A review of experimental methods to determine bioaerosol transfer in energy recovery ventilators

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Abstract

Increasing ventilation is an effective method to reduce indoor airborne disease transmission. An Energy recovery ventilator (ERV) is a passive energy recovery device used to reduce the energy consumption of heating, ventilation and air-conditioning (HVAC) systems for conditioning the ventilation air. It preconditions the ventilation air by transferring energy from building exhaust air. Therefore, the ventilation and exhaust air streams interact directly/indirectly in the ERV for energy transfer. It is surmised that the ERV may transfer bioaerosols (with pathogens) from the exhaust air to ventilation air, resulting in the spread of infectious diseases. Consequently, many pandemic HVAC guidelines recommend that the use of ERVs be limited. This is a highly unsustainable direction given the increased energy requirements associated with the high ventilation provision advocated for pandemic operation. It must be noted that no validated experimental evidence exists in literature for bioaerosol transfer in ERVs. Hence, it is necessary to conduct extensive bioaerosol transfer research before adopting the unsustainable practice of limiting the utilization of ERVs. The main objective of this review study is to summarize the experimental methods and instrumentation for bioaerosol transfer research in ERVs. This comprehensive article provides a detailed overview of the generation, sampling, and analysis of bioaerosols for conducting the experiments. Further, it explains the possible mechanisms for bioaerosol transfer in various types of ERVs based on which the ERVs that need immediate attention are identified. The main contribution of this research paper is that it provides a novel experimental method which encompasses the biosafety aspects, instrumentation, performance parameters and uncertainties in conducting virus contained bioaerosol transfer study in ERVs. The findings from this review will be helpful in designing bioaerosol transfer experiments and developing future ERV test standards for such experiments.

Keywords: Energy recovery exchangers, bio-aerosol, experimental design and analysis, pandemic ventilation

Nomenclature

ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
BTR	Bio-aerosol transfer ratio
C	Concentration
C*	Heat capacity ratio
COP	Coefficient of Performance
EA	Exhaust airside
EATR	Exhaust air transfer ratio
ERV	Energy recovery ventilators
ESP	Electrostatic precipitator
EX	Exchangers
FBR	Fixed-bed regenerator
GTC	Condensational growth tube collector
HEPA	High-efficiency particulate air
HVAC	Heating, ventilation and air conditioning
ISHRAE	Indian Society of Heating, Refrigerating and Air Conditioning Engineers
LAMEE	Liquid-to-air membrane energy exchanger
$\dot{m}$	Mass flow rate (kg/s)
NTU	Number of Transfer Units
OA	Outdoor air
OAS	Optical aerosol spectrometers
P	Pressure
PCR	Polymerase chain reaction
PFU	Plaque-forming units
RA	Return airside
RAMEE	Runaround membrane energy exchanger
REHVA	Federation of European Heating, Ventilation and Air Conditioning Association
RH	Relative humidity
RT-PCR	Real-time PCR technique
SA	Supply airside
U	Uncertainty
VOC	Volatile Organic Compound
WHO	World Health Organization

Greek letters

δ	Maximum deviation of the measurement from its mean value
ω	Humidity ratio (kg of water/ kg of dry air)

Subscripts

min	Minimum

1. Introduction

The substantial growth in the population, rapid urbanization, and development of international transport infrastructure witnessed at a global level have led to the rapid transmission of infectious diseases both within and across countries. This is evident in the outbreak of the unprecedented COVID-19 pandemic, which has become one of the most dangerous health threats in world history. As per the World Health Organization (WHO), there are 767,984,989 confirmed cases of COVID-19 globally, including 6,943,390 deaths as of June 15, 2023 [1]. Infectious diseases like COVID-19 not only affect public well-being (physical as well as mental health) but also lead to substantial economic loss and significant changes in the functioning of society, such as people's behavior, lifestyle, etc.

Outbreaks of pandemic diseases are not new to the world. A plague outbreak caused by the flea-borne bacteria Yersinia pestis killed around 100 million people in the Roman Empire between 541 and 543 AD. A recent review reported that the world faced 17 major pandemics before COVID-19 [2]. However, not much importance has been accorded to airborne transmission which is one of the major modes of disease transmission. This is attributed to the difficulty in traceability, lack of research studies and continual misunderstanding. Generally, there are inconsistencies while addressing the different sources of environmental infections. Greater attention has been given to waterborne and foodborne transmission modes compared to the airborne transmission of diseases. This is evident from the large number of well-established standards for food and water processing (including wastewater and sewage) and professional government officials to oversee food and water quality [3]. It is imperative that airborne transmission be accorded attention equal to that of foodborne and waterborne infections to ensure public safety and the well-being of society.

Ventilation plays a crucial role in providing good quality air and mitigating airborne transmission in an enclosed space, as shown in Figure 1 [4], [5]. It can be an effective engineering control measure when designed properly. There are studies documented in literature establishing the direct relationship between improper ventilation and disease transmission [6], [7]. Hence, to ensure an effective ventilation system to control the airborne transmission of infectious diseases, countries include recommendations about ventilation in all the 17 pandemic guidelines [8]. In the ventilation technique, the outdoor airflow rate is increased to dilute the concentration of infectious aerosols indoors, thereby minimizing disease transmission. However, increasing the supply of outdoor air is not feasible if the prevailing climatic conditions are far away from human comfort conditions. For example, the average monthly temperature in Saskatoon, Canada is -9°C in winter (January) and in Mumbai, India is 30°C during summer (May) [9]. Supply of ventilation air at these extreme outdoor conditions will lead to an uncomfortable indoor environment which can cause thermal stress to the occupants. The thermal stress may be life-threatening and can also lower human resistance to infection [10]. Hence, it is essential to condition the outdoor air before supplying it to an indoor environment. However, this increases the energy consumption of heating, ventilation and air conditioning (HVAC) systems.

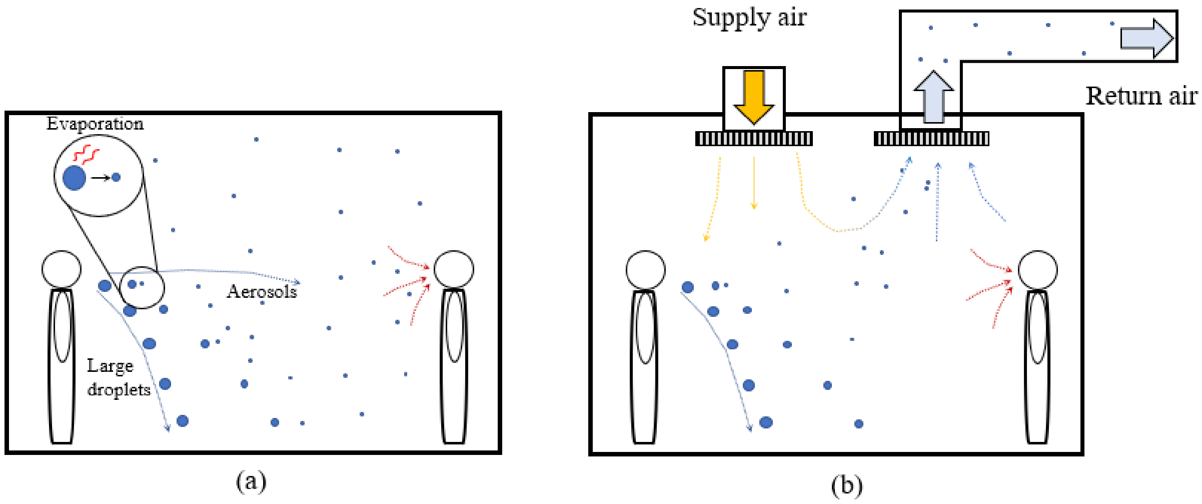


Figure 1: (a) Infectious aerosols from an individual can vary in size from micrometer to nanometer-sized particles. Secondary nanometer-size aerosols are further generated from the large droplets due to evaporation. These can infect individuals even at a significant distance apart in enclosed spaces where the air replacement is poor and (b) Ventilation decreases the aerosol concentration by fresh air dilution and exhaustion of room air, reducing the probability of infection [4], [5].

The most common pandemic guidelines of HVAC systems, in addition to ventilation, are (i) avoiding recirculation which in turn averts the possibility of pathogen transfer across the air-conditioned rooms of a building and (ii) increasing operating time to increase the air change per hour which reduces the concentration of infectious aerosols indoors. However, all these guidelines significantly increase the energy consumption of HVAC systems. The increase depends on the prevailing climatic conditions and operational conditions of the building. A study assessing the climatic conditions of China predicted that the increase in energy consumption of buildings was likely to be as high as 140% [4]. Thus, energy conservation is essential to achieve sustainability (specific to Sustainable Development Goals: 7.3 “Energy Efficiency” and 11.6 “Air Quality”) of HVAC systems while providing adequate ventilation.

There are different passive techniques available to reduce the energy consumption of HVAC systems during pandemic operation which ideally requires 100% fresh air supply. In general, the passive cooling/heating techniques use low/high temperature natural resources as a heat sink/source and thereby condition the ventilation air with least energy input. For example, the earth air heat exchanger uses the low temperature ground as a heat sink during summer in order to lower the temperature of the supply ventilation air. After a certain depth, the ground temperature is almost constant throughout the year. Of late, radiative cooling technique is gaining more popularity; it uses the sky as a heat sink. This technique uses spectrally selective surfaces/films, which have the ability to achieve a sub-atmospheric temperature due to long wave irradiation into the sky and can be used to cool the ventilation air. Evaporative cooling is another passive technique that reduces the temperature of non-saturated air by evaporating the water present in it due to humidity difference. The recent development of dew-point evaporative coolers has significant potential to reduce the temperature of the ventilation air depending on the prevailing climatic condition [11], [12].

Energy recovery ventilator (ERV) is a passive energy recovery device that can be used to reduce the energy consumption of an HVAC system. Table 1 shows the energy savings or HVAC system performance improvement by using different types of ERVs. It also reduces operating costs, especially during pandemic operations when the required ventilation rate is substantially higher than normal operating times. In ERV, the energy from the exhaust air is used to precondition the fresh outdoor ventilation air. While exchanging energy between exhaust and supply airstreams, it is likely that bio-aerosols/contaminants or other indoor pollutants may be transferred due to the cross-contamination (with or without mixing of exhaust and supply air streams). For Volatile Organic Compounds (VOCs) and other pollutants, it is evident from literature that cross-contamination occurs due to carryover, leakage, adsorption/desorption, evaporation/condensation, and absorption. Hence, the operation of ERVs may lead to the transfer of bioaerosols (a type of airborne material that has microorganisms originating from living organisms) from the exhaust air to the fresh ventilation air entering the building, similar to that of VOCs and other pollutants. Consequently, it may lead to transmission of infectious disease-causing pathogens in the building. ERVs components such as desiccant coating (in enthalpy wheels and fixed-bed regenerators) and porous or dense membranes (in membrane exchangers) have crucial role in the contaminant/aerosol transfer.

During the COVID 19 pandemic situation, a majority of standards and certification agencies recommended limiting the use of energy recovery ventilators due to the possibility of cross-contamination of bioaerosols through the ERVs [4], [8]. However, there is a distinct lack of experimental / field evidence available in the open literature. Therefore, it is necessary to conduct the relevant experimentations on ERVs before following the unsustainable practice of bypassing or operating ERV with constraints, as prescribed in many pandemic HVAC guidelines [4], [8]. This identified research gap forms the motivation for the present study.

Table 1: Energy savings and performance improvement of HVAC systems on using different ERVs

Type of ERV	Performance improvement	Operating condition	Type of study
Heat pipes [13]	Effectiveness = 43% - 63%	OA temperature: 30°C - 45°C RA temperature: 30°C	Field study
Membrane energy recovery ventilator [14]	Reduction in energy consumption: Heating: 30% Cooling: 20%	Winter RA temperature: 20°C Summer RA temperature: 28°C Winter OA temperature: 6-9°C Summer OA temperature: 32-36°C	Field study
Fixed bed regenerator [15]	Energy saving: 18.7 MJ/day for a 210 m^2 floor area	RA temperature: 24°C OA temp: -35 to 0°C	Field study
Energy wheels [16]	COP: 1.5 - 8.2	16°C temperature difference between indoor and outdoor	Field study
Runaround Membrane Energy Exchanger [17]	Decrease in heating energy: 60% Decrease in cooling energy: 4%	Summer RA temperature: 24°C Winter RA temperature: 22°C City: Saskatoon	Computer simulation - TRNSYS and MATLAB
Thermosiphon [18]	Heating energy saving: 65%	Indoor temperature: 20°C to 25°C City: Lhasa	Computer simulation - DeST-c software

The main objective of this work is to summarize the available experimental instrumentation for bioaerosol transfer studies and propose a test method to quantify the transfer of bioaerosols in ERVs. A new performance parameter is proposed along with the test methods and uncertainty bounds for the experiments. Unlike conventional heat and mass transfer performance testing, the tests to determine the transfer of aerosols in ERVs are quite different and challenging due to the instrumentation, material preparation, need for accuracy, reliability, and safety requirements. This review article summarizes the available experimental approaches and information to address the aforementioned challenges in the bioaerosol transfer tests in

ERVs. To the best of the authors' knowledge, there is no literature available on this novel and multi-disciplinary research topic except a very preliminary study by Shirey et al. [19]. Hence, the authors believe that the proposed experiments, instrumentation and performance parameters would be useful in designing and conducting bioaerosol transfer experiments in ERVs, and also for framing test standards (such as ASHRAE 84) for ERVs.

2. Current Status, Challenges and Future Direction of Energy Recovery Exchangers

It has been proven that the energy recovery ventilator (ERV) can significantly reduce the energy consumed by HVAC systems. As a result of the high energy-saving potential, several types of ERVs have been developed over the last decade. HVAC systems have adopted various types of ERVs to reduce their energy consumption [20], [21]. Energy wheels and plate exchangers have been used for decades, while fixed-bed regenerators and run-around membrane energy exchangers are relatively new for building energy recovery applications [22], [23]. A majority of the current research work on ERVs focuses on the geometry [24], extreme climate performance [25], alternative testing methods [26]–[28], and new desiccant materials [29]–[31].

It is well known that ERVs are one of the most efficient methods for ensuring decarbonization and sustainability of HVAC systems. However, there are evidences documented in literature that while transferring energy, ERVs may transfer contaminants from the exhaust into the supply air [32]–[34]. Studies have shown that cross-contamination is an unavoidable phenomenon that depends on the chemical and physical properties of the contaminants [35], [36]. Consequently, the applications of ERVs are rather restricted, particularly during the pandemic operation of the HVAC system. This is because the transfer of biological contaminants (i.e. bio-aerosols) in ERVs may lead to the transfer of infectious pathogens from the source room to the connected rooms of a building, as shown in Figure 2. Hence, the ERV is either not recommended or recommended with constraints in the pandemic HVAC guidelines drawn up by different countries, as listed in Table 2.

In order to ensure its future applications, ERVs should be installed and operated without compromising indoor air quality, which is directly related to the health and productivity of occupants. It is evident that disease transmission through ERV is possible if there is bioaerosol transfer. However, there is no detailed experimental evidence of such transfer in most types of ERVs. Shirey et al. [19] studied the transfer of T1 E. coli phage in the energy wheel (a type of ERV) for research lab application (i.e. tested at the US National Cancer Institute). The results showed that the wheel had less than 0.1% transfer of bioaerosols. The authors concluded that the biological risk due to this transfer was very minimal. There is no literature evidence for the bioaerosol transfer in other types of ERVs. Hence, it is essential to quantify the bioaerosol transfer in ERVs and if there is any transfer, then research should focus on mitigating the transfer to develop sustainable HVAC systems utilizing ERVs for providing ventilation in an energy-efficient manner.

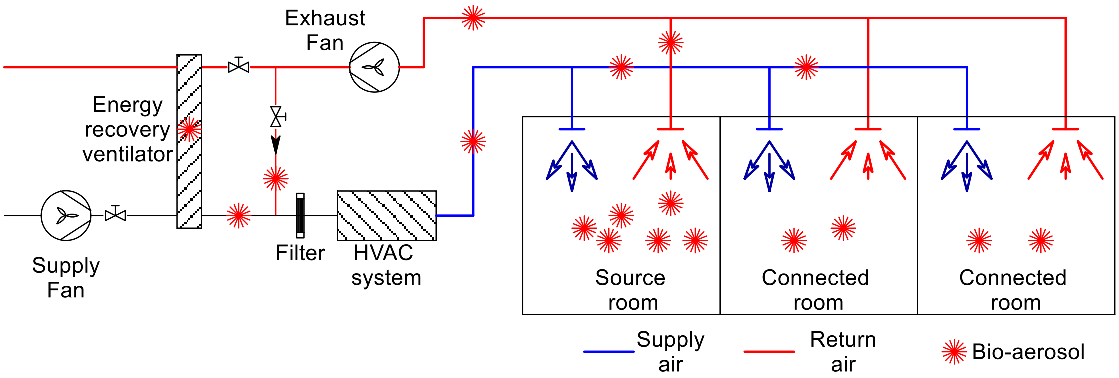


Figure 2: Bio-aerosols from the source room (has an infected induvial) can be transferred to the connected rooms through recirculated air and energy recovery ventilators (ERV). This transfer may lead to disease transmission across different rooms of a building.

Table 2: Recommendations for ERVs in HVAC pandemic guidelines

Association	Date	Document	Guideline
American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE)	April, 2020	ASHRAE Position Document on Infectious Aerosols [10]	ERV must be bypassed to prevent leakage of infectious building return air to the supply air
	June, 2020	Practical Guidance for Epidemic Operation of Energy Recovery Ventilation Systems [37]	ERVs can remain operational in commercial and residential facilities provided they are well-designed and maintained. This document provides detailed guidelines for pandemic operation
Federation of European Heating, Ventilation and Air	March, 2020	REHVA COVID-19 guidance document version 1 [38]	Rotary wheels must be temporarily turned off during the occurrence of SARS-COV-2 outbreak

Conditioning Associations (REHVA) / European Centre for Disease Prevention and Control	April, 2020	REHVA COVID-19 guidance document version 2 [39]	• Energy recovery devices such as membrane energy exchangers that are able to completely separate the return and supply air are less prone to virus transmission compared to regenerators such as rotary wheels • Rotary wheels need not necessarily be switched off during pandemics as the wheel speed does not impact leakage • Carry-over leakage can be reduced by increasing the outdoor ventilation rate • Regenerators can be used with purge sections and good sealing • A threshold leakage of 5% is allowed in existing systems provided the outdoor ventilation rate is increased • Leakage to supply air is mainly caused by higher pressure of the exhaust air. This can be mitigated by bypassing the recovery section or using dampers to control the pressure differences
	August, 2020	REHVA COVID-19 guidance document version 3 [40]	Guidelines remain the same as in the version 2 document. In addition, some additional guidelines to reduce internal air leakages in rotary wheels are provided
	April, 2021	REHVA COVID-19 guidance document version 4 [41]	Guidelines remain the same as in the version 2 or and version 3 documents. Additional guidelines about membrane-based ERV are added in the appendix
Society of Heating, Air-Conditioning and Sanitary Engineers of Japan	May, 2020	Operation of air-conditioning equipment and other facilities for SARS-CoV-2 infectious disease control [42]	Leakage of return air to supply air must be maintained below 5% and the outdoor ventilation rate must be kept high. In addition, the return side air pressure must be lower than the supply air pressure
Canadian Committee on	August, 2020	Addressing COVID-19 in	ERVs that can completely prevent leaks with added measures such as favorable

Indoor Air Quality		Buildings version 1 [43]	pressure difference and filters must be employed. However, it is recommended to bypass the ERVs
	June, 2021	Addressing COVID-19 in Buildings version 2 [44]	Guidelines remain unchanged with respect to version 1
The Architectural Society of China	February, 2020	Guidelines for office buildings to deal with “new coronavirus” operational management emergency measures [45]	ERVs that cannot completely separate the return and supply air (such as rotary wheels and membrane ERVs) should be bypassed. In the absence of bypass valves, the fresh air supply must be switched on and the return air fan must be switched off. Building pressure must be maintained by natural ventilation or other means
Indian Society of Heating, Refrigerating and Air Conditioning Engineers (ISHRAE)	April, 2020	ISHRAE COVID-19 Guidance Document for Air Conditioning and Ventilation [46]	Rotary wheels must be switched off to prevent leakage

ASHRAE Standard 84 [47] provides recommendations for quantifying the transfer of contaminants in ERVs. However, it was originally developed in order to quantify the transfer of inert tracer gases (such as SF_6) due to leakage in the supply and exhaust sides of ERVs. In addition, the instrumentation, tracer chemical, injection, and measurement methods of gaseous contaminants are significantly different from those for biological contaminants (i.e., bio-aerosols). Therefore, experimental methods should be developed to quantify the bioaerosol transfer in ERVs. Hence, this paper provides the necessary background and guidelines for HVAC researchers to design and analyze the bioaerosol transfer in various types of ERVs.

3. Types of ERVs

It is necessary to understand the operation of ERVs to identify the mechanisms and analyze the bioaerosol transfer between air streams. ERVs are broadly divided into recuperators and regenerators based on their principle of operation. In regenerators, the outdoor air and return air flow alternatively through the exchanger, and they exchange the heat/energy with the exchanger. Regenerators can be further divided into rotary wheels and fixed-bed regenerators based on their configuration. Recuperators simultaneously exchange heat/energy between the air streams through a dividing plate or a membrane. Plate, tubular, and membrane-type exchangers are examples of recuperators [48], [49]. The operating principle of most common ERVs is explained in the following subsections. It should be noted that most recent research studies on heat and mass transfer exchangers mainly focus on heat transfer augmentation [50]–[52], effect of innovative flow channel configurations [53]–[56] on heat transfer coefficients and pressure drop, and evaluation of flow structure and its impact on thermo-hydraulic performance [56]–[58]. New advancements in the materials and geometry help to develop high-performance ERVs with minimum material/size requirements.

3.1 Rotary wheel

Rotary wheels can be categorized into heat wheels, enthalpy wheels, and desiccant wheels based on their applications. Enthalpy wheels are desiccant-coated wheels in which heat and moisture are transferred between the supply and exhaust airstreams during their rotation. The typical rotational speed is 15-20 rpm. Aluminum is the commonly used base material (substrate) with silica gel or molecular sieve desiccants. Enthalpy wheels are loaded with a lesser amount of desiccants and are designed to operate between 30-60% RH conditions. Desiccant wheels are solely used for humidity control or drying applications. Typically, they are made of silica gel desiccant with a fiberglass substrate. Compared to energy wheels, these wheels are loaded with a higher quantity of desiccants, which results in high dehumidification capacity. Furthermore, the desiccant wheel requires a heat source for regenerating the desiccants (or removing the water vapor).

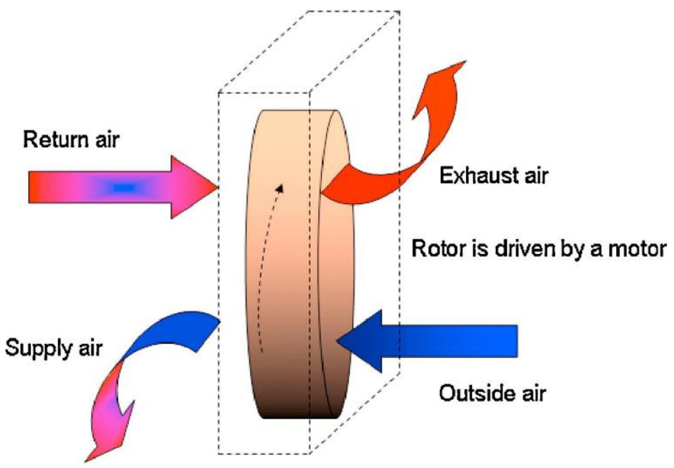


Figure 3: Schematic of rotary wheel for heat or energy recovery between air streams. Rotor is driven by a motor and coated with a desiccant for energy recovery [60].

Usually, desiccant wheels operate at a very low speed of 15-20 rph. Heat wheels are identical to enthalpy wheels except for the fact that they do not have any desiccant coating and are primarily used for heat exchange applications. As the wheel rotates, the heat and/or moisture is continuously transferred between the supply and exhaust airstreams, as shown in Figure 3. When hot and humid air (outdoor air in summer and return air in winter) flows through the wheel, the heat and/or moisture are transferred and get stored in the matrix. As the wheel rotates, the matrix is exposed to the cold and dry air stream, and then the stored heat and/or moisture is released. This process is repeated for continuous heat/energy recovery [49], [59], [60].

3.2 Fixed-bed regenerator

Fixed-bed regenerator (FBR) is a stationary type of ERV that stores and releases only heat or heat and moisture (depending on the presence of desiccant coating) intermittently with the incoming airstreams. The schematic of a FBR with two stationary exchangers (EX 1 and EX 2), dampers, and supply and exhaust fans is shown in Figure 4. The dampers are used to change the direction of airflow through the exchangers. The exchangers are preferably made of corrugated metal plates to achieve (i) a higher surface area for a given volume and (ii) a high convective heat transfer coefficient. In FBRs, heat transfer surface area densities of 82,000 m^2/m^3 are achievable; the typical heat transfer coefficient range is 50 to 200 W/ m^2.K, according to Shaha and Sekulic [61]. The plates are coated with a desiccant for energy recovery [22], [62].

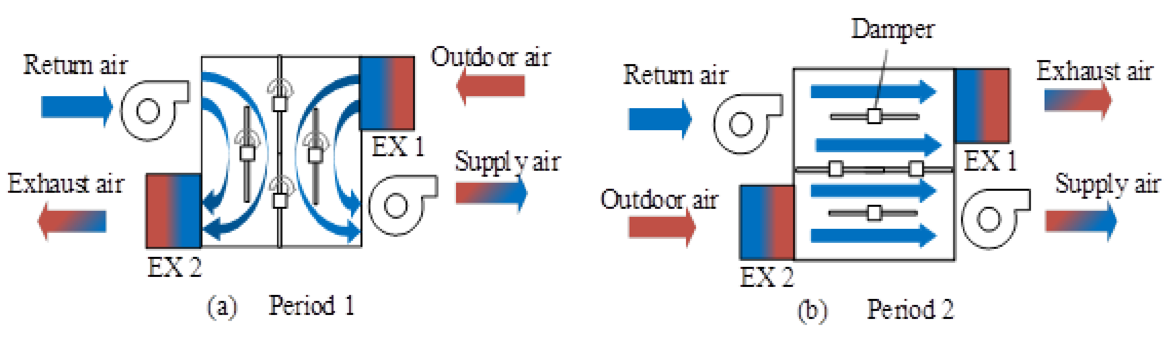


Figure 4: Schematic of fixed-bed regenerator (FBRs) with two stationary exchangers. Energy stored in exchanger (EX) 2 in period 1 is used to condition the outdoor air in period 2 [62].

One complete operational cycle of the FBR comprises of two periods. During the first period of energy recovery, hot and humid outdoor air (during summer climatic conditions) flows through EX 1 and heat and moisture from the outdoor air get stored in the desiccant-coated plates. As a result, the air at the FBR outlet (supply air) is cold and dry. During the beginning of the second period, the damper rotates to 90° (Figure 4(b)), redirecting the return air through EX 1, which releases the heat and moisture stored during the previous period to the airstream. Both exchangers work simultaneously for continuous energy recovery [22], [62].

3.3 Plate exchanger

Plate exchanger is made by stacking several thin metallic plates together to form flow channels, they exchange only heat between the air streams. The metallic plates can be flat or corrugated and the flow configurations can be parallel flow, counterflow, or crossflow, depending on the requirement. Figure 5 shows the schematic of a plate heat exchanger. Generally, this type of exchanger is a non-contact type, and its sensible effectiveness is highly dependent on the geometry and the material of the plate. The major disadvantage of plate heat exchangers is fouling and clogging over time which in turn reduces the effectiveness of heat recovery [24], [60], [63].

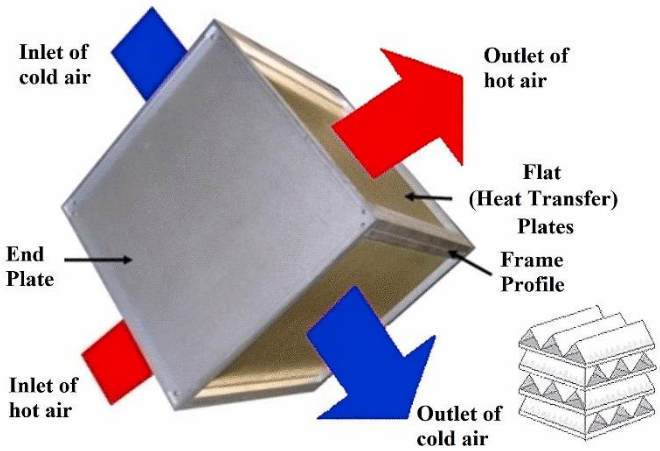


Figure 5: Schematic of counter flow plate exchanger for heat recovery between air streams [63].

3.4 Membrane exchanger

The construction and operation of membrane exchangers (Figure 6) are very similar to the plate exchanger, except for the use of porous/dense membranes instead of metallic plates. The membranes allow the transfer of moisture in addition to heat. The membrane exchangers are less susceptible to frost formation compared to plate exchangers [64]–[66].

3.5 Heat pipe

Heat pipe transfers heat from one side to the other using the pressure generated by the temperature difference. It consists of individual closed tubes filled with a wick and working fluid, as shown in Figure 7. When a heat source generates heat, the fluid vaporizes (evaporator section) and moves to the other end of the heat pipe, using pressure generated by the temperature difference. At the condenser section, the fluid gives up the stored heat which is rejected to the sink in the form of latent energy (condensation). Then, the working fluid returns to liquid form and moves to the evaporation section through the wick via capillary force [67], [68].

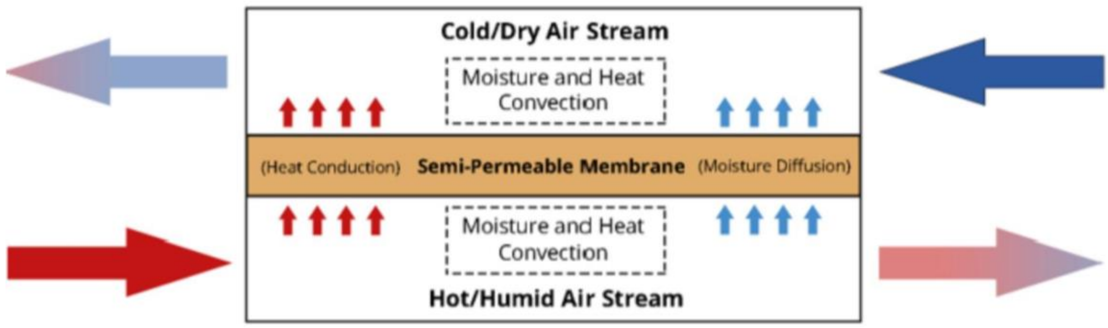
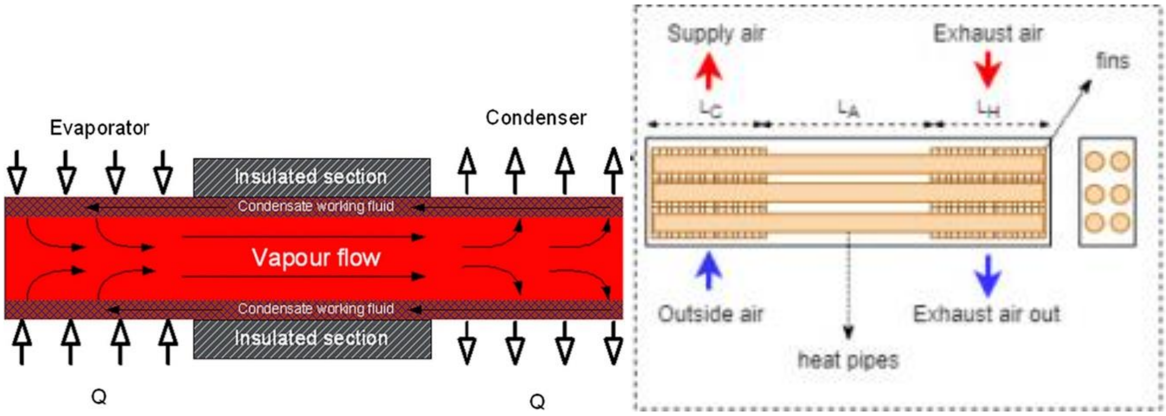


Figure 6: Schematic of a counter flow membrane exchanger for energy recovery between air streams [66].



(a) (b)

Figure 7: Schematic of (a) basic operation of vapor generation, condensation and flow of vapor and condensate and (b) heat recovery across air streams in heat pipe where supply air gives the heat for evaporation and the exhaust air provides cooling for condensation [67, 68].

3.6 Runaround coil loop

A basic runaround coil loop (Figure 8) consists of two heat exchangers (or coils) to exchange the energy between supply and exhaust airstreams and a pump to transfer the working fluid through these exchangers. During winter operation, the fluid in the exhaust coil stores the energy from exhaust air and is used to heat the incoming cold outdoor air while the process is vice versa during summer [69]. The coil geometry and heat losses during transportation significantly influence the performance of the runaround coil loop [70]. Runaround membrane energy exchanger (RAMEE) is the advanced version of runaround coil and employs membrane exchangers for energy recovery. Liquid desiccant is the circulating fluid in the RAMEE. It has the capability of absorbing the moisture from the air due to its hygroscopic nature. Hence, RAMEE can transfer both heat and moisture by circulating liquid desiccant between the exchangers, as shown in Figure 9(a). The exchangers are referred to as liquid-to-air membrane energy exchangers (LAMEE). Figure 9(b) shows the schematic of a LAMEE.

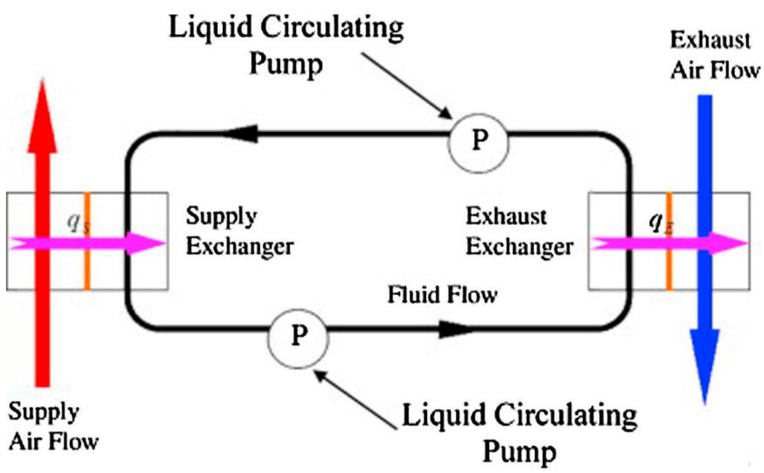


Figure 8. Schematic of runaround coil for heat recovery between air streams using two exchangers and an intermediate heat transfer fluid [69].

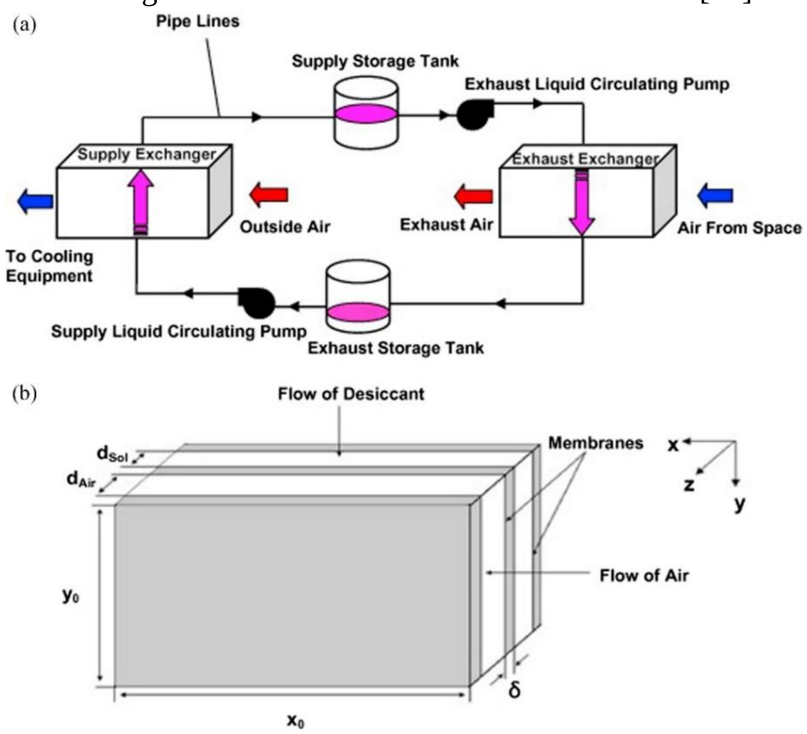


Figure 9: (a) Schematic of the run-around membrane energy exchanger (RAMEE) system for energy recovery across air streams using two liquid-to-air membrane energy exchangers (LAMEEs) and an intermediate liquid desiccant and (b) schematic of cross-flow LAMEE in which the liquid desiccant is used for energy recovery from air [70].

3.7 Thermosyphon

Thermosiphon consists of an evaporator, a condenser, interconnecting piping, and an intermediate working fluid that is present in both liquid and vapor phases [71]. Figure 10 shows the schematic of the operation of a coil-type thermosyphon. Heat is transferred by the evaporation and the condensation of a working fluid, which is circulated in a cavity. The thermosiphon transfers heat when there is a temperature difference across its ends. The section where liquid evaporates (warmer end) using the latent heat by the heat source acts as the evaporator [59]. The vapor then flows to the cooler side where it condenses by releasing the latent heat to the heat sink (or condenser). The condensate returns to the evaporator through capillary action or by gravity. The working is similar to that of a heat pipe except for the presence of the wick.

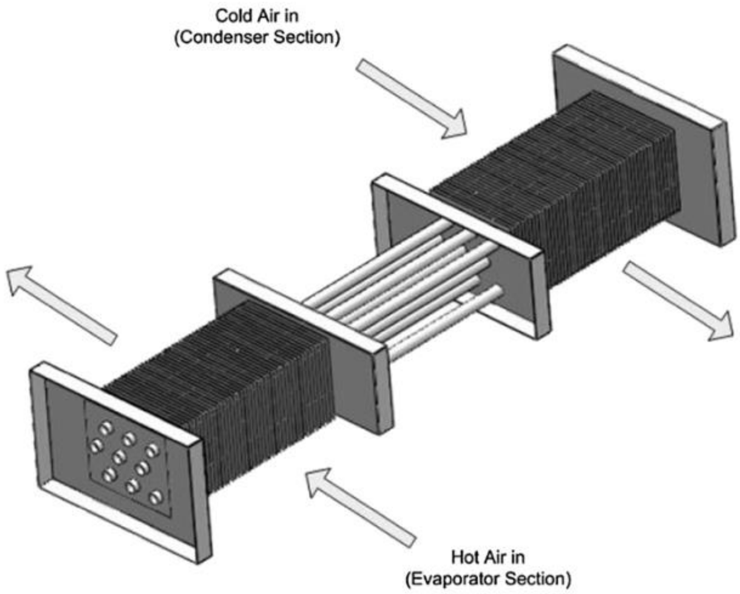


Figure 10: Schematic of a thermosiphon for heat recovery between air streams where supply air gives the heat for evaporation and the exhaust air provides cooling for condensation [71].

The working principle of the thermosyphon and heat pipe is similar. However, the thermosyphon uses gravity for moving the liquid back from the condenser and evaporator whereas the heat pipe utilizes capillary force for the liquid movement. Hence, only a vertical orientation is possible with the thermosyphon (i.e., condenser/ exhaust air flow in the top portion). On the other hand, the thermosyphon can transport more heat due to more vapor space which is partially occupied by the sintered wick in case of heat pipe. In addition, it can transport the heat for a longer distance [72], [73].

3.8 Potential ERVs for priority research

ERVs can also be categorized according to ducting arrangements and their ability to transfer heat or heat and moisture between the air streams, as shown in Figure 11. Previous studies evaluating the transfer of gaseous contaminants found that most ERVs transfer contaminants while exchanging energy (heat and moisture) between air streams [74]. This is due to the fact that most of the energy exchange ERVs have adjacent ducts which could facilitate transfer of contaminants including bioaerosols between the air streams. A recent review article on gaseous contaminant transfer in ERVs reported that energy wheels (i.e., desiccant-coated rotary wheels) were more susceptible to contaminant transfer, with a transfer rate ranging from 0-75% for different contaminants [74]. Rotary wheels are the most common ERV due to their relatively higher effectiveness, as listed in Table 3. Hence, experimental study of bioaerosol transfer in rotary wheels should be considered priority.

Table 3. Characteristics such as sensible and latent effectiveness, and exhaust air transfer ratio of ERVs [59]

Energy recovery ventilators		Sensible effectiveness (%)	Latent effectiveness (%)	Exhaust air transfer ratio (%)
Regenerator	Rotary energy wheel	up to 90	50-85	0.5-10
	Fixed-bed regenerator	50-85	50-85	0-5
Recuperator	Membrane exchanger	50-75	50-70	0-5
	Plate exchanger	50-80	--	0-2
	Heat pipe	50	--	0-1
	Runaround coil loop	45-65	--	0
	RAMEE	40-60	50-75	0
	Thermosiphon	40-60	--	0

Membrane exchangers have a relatively low contaminant transfer potential due to their water selectivity and small pore size. However, these results from past studies which were based on a few contaminants and need to be verified for bioaerosol transfer. It is perceived that there are no studies available on the transfer of bioaerosols or non-biological contaminants in FBRs till date. Since their principle of operation (i.e., theory behind the heat and mass exchange process) is the same, it is expected that FBRs will perform similar to that of rotary wheels. Thus, membrane exchangers and FBRs on par with those on rotary wheels. Other ERV types are anticipated to have a minimum transfer rate and can therefore be accorded lesser importance when considering the list of potential ERVs for bioaerosol transfer research.

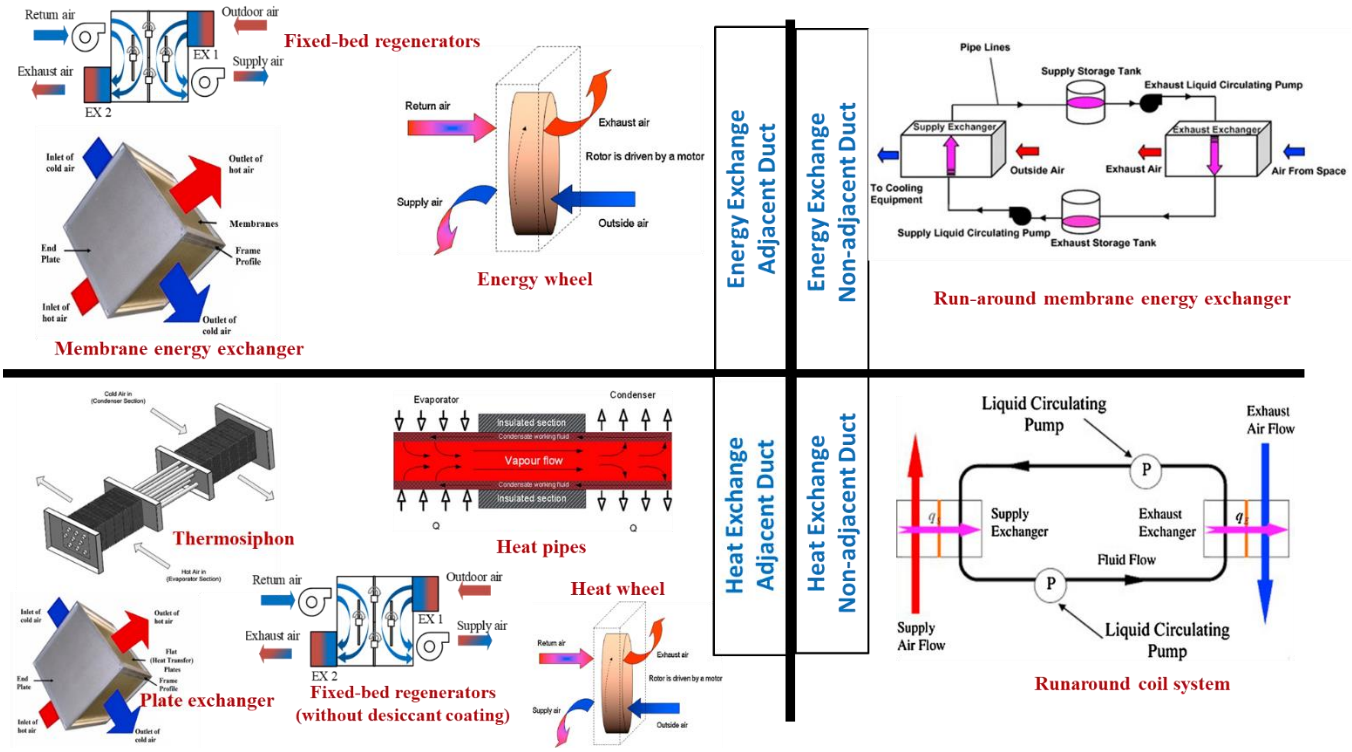


Figure 11: Classification of ERVs based on duct arrangements and energy exchange process. ERVs with adjacent ducts for energy exchange poses (energy wheel, membrane and fixed bed regenerators) a higher proabablity for bio-aerosol transfer between air streams.

4. Contaminant transfer in ERVs

Although there are no research articles available on the cross-contamination of bioaerosols in ERVs, a few studies have explored the transfer of gaseous contaminants and volatile organic compounds (VOCs) through ERVs and their impacts on indoor air quality. Despite the differences between the structure and composition of bioaerosol and gaseous contaminants, it is reasonable to assume that similar transport mechanisms exist, including carryover (if the device is rotary or fixed bed), leakage, adsorption, condensation/evaporation, and absorption [74], [75]. In recent studies on the transfer of gaseous contaminants in total energy wheels, it was reported that the amount of contaminants transferred ranged from 0% to 80% depending on the design of the exchanger, operating conditions, desiccant material, and the physio-chemical properties of the contaminants [74], [75]. The investigations from [75] found that the ammonia transfer in rotary type ERVs was around 60% more than that of transfer of SF6. This could be due to the fact that SF6 is a non-reactive gas whereas ammonia is a highly polar compound with a small kinetic diameter (0.26 nm) [76]. Studies by Patel et al. [69] on RAMEE exchanger showed that the transfer of contaminant did not depend on Number of Transfer Units (NTU) and heat capacity ratio (C*) and remained the same irrespective of operating conditions.

They found the highest transfer for toluene when compared to SF6 and formaldehyde. Another investigation by ref [74], [75], [77] confirmed that the adsorption/desorption mechanisms played a significant role in cross-contamination compared to other mechanisms. An experimental study on cross-contamination in porous membranes by Mathews [77] reported that the transfer rate variation was inversely proportional to the flow rate. It did not change with pressure difference across the sides of the membranes and it varied depending on the type of contaminant as well as type of membrane. Table 4 summarizes the transfer of selected contaminants in various types of ERVs.

Table 4: Gaseous contaminant transfer in ERVs

ERV type	Gaseous contaminants	Contaminant Transfer rate	Reference
Energy wheels	Carbon dioxide	5%	[35], [78], [79]
	Ammonia	46%-80%	[33], [78]
	Sulfur hexafluoride	2%-26%	[79]–[82]
	Formaldehyde	6-35%	[33], [78], [79], [81]
	Nitrous oxide	54%	[32]
Membranes/Air to air membrane exchangers/Flat plate enthalpy exchangers	Sulfur hexafluoride	5-23%	[77], [81]
	Ammonia	9%-39%	[34], [77]
	Carbon dioxide	1%-24%	[77], [83]
	Methanol	28%	[77]
Run around membrane exchanger	Formaldehyde	6%	[69]
	Toluene	4%	[69]

Though several literature reported the transfer rates for various contaminants, neither the mass balance nor the uniformity of inlet concentrations were reported in the experiments. These parameters are critical to assure the quality of test data and for establishing the validity of the experiments. Similarly, it is crucial to ensure mass balance and uniformity of aerosol injection in bioaerosol transfer experiments in order to reduce measurement and result uncertainties.

5. Possible bioaerosol transfer mechanisms in ERVs

Based on the inputs gathered from a recent review on contaminant transfer (non-biological) in ERVs [74], the possible mechanisms for bioaerosol transfer are explained in the following subsections.

5.1 Carryover

The carryover mechanism is applicable for bioaerosol transfer in regenerative-type ERVs. Carryover is defined as the mixing of contaminated return air from the buildings with the incoming fresh air due to the trapped air volume inside the porous structure of ERVs during their cyclic operation. In rotary wheels, some of the air is trapped inside the matrix while the wheel rotates to the outside/supply airside (OA/SA) from the return/exhaust airside (RA/EA), as shown in Figure 12. This entrapped air can mix with incoming fresh outdoor air and leads to bioaerosol transfer in ERVs. The carryover can be reduced by including a purge section in the wheel. The purge section isolates a portion of the wheel on the boundary between the RA/EA path and the OA/SA path at the point where the wheel rotates from the RA/EA path into the OA/SA path. In FBR, at the end of each period, a small amount of return air will remain inside the exchanger and will get mixed with supply air which is unavoidable. Such mixing may facilitate the bioaerosol transfer in FBR-type ERV.

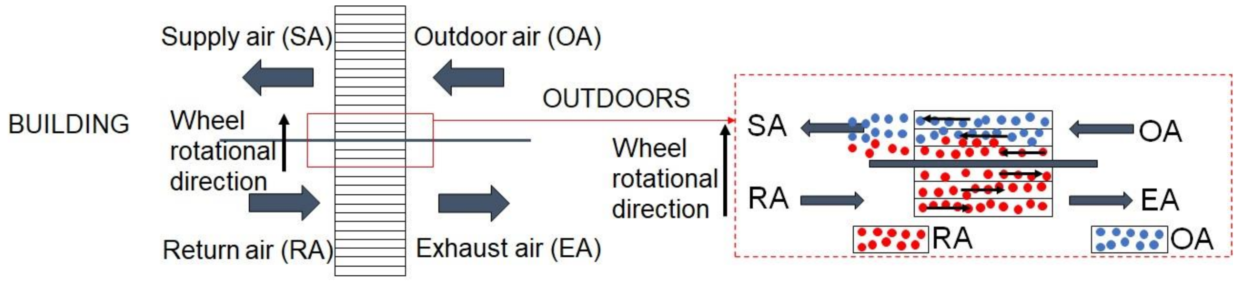


Figure 12: Schematic of carryover mechanism in energy wheel ERV. Assuming red coloured particles are the contaminants transferred from the return air to supply air [74].

5.2 Leakage

Leakage plays an important role in gaseous contaminant transfer in regenerative type ERVs and hence, it is also suspected to be a cause for bioaerosol transfer. In rotary wheels, air leaks through the interface (seals) of return and supply airstreams due to the pressure difference (Figure 13) and can occur either from supply to return airstream or vice versa, depending on the airstream pressure. The leakage to the supply side from the exhaust side can be minimized by maintaining high pressure on the supply side (Psupply > Preturn). Improper installation or maintenance is the main cause of leakage in recuperator-type ERVs.

5.3 Adsorption/desorption

In desiccant-coated regenerative type ERVs, the desiccant adsorbs the contaminant from one airstream, and stores the contaminant until it is desorbed in the other airstream similar to the transfer of water vapor, as shown in Figure 14. Hence, the bioaerosol may be stored in the pores of the desiccant that is coated in ERVs and gets transferred across the air streams.

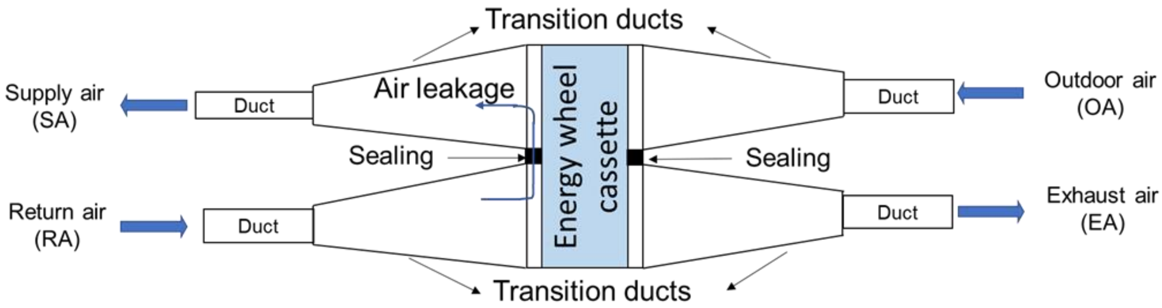


Figure 13: Schematic of leakage mechanism in energy wheel type ERV in which the contaminants are transferred to supply air from the return air through the sealing [74].

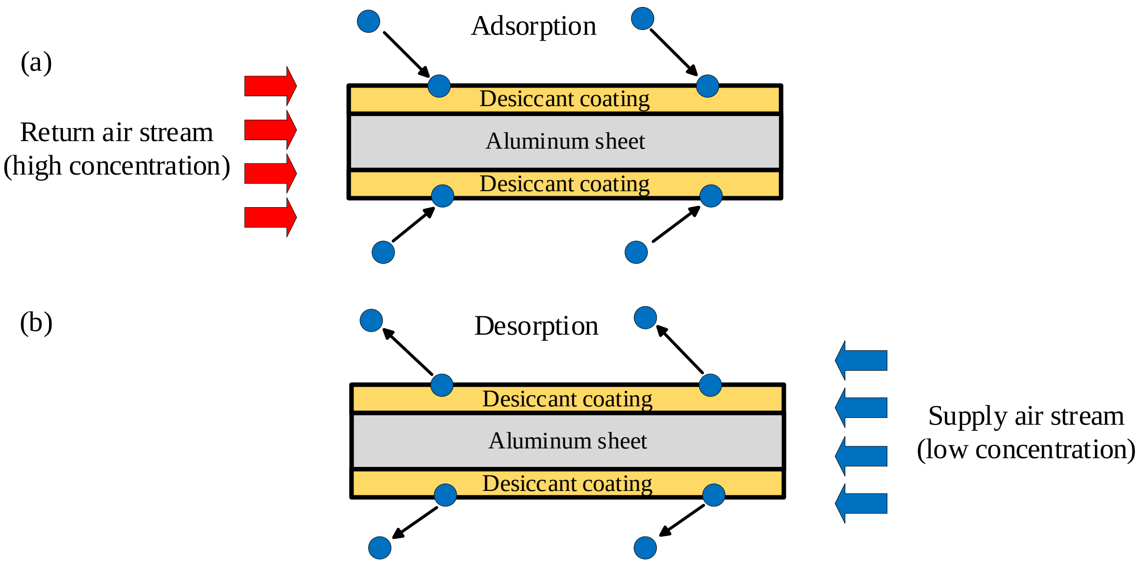


Figure 14: Schematic of (a) adsorption of contaminant from return air (b) desorption of contaminant to the supply air [74].

5.4 Condensation

The condensation of gaseous contaminants will occur if the concentration of the contaminant reaches the saturation level. Although such high concentrations are expected to be very rare for ERV applications, it may be possible for a contaminant to condense on the exhaust side of the wheel and evaporate on the supply side of the wheel. It is suspected that the pathogen from the bioaerosol may be trapped in the contaminant condensate and transferred to the supply side of the ERV [74].

6. Research Overview of Bio-aerosols

Bioaerosol transfer in ERVs is a field that remains as yet unexplored by the research community. Bioaerosol is primarily classified into two types, dry (particles) and liquid (droplets) according to its pathogen type. Table 5 lists the various types of pathogens which can spread by airborne transmission. The human airborne pathogens, namely pollens and fungi spores fall under the dry type whereas most bacteria and viruses are categorized as liquid type. The new avenues of exploration from the present study for HVAC researchers whose focus is on ERV are as follows: (i) preparation and storage of pathogen, (ii) aerosol generation, (iii) aerosol characterization, and (iv) pathogen characterization (Figure 15). A detailed overview of these aspects is presented in the following subsections.

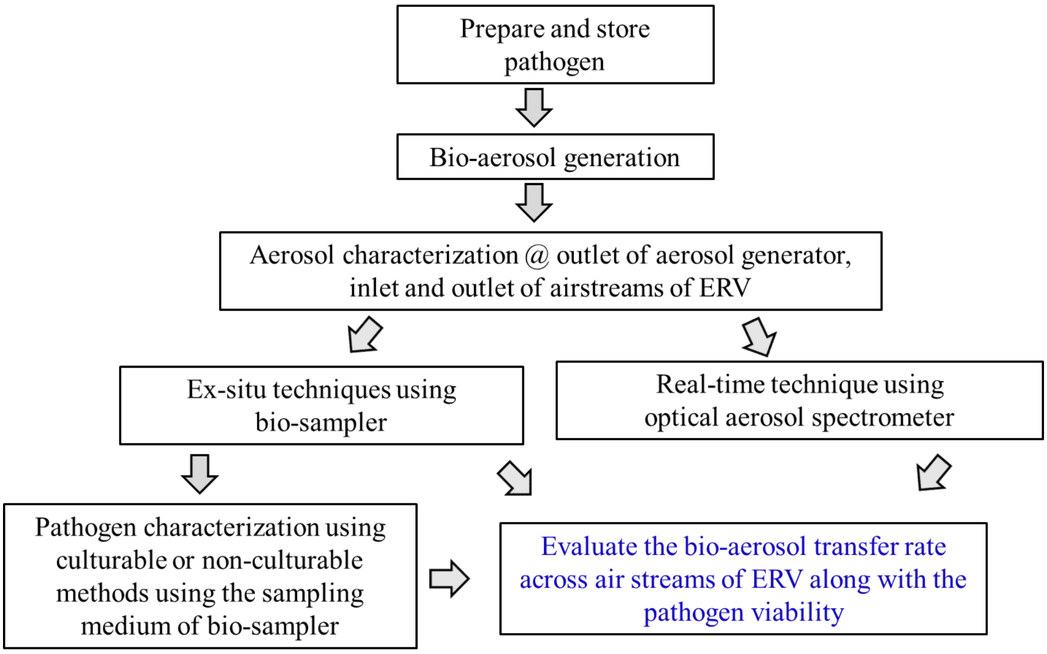


Figure 15: Steps relevant to generation and characterization of bio-aerosol for quantifying its transfer between air streams of ERVs.

Table 5. Various types of pathogens spread by airborne transmission [84]–[86]

Virus	Bacteria	Fungi
• Adenovirus • Chickenpox • Coronaviruses • Hantavirus • Influenza virus • Measles • Monkeypox/smallpox • Mumps • Norovirus • Rabies virus • Rhinovirus • Rotavirus	• Bacillus anthracis • Clostridium difficile • Legionella pneumophila • Mycobacterium tuberculosis • Nontuberculous mycobacteria • Staphylococcus pneumoniae	• Aspergillus spp • Blastomyces dermatitidis • Cladosporium spp • Cryptostroma • Fusarium • Penicillium spp • Stachybotrys chartarum

6.1 Preparation and storage of pathogens

The preparation methods are crucial for analyzing the results of bioaerosol transfer experiments since they affect the characteristics of the pathogens. The initial culture conditions of the preparation method can affect the survival and physical properties of pathogens in the experimental systems [87]. The general procedure for preparing the pathogen is as follows (i) the pathogen stock is pre-cultured in a growth medium under controlled lab conditions (ii) the culture medium is incubated at a prescribed temperature and (iii) the pathogens are separated from the culture media, mostly by centrifugation. The culture conditions vary according to the pathogen type. For example, the bacterial stock and fungi are directly cultured in a culture or growth media whereas the viral stock is cultured using the bacterial media as host. The incubation time of bacteria and viruses is lower than that of the fungi. The storage temperature of bacteria and fungi is relatively high when compared to that of the viruses. For example, the gram-negative bacterium Escherichia coli is stored at 4°C whereas the MS2 bacteriophages (a type of virus) is stored at -80°C [88]–[90].

Earlier studies found that the dried type pathogens can aggregate while storing due to moisture and inter-particle attractive forces (mostly occurring in particles of size less than 10 µm). Consequently, it affects the dispersal of bioaerosol in the experimental system [91]. Preparation and storage methods influence the reproducibility of the bioaerosol generation during experiments. Hence, for consistency, it is recommended that sufficient quantity of pathogen for the given set of experiments is prepared in advance and aliquoted as per the requirements. The preparation methods and storage conditions along with the characteristics of pathogens should be reported in the experimental methodology for future comparison of bioaerosol studies of ERVs [87].

6.2 Bioaerosol generation

Ideally, bioaerosol generation in laboratory experiments should be designed to imitate that in natural processes. In most of the laboratory studies, the biodiversity and concentration peaks (which are crucial factors) of the actual natural process are not considered or replicated. Figure 16 shows the different methods of experimental aerosol generation. Most of the methods are adopted from the non-biological processes and thus, such methods are not optimized for bioaerosol experiments [87], [92].

6.2.1 Liquid bioaerosol generation

In laboratory experiments, the natural bioaerosol generation process is replicated by the fragmentation of liquid [87]. The droplet size, hygroscopic growth, and evaporation kinetics during the fragmentation are dependent on the liquid (referred to as spray fluid) properties, namely solute/solvent composition, density, viscosity, and surface tension [93]. Spray fluids during laboratory experiments are generally taken as the pathogen culture media (liquid broth, solid agar and other nutrients) [94] or artificial saliva [89], [95].

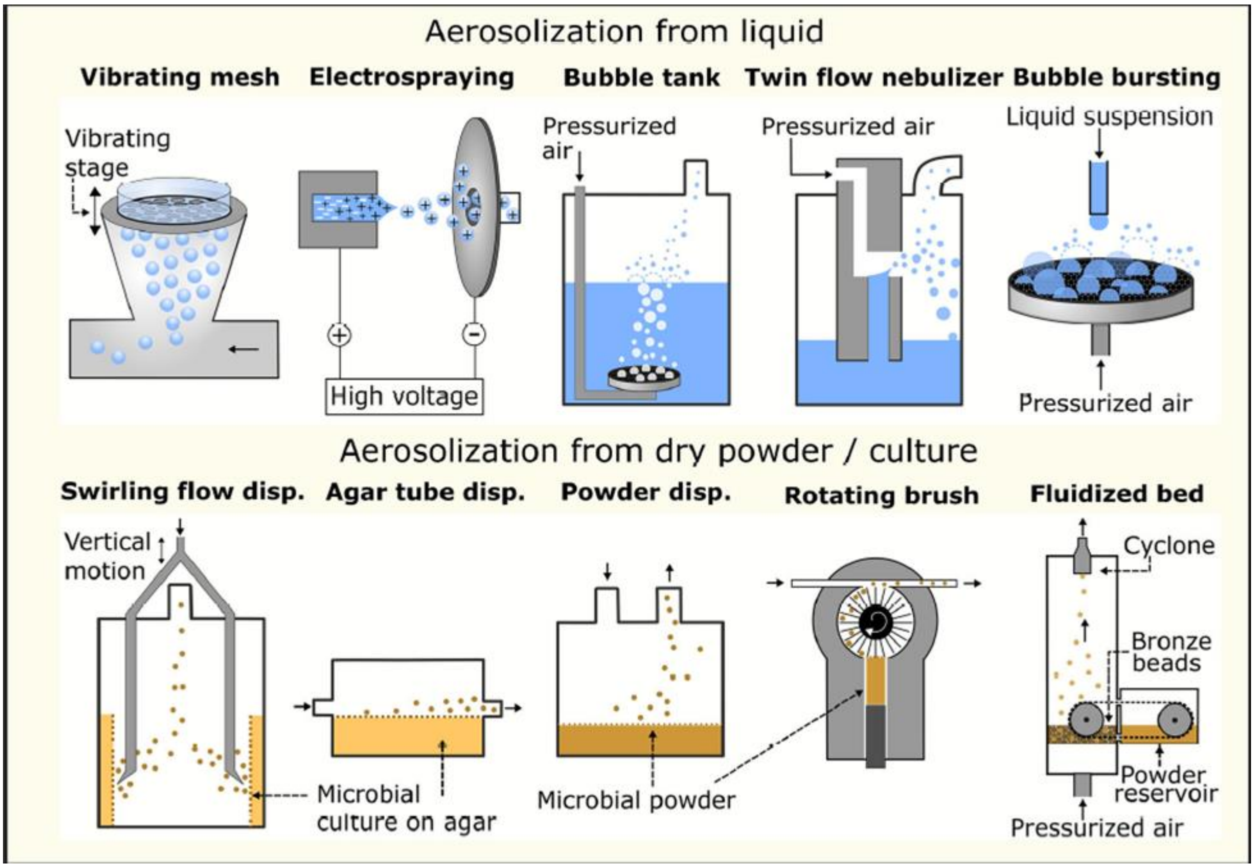


Figure 16: Experimental methods of dry and liquid types bio-aerosol generation [87].

A frequently used liquid bioaerosol generator is a twin-fluid collision nebulizer which can generate particles with an average size lower than 2 µm [87]. Its advantages are the relatively minimum requirement of pathogen and high output [96]. It is recommended that the design and operating parameters of the generator be included in the methodology report for better repeatability and future comparison of bioaerosol studies of ERVs [87].

The efficiency of generation is measured using the size distribution of bioaerosol (in terms of mass median or geometric standard deviation of aerodynamic diameter) and spray factor which is a ratio of the concentration of pathogen in the bioaerosol to the concentration in the spray fluid [87]. Inside the experimental system, evaporation alters the size of the aerosol and it depends on the temperature, relative humidity, volatility and composition. Eventually, the bioaerosol reaches an equilibrium size. In addition, there are bioaerosol losses (leads to decrease in the concentration) within the experimental system due to the surface or sampler deposition. Hence, for better analysis of the laboratory experiments, the bioaerosols are monitored both at the source (i.e., closer to the outlet of the generation device) and downstream before the experimental process (i.e., before ERV in the present study) [87]. Furthermore, it is advised to conduct a few initial experiments with physical tracers (e.g., fluorescein or uranine chemicals, bacterial spores, radiolabeled biological material or liquid, and fluorescent microspheres) to understand the bioaerosol losses [95]. Tracer experiments are useful in optimizing the parameters for the bioaerosol generation method but are rather expensive. It is essential to monitor the bioaerosol for the entire duration of the experiment since the spray liquid may evaporate over time which in turn may alter the size distribution [87].

6.2.2 Dry bioaerosol generation

The generation technique of dry bioaerosol has been relatively less studied when compared to that of the liquid type. However, it is important for the bioaerosol studies of pollen grains, as well as fungal and bacteria spores. The dry bioaerosol generation method is primarily of two types (i) air is forced towards the powdered material or a sporulating fungal agar culture and thereby the dry material is attached to the air (ii) there is a separate scraping/brushing mechanism for attaching the dry material to the air. Similar to liquid bio-aerosol, the dry bioaerosol needs to be monitored both at the source and downstream before ERV trials for the entire duration of the experiments to understand the bioaerosol losses in the experimental setup [87], [97].

6.3 Bioaerosol characterization

Bioaerosols can be characterized using two techniques: (i) real-time optical-based measurement and (ii) ex situ measurement in which the aerosols are collected in a substrate and subsequently analyzed.

6.3.1 Real-time technique

Real-time technique operates on the principle of light scattering and detection, as shown in Figure 17. Light rays from a laser diode are irradiated onto the sheath of sampled air. Particles in the air sample scatter light at various intensities which are detected by the photodetector to evaluate the concentration and particle size distribution [98]. The size of the bioaerosol is determined based on the calibration data of the instrument. Calibration of these instruments is performed by measuring the voltage signals of bioaerosol of known sizes [99]. The scattered light intensities of different bioaerosols are classified into different bins and the particle size distribution is plotted [100], [101]. The aerosol concentration in the sampled air is determined based on the time period of signal detection and the air sampling rate. Since light scattering occurs only when the size is close to the wavelength of the light source, these instruments have a lower detection limit of 100 nm [102].

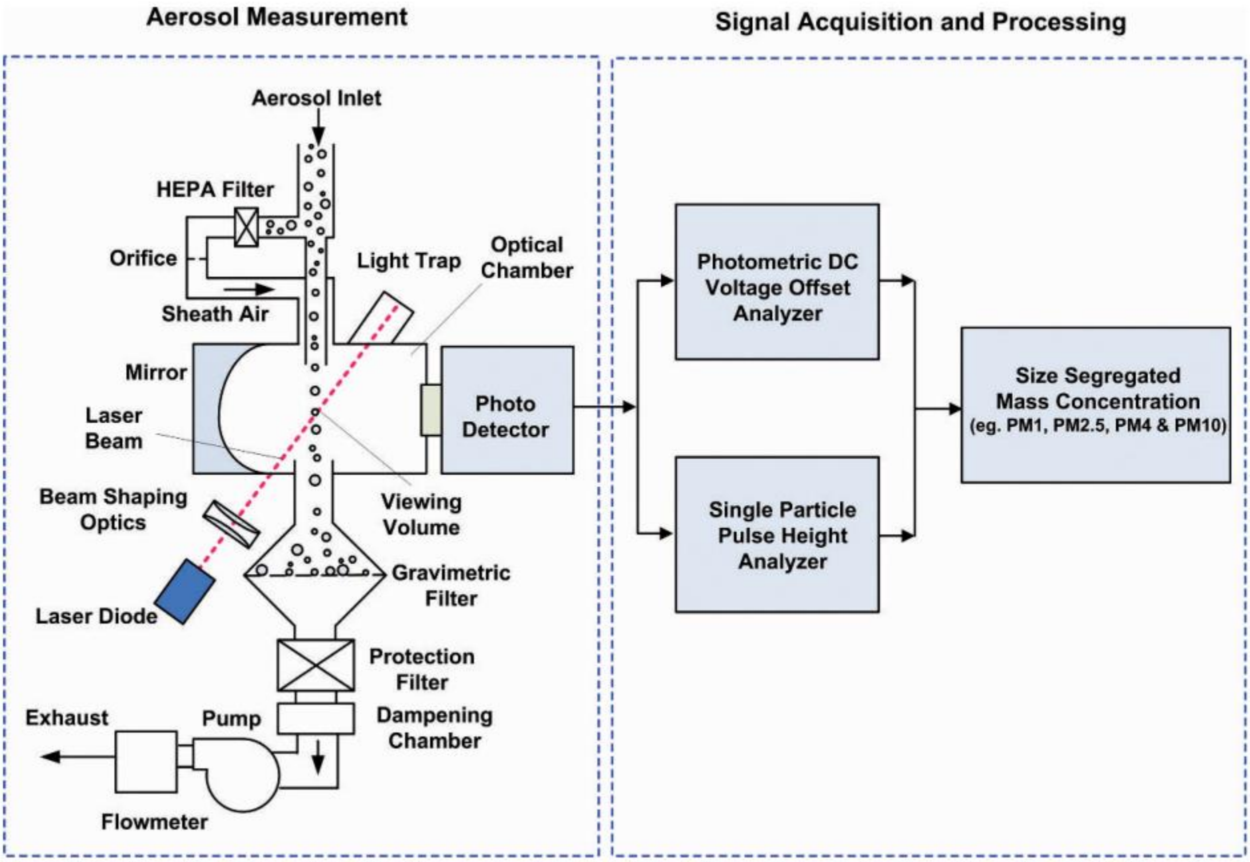
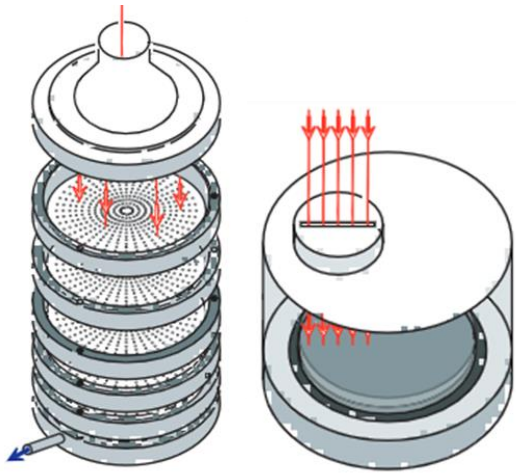


Figure 17: Measurement principle of an optical aerosol spectrometer. Light rays from a laser diode are irradiated onto the sheath of sampled air. Particles in the air sample scatter light at various intensities which are detected by the photodetector to evaluate the concentration and particle size distribution [101].

6.3.2 Ex situ techniques

Ex situ techniques are the most common method of characterization since they are cheaper compared to the optical method. In the ex situ technique, the air is sampled using a bio-sampler. The aerosols are collected in their substrate and the substrate is then characterized to determine the size and concentration of the bio-aerosol. Sodium chloride and polystyrene latex particles are aerosolized for size and concentration calibration of samplers [103]. It is noted that, even though the real-time optical measurement is more efficient than ex situ measurements, it is still necessary to avail samplers in the experimental setup for collecting a sample for pathogen detection.

6.3.2.1 Solid impactors: Cascade impactors and slit sampler impactors are the two most common types of solid impactors. They fall under the active category and are most efficient in collecting the larger-sized aerosols. Using a vacuum pump, the aerosols are accelerated through a series of nozzles and are impacted onto a collection media (viz. filter media or agar plate) which is placed normal to the flow, as shown in Figure 18. Large aerosols are separated due to inertia while smaller aerosols follow the airstream. The multi-staging of this nozzle-collection media pair in cascade impactors enables the determination of the aerosol size distribution. The nozzle size is reduced in each stage, increasing the velocity and thus the cut-off size reduces in each stage [104]. The lowest cut-off size of the impactors is 0.2-0.3 µm which is more suitable for sampling bacteria and fungi than viruses [92], [105]. The time-dependent variation of the concentrations can be detected with the help of slit samplers. It consists of a rotating petri dish onto which the accelerated aerosols impinge. The petri dish can be made of solid culture media (for bacteria) alone or a liquid layer covering this media (for viruses) [92].

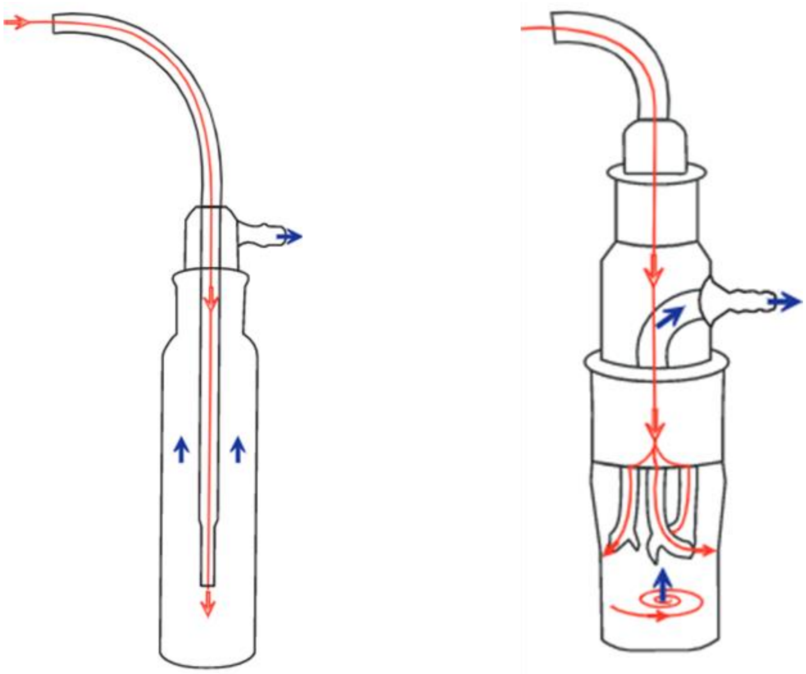


(a) (b)

Figure 18: Schematic of (a) Cascade impactors and (b) slit sampler which are used to characterize the bio-aerosols using their inertial force [92].

6.3.2.2 Liquid impingers: Liquid impingers (Figure 19 (a)) work on a similar principle as that of an impactor, except that the sampling flow is deposited onto a liquid media [106]. The aerosols are collected by inertial impaction as well as particle diffusion due to the formation of small bubbles. The physical collection efficiency can be improved by replacing the single nozzle with three tangential sonic nozzles. This design is called Biosampler and is shown in Figure 19 (b) [92].

6.3.2.3 Filters: Filters have better physical collection efficiency than impactors and impingers in collecting bioaerosols with an aerodynamic size of <500 nm. In filters, the collection of small aerosols depends on diffusion phenomena whereas inertial impaction and interception mechanisms influence the collection of larger aerosols. However, all these three phenomena are at their lowest for an aerosol size of 0.3 µm and hence, the collection efficiency is lowest at this size which is considered as a benchmark. The efficiency increases with both the increase and decrease of size from 0.3 µm. Gelatin filters have become popular due to their ability to dissolve in liquid, thereby providing an easier mechanism for aerosol enumeration without compromising viability [92], [107].



(a) (b)

Figure 19: Schematic of (a) liquid impinger (b) Biosampler which are used to characterize the bio-aerosols using their inertial impaction and particle diffusion [92].

6.3.2.4 Electrostatic precipitator: An electrostatic precipitator (ESP) makes use of the principle of motion of charged particles in an electric field, as shown in Figure 20. The bioaerosols are charged using a corona discharge before passing them through oppositely charged electrodes. Mostly, it combines with a pre-impactor which first collects the large-sized bioaerosols and then, ESP collects the small bioaerosols [92], [107].

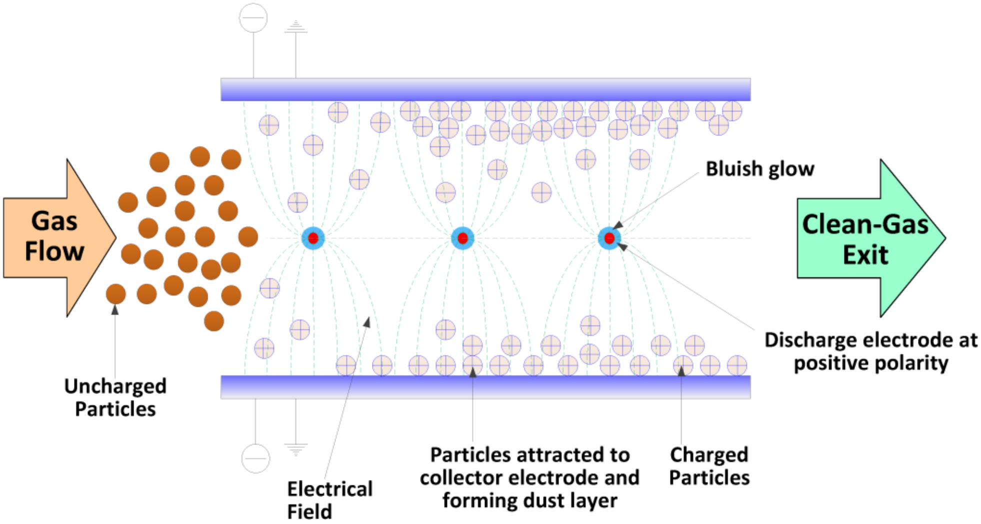


Figure 20: Schematic of an electrostatic precipitator which characterize the bio-aerosols by charging and then collected to its collector electrode [108].

6.3.2.5 Condensational growth tube collector: A water-based condensational growth tube collector (GTC) works on the principle of differential diffusion of heat and vapor in a laminar flow. From Figure 21, the first two sections, i.e. conditioner and initiator tube walls are lined by a water-saturated hydrophilic porous media. The conditioner serves the purpose of regulating the temperature (to condition temperature) and relative humidity (to 100% RH) of the incoming flow. In the initiator, water vapor from the porous media diffuses to the centreline faster than heat due to the higher diffusivity of water and increases the saturation ratio at the centreline. This enables condensation to occur on the surface of ultrafine bioaerosols as small as 5-10 nm [109], [110]. Then, the amplified aerosols are collected in the collection chamber via impaction on the collection liquid. The flow of aerosol droplets to the collection chamber is through a set of nozzles to reduce the impaction stress and surface disruption. Growth tube collectors (GTCs) characterize the bioaerosols with airborne viruses in the size range of 30 nm-10 μm [109]. A comparison of the samplers based on their relevance for ERV applications is presented in Table 6.

6.4 Pathogen characterization

If bioaerosol transfer is detected in the ERV, then infectivity characterization of the pathogen after the transfer between the air streams is essential since the pathogen may get deactivated by the process or material of the ERV. For example, the liquid desiccant in RAMEE has a few inherent properties that may deactivate or reduce the infectivity of the pathogen. This deactivation or less infectivity can potentially reduce the disease transmission due to bioaerosol transfer in ERVs. The methods used to characterize the pathogens in the bioaerosol samples are explained as follows.

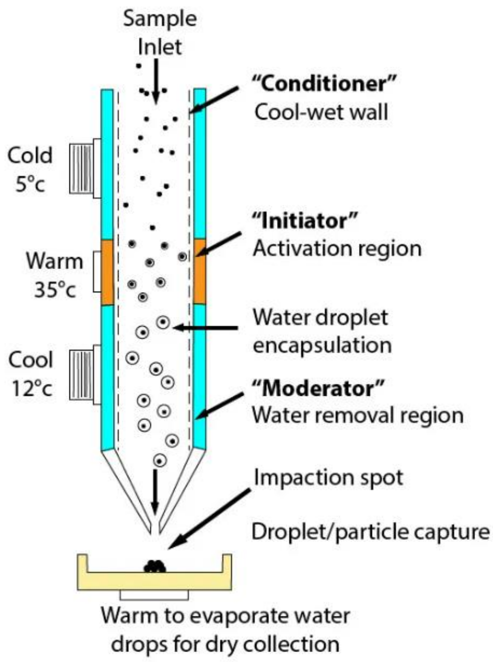


Figure 21: Schematic of condensational growth tube collector which works based on differential diffusion of heat and vapor [109], [111].

Table 6. Comparison of different bioaerosol samplers [104], [105], [107]

Sampler	**Cut-off diameter**	**Sampling flow rate (LPM)**	**Advantages**	**Disadvantages**
Impactors	0.2-0.3µm	~30	• Cascade samplers can provide the size distribution of the aerosol • Slit samplers provide the aerosol concentration as a function of time • Good physical collection efficiency for aerosol size above the cut-off diameter	• Low biological collection efficiency due to large impaction forces • Low physical collection efficiency for aerosol size less than the cut-off diameter
Impingers	0.3µm, >20 nm (packed glass beads)	~12.5	Good physical and biological collection efficiencies for aerosol size above the cut-off diameter	• Re-aerosolization from the collection fluid impacts the physical collection efficiency • Low physical collection efficiency for aerosol of size less than the cut-off diameter

Sampler	Cut-off diameter	Sampling flow rate (LPM)	Advantages	Disadvantages
Filters	>60 nm. However, variations reported with type of filter	~2 - 30	Excellent physical collection efficiency for nanometer-sized aerosols	Poor biological efficiency due to desiccation of the pathogens
Electrostatic precipitator	Variable	~1.2 - 10	• Less energy consumption • Portable	Collection efficiencies with large uncertainties reported due to particle aggregation and pathogen inactivation by ozone
Condensational growth tube collector	> 5 nm	~12.5	Excellent physical and biological collection efficiencies	Bulky and sophisticated

6.4.1 Analysis of culturable bioaerosols

The infectivity of the pathogens present in the collected bioaerosol sample is enumerated using either the plaque assay or fifty percent tissue infective dose assay techniques; the former is more widely used [105], [112], [113]. Plaque assays provide a quantitative estimate of the total culturable pathogens in the sample. The pathogen concentration is reported in plaque-forming units (PFU) per ml of sampled aerosols. A schematic of the steps involved is shown in Figure 22. The incubation time to form a pathogen colony can range from a few hours to days with different temperature requirements for each species of the pathogen. Thus, this procedure is time-intensive. Moreover, determining the pathogens through cultivation is a severe gross underestimation of the total pathogens actually present in the air as the viable non-culturable pathogens will not be included in the counting [105], [114].

6.4.2 Analysis of non-culturable bioaerosols

Microscopy, immunoassays and molecular techniques are the three kinds of non-culturable methods used for pathogen detection. Among these, microscopy and immunoassay techniques are qualitative; they can only determine the presence of the pathogen in the sample and are not used to count the pathogens [114]. The most accurate method of pathogen detection is the molecular method. It includes the various types of polymerase chain reactions (PCR), mass spectrometry and gene sequencing. However, these molecular methods are very sensitive to the presence of any contaminants present in the sample that can inhibit the detection process [115].

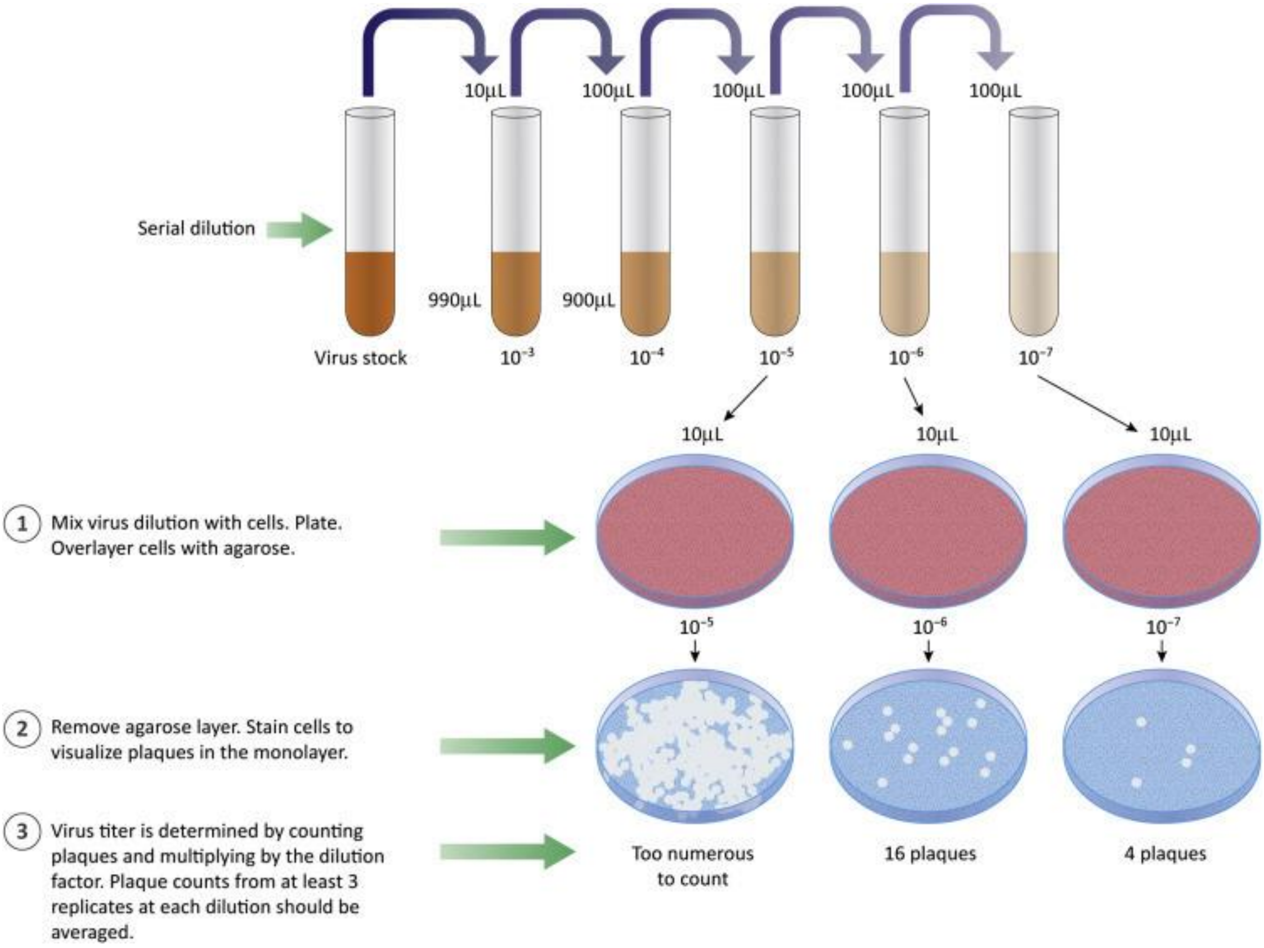


Figure 22: Schematic of the steps involved in the plaque assay type culturable method for characterize the pathogens in bio-aerosols [116].

7. Design of Experimental Setup and Experiments

The experimental design of bioaerosol transfer research in ERV is similar to the gaseous contaminant transfer research except that the contaminant is a biological type. Hence, preliminary research in this field can refer to "ASHRAE Standard 84 - Method of testing air-to-air heat/energy exchangers [47]" for initial experimental design.

7.1 Biosafety

The laboratory experiments require an appropriate containment strategy according to the biosafety level of the pathogen in the bioaerosol and the minimum biosafety level required for experiments is 2 [117]. The safety measures should increase when the concentration of bioaerosol is high for the experiments. To increase the biosafety of the experiments, it is recommended that standardized and validated surrogates be used which are non-pathogenic to humans and can be used to understand the characteristics of pathogenic microorganisms. For example, bacteriophages are considered as a surrogate for human pathogens. Bacteriophage MS2 is often used as a surrogate for the pathogenic virus [92]. The human coronavirus OC43 (HCoV-OC43; BSL-2) is a non-severe coronavirus strain that causes cold and is considered as a surrogate virus for the actual SARS-CoV-2 virus of COVID-19 [118]. Even though the surrogate mimics the actual behavior, surrogates are not 100% reliable for pathogen-based bioaerosol transfer assessment. However, it is safe to conduct the initial experiments with surrogate based bioaerosol followed by actual pathogen based bioaerosol for a few conditions to validate the extrapolation of surrogate results.

7.2 Proposed small-scale experimental facility

Figure 23 shows the schematic of the proposed experimental facility for the bioaerosol transfer study in the ERV. It is recommended that the small-scale methodology be adopted to design the bioaerosol transfer experiments. The test methodology can predict the performance of a large-scale ERV using a small-scale ERV considering similar non-dimensional design parameters for both ERVs [119]. In addition to low cost per test, the other advantages such as utilizing small-scale exchangers, short duration experiments, low volume of conditioned airflow and less need of laboratory space contribute to maintaining biosafety in the laboratory study.

The experimental setup shown in Figure 23 is similar to that given in the literature [120] for the energy performance evaluation of ERVs, except the aerosol generation and sampling. As shown, the set up consists of two air lines, i.e., supply and exhaust lines which represent the actual supply air (outdoor ventilation air) and building exhaust air lines in a typical HVAC system. The required inlet humidity and temperature of airstreams can be achieved in the experiment using the bubble humidifier and heater/cooler, respectively. The flow mixer facilitates uniform conditions for air property measurement whereas the flow conditioner maintains the uniform flow at the inlet of the ERV.

The bioaerosols are injected into the exhaust air (representing air from space with an infected person), and the transfer of bioaerosols to the supply air is measured. The injection and sampling stations are shown in Figure 23. As discussed in Section 5.2.1, the aerosol size varies after generation due to evaporation and reaches its equilibrium size if it is liquid type. Hence, a heater and dehumidifier are often used to accelerate evaporation. Neutralizers can be used to remove the charges of the aerosol which in turn prevents uncommon aerosol behaviour during experiments. Both lines have high-efficiency particulate air (HEPA) filters at their inlets to avoid the influence of external particles present in the ambient air on the experiments. The filters at the outlet are essential to contain the pathogens in the experimental system.

The bioaerosol generation, sampling and detection technique should be selected according to the type of pathogen that is investigated in the experimental study. For example, for conducting COVID-19 related bioaerosol transfer study (i) MS2 bacteriophage can be used as a surrogate pathogen (ii) collision nebulizer can be employed as a bioaerosol generator (iii) liquid impinger and/or optical aerosol spectrometer can be utilized to characterize the bioaerosol and (iv) viability of the pathogen can be analyzed by plaque assay method. As discussed earlier in Section 5.1, it is recommended that sufficient quantity of pathogens be prepared for the required set of studies to ensure the repeatability of the experiments.

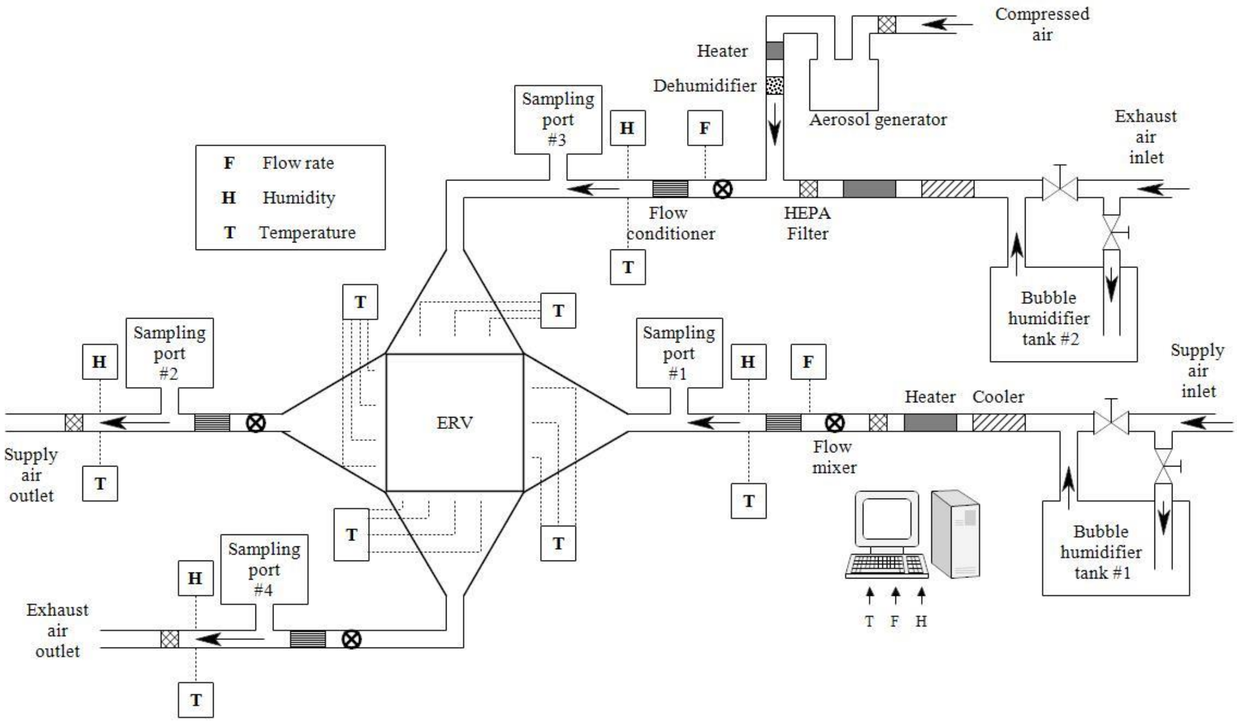


Figure 23: Schematic of an experimental setup for measuring the bio-aerosol transfer between air streams of ERVs.

The experimental setup should be subjected to a leak test preferably at a higher pressure than the working pressure. Moreover, to avoid the possibility of any leakage to the surroundings, it is recommended that the containment zone (the surrounding area of the experimental set up according to the microorganism of the bio-aerosol) be maintained at negative pressure if possible. It is also recommended that the exposure risks of the research personnel be fully evaluated before commencing the experiments. It is recommended that the energy performance and tracer chemical transfer tests are conducted prior to the bioaerosol transfer study. The energy performance test is useful to validate the experimental facility. The tracer test can be used to understand the aerosol losses within the experimental system thereby optimizing the operating parameters of the bioaerosol generation process. Figure 24 shows the flowchart of the experimental procedures.

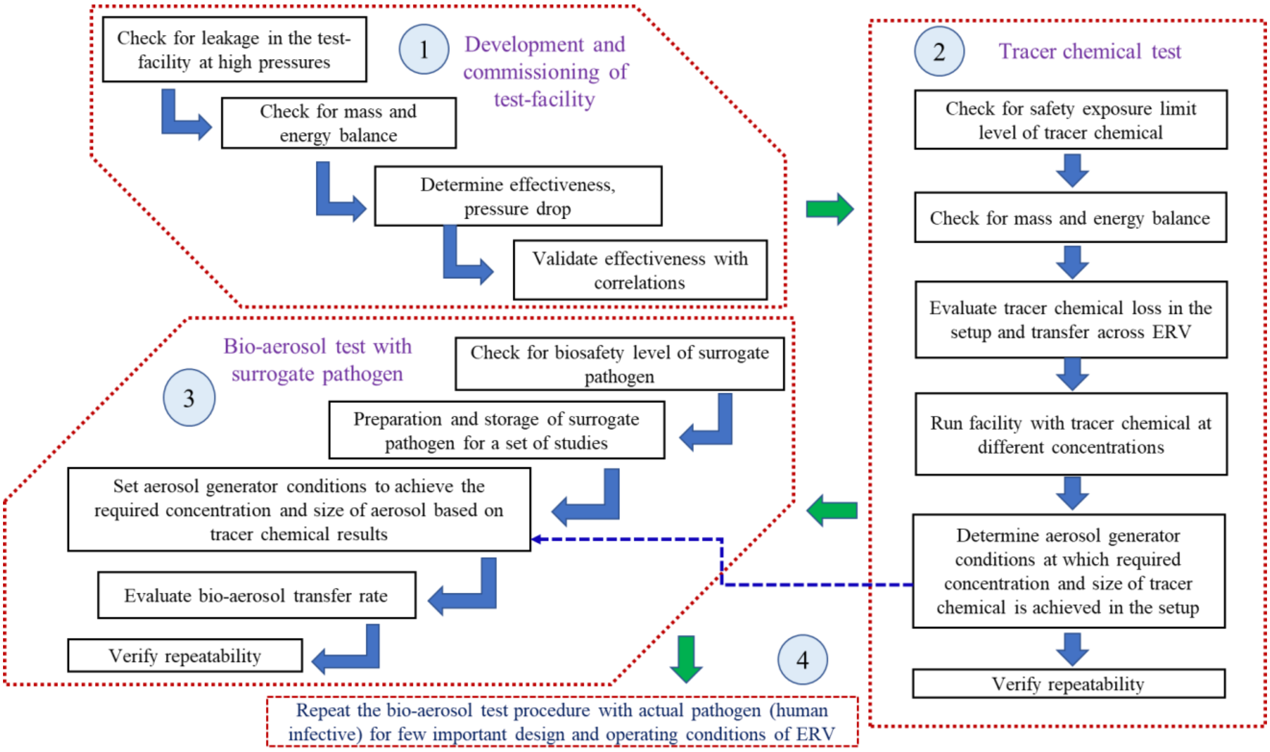


Figure 24. Flowchart of the experimental procedures for measuring the bio-aerosol transfer between air streams of ERVs.

7.3 Parameter criteria for acceptance of test results

ASHRAE Standard 84 [47] specifies certain criteria for the rejection of test data during the performance testing of ERVs and such criteria are listed in Table 7. The limits listed in Table 7 are applicable for gases or vapors and cannot be directly used for the acceptance of evaluating bioaerosol transfer test data. The reasons are as follows:

- The characteristics of tracer chemicals are different from those of the tracer gas and hence, a new inlet inequality limit needs to be introduced for the most common chemicals.
- The instruments used for estimating bioaerosol transfer ratio (BTR) are different than those for Exhaust Air Transfer Ratio (EATR). Hence, the uncertainty limit of EATR mentioned in the standard cannot be used for BTR. Uncertainty in bio-sampler and optical aerosol spectrometer contributes to the uncertainty of BTR. As a result, it is expected that the uncertainty limit of BTR may be higher than that of EATR [120].

Table 8 lists the typical losses in the bio-sampler and optical aerosol spectrometer that can contribute to the uncertainties.

7.4 Mass balance of bioaerosol experiments

To establish the mass balance of the experiments, it is important to quantify the transmission losses of bioaerosol in the setup. Aerosols can be lost in the supply/exhaust air ducts, test sections of the ERV and sampler ducts. Hence, a large number of aerosols can be lost from the air sample before reaching the sampler. These losses must be quantified for the particular operating conditions of the ERV. Once the air reaches the bio-samplers, further losses occur due to the inefficiency of the samplers. A schematic representation of the bioaerosol losses is shown in Figure 25.

Table 7. Criteria for the acceptance of test data as per ASHRAE standard 84 [47]

Parameter		Inequality/ Limit
Fluctuation of inlet conditions	Inlet humidity ratios*	$\frac{\lvert\delta\omega_1\rvert}{\lvert\omega_1-\omega_3\rvert}\begin{cases} < 0.05 \text{ for } (\omega_1 > \omega_3) \\ < 0.1 \text{ for } (\omega_1 < \omega_3 \end{cases}$
		$\frac{\lvert\delta\omega_3\rvert}{\lvert\omega_1-\omega_3\rvert}\begin{cases} < 0.05 \text{ for } (\omega_1 > \omega_3) \\ < 0.1 \text{ for } (\omega_1 < \omega_3 \end{cases}$
	Tracer gas inequality	$\frac{\lvert\dot{m}_1 C_1-\dot{m}_2 C_2+\dot{m}_3 C_3-\dot{m}_4 C_4\rvert}{\dot{m}_{min(1,3)}\lvert C_1-C_3\rvert} < 0.15$
Uncertainty	Exhaust air transfer ratio (EATR)	$U(EATR) < 3\%$

* δ refers to the maximum deviation of the measurement from its mean value

Table 8. Contribution to uncertainty due to different bio-aerosol loss mechanisms

Instrument	Losses	Maximum contribution to uncertainty
Bio-sampler	Re-aerosolization and sampler adhesion loss	31 ± 23% [121]
	Aspiration loss	Depends on the sampling flow rate and sampler orientation. Uncertainty could be evaluated using equations found in [122], [123]
Optical aerosol spectrometer	Coincidence error	25% [123], [124]
	Characterization loss	10% [120]

7.5 Performance parameter

The bioaerosol transfer ratio (BTR) between the airstreams of the ERV can be quantified using Eqn. (1).

$$BTR = \frac{C_2 - C_1}{C_3 - C_1} \text{ .... } (1)$$

Where, C_1 to C_4 are the concentrations of bioaerosol measured at sampling ports 1 to 4 (shown in Figure 23). BTR varies between 0 and 1. As discussed in Section 5.4, in order to understand the disease transmission risk due to bioaerosol transfer in the ERV, the results need to be reported as BTR and the viability of the pathogen must be evaluated.

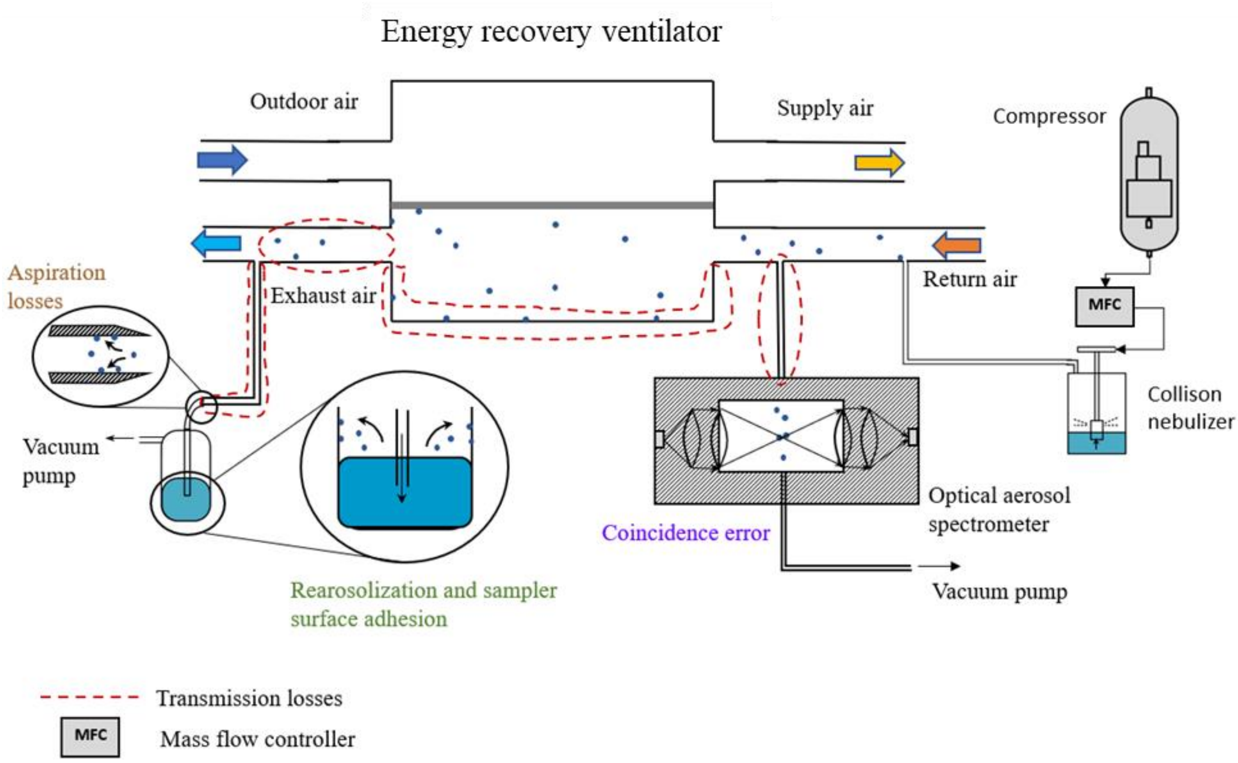


Figure 25: Schematic of the loss mechanisms of bio-aerosols in the test-facility as well as in measuring instruments namely bio-sampler and optical aerosol spectrometer.

8. Conclusions

Energy recovery ventilators (ERVs) are vital for developing sustainable heating, ventilation and air-conditioning (HVAC) systems for providing ventilation to control airborne disease transmission in indoor environments. Even though there is no detailed literature or filed evidence of bioaerosol transfer, ERVs have mostly been bypassed during the pandemic operation due to the constraints recommended in the pandemic HVAC guidelines. Hence, bioaerosol transfer in ERVs is a crucial topic that warrants immediate research attention to ensure the future applications and safe operation of ERVs in HVAC systems. This investigative paper provides important information and guidelines for designing experiments to quantify the bioaerosol transfer in ERVs. The paper summarizes the possible mechanisms behind aerosol transfer, generation and characterization methods of bio-aerosols, which are useful for selecting appropriate instruments/equipment for the experiments in ERVs. The paper also presents a novel experimental method for conducting infectious virus containing bioaerosol transfer study in ERVs. The conclusions from the present review are listed as follows.

- According to the principle of operation behind the heat and mass exchange process, three ERVs, namely rotary wheels, membrane exchangers, and fixed bed regenerators, should be considered a priority for the experimentation of bioaerosol transfer.
- Among the possible mechanisms of contaminant transfer (non-biological) in ERVs, bioaerosols are most likely to transfer pathogens due to carryover and leakage rather than adsorption/desorption and condensation.
- Preparation and storage methods of the pathogens influence the reproducibility of the bioaerosol generation during experiments. Hence, for consistency, it is recommended that a sufficient quantity of pathogen for the given set of experiments be prepared in advance and aliquoted as per the requirements.
- It is advisable to conduct initial experiments with physical tracers (e.g., fluorescein chemicals) to understand the bioaerosol losses in the experimental setup, which are crucial in optimizing the parameters for the expensive aerosol generation process.
- Liquid impinge is the most common bio-sampler with the limitation of aerosol cut-off size. Condensational growth tube collector appears promising because of its high physical and biological collection efficiencies. However, it is bulky and needs more research for size optimization.
- Small-scale test methodology can be a potential experimental method for bioaerosol transfer experiments, particularly from the perspective of biosafety.

9. Suggested topics for future research

Based on this review and the authors' previous research experience with ERVs, the potential topics that need immediate consideration are as follows.

- Experimentation of bioaerosol transfer ratio (BTR) in ERVs with potential airborne human pathogens (i.e., virus, bacteria, fungi). In the case of any transfer, BTRs must be quantified for various ERV designs and operating conditions. Furthermore, measuring the BTR as well as pathogen viability is crucial because ERV may deactivate or reduce the pathogen's infectivity.
- The guidelines listed in ANSI/ASHRAE Standard 84 (Method of Testing. Air-to-Air Heat/Energy Exchangers) may not be applicable to bioaerosol transfer experiments. Thus, new criteria and uncertainty limits should be developed based on the

characteristics of tracer chemicals and instruments/equipment used to generate and characterize bio-aerosols.

- Small-scale methodology is a feasible experimental method for bioaerosol transfer experiments, particularly from the perspective of biosafety. However, validation of the extrapolation of BTR test results from small-scale to full-scale studies is critical for the future use of the small-scale method.
- The probability of infection in a building resulting from bioaerosol transfer through ERVs must be examined in order to gain a better understanding of the broader role of ERVs in facilitating infection transmission. A recommendation about ERV in the HVAC pandemic guidelines needs to be developed accordingly.

Author Contributions

Gurubalan Annadurai: Conceived the idea, literature review, methodology development, project administration, writing original draft, reviewing and editing. **Ashwin Joseph Mathews:** literature review, preparation of figures and writing original draft and editing. **Easwaran N. Krishnan:** literature review, writing original draft and editing**. Carey J. Simonson:** supervision, funding acquisition and reviewing

Conflicts of interest

There are no conflicts to declare

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