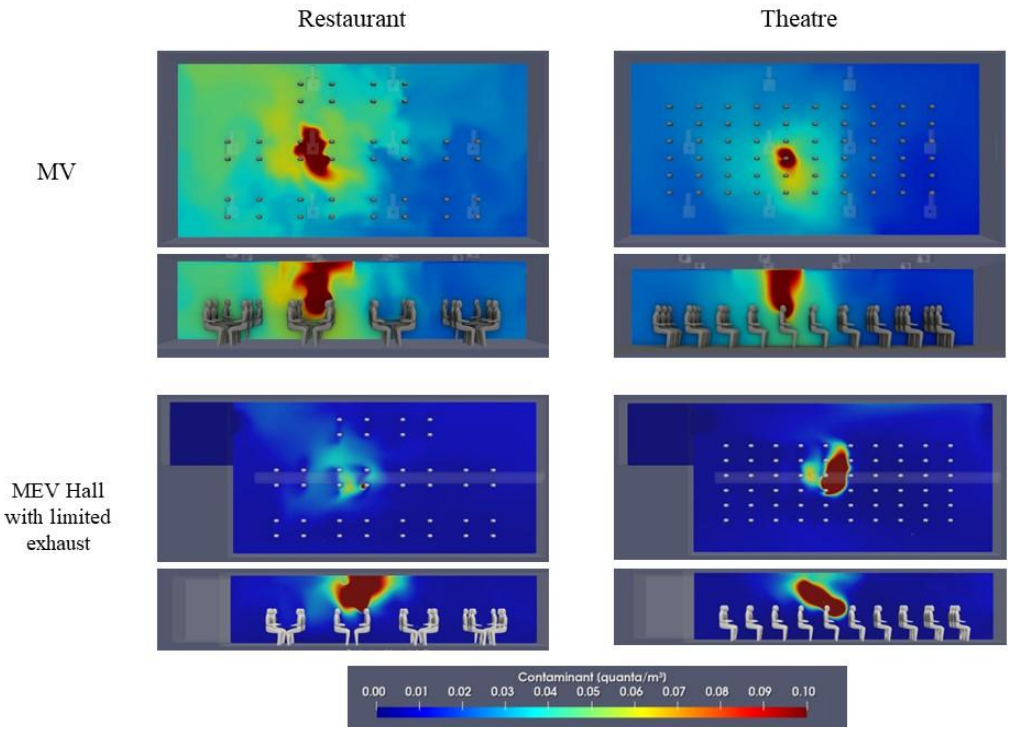

Figure 6 Viral contaminant concentrations on a horizontal and vertical cross-sections for mixing ventilation (MV), and "MEV Hall with limited exhaust" for the restaurant (left) and theatre (right) occupancy settings.

CONCLUSION

In this paper, an alternative ventilation solution is proposed to address technical and economic constraints of public indoor spaces. In the "MEV Hall" system, air is supplied through a single opening in a hall or corridor and transferred to the occupied room where it is mechanically extracted. An economic study was conducted and showed that the MEV Hall system is a cost-efficient alternative to standard ventilation systems.

CFD simulations were realised to study the air distribution and IAQ performance of the "MEV Hall" system for two different exhaust layouts: the exhaust openings are either distributed over the whole ceiling or limited to a central duct. Mixing and displacement ventilation strategies were included as well as reference cases. The four ventilation strategies were analysed in two different occupancy settings, to represent the typical cases of a restaurant and small theatre. First, results indicate that "MEV Hall" strategies have a behaviour similar to displacement ventilation since a vertical gradient of CO_2 concentration is observed. These strategies result in lower concentrations at breathing level compared to mixing ventilation. Then, there was no significant difference in the CO_2 levels for the two different exhaust layouts of the "MEV Hall" system. It means that this strategy is equally performant with exhaust limited to a central duct or distributed over the whole ceiling for this case study. This is an encouraging result for existing buildings where technical constraints often prevent from widely distributing supply and exhaust.

Since ventilation plays an important role in preventing airborne transmission, a contagious occupant was included in the simulations. The analysis of virus concentrations indicates that "MEV hall" strategy results in lower long-range concentrations compared to mixing ventilation. This observation points out that "MEV hall" shows better performance to reduce airborne transmission than mixing ventilation for this case study. Since only one position of the infected occupant was studied, further work should include several other locations of the infected occupant.

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ABBREVIATIONS

IAQ	=	Indoor Air Quality
CFD	=	Computational Fluid Dynamic
MEV	=	Mechanical Exhaust Ventilation
BV	=	Balanced Ventilation
MV	=	Mixing Ventilation
DV	=	Displacement Ventilation

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