Aerosol transmission in rotary wheel heat exchangers

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Abstract. Transmission by aerosols is considered the main route of COVID-19 infections indoors. Therefore, limiting air transfer between supply and extract air in ventilation systems is critical. Heat recovery components (HRCs) are used as standard in new ventilation systems. Rotary wheels are very efficient, but have a higher exhaust air transfer ratio (EATR) compared to other types. The fact that the surface of rotary wheels is touched by both supply and exhaust air allows humidity recovery, but also carries a risk of transferring undesirable substances. Aerosols can deposit on the surface if they come into contact with it. The characteristics of rotary wheels raise the question whether a relevant transfer of aerosols can take place and whether this is different from the EATR. Experimental investigations were carried out with two rotary wheels. The aerosol used was a water-glycol mixture whose properties compare well with human lung aerosols. Particle sensors were installed at all four duct connections of the HRC. In parallel, the EATR was determined with tracer gas. In 16 measurement series, the air velocity, rotor speed and air conditions were varied. The determined aerosol transfer ratio was typically 1 to 2 percentage points below the EATR. The results allow the conclusion that rotary wheels designed and operated according to current standards transfer only a non-relevant small amount of aerosols and thus do not pose an infection risk for COVID-19 in applications such as offices where the frequency of highly infectious individuals is low to moderate. However, aerosol transmission in hygienically relevant quantities is conceivable in poorly designed systems with incorrect pressure ratios and inadequate filters at the same time, but this does not only affect rotary wheels. Although first positive results are available, further investigations are planned. The understanding of aerosol absorption and HRCs surface's properties is to be deepened.

Keywords. Ventilation, aerosol transmission, heat recovery, rotary wheel
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1 Introduction

Aerosols are considered a main cause of COVID-19 infections indoors. Therefore, limiting air transfer between supply and extract air in ventilation systems is critical.

In bidirectional ventilations systems, heat recovery is state of the art and is even required in the European regulation for ecodesign requirements for ventilation units [1]. Rotary heat exchangers (RHE) are an efficient and economically interesting solution and are therefore widely used. A disadvantage of RHE is that due to the physical principle and the mechanical implementation a higher exhaust air transfer ratio (EATR) can occur than with other common heat recovery categories such as plate heat exchangers or run around coil systems. Measures to minimise and evaluate the EATR of RHEs are well known and recommended e.g. in the REHVA COVID-19 Guide [2]. Special attention must be paid to the correct pressure ratios and purge sector. However, RHEs are not generally equipped with purge sectors, and in older AHUs the pressure ratios are not always optimal. Another aspect is the fact that the surface of an RHE is touched by both supply and extract air.

Although this enables humidity recovery, it also carries the risk of transferring undesirable substances. However, aerosols can adhere to the surface if they come into contact with it. Associated with adhesion are deposition and release [3].

The characteristics of RHEs raise the question of whether relevant aerosol transfer can take place and whether this differs from EATR. For hygienically demanding applications of RHEs, it is crucial to have more knowledge about the phenomenon of aerosol transfer. Additional knowledge is important for the acceptance of RHEs by both experts and occupants. Against this background, the industry is looking for answers.

On the initiative of a company, the University of Applied Sciences and Arts Lucerne (HSLU) together with the Swiss Centre for Occupational and Environmental Health (SCOEH) carried out first experimental investigations in January 2021 [4]. In the second half of 2021, the idea was supported by a manufacturer group under the administration of the association FGK Fachverband Gebäude-Klima e. V.. The investigations from the first project will be continued with further types of RHEs and conditions. The second project had not yet been completed at the time this paper was submitted. Therefore, only results from the first project are presented here.

Common to both projects was the use of an aerosol that behaves in the laboratory test system similar to human exhaled aerosols thus it had to be liquid, hygroscopic, moderately viscous and of similar size.

2 Research methods

The Building Technology Laboratory of the HSLU operates a test rig for heat recovery devices. In Figure 1 the scheme of the test rig is shown. In all four air streams temperature, humidity, air flow rate and tracer gas concentration can be measured. For the aerosol measurements, a particle generator was installed in the exhaust air inlet duct and additional measuring devices in all four air streams. In addition, the ambient conditions were measured.

Test objects were two RHEs with a free diameter of 1000 mm: a condensation rotor (aluminium) and a sorption rotor (aluminium with molecular sieve coating). With the diameter of 1000 mm the nominal airflow is between 1'400 to 4'199 m^3/h for a face velocity of 1 – 3 m/s under standard conditions. On both sides air inlet temperatures were 20°C ± 1K and air inlet humidity 40% RH ± 10% RH.

The transfer of tracer gas and aerosols was measured by dosing up the exhaust air. In order to make a conclusion of the aerosol transmission, the EATR and the aerosol transfer ratio (ATR) were determined and compared. In this first round of experiments, the RHEs were installed in the test casing without a purge sector.

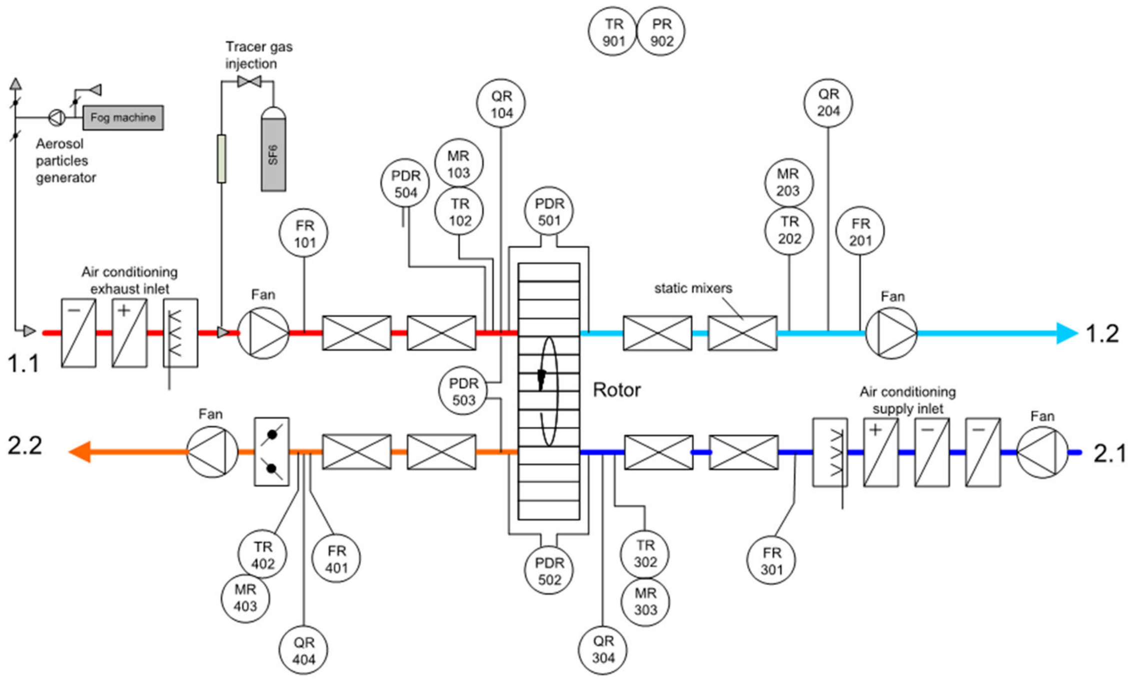

Fig. 1 - Scheme of the test rig for heat recovery devices. Symbols: **first letter** F air flow rate, P pressure, T temperature, M humidity, Q concentration; **subsequent letter** D difference; **auxiliary letter** R registration; **air flow type** 1.1 exhaust inlet, 1.2 exhaust outlet; 2.1 supply inlet, 2.2 supply outlet

2.1 *Exhaust Air Transfer Ratio (EATR)*

The EATR was measured based on EN 308:2021 [5] by injecting Sulphur Hexafluoride (SF_6) tracer gas in the duct of the exhaust air inlet. The SF_6 concentration was subsequently determined with a photoacoustic IR-gas monitor with a multipoint sampler in exhaust air inlet, supply air inlet and supply air outlet . The EATR can be calculated with the following formula:

$$EATR = \frac{a_{22} - a_{21}}{a_{11} - a_{21}} \times 100\ [\%] \qquad (1)$$

where

a_{11} is SF_6 concentration exhaust inlet [ppm],
a_{21} is SF_6 concentration supply inlet [ppm],
a_{22} is SF_6 concentration supply outlet [ppm].

In the given measurement range, a relative measurement uncertainty of the EATR between 3 and 5% is typical. In the sense of a rather conservative estimate, 5% relative is used in the evaluation.

2.2 *Aerosol Transfer Ratio (ATR)*

The test setup for the ATR measurements was done in the same way as for the EATR measurements. Two aerosol measuring devices were installed in each of the four air streams. The sensors count the particulate matter based on laser scattering in a size of 0.3 to 10 µm. To keep the aerosol concentration in the supply inlet air as low as possible, the installed filters of the class ISO ePM1 50% (F7) were replaced with HEPA filters H14. During the measurement, aerosol was applied in pulses in the duct of the exhaust inlet air. The aerosol used has an average diameter of just over one micrometer and is therefore comparable in size to exhaled aerosol [6]. The aerosol, like human exhaled aerosol, is liquid at normal ambient temperatures. It is produced by evaporation and condensation of a water-glycol mixture by a fog machine and is stable in air for a longer time [7]. The mixture used in the studies consists of triethylene glycol, monopropy-lene glycol and dipropylene glycol. The maximum peak heights at exhaust air inlet, supply air inlet and outlet were used for evaluation according following formula:

$$ATR = \frac{b_{22} - b_{21}}{b_{11} - b_{21}} \times 100\ [\%] \qquad (2)$$

where

b_{11} is peak PM10 exhaust inlet [P/cm^3],
b_{21} is peak PM10 supply inlet [P/cm^3],
b_{22} is peak PM10 supply outlet [P/cm^3].

The measurement uncertainty was determined with the device-to-device variability after internal cross-correction for the test aerosol for the number of PM10. With this method, the relative measurement uncertainty for applications such as indoor measurements is given as 3%. For the new application in the test rig for heat recovery components, a relative measurement uncertainty of 10% is used as a conservative estimate in the evaluation.

3 Results

3.1 *Condensation rotary heat exchanger*

Table 1 shows the results of the condensation RHE. The measurements were conducted with three different air face velocities (v) of 1, 2 and 3 m/s. Rotor speed (n) was 20 rpm and pressure difference between supply outlet and exhaust inlet ($\Delta p_{22\text{-}11}$) 10 Pa. One additional measuring point with a difference of 250 Pa between supply outlet and exhaust inlet was conducted. In the project, additional measurements were made to determine the ATR without determining the EATR under the same conditions. These results are not presented.

Tab. 1 – Results EATR and ATR, condensation wheel

MP	v	n	$\Delta p_{22\text{-}11}$	EATR	ATR
-	m/s	rpm	Pa	%	%
1.1	1	20	10	10.4	7.5
1.2	2	20	10	4.7	3.8
1.3	3	20	10	3.3	2.4
1.4	3	20	250	2.6	1.6

Figure 2 shows that at all four measuring points (MP) the ATR value is below the EATR value. The difference is clearly higher than the measurement uncertainty.

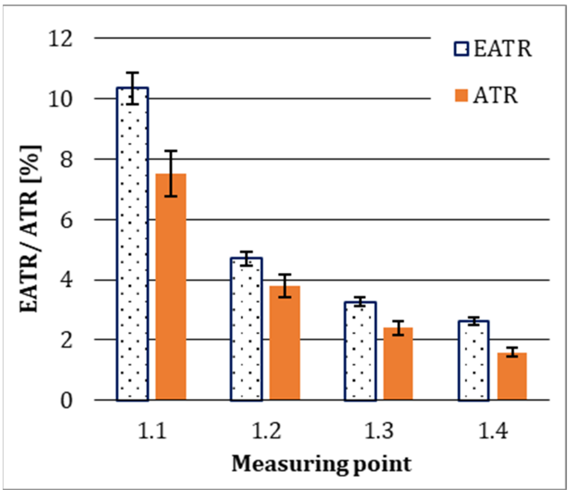

Fig. 2 - Results EATR and ATR, condensation wheel at isothermal condition 20°C, 40% RH

3.2 *Sorption rotary heat exchanger*

As with the condensation RHE, measurements with the sorption RHE were carried out at three different face air velocities. Pressure difference between supply outlet and exhaust inlet were 10 Pa. With the sorption RHE additional to the measurements with 20 rpm, measurements with 10 rpm rotor speed were conducted. Table 2 shows the results of the sorption RHE.

Tab. 2 – Results EATR and ATR, sorption wheel

MP	*v*	*n*	$\Delta p_{22\text{-}11}$	EATR	ATR
-	m/s	rpm	Pa	%	%
2.1	1	20	10	8.2	6.3
2.2	2	20	10	4.7	2.7
2.3	3	20	10	3.2	1.7
2.4	1	10	10	4.5	2.8
2.5	2	10	10	2.3	0.9
2.6	3	10	10	1.5	0.6

Comparable to the results of the condensation RHE Figure 3 shows that also with the sorption RHE at all six measuring points the ATR value is below the EATR value.

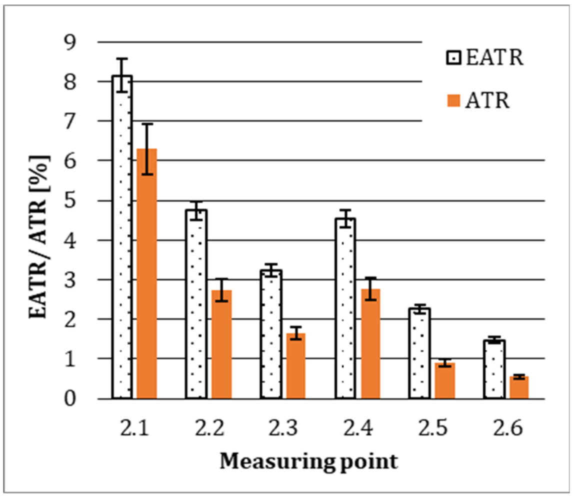

Fig. 3 - Results EATR and ATR, sorption wheel isothermal condition 20°C, 40% RH

4 Discussion

4.1 Significance of the results

AHUs that comply with the European Ecodesign Regulation [1] are typically designed for a face velocity (related to the inner cross-sectional area of the casing) of about 1.6 to 1.8 m/s at nominal air flow rate. Since the face area of the of the RHE is about 10 to 20% smaller than the cross-sectional area of the AHU, the nominal face velocity of a RHE is typical approx. 2 m/s. In applications such as office buildings and schools, face velocities in the range of about 1 m/s often occur in partial load operation mode. On the other hand, the REHVA COVID-19 guideline recommends not using partial load operation in pandemic situations. Therefore, the measured EATR and ATR at 2 m/s are considered for the infection risk assessment.

For condensation RHEs the rotor speed is in a range of 10 to 20 rpm, depending on design characteristics, e.g. foil thickness. For sorption RHEs 20 rpm can be seen as typical speed. Therefore, for the contamination risk assessment for both RHE types the measured values at 20 rpm are chosen and rounded up to the nearest integer percentage. This is to be understood as a rather conservative estimate for the two investigated RHEs. For the calculation of the contamination risk the following values are used:

- EATR for both RHE types 5%
- ATR for condensation RHE 4%
- ATR for sorption RHE 3%

It goes without saying that these data are valid only for the tested RHE when using this specific fog aerosol. They should not be taken as universally valid in the current state of knowledge. Nevertheless, the two RHEs examined are real products that are judged to be typical in a market comparison.

The draft revision of the European Ecodesign Regulation from [8] serves as a comparison. In this draft a maximum EATR at nominal flow and nominal pressure of 5% is required. With reference to this source, a maximum EATR of 5% can be considered state of the art.

However, for hygienically sensitive applications, such as public buildings, the authors recommend taking measures to achieve a lower EATR. For RHE with a purge sector, an EATR below 0.5% can be achieved.

4.2 State of the art in filters

In German speaking countries the VDI 6022-1 [9] is considered reflecting the state of the art. The minimum filter class for supply air is ISO ePM1 50%. The extract air before entering a RHE shall pass a filter of class ISO ePM10 50%. As general estimation for the separation efficiency of lung aerosols the gravimetric arrestance of the filters up to a particle size of PM10 can be used:

- For class ISO ePM1 50%: 85% [10]
- For class ISO ePM10 50%: 50%
  (by definition of the class)

A typical solution is that in the outdoor air (before entering the RHE) and in the extract air (before entering the RHE) an ISO ePM1 50% filter is placed. Thus, the potentially contaminated air passes through only one filter.

4.3 Estimation of the ATR including filter

The aerosol transfer ratio of an AHU ATR_{AHU} can be estimated as follow:

$$ATR_{AHU} = ATR_{RHE} \cdot (1 - f_{F,eta}) \cdot (1 - f_{F,sup}) \qquad (3)$$

where

ATR_{RHE} is the ATR of the RHE, acc. to Equation (2),

$f_{F,eta}$ is the separation efficiency of lung aerosols of an extract air filter (positioned before RHE),

$f_{F,sup}$ is the separation efficiency of lung aerosols of a supply air filter (positioned after RHE).

With the values shown in chapters 4.1 and 4.2, an ISO ePM1 50% filter in extract air and no additional filter in supply air, the result is an $APTR_{AHU}$ of approx. 0.005 to 0.006 or 0.5% to 0.6% respectively. This applies to RHEs without purge sectors. With purge sector, values 10 times lower can be achieved without problems. In addition, the ATR can be halved again if, for example, an ISO ePM10 50% filter is also used on the extract air side combined with an ISO ePM10 50% filter in supply air.

4.4 Estimation of the infection risk

The amount of virus released into the air can be done by combining the concentration of viruses in the lung lining liquid with the size-distribution of micro-droplets released during breathing and speaking and by taking into account the proportion that sediments rapidly [11]. To estimate the viral concentration at steady state in different situations, we used an indoor scenario simulator that is based on this emission concept [12]. In all the calculated scenarios, we assumed that a very contagious person (a so-called super-emitter) is in a room of 100 m³ volume and 3 air changes per hour. We then simulated a quiet office, a loud office (e.g. call centre) and a hospital situation with coughing COVID-19 patients. We further assumed that 1000 people are in this building with a ventilation flow rate of 30'000 m³/h. For the general population, a very high infection rate of 1% is assumed, for the hospital wing with COVID-19 patients a rate of 50% (50% patients, 50% staff). Table 3 summaries the simulated virus concentrations in these scenarios in the individual rooms and in the extract air of the building.

The concentrations indicate viral copies as assessed by RNA assays. For the Delta variant about 1 in 300 and for the Omicron variant about 1 in 100 of these copies was found to be able to infect cells [13]. Thus, doses above 300 or even only 100 virus-copies seems to be critical for viral infections. This is supported by simulation of super-spreading events where the virus dose (the amount taken up) was estimated in the range of a few thousand viruses.

Tab. 3 – Simulated virus concentrations (copies/m³) in individual rooms and in the extract air in different scenarios.

Scenario	*Infection rate*	*Steady state in room*	*Extract air*
	%	*Copies /m³*	*Copies /m³*
Quiet office	1	1200	1.2
Call centre	1	40'000	40
Hospital, COVID section	50	500'000	250'000

For the example of the call centre, it can be said that with the aerosol transfer ratio of an air handling unit of 0.6% shown in 4.1 and the virus concentrations in the extract air according to Table 3, the virus concentration in the supply air is 0.2 copies/m³. Even if the personnel directly inhale the supply air during an 8-hour shift (breathing air volume 0.6 m³/h), the amount of inhaled viruses is two orders of magnitude below the critical value for an infection risk. However, in a hospital situation with many highly emitting patients, the situation could rapidly become critical. Thus, the recommendation to use heat recovery systems without any risk of exhaust air transfer to supply air (e.g. tight plate heat exchanges or run around coil systems) [14] in such settings is well warranted.

Eurovent 6/15 - 2021 [15] deals comprehensively and in detail with the prevention of air leakage in air handling units. According to this, an elementary measure is to ensure correct pressure conditions in air handling units. This depends primarily on the fan positions. For hygienically sensitive applications, a purge sector is also recommended. AHUs operated with proper pressure conditions and well-designed purge sectors can achieve an EATR of practically zero.

It should be mentioned that the risk of exhaust air transfer also exists with other leakages in AHUs and ventilation systems that are not the subject of this paper.

5 Conclusion and outlook

The project investigated how aerosols, which behave similarly to human lung aerosols, are transferred in rotary heat exchangers without a purge sector under isothermal conditions. In the measurements on a condensation rotor, the exhaust air transfer ratio of the aerosols was around 1 percentage point lower than the exhaust air transfer ratio (EATR) of tracer gas. For a sorption rotor it was 2 percentage points lower. The results suggest that there is no risk of the used aerosols being transferred through the matrix with these rotary heat exchangers.

However, further investigations are needed to generalise the statement. In particular, we are interested in whether this also applies to different air conditions (temperature and humidity) and which transfer ratios result with purge section. For validation, measurements with additional products are also of interest. In the follow-up project further measurements were carried out, but these had not yet been completed when this paper was submitted. These results are expected to be available in spring 2022.

6 Acknowledgment

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The data sets analyzed in this study are not publicly available because they are private measurements, but the authors can provide excerpts upon request if necessary.