Determination of ventilation effectiveness with tracer gas methods under COVID-19 conditions

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Abstract. We report in this paper on the use of tracer gas methods and two tracer gases to determine ventilation effectiveness under COVID-19 conditions in a large concert hall in Lucerne, Switzerland. The occupancy of the concert hall was simulated by using thermal dummies and partial occupancy of people because of the COVID-19 protection regulations. Contaminants are removed very efficiently in the parquet (by factors better than with mixed ventilation). On the stage and balconies, the local ventilation effectiveness with displacement ventilation is partly comparable to mixed ventilation or even lower. The ventilation of balconies and galleries is demanding and must be carefully assessed in the case of pandemic risks. For the assessment of infection risk through aerosol transmission, a characteristic value for the entire room is not sufficient. The ventilation effectiveness and contaminant removal effectiveness depend very strongly on local boundary conditions and the prevailing flow conditions when dosed locally. The investigations show that the tracer gases sulphur hexafluoride (SF_6) and 2,3,3,3-tetrafluoropropene (R1234yf) provide comparable results in determining the air exchange rate and ventilation effectiveness. With both tracer methods, it is possible to gain knowledge about the operation of the ventilation system (e.g. volume air flows, heat recovery leakage).

Keywords. Tracer methods, Ventilation effectiveness, SARS-Cov-2 aerosols
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1. Introduction

Lucerne University of Applied Sciences and Arts has been using tracer gas methods to determine large volume flows in road tunnels and buildings for 20 years. These methods are also used to investigate the ventilation effectiveness in occupied rooms of buildings. The COVID-19 pandemic triggered the authors of this paper to start thinking about this issue long before. The discussions about aerosol transport suggested a fundamental investigation of transport mechanisms through indoor air flow. The resulting questions about the ventilation of occupied rooms and the transport of pollutants led to a bachelor thesis [1] being initiated by the authors Frei and Huber at the beginning of 2021 and carried out by the co-authors Bienz and Bucheli. Clarifications and preliminary investigations into the replacement of the tracer gas sulphur hexafluoride were already carried out beforehand. For climate protection reasons, the use of the otherwise ideal tracer gas sulphur hexafluoride (SF_6) is no longer opportune, as it has a high global warming potential. The bachelor thesis and the associated preliminary work have shown that the tracer gas 2,3,3,3-tetrafluoropropene (R1234yf) is a suitable substitute for SF_6. The determination of the ventilation effectiveness leads to comparable results. The equipment used for dosing and detecting the tracer gas can still be used. The investigations carried out so far include the parliament chamber of a government building, several classrooms and a large concert hall.

2. Building

2.1 Description

The Culture and Convention Centre Lucerne (KKL) is a multifunctional building that was opened in 1998. It contains a large concert hall, a multifunctional hall, an art museum, various restaurants and several congress and meeting rooms. The KKL was built according to the plans of the architect Jean Nouvel. The large concert hall, which is famous for its acoustics, is the centrepiece of the KKL [2].

2.2 Geometry and Occupation

The room volume of the large concert hall is variable and can be adapted to the different acoustic requirements of the musicians and orchestras. The room volume without the echo chamber is 19'000 m^3. Taking the echo chamber into account, the room volume is 26'000 m^3.

The geometric dimensions of the concert hall

- Total height 23 metres
- Hall width 23 metres
- Total length 46 metres

Number of seats (total at full occupancy 1839 seats)

- Parquet 725 seats, incl. Parquet gallery
- 1st balcony 228 seats, incl. gallery
- 2nd balcony 214 seats, incl. gallery
- 3rd balcony 234 seats, incl. gallery
- 4th balcony 314 seats

Organ loft on level 1st balcony 124 seats (rarely for visitors)

Number of musicians on stage: max. 120 musicians

2.3 Heating, Ventilation, and Air Conditioning

The concert hall is conditioned by two air-conditioning units of equal size installed in the attic. The supply air is centrally humidified and dehumidified. The reheating takes place in three zones each. Heat and humidity recovery is achieved with rotating heat exchangers. The supply air is routed via a pressure chamber and flows in at the bases of the seats. The exhaust air is discharged at a total of four exhaust air inlets on the hall ceiling. According to the system documentation, the target value of the supply air volume flow in concert mode is 29'290 m^3/h per air handling unit. The basic setting of the room air temperature is 22°C. The target value of the room air humidity is set to 55 % RH.

3. Research methods

Experimental methods will be used to demonstrate the effectiveness of ventilation and the removal of pollutants in the concert hall under realistic conditions. Two tracer gases and aerosol mist are used. This conference paper reports on the use of normative tracer gas methods [3]. The tracer gas method of pulsed emission was used to investigate how the release of SARS-Cov-2 aerosols in spatially distributed positions can be quantified by releasing the tracer gas SF_6. On the one hand, the time lag of the pulse from release to local detection is of interest. On the other hand, the local exposure can be determined from the ratio of the tracer gas mass released in a pulse and the tracer gas mass inhaled locally. The tracer mass released with a rectangular pulse was recorded with a thermal mass flow sensor. The time-dependent evolution of the tracer gas concentration was detected by means of fast Fourier transform infrared spectroscopy (FTIR). The results were evaluated and interpreted by numerically integrating the tracer gas concentration over time. The tracer method of constant emission was used to investigate how the removal of SARS-Cov-2 aerosols in spatially distributed positions can be quantified by releasing the tracer gas R1234yf. For this purpose, first a defined tracer gas mass flow was dosed into the space to be investigated over a fixed period of time. Afterwards, the decay behaviour of the tracer gas concentration at local positions was detected by means of non-dispersive infrared spectroscopy (NDIR).

3.1 Dosing of tracer gas

The tracer gases SF_6 and R1234yf were used. For all doses, the tracer gas mass flows were kept constant according to **Tab. 1.**

Tab. 1 – Tracer gases used in this study.

Description	Symbol	Tracer	
		Sulphurhexa-fluoride	Tetrafluor-propene
Chemical		SF_6	$C_3H_2F_4$
Formula			R1234yf
Density	ρ_N	6.63 kg/m^3	4.8 kg/m^3
[a]	GWP	23'900	4
Mass flow	$q_{m,tr}$	110 mg/s	77 mg/s

[a] Global warming potential (GWP)

R1234yf was dosed in the concert hall with constant emission. SF_6 was mainly used in pulsed emission mode.

3.2 Constant emission tracer method

Equation (1), formulated by Frei and Kägi [4], allows to calculate the volume flow of air, $q_{V,air}$, at the measuring point from the measured concentration of tracer gas and its mass flow at the dosing point.

$$q_{V,air} = 10^6 ppm \cdot \frac{1}{\rho_{air}} \cdot \frac{R_{tr}}{R_{air}} \cdot \frac{q_{m,tr}}{c_V} \; [m^3/s] \qquad (1)$$

where

$q_{m,tr}$ mass flow of tracer at the dosing point in kg/s

R_{tr} specific gas constant of the tracer in J/(kg K)

R_{air} specific gas constant of the air in the exhaust duct in J/(kg K)

c_V volumetric tracer gas concentration at the measuring point in ppm

ρ_{air} density of the moist air at the measuring point in kg/m^3

3.3 Pulsed emission tracer method

A tracer gas pulse with a mass flow rate of $q_{m,tr}(t)$ is injected upstream or locally in the room and the time-dependent tracer gas concentration c(t) is measured downstream or locally elsewhere in the room. For mass flow calculations it is essential that the tracer gas is well mixed with the air. Furthermore, the whole amount of tracer gas must have left the duct at the time t_2. If that is the case the following integral mass balance, equation (2), reported by Persily and Axley [5], is applicable.

$$\int_{t1}^{t2} q_m(t) \cdot c(t) \cdot dt = \int_{t1}^{t2} q_{m,tr}(t) \cdot dt; \quad q_m(t) \geq 0 \tag{2}$$

Assuming a constant air mass flow, q_m, during the observed time interval, and assuming that the mass flow of the tracer gas is negligible compared to the air mass flow, the mass flow of air can be calculated according to equation (3):

$$\overline{q}_m(\xi) = \frac{\int_{t1}^{t2} q_{m,tr}(t) \cdot dt}{\int_{t1}^{t2} c(t) \cdot dt} \quad t_1 \leq \xi \leq t_2 \tag{3}$$

Considering the volumetric concentration rather than the mass concentration of the tracer gas in the air, equation (3) is transformed to the following:

$$\overline{q}_{m\ air} = 10^6 \ \frac{R_{tr}}{R_{air}} \cdot \frac{\int_{t1}^{t2} q_{m,tr}(t) \cdot dt}{\int_{t1}^{t2} c_V(t) \cdot dt} \tag{4}$$

where

$c_V(t)$ measured volumetric tracer gas concentration at time t in ppm

$q_{mTracer}(t)$ mass flow rate of tracer gas at time t in kg/s

Equation (4) is equivalent to equation (1) with the difference that the mass flow of the tracer gas at the dosing point as well as the measured concentration are no longer constant and must be integrated over time.

3.4 Decay tracer method

The tracer gas is metered in at a constant emission rate either locally in the room or centrally via the supply air. It is important that the tracer gas is well mixed with the room air. Depending on the time, a steady-state concentration will be reached if the boundary conditions remain constant. After that, the tracer gas dosing can be stopped. The mechanically or naturally induced air exchange will reduce the initial tracer gas concentration in the room air. Depending on the time, the tracer gas concentration will decay. The air exchange rate over time can be calculated from the decay behaviour [6].

3.5 Supply air volume flow and concentrations in the equilibrium state

The supply air volume flows were determined by dosing tracer gas in the outdoor air of the two air handling units (monoblocs) of the concert hall. The concentrations were measured in the supply air and exhaust air.

The exhaust air transfer rate of the rotational heat recovery units (rotors) was estimated on the basis of various measurements in which the concentration in the exhaust air was above 0.5 ppm for at least half an hour. Due to their coating, the rotors transfer a higher proportion of tracer gas R1234yf than of air. For the tracer gas SF_6, it is known from the literature that the transfer rate is the same as for air.

The outdoor air flow rate supplied to the room is calculated using equation (1), assuming that there is no tracer gas concentration in the outdoor air (less than 0.002 ppm).

The supply air flow rate supplied to the room is calculated with equation (5), assuming that there is no tracer gas concentration in the outdoor air (less than 0.01 ppm).

$$\boldsymbol{q_{v,ODA} = q_{v,tr} \cdot \frac{1 - TGTR}{(c_{SUP} - c_{ETA}) \cdot TGTR} \cdot (1 - OATR) \cdot 10^6} \tag{5}$$

where

$q_{v,ODA}$	Outdoor air volume flow in m^3/h
$q_{v,tr}$	Volume flow rate of tracer gas in m^3/h
c_{ETA}	Tracer gas concentration in the exhaust air in ppm
c_{SUP}	Tracer gas concentration in the supply air in ppm
$TGTR$	Tracer gas transfer ratio from exhaust air to supply air
$OATR$	Outdoor air transfer ratio into the exhaust air

$$\boldsymbol{q_{v,SUP} = \frac{q_{v,ODA}}{(1 - \cdot EATR)}} \tag{6}$$

where

$q_{v,SUP}$	Supply air volume flow in m^3/h
$q_{v,ODA}$	Outdoor air volume flow in m^3/h
$EATR$	Exhaust air transfer ratio into the supply air

3.6 Ventilation effectiveness

In this paper, we use the term "ventilation effectiveness" to express the quality of a ventilation system in how it reduces the risk of transporting pollutants from an emitter (issue position) to a receiver (immission position) (see **Fig. 1**). This definition is not found in the literature, but we consider it meaningful in the context of an infection risk from aerosols.

In the case of **constant dosing (step-up)** with tracer gas, the ventilation effectiveness corresponds to the ratio of the tracer gas concentration in the extract air to the tracer gas concentration at a certain point in the room that is in a steady state. The concentration of the supply air must be subtracted from the measured values.

$$\varepsilon_{C,i} = \frac{c_{ETA} - c_{SUP}}{c_{IDA,i} - c_{SUP}} \tag{7}$$

where

$\varepsilon_{C,i}$ Ventilation effectiveness at the position i

c_{ETA} Tracer gas concentration of the exhaust air in ppm

$c_{IDA,i}$ Tracer gas concentration of the room air at the position i in ppm

c_{SUP} Tracer gas concentration of the supply air in ppm

With **pulsed emission dosing**, the ventilation efficiency is determined with:

$$\varepsilon_{C,i} = \frac{m_{tr,em}}{q_{m,tr,ETA}} \cdot \frac{c_{ETA} - c_{SUP}}{\sum(\Delta c_{IDA,i}(t) \cdot \Delta t)} \quad (8)$$

where

$m_{tr,em}$ tracer gas mass emitted at the emission position in g

$q_{m,tr,ETA}$ Tracer gas mass flow to achieve c_{ETA} in g/s

c_{ETA} Tracer gas concentration in the exhaust air at equilibrium (at tracer gas mass flow $q_{m,tr,ETA}$) in ppm

$\Delta c_{IDA}(t)$ Difference caused by the pulse in the tracer gas concentration in the room air (at immission position i) compared to the background concentration at time t, in ppm

Δt Time step in s

The ventilation effectiveness indicates the factor by which fewer pollutants (e.g. aerosols) are transferred from the issue position to the immission position than with an ideal room air mixture. Thus, with a value greater than 1, fewer pollutants are transferred than with an ideal mixture and with a value less than 1, more. This means that the higher the value $\varepsilon_{C,i}$ the better the ventilation effectiveness. The definition of ventilation effectiveness used always applies only to the transmission direction from one spatially defined issue position to a second spatially defined immission position. The transmission rate in the other direction can be significantly different. This can be illustrated, for example, if the issue position were directly in front of the supply air diffuser. In this case, a ventilation efficiency of ≤ 1 would be expected. In the opposite direction, however, the ventilation efficiency would be >>1.

With **pulsed emission dosing**, the time lag between the release of the pulse and its arrival at the immission position is also determined (**Fig. 1**)

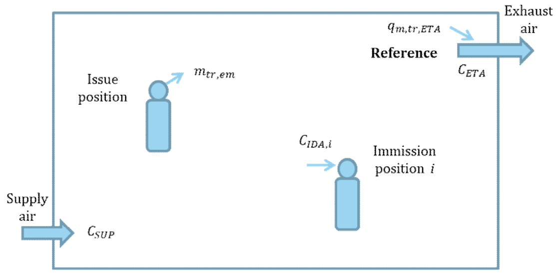

Fig. 1 – Model for ventilation effectiveness.

3.7 Short description of measurements

The measurement campaign was carried out over two days. The focus of the first measurement day was on the stage and the stalls of the concert hall. On the second day, the balconies of the concert hall were examined.

Fig. 2 shows the placement of dummies, spotlights and people as internal loads in the concert hall on the first day of measurement.

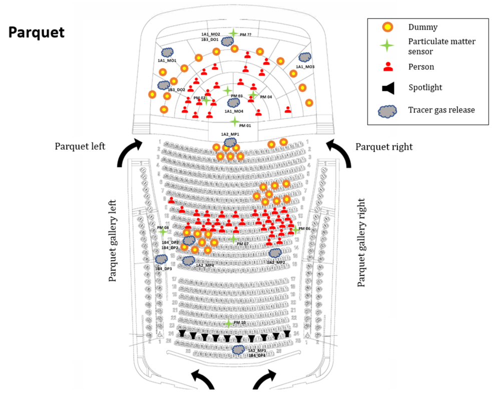

Fig. 2 – Disposition of internal loads in the concert hall.

3.8 Boundary conditions

Tests for the ventilation efficiency were carried out with an audience, that was simulated with locally distributed thermal loads and partial occupancies. The air flow rates were determined without internal heat load. The orchestra rehearsed to a reduced extent during the measurement campaign.

3.9 Occupancy and heat loads

The heat loads and occupancy on the first measurement day are listed below. The values in brackets apply to the second measurement day.

Persons:

25 (22) orchestra

40 (35) audience (1st to 3rd balconies and galleries)

8 (8) staff

Other heat loads:

46 dummies stalls (2nd to 4th balconies) (7.1 kW)

10 luminaires in the parquet (10 kW)

7 luminaires in 1st balcony (7 kW)

Measuring devices (approx. 0.5 kW)

Total sensible heat load in the hall approx. 30 kW (29.6 kW) (both without hall lighting) or equivalent approx. 420 (415) persons.

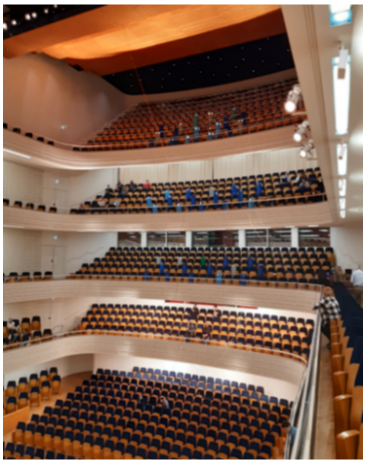

Fig. 3 – Balconies of the concert hall with dummies.

4. Results

4.1 Supply air volume flows

Tab. 2 summarises the determination of the air volume flows (referred to 20°C) of the two air handling units. It is assumed that the Outdoor air transfer ratio (OATR) is the same as the Exhaust air transfer ratio (EATR). The measurement uncertainty of the air volume flows is estimated at 5 %.

Tab. 2 - Determination of the air volume flows

Symbol	AHU LC01 Concert hall west	AHU LC02 Concert hall east	Sum for both AHU units
-	SF_6	R1234yf	-
EATR	0.035	0.035	-
TGTR[a]	0.035	0.045	-
$q_{v,ODA}$	28'300 m^3/h	28'100 m^3/h	56'400 m^3/h
$q_{v,SUP}$	29'300 m^3/h	29'100 m^3/h	58'400 m^3/h

[a] Tracer gas transfer ratio from exhaust air to supply air (TGTR)

4.2 Concentrations in the equilibrium state

Tab. 3 lists the theoretical tracer gas concentrations in the equilibrium state that result from homogeneous mixing with the total air volume flow of both air handling units and when the tracer gas mass flows are metered in according to **Tab. 1**
For the assessment of the ventilation effectiveness in the concert hall, the differences between supply and extract air are used.

Tab. 3 - Theoretical tracer gas concentrations in the equilibrium state

Designation	Symbol	Tracer gas SF_6	Tracer gas R1234yf
Concentration in the supply air	c_{SUP}	1.30 ppm	1.17 ppm
Concentration in the exhaust air	c_{ETA}	0.05 ppm	0.05 ppm
Difference in concentration of supply and exhaust air	Δc_{SUP}-c_{ETA}	1.25 ppm	1.12 ppm

4.3 Air exchange rate of concert hall

Measurements with constant dosing with the tracer gas R1234yf in the concert hall were concluded to be a difference between supply and extract air of 1.07 to 1.10 ppm rather than the value listed in the table. One reason for the difference is the measurement uncertainty. However, it is also possible that the total extract air volume flow is slightly higher than the total supply air volume flow. A rounded value of 1.1 ppm is used in the evaluations. The measurements were carried out with closed echo chambers. According to the client, the volume of the concert hall is 19'000 m^3. The supply air spaces under the stalls are not included.
The air exchange rate of the supply air volume flow in relation to the room volume is 3.07 h^{-1}. The nominal time constant (reciprocal value of the air exchange rate) is 0.325 h.

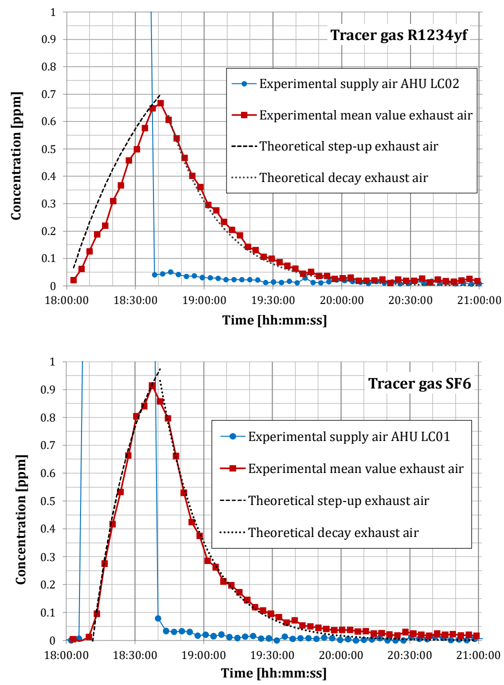

Fig. 4 – Constant emission of tracer gases R1234yf and SF_6, decay of tracer concentrations, without internal loads.

Fig. 4 shows the step-up dosing of the tracer gases R1234yf and SF_6 into the outdoor air of the air handling units LC01 and LC02. The decrease of the tracer gas concentration in the exhaust air of the concert hall for both tracer gases is shown depending on time. Due to the large volume of the concert hall and the time available, the state of equilibrium could not be achieved.

For comparison, the theoretical course of the tracer gas concentration during dosing and removal through the ventilation system is shown. The model of ideal mixed ventilation and the measurements agree very well. The concentration in the exhaust air is practically at an ideal mixed ventilation.

After that, the time lag of the tracer gas in the room obviously increases.

4.4 Ventilation effectiveness

Tab. 4 to Tab. 7 show experimentally determined values for ventilation effectiveness at the stage, on the parquet and on the balconies. The ventilation effectiveness was determined using the constant emission method (R1234yf) and the pulsed emission method (SF_6). In addition, the pulsed emission method was used to determine the time lag for tracer propagation from the source to the target.

The duration of a single pulse of SF_6 was 60 s and the injected tracer gas mass was 6.3 g in each case.

The measurements were carried out with person occupancy and heat loads (dummies) on the stage and in the stalls.

5. Discussion

5.1 Supply air volume flows

By dosing tracer gas into the outdoor air, the following supply air volume flows (referred to 20°C) of the two air handling units LC01 and LC02 of the concert hall were determined

Concert Hall West unit (LC01) 29'300 m^3/h

Concert Hall East unit (LC02) 29'100 m^3/h

Total of both units 58'400 m^3/h

These air volume flows are practically identical to the target values according to the system documentation.

The air exchange rate in relation to the room volume is thus 3.07 h^{-1}. The nominal time constant (reciprocal value of the air exchange rate) is 0.325 h.

5.2 Ventilation effectiveness

The ventilation effectiveness on the balconies is obviously strongly influenced by heat loads (upward currents). Ventilation effectiveness can occur that are significantly worse than with ideal mixed ventilation. In four cases, however, better ventilation efficiencies were also observed. The high relative standard deviations in the measurements with constant dosage indicate unstable flow conditions (swath behaviour). This is also evident in comparison with the pulse measurements. When dosing in the parquet and measuring in the 1st balcony, row 2, there were markedly different ventilation effectiveness with constant dosing and pulse dosing. Possible causes are unsteady currents and locally strongly differing conditions at the dosing points (which, however, had a distance of max. 2 m). Furthermore, the two pulse measurements with the transmission from the 1st balcony in the front to the 2nd balcony, row 4, also showed clear differences.

In conclusion, the indoor air flow in the area of the balconies can be described as unstable and hardly locally predictable.

5.3 Air handling units

The two air handling units (AHU) of the concert hall are equipped with rotating heat recovery units (rotors). From the tracer gas measurements, it was estimated that 3.5 % of the exhaust air volume flow is transferred to the supply air (EATR). This value is in a good range and can be considered uncritical from a hygienic point of view. According to the system documentation, the exhaust air is filtered with class F7 fine dust filters. Depending on the filter product and condition, around 80 to 90 % of the aerosols contained in the exhaust air are retained in the exhaust air filters. This means that only about 0.5 % of the aerosols get into the supply air. Since the exhaust air has the characteristics of ideal mixed ventilation, the average age of these aerosols is about 20 minutes. The potential transmission of virus copies via this route is thus about two orders of magnitude lower than the (very low) potential transmission from the stage to an audience member in the parquet.

The F7 filters used correspond to the state of the art in ventilation hygiene guidelines. It is recommended to keep this filter class.

6. Conclusions

6.1 Concert Hall KKL

Contaminants are removed very efficiently in the parquet (by factors better than with mixed ventilation). On the stage and balconies, the local ventilation effectiveness is partly comparable to mixed ventilation or even lower. It is interesting to know what proportion of the emitted particles is inhaled. This is calculated by dividing the inhaled air volume flow by the supply air volume flow. This ratio is divided by the ventilation effectiveness according to equation (7) or (8).

Tab. 4 – Ventilation efficiency at four positions in the stage and parquet area

Position measurement	Ventilation efficiency with standard deviation at position dosing Centre stage	Parquet, row 1	Comment Constant dosing with tracer gas R1234yf
Conductor	(close range)	0.23±0.32[a]	"Overflow"
Orchestra left	1.23±0.16	0.84±0.19	Approximately mixing ventilation
Parquet, row 1	2.3±1.5	(close range)	Approximately mixing ventilation
Parquet, row 7	8±5	108±50 (approx.)	Displacement ventilation

[a] The standard deviation does not result from a measurement uncertainty, but from non-stable conditions (unsteady flow conditions, swath behaviour).

Tab. 5 – Pulse measurements with tracer gas SF_6 on stage, with personal exposure and heat sources: time lag and ventilation effectiveness

Position measurement	Ventilation effectiveness/ time lag for dosing position Orchestera back	before conductor	Comment Pulse dosing with tracer gas SF_6
Orchestra right	5.7 / 5'20"	-	Good contaminant removal
Orchestra centre back	-	2.3 / 3'34"	Approximately mixing ventilation

Tab. 6 – Ventilation effectiveness for positions on the balconies

Position measurement	Dosing on parquet at the rear, row 24 without thermal load	with thermal load	Comment Constant dosing with tracer gas R1234yf
1st balcony, row 2	1.3±0.4	4.7±3.5[a]	Approximately mixing ventilation[a]
2nd balcony, row 2	0.76±0.11	0.40±0.08	Transfer from parquet to balcony
3rd balcony, row 4	0.58±0.13	0.59±0.09	Transfer from parquet to balcony
4th balcony, row 5	2.0±0.9	1.1±0.1	Approximately mixing ventilation

Tab. 7 – Measurements with pulsed emission tracer method, with personal exposure and heat sources: time lag and ventilation effectiveness

Position measurement	Position dosing	Time lag mm:ss	Ventilation effectiveness	Comment Pulsed emission with tracer gas SF_6
1st balcony, row 2	Parquet back	02:16	0.28	Possibly swaths
2nd balcony, row 4	1st balcony front	03:05	1.0	Approximately mixing ventilation
2nd balcony, row 4	1st balcony back	03:20	2.4	Good ventilation effectiveness
3rd balcony, row 4	3rd balcony front	04:39	0.63	Rather low ventilation effectiveness
4th balcony, row 5	1st balcony back	06:53	0.85	Approximately mixing ventilation

Thanks to the large supply air volume flow, with a ventilation effectiveness of 1 and an assumed breathing air volume flow of 0.5 m^3/h (person in the audience), only 9 out of 1million emitted particles are inhaled. In the measurement with the least favourable ventilation effectiveness, the number of particles inhaled is around 30 out of 1 million.

It is not the purpose of this paper to assess the infection risk. However, this was done by a hygienist in the course of the accompanying investigation of the tracer gas measurements and is documented in the overall report of the investigation [7]. According to this assessment, there is generally a low risk when masks are worn.

6.2 Tracer gas methods

Working with two tracer gases makes sense in complex rooms and installations. New tracer gas R1234yf has proven itself for measurements in large rooms (requires safety awareness). The disadvantage of R1234yf is its high flammability. This requires safety measures and trained personnel. Both the pulsed emission dosing method and constant dosing method are justified. In the concert hall of the KKL Lucerne and in a preliminary study in a parliament hall, the tracer gas measurements led to the same conclusions as a parallel conducted aerosol measurement study. The investigation has shown that with both tracer gases, a concentration of 1 ppm is sufficient to obtain qualitatively and quantitatively meaningful results when using high-quality measuring equipment.

6.3 General considerations

Fig. 5 – 3rd Balcony of the concert hall with dummies and sampling points, view down to stage.

The ventilation of balconies and galleries is demanding and must be carefully assessed in the case of pandemic risks. For the assessment of infection risk through aerosol transmission, a characteristic value for the entire room is not sufficient. An aeorosol transmission from point A to B is not equal to the transmission from B to A (see **Fig. 6**).

Further research and efforts are needed to clarify these issues.

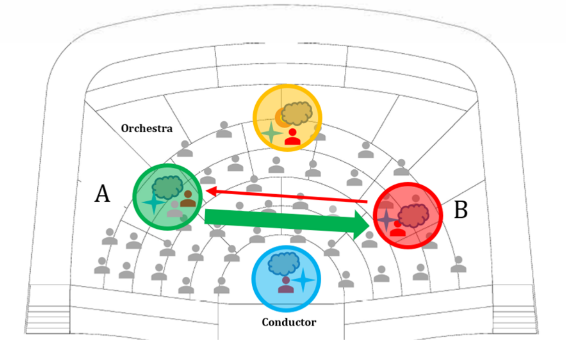

Fig. 6 – Considerations for aerosol transport.

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