Aerosol Transfer through Semi-Permeable Membranes used in Membrane Energy Exchangers

A Thesis Submitted to the

College of Graduate and Postdoctoral Studies

In Partial Fulfillment of the Requirements

For the Degree of Master of Science

In the Department of Mechanical Engineering

University of Saskatchewan

Saskatoon

By

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ABSTRACT

Air conditioning societies and indoor air quality committees in North America have recently released guidelines for control of infectious aerosols in indoor spaces after the COVID-19 pandemic, recommending that more outdoor air be supplied to indoor spaces. Bringing in more outdoor ventilation air requires additional energy for heating and cooling the air to a comfortable temperature and relative humidity. Energy recovery devices such as membrane energy exchangers (MEE), can be used to reduce the energy required to condition outdoor ventilation air. MEE's use a semi-permeable membrane to transfer heat and moisture between the outgoing exhaust air and the incoming ventilation air. However, these membranes may also transfer aerosols from the building exhaust air to the outdoor ventilation air. Measuring aerosol transfer through membranes is challenging and has many sources of error. This research is a first attempt to conduct these difficult measurements.

In this thesis, a test method to measure aerosol transfer through membranes for energy exchangers was developed and experiments were conducted using two common types of semi permeable membranes (dense and porous membranes) and two types of aerosols (dust and bacteria aerosols). The dust aerosols were dry and bacteria aerosols were wet representing the two common types of aerosols found in the ambient air. The aerosol transfer was quantified using exhaust contaminant transfer ratio (ECTR), the ratio of the mass transfer rate of aerosols transferred from the exhaust air stream to the supply air stream normalized by the maximum possible mass transfer rate of aerosols between the two airstreams.

Aerosol size and shape were the two important properties affecting whether the aerosols were transferred or deposited within the membrane. Deposition within the membranes dominated transfer through the membranes tested. While additional improvements are recommended to accurately quantify aerosol contaminant transfer, the method developed in this thesis was able to conclude that dust (dry) and bacteria (wet) aerosol transfer through the porous (Tyvek) and dense (Polyamide) membranes that were tested was negligible.

ACKNOWLEDGEMENTS

I am grateful to my supervisor, Prof. Carey Simonson for his support, guidance, advice and patience with me during the completion of my MSc studies. I am also grateful to the feedback, guidance and support from my committee member, Dr. Shelley Kirychuk for walking me through challenging times during my experiments with bacteria.

I would like to express my heartfelt thanks to Heather Neufeld, Brooke Thompson and Pezhman Zolfaghiri who taught me to handle and work with bacteria and patiently answered my questions during the process. I have learnt a lot of microbiological methods and procedures for which I am indebted to discussions with members of the Canadian Center for Rural Agriculture and Health.

Special thanks to Dr. Melanie Fauchoux for helping me develop standard operating procedures and supporting me to get my experiments up and running. I would also like to thank Dr. Albin Joseph, Tyrone Keep, Shawn Reinink, Helen Yin and Matthews Ashwin Joseph for helping me with the experiments. I would also recognize the help of Eiko from the Western College of Vetenary Medicine, NanFang Zhang and Sandeep Yadav for helping me obtaining SEM images of samples. I am also thankful to my lab members, Ernest Agyekum, Tahmid, Amirreza Mahmoudi for their comments during our group meetings. Finally to my fellow lab member Siddhartha Gollamudi who I went to long coffee walks with, and Amy, staff member at the Tim Hortons who served coffee to us with a smile, I owe my think tank to you.

I am grateful for the emotional and financial support from my parents Gurpreet Binepal, Navjot Pannu and my little brother Jasraj Binepal. After each day successful or unsuccessful, I would look forward to going home to my family.

I would like to acknowledge the financial support from the National Science and Educational Research Council of Canada, Fredeen scholarship, Russell (Russ) William Haid Memorial Award, Dean's Scholarship, George Carter Scholarship, the ASHRAE Saskatoon's Winter Conference Travel Award and the College of Engineering Travel Award which helped me cover tuition and travel expenses during my program and focus on my research.

DEDICATION

ਸਲੋਕੁ ॥

(Salok)

ਗਿਆਨ ਅੰਜਨੁ ਗੁਰਿ ਦੀਆ ਅਗਿਆਨ ਅੰਧੇਰ ਬਿਨਾਸੁ

The Guru has given the healing ointment of spiritual wisdom, and dispelled the darkness of ignorance.

ਹਰਿ ਕਿਰਪਾ ਤੇ ਸੰਤ ਭੇਟਿਆ ਨਾਨਕ ਮਨਿ ਪਰਗਾਸੁ ॥੧॥

By the Lord's Grace, I have met the Saint; O Nanak, my mind is enlightened.

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NOMENCLATURE

Acronyms

ASHRAE	American Society of Heating, Refrigeration and Air conditioning Engineers
ATCC	American Type Culture Collection
cfm	cubic feet per minute
COVID-19	Coronavirus Disease of 2019
CFU	Colony Forming Units
CSA	Canadian Standards Association
Dia.	Diameter
EATR	Exhaust Air Transfer Ratio
EC	Ethylene Cellulose
E-Coli	Escherichia Coli
ECTR	Exhaust Contaminant Transfer Ratio
EDS	Energy Dispersive Spectrometry
HEPA	High-Efficiency Particulate Absorbing Filter
HVAC	Heating Ventilation and Air- conditioning
ISO	International Organization for Standardization
MEE	Membrane energy exchanger
NaCl	Sodium Chloride
NIOSH	National Institute of Occupational Safety and Health
NTU	Number of Transfer Units
Psi	pounds per square inch
PBS	Phosphate Buffered Saline
PDMS	Polydimethylsiloxane
PE	Polyethylene
PM	Particulate Matter
PP	Polypropylene
PVA	Polyvinyl alcohol
RP	Research Project

Std.	Standard
UV	Ultra Violet
W.C.	Water column
TSA	Tryptic Soy Agar
TSB	Tryptic Soy Broth

English Symbols:

A	Area [m^2]
B	Systematic Uncertainty
c	concentration of aerosols
C	Concentration of gases
CV	Coefficient of variation with respect to the mean value
d	Particle/ Fiber diameter
dN	Number of particles in a particular size range
D	Diffusion Coefficient of a Species in Air
Den	Denominator
g	Acceleration due to gravity
G	Gravitational Settling
h	Enthalpy
hr	hours
l	Obstacle characteristic length
log	logarithm
ln	natural logarithm
$\dot{m}$	mass flow rate
min	minutes
n	number of particles in a size bin
N	Number of total particles
Num	Numerator
OD	Outer Diameter

P	Pressure
$\dot{Q}$	Volumetric flow rate
R	Interception governing ratio
Re	Reynolds number
RH	Relative Humidity
S	Stopping distance
Shp	Shape correction factor
SP	Static Pressure
Stk	Stokes number
t	time
T	Temperature
U	Mass transfer coefficient/ Uncertainty
V	Velocity
Volume	Sensor measurement volume
W	Humidity ratio
X	Particle size

Greek Symbols

Δ	Difference delta
ρ	Density
ν	Dynamic viscosity
δ	Delta
ε	Latent effectiveness
ϕ	Mass balance inequality
μ	Micrometer
σ	Standard deviation

Subscripts

a	Air

c	Characteristic
deposit	deposited
EA	Exhaust Air
f	Fiber
fl	Flow
g	Geometric
i	Individual aerosol particle(s)
m	Mass
mean	Mean value
meas	Measured value
min	Minimum
O	Characteristic unit size
OA	Outdoor Air
p	Particle
RA	Return air
S	Cunningham correction
SA	Supply Air
ts	terminal
1	Outdoor air station/ Supply inlet
2	Supply air station/ Supply outlet
3	Return air station/ Exhaust air inlet
4	Exhaust air station/ Exhaust air outlet

CHAPTER 1

INTRODUCTION

1.1 Motivation

People spend a majority of their time, more than 90%, in indoor environments, such as office buildings [1]. While people pay close attention to the food and water they consume making sure it's healthy and nutritious, people assume that the air they breathe (more than 18000 L/day) in indoor spaces and outdoors is free of contaminants. The air we breathe in indoor environments is not always free of contaminants and often has different types of contaminants [2]. Amongst the different types of indoor contaminants, aerosols suspended in the air, are a common type. Aerosols are solid or liquid particles suspended in a gas [3]. One specific type of aerosols are bio-aerosols which are aerosols of biological origin such as bacteria and viruses. Bio-aerosols in a high concentration can often cause infectious diseases, such as influenza. Reducing the concentration of bio-aerosols in indoor spaces, by diluting them with fresh outdoor air, is one way of reducing the risk of infectious diseases caused by these aerosols.

Increasing the amount of outdoor air brought into the building leads to higher energy consumption to condition the air to a comfortable temperature and humidity [4]. One way to reduce the energy consumed for heating and cooling while increasing the amount of ventilation air is by using energy exchangers such as membrane energy exchangers [5]–[7]. During the recent COVID-19 pandemic, the use of energy recovery devices such as heat wheels was restricted due to the concern that they may transfer aerosols in addition to heat and moisture [8]. Membrane energy exchangers are a type of energy exchanger that transfer heat and moisture between the buildings exhaust air and the outdoor air using a semi-permeable membrane. While gaseous contaminant transfer and particulate

matter fouling in membrane energy exchangers has been researched [5, 6, 9] there has been limited research in whether aerosols transfer through these exchangers.

The aim of this research is therefore to determine whether aerosols transfer through membranes used in energy exchangers. As aerosol transfer through membranes has not been quantified before, the first step is to develop a test methodology to quantify aerosol transfer through membranes. The test method needs to be capable of measuring concentration of active bio-aerosols to determine if transfer of aerosols through the membrane poses a risk of infection. It is possible that the aerosols might diffuse through the pores in these membranes due to high concentration of aerosols in the exhaust air stream than the outdoor air stream.

1.2 Background

The different types of aerosols in the exhaust air, the principle behind the operation of a membrane energy exchanger, possible methods of aerosol transfer through membranes, current test methods and gaps in these methods will be discussed briefly in this section.

1.2.1 Aerosols in indoor air

Aerosols in the air are often classified based on size [3]. The aerosols in the ambient air are often referred to as particulate matter (PM). There are three common aerosol size ranges: PM 10 for particles less than 10 µm, PM 2.5 for particles less than 2.5 µm and PM 1 for particles less than 1 µm. PM in indoor environments include bio-aerosol such as bacteria, fungi and pollen which can cause diseases if inhaled [10]. The size of the aerosol is important because it dictates how far the aerosol can travel inside the body after inhalation, as shown in Figure 1.1. Larger particles (PM 10), such as dust, can deposit in the airways close to the nose and the trachea. Smaller particles less than 5µm can travel further down in the respiratory system depositing in the alveoli in the

lungs. As illustrated in Figure 1.1 some finer particles (PM 1) can diffuse through the alveoli into the bloodstream reaching the brain and other internal organs.

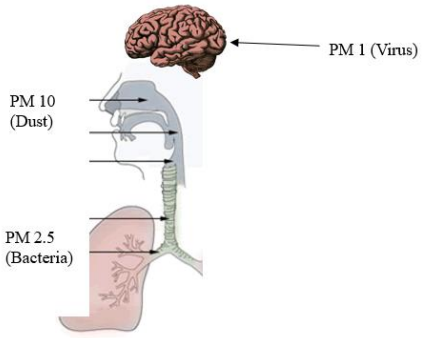

Figure 1.1: Travel distance of an inhaled aerosol based on size

Typical viruses are smaller than 1 µm whereas the bacteria are typically 1 µm - 10 µm. Figure 1.2 gives the size ranges of the bio-aerosols and other aerosols. The atmospheric aerosols in the PM 1 level can be as small as 1 nm -10 nm [3].

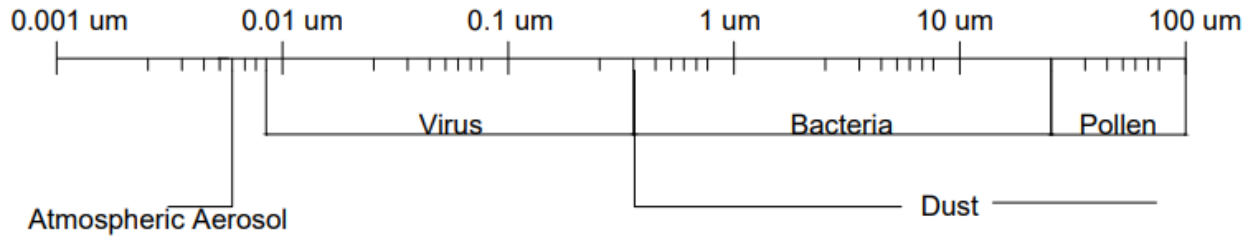

Figure 1.2: Different aerosol size ranges in the ambient air

1.2.2 Operation of a membrane energy exchanger

Figure 1.3 shows an example of the implementation of an air-to-air membrane energy exchanger in a building HVAC system. There are two fans that draw or push fresh outdoor air and building exhaust air into the energy exchanger. These air streams are separated using a semi-permeable

membrane inside a core. The membrane inside the core is semi-permeable implying it is permeable to water vapor but is relatively impermeable to other gases or aerosols. Such a membrane can be said to selectively transfer heat and moisture. The design intent of the membrane energy exchanger is to allow water vapor/moisture transfer but not transfer of contaminants such as aerosols through the membrane.

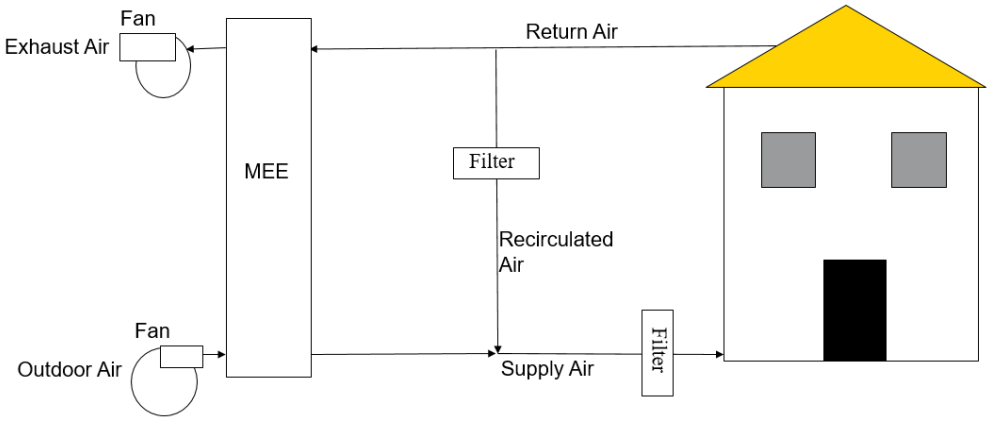

Figure 1.3: Schematic of membrane energy exchanger in a building HVAC system

Using a high efficiency filter, such as a HEPA filter, in the return air stream is an effective way of preventing aerosol particles from reaching the membrane energy exchanger. It is recommended by manufacturers to add filters at the inlets of the exchanger to prevent deposition of large particles. However, filters add a higher pressure drop to the system, which leads to higher fan energy consumption [8, 11]. Thus, the building exhaust might be unfiltered, and aerosols in the building exhaust air can enter the membrane energy exchanger. The size and shape of the aerosol particles entering the membrane energy exchanger, as well as the type of membrane used in the exchanger, are factors that determine whether the aerosols will transfer through the membrane into the supply air.

1.2.3 Mechanisms of aerosol transfer through membranes

The membranes used in a membrane energy exchanger can be classified into two main types (porous and dense) based on pore size [12]. Porous membranes have pore sizes in the order of micrometers, typically (0.3 μm – 1 μm) but may have larger defects [5]. If defects are present, aerosol particles might diffuse through these defects based on pressure and concentration differences between the air streams on either side of the membrane. They may also diffuse through the pores like water vapor and other gases do due to differences in concentration [5]. If the shape of the aerosol particle is non-spherical, the orientation of the particle will also contribute to whether the particle will transfer through the pore or the defect in the membrane.

Dense membranes have pore sizes in the order of 0.1 nm [12]. Often a dense layer is coated over a porous substrate, which provides mechanical strength to the dense membrane layer [13]. The dense membrane is composed of polymer chains which can spin around their axis and create free volumes based on temperature [5]. The aerosol particles might diffuse through these free volumes and get transferred to the outdoor air. In addition to the free volumes, the aerosol might be adsorbed on the membrane surface, diffuse through the membrane and desorb in the outdoor air stream in a similar way as the water vapor transfers through these dense membranes.

1.2.4 Existing test methods and standards for aerosol testing

Experimental research on aerosols in the ambient environment is prevalent for indoor and outdoor air quality monitoring. Standard processes referred to as test methods are also available in the literature for aerosol concentration monitoring and experiments and are described later. Similarly, test methods are available for heat and moisture transfer performance of membrane energy exchangers and are described later. In addition, these test methods also specify the limits of air leakage from the building exhaust air to the outdoor air stream using tracer gas tests and

quantifying the percent of air transferred as exhaust air transfer ratio (EATR). The air leakage quantified by the EATR is often due to improper sealing of the edges as well as defects in the membrane. In addition, if a pressure gradient exists between the airstreams, air would transfer through the membrane and air transfer can be quantified using the Darcy air permeability [14]. In North America there are two test methods for determining the performance of an energy exchanger, American Society of Heating, Refrigeration and Air Conditioning Engineers (ASHRAE) Standard 84 [15] and Canadian Standards Association (CSA) Standard C439, but they do not contain a test procedure for aerosol testing.

There are a few standards that specifically use aerosols, such as dust particles, and bacteria for filter testing. ASHRAE Standard 52.2 [16] outlines test method for generation and sampling of dust aerosols for filter testing, but is challenging to extend for small-scale membrane energy exchangers due to the high air flow rates required in the Standard. National Institute of Occupational Safety and Health (NIOSH) method 0801 [17] outlines collection volume and instrumentation for aerobic and anaerobic bacteria sampling. However, neither ASHRAE standard 52.2 nor NIOSH Method 0801 are directly applicable for aerosol transfer through membrane energy exchangers. To address this gap a test methodology will be developed in this thesis using both solid and liquid aerosols, the common types found in the indoor air, to determine aerosol transfer in a membrane exchanger. Wherever applicable, standard procedures and guidelines from ASHRAE Standard 52.2 and NIOSH Method 0801 will be followed.

1.3 Objectives

From the review of existing literature, the main aim of this research is to quantify aerosol transfer in membrane energy exchangers. A test method will be developed for an existing experimental test

facility and used to determine aerosol transfer in different membranes. This MSc thesis has the following objectives:

1) Develop a test method to quantify aerosol transfer in membrane energy exchangers
2) Apply method developed in objective 1 to quantify aerosol transfer in i) dense and ii) porous membranes

1.4 Thesis structure

The thesis follows a manuscript style with five chapters and six appendices. Chapter 1 presents the motivation for the work, background and objectives of the research. Chapter 2 describes the literature relevant to aerosol transfer in membrane energy exchangers. Chapter 3 describes the test methodology used for experiments and applies the test method for a case of a dense membrane. Chapter 4 describes the transfer of aerosols in porous membranes and presents a test method that can be used to determine active bacteria transfer in a membrane energy exchanger. Conclusions from the research and future work are outlined in Chapter 5.

1.5 Publications

Chapter 3 of this thesis is based on a conference paper presented at the 2024 ASHRAE winter conference. Some modifications have been made to the content of the original paper as the test methods was improved after the conference. Chapter 4, which is a journal paper that is in progress, presents the experimental results of aerosol transfer in porous membranes that will be submitted to *Science and Technology for the Built Environment*.

Chapter 3: T.S. Binepal, P. Zolfaghari, B. Thompson, M. Fauchoux, A. Joseph, C. Simonson, S. Kirychuk, “Test methodology to determine aerosol transfer in membrane

energy exchangers", *in Proceedings of the 2024 ASHRAE Winter Conference*, Jan 20-24, 2024, Chicago, Illinois, USA.

Chapter 4: T.S. Binepal, M. Fauchoux, B. Thompson, A. Joseph, S. Kirychuk, C. Simonson, "Bio-aerosol transfer through porous membrane used in membrane energy exchangers" (to be submitted to Science and Technology for the Built Environment)

CHAPTER 2

LITERATURE REVIEW

2.1 Overview

This chapter presents the theory and background to understand aerosol transfer through membranes used in energy exchangers. This includes behaviour of aerosol particles moving with an airstream in a duct, physical characteristics of aerosols such as particle size and distribution, test methods and instruments used for aerosol generation and sampling.

The behaviour of aerosol particles in an airstream within a duct is influenced by the aerosol particle size, shape and air speed. The particle size and shape can be used to calculate the Reynolds and Stokes numbers which determine the mechanics of aerosol movements around obstacles such as sampling devices and previously settled particles. The theory from this section is used to interpret and discuss results from aerosol transfer experiments using dense and porous membranes in Chapter 3 and Chapter 4 of the thesis.

The goal of the research is to determine how well the membranes can transfer water vapor while acting as a barrier to aerosol particles. The theory describing water vapor transfer in membrane energy exchangers is well developed. The equations used to calculate water vapor transfer in membrane energy exchangers are presented in this chapter. While theoretical relations for aerosol transfer in these exchangers are not developed, the amount of transfer can be determined experimentally by calculating the exhaust contaminant transfer ratio (ECTR). The ECTR is the ratio of concentration aerosols transferred into the outdoor air to the concentration of aerosols in the building exhaust air. Available equations for water vapor transfer in membrane energy exchanger as per ASHRAE Std. 84 [15] are used to determine the percentage of water vapor

transfer using the measured relative humidity. The ECTR is quantified using the measured concentration of aerosols at the supply air outlet, the return air inlet, outdoor inlet and the relation for ECTR is discussed in this chapter. The calculated quantities of aerosol and water vapor transfer from these relations are then used for comparison in the future chapters on how selective the membranes are to water vapor transfer over aerosol transfer.

There is limited research on interaction of aerosol particle with membranes used in energy exchangers, a case where the membrane is oriented parallel to the flow [6]. Research on interaction of aerosols with filters made of membranes oriented perpendicular to the flow is extensive [18-20]. The filter efficiency can be calculated using analytical relations for a singe fiber when flow is perpendicular to the fiber [3]. These analytical relations developed for filtration have not been explored for a case of membrane oriented parallel to the flow such that it could be used to analytically determine the transfer through the membrane separating the two air streams in a membrane energy exchanger. In addition, to determine the active bio-aerosols transferred if such is the case, experiments are required. Therefore this chapter reviews the testing methods and protocols for aerosol generation and sampling that can be used for experiments. In addition, previous research for aerosol interaction with heat and energy exchangers is briefly reviewed. The review of protocols and existing research will be used to determine the test method, sampling procedure and selecting aerosols used for experiments, referred to as challenge aerosols in Chapter 3 of the thesis.

2.2 Behaviour of aerosol particles and parameters influencing behaviour

A brief description of aerosol particles in ambient air was provided in Chapter 1. A further review aerosol concentrations typically encountered in indoor environments is provided in this section. The domination of viscous or inertial forces on a particle as well as the ability of the particle to

react to obstacles is qualitatively described using Reynolds and Stokes number. In understanding the behaviour of aerosols, it is important to understand that aerosol particles have an affinity for deposition to surfaces. Thus the mechanisms that determine the deposition for aerosols are presented. In addition, the deposited aerosols might be resuspended in the airstream randomly which is challenging to predict.

2.2.1 Aerosol particles in the ambient environment and aerosol distributions

Aerosols in the ambient environment occur in a polydisperse form [3], which is an aerosol particle distribution consisting of particles of different sizes. The opposite form of polydisperse aerosols are monodisperse aerosols. Monodisperse aerosols consist of aerosol particles of the same size [3] and can be used for lab based testing. Examples of aerosol particles in the ambient air include fog, dust, smog, and bio-aerosols. Ambient aerosol distribution varies according to geographic location and the building facility being sampled for example, an office environment compared to a poultry farm. In a literature review of bio-aerosols in indoor and outdoor environments, different types of bacteria species were found in North America compared to Europe [10, 21]. While *bacillus*, *micrococcus* and *staphylococcus* were the bacteria found in an indoor office environment in Poland, in concentrations of 14 cfu/m^3 – 494 cfu/m^3 [10] where cfu/m^3 represents the active bacteria colony forming units in a unit m^3 of air; *Staphylococcus*, *Salinicoccus*, *Lactobacillus* were the bacteria species found in a poultry industry environment in Texas in concentrations of 74 cells/m^3 – 2187 cells/m^3 [22] where cells represent individual bacteria cells as apposed to colony forming units. If a single cell (bacteria) is active and culturable it grows into a colony when plated and can be counted as a colony forming unit as discussed above.

The methods used to generate aerosols that can represent ambient aerosols have been reviewed in literature, and standards used for different applications recommend different generation methods.

ASHRAE Standard 52.2 recommends using potassium chloride (KCl) particles and dust particles in the size range 0.3 μm – 10 μm for filter efficiency testing. In comparison, using monodisperse particles, such as polystyrene latex spheres, requires significantly longer testing time. It is also difficult to generate a sufficient concentration quantity of the particles. Solid aerosol particles were recommended by ASHRAE Standard 52.2 committee for testing aerosol choice or the challenge aerosol as particles > 3 μm bounce off fibers. Since these particles "bounce off" rather than "attach to" the fibers they are a suitable choice to test different filter materials. This is because effective filtration is based on the ability of the filter material to get the aerosol to deposit on the surface of the material thus 'filtering' it out of the airstream. The aerosol deposition mechanisms are described later in this chapter.

Solid particles and KCl aerosols were recommended as the test or "challenge" aerosol for filter performance testing as per ASHRAE Standard 52.2. ASHRAE also suggests potential challenge bio-aerosols for testing of micro-organism disinfection techniques such as Ultra Violet (UV) light based inactivation. *Mycobacterium parafortuitum* (ATCC 19686) and *Aspergilus sydowii* (ATCC 36542) are two aerosols recommended in ASHRAE Standard 185.1 for Ultra Violet (UV) lights based inactivation of airborne microorganisms. Annadurai et al. [4] reviewed generation methods for bio-aerosols and concluded it is difficult to achieve the same distribution as ambient bio-aerosols. Since some bio-aerosols in the indoor environment such as airborne bacteria and viruses have a potential to cause disease, it is also important to use a safe substitute to mimic the behaviour of these bio-aerosol particles. In addition, based on the review of ASHRAE Standard 52.2, it is important to use a solid aerosol with a polydisperse distribution [16]. The aerosol should have size ranges representing the PM 1, PM 2.5, and PM 10 size ranges in a sufficient concentration for testing. Aerosol size is an important physical parameter that can be used to understand aerosol

behaviour and is described in the next section. In summary, the available literature reviews and test methods recommend testing with solid and liquid aerosol particles with a large size distribution (PM1, PM 2.5, PM10). For testing with bio-aerosols, it is proposed to use a safe bacteria or fungi with a low risk to cause diseases. On a scale of level 1 to 4, the low risk organisms would typically fall under the level 1 category. Therefore while selecting the aerosols in experiments for this research, liquid and solid aerosols with a large size distribution would be selected. For selection of bio-aerosols, the recommended bio-aerosols in ASHRAE Standard 185.1 would be explored but preference will be given to easy to handle level 1 bacteria or fungi.

2.2.2 Aerosol particle size

Aerosol particles can exist in both solid and liquid forms. While liquid aerosol particles tend to have a spherical shape, solid aerosol particles have irregular shapes. Thus it is common to express the size of these irregular solid aerosol particles as equivalent spheres. Often these spherical particles will have the same characteristics as the irregular particle such as density or terminal velocity [3].

Aerosol particles are often measured in the size range of micrometers [µm] and can remain airborne for many hours due to their small size. Airborne bio-aerosols in high concentration can cause an infection if inhaled. Thus, particle settling velocity or, the terminal velocity a particle achieves while falling under the influence of gravity is an important property. The terminal velocity dictates the time it takes for a particle to settle or alternatively the time the particle remains airborne. For non-spherical particles the aerodynamic diameter, which is the diameter of a spherical particle with a density of 1000 kg/m^3 and the same settling velocity as the non-spherical particle, is commonly used to describe size [3]. Figure 2.1 provides an illustration of an irregular particle and the equivalent aerodynamic diameter. In a large room with still air and a well mixed

aerosol distribution, aerodynamic diameter is an effective way of describing aerosol size. Droplets generated by an infectious person in such a room will become airborne and settle down based on the aerodynamic diameter of each droplet.

The Stokes diameter is a better representation of aerosol particle size in cases such as airflow in a duct. This is because particle inertia will play an important role in the path of the particle. The Stokes diameter is the diameter of a spherical particle with the same settling velocity and density as the irregularly shaped solid aerosol particle [3]. Since this work involves studying aerosols in air ducts, the Stokes diameter is used when reporting aerosol sizes. Figure 2.1 shows an irregularly shaped particle and the equivalent Stokes diameter.

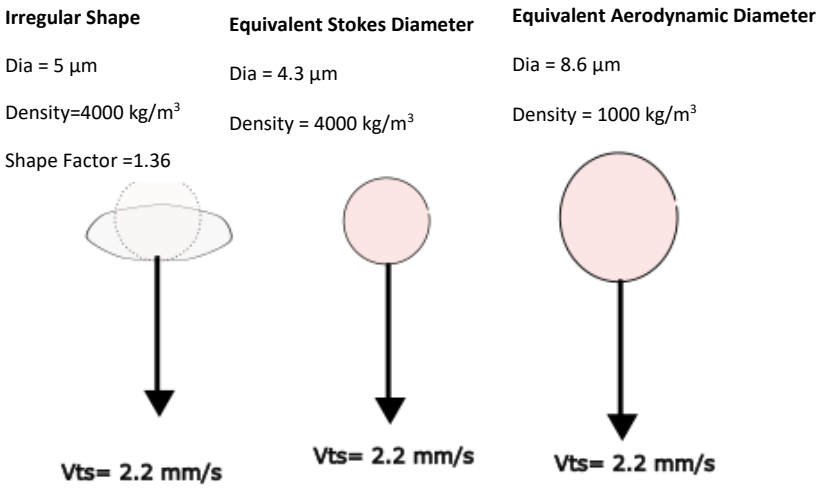

Figure 2.1: Different ways of representing an irregular solid aerosol particle based on b) equivalent Stokes diameter and c) equivalent aerodynamic diameter

A collection of aerosols commonly consists of a large range of particle sizes, which often vary within two orders of magnitude. The distribution of aerosol sizes does not follow a normal distribution trend, but rather is skewed with a peak in a particular size range and a long tail as seen in Figure 2.2. This type of distribution has different mean, median and mode values. Since the aerosol distribution has three different statistical properties, it is difficult to determine the

important one to represent. In comparison, a normal distribution has the mean, median and mode coincide and it's sufficient to report a single mean value. Plotting the number fraction, the number of particles in a particular size over the total number of particles, (dN/N) with respect to particle size (d_p) is one of the many methods to graphically represent this distribution. In Figure 2.2 below the particle size is represented using X [µm]

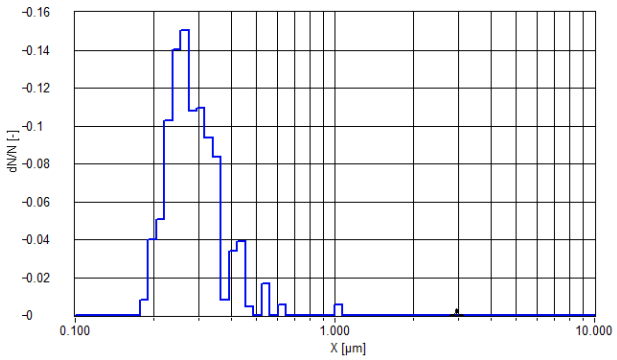

Figure 2.2: An example of an aerosol particle size distribution

It is valuable to know the number fraction for bio-aerosols where the number of aerosols helps determines the infectious dose and the ability to cause infection [23]. In other cases where inactivation of these aerosols by a chemical is the focus, the surface area might be an important parameter and the distribution of the normalized surface area rather than the number might be plotted. A unique property for aerosols compared to other distributions like the population, number of manufactured parts of a machine is that properties like the surface area depend on particle size raised to a power (moment), in this case the power 2 for area (d_p^2). Similarly the mass of the particle is dependent on power 3 for volume (d_p^3) as mass is the product of the density and the volume. It is uncommon to see (population)^2 or the (manufactured parts of a machine)^3 [3]. These unique distributions are referred to as moment distributions.

To simplify reporting of the distribution using two parameters, the mean and the standard deviation, the lognormal distribution is often used. This converts the skewed aerosol distribution shown in Figure 2.2 to a form similar to normal distribution and avoids the use of different mean, median and mode values. To plot the lognormal distribution, the number fraction (dN/N) is normalized using the logarithmic interval width (Δ log d) and plotted on the y-axis. On the x-axis instead of particle size (d_p), the logarithm of (d_p/d_0), the ratio of particle size (d_p) to d_0 (1μm) is plotted. There are two important properties that can be used to describe the lognormal distribution, the geometric mean (d_g) given using Equation (2.1) and the geometric standard deviation (σ_g) computed using Equation (2.2).

$$\ln d_g = \frac{\sum n_i \ln d_i}{N} \tag{2.1}$$

$$\ln \sigma_g = \left(\frac{\sum n_i \left(\ln d_i - \ln d_g\right)^2}{N-1}\right)^{1/2} \tag{2.2}$$

where, n_i is the number of aerosol in a particle size range with a mean diameter d_i, and N is the total number of aerosols. The geometric mean d_g and geometric standard deviation σ_g of equivalent Stokes diameter will be used to describe the size distribution of the aerosol being used for testing. The geometric mean and geometric standard deviation can be used to obtain other aerosol moment distributions and particle mean diameters such as the mass mean diameter using the Hatch-Choate equations provided the aerosol distribution is lognormal [3].

Other parameters, such as the particle Reynolds number and particle Stokes number are also dependent on the aerosol diameter. For a monodisperse aerosol distribution, since all particles have the same size, the particles have the same Reynolds and Stokes numbers. In a polydisperse aerosol

distribution there are numerous particles of different sizes, so the Reynolds and Stokes numbers would be different.

2.2.3 Particle reynolds number

The Reynolds number of a particle is the ratio of the inertial forces of the particle to the frictional forces due to viscous drag. The Reynolds number of a particle can be determined using Equation (2.3) [3] based on the particle size (d_p), velocity (V), density of air (ρ_a) and the dynamic viscosity of the air (ν):

$$\mathrm{Re_P} = \frac{\rho_a V d_p}{\nu} \tag{2.3}$$

For $\mathrm{Re_P} < 1$, the viscous forces dominate and the flow around the particle is laminar with steady streamlines. For $\mathrm{Re_P} > 1$, there is formation of eddies downstream of the particle (turbulence) and the inertial forces of the particle based on its mass dominate. While in an environment of still air, such as in a room, the aerosol particle begins to fall under the influence of gravity and reaches its terminal velocity. For instance, when a person sneezes and generates aerosol droplets in a room, $\mathrm{Re_p}$ is often less than 1. However, when suspended inside a moving airstream such as in a duct, the particle tends to reach the velocity of the airstream and has $\mathrm{Re_p}$ much larger than 1. In this case the particle's inertial forces are more likely to dominate the particle behavior.

To determine whether the particle's inertia is likely to overcome its tendency to follow the flow streamlines or how it would react to obstacles such as previously settled aerosol particles, or sharp curves in the duct, the Stokes number can be used.

2.2.4 Particle stokes number

The Stokes number of a particle represents the ratio of the stopping distance of the particle (S) to the characteristic dimension of the obstacle (l_c) the particle encounters. The Stokes number of a particle can be determined using Equation (2.4) [3]:

$$Stk = \frac{S}{l_c} \tag{2.4}$$

When the Stk << 1, the particles tend to follow the flow streamlines of the air. If this is not the case and the particle Stk >> 1, it is likely that particle inertia forces will cause the particle to continue in its direction of motion. The two different situations are represented in Figure 2.3. Depending on whether Stokes number is much larger than 1 or much smaller than 1, the angle of sampling will play an important role in determining whether the concentration measured from the sample is a true representation of the sample concentration. If many of the particles bypass the sampling port, the sample will be under-represented, and the resulting concentration will be lower than the true value. Therefore, sampling flow rates, sampling angles and flow rate in the duct need to be carefully selected so that the measurement can give an appropriate representation of the concentration in the duct. In order to get the most representative sample, the isokinetic sampling procedure is followed. In an isokinetic sampling case the probe is centered in the duct rather than being off side and the velocity of the particle matches the velocity of the particle in the sampling probe. It is important to meet both criteria, if the velocity magnitude is matched but the probe is off center by 60°, the concentration error with respect to the original concentration can be as high as 50% [3].

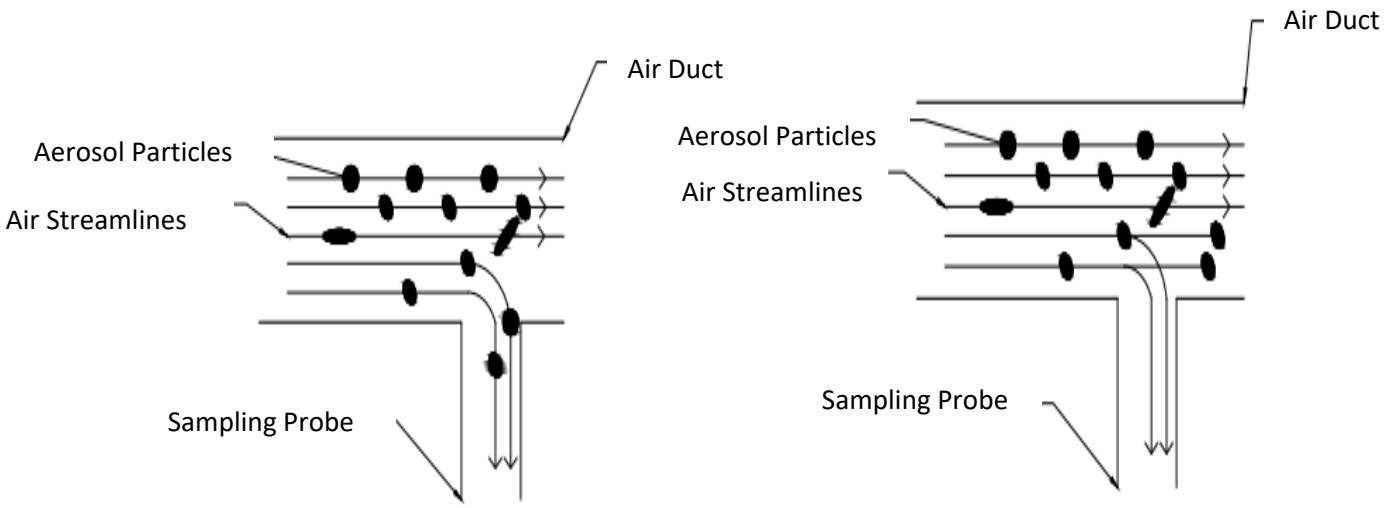

Figure 2.3:a) Sampling for Stk <<1 and b) Sampling for Stk >>1. For case a) Particle inertia is not significant but for case b) Particle inertia is significant

2.2.5 Aerosol deposition mechanisms

It is possible that the aerosols first deposit and then transfer through the membrane. It is therefore important to understand deposition of aerosols in ducts and membranes. There are five major deposition mechanisms that govern the deposition of aerosols as they travel through the air ducts and the exchanger. These five deposition mechanisms are interception, inertial impaction, diffusion, gravitational settling and electrostatic attraction [3, 24] . The filter efficiency is the sum total of all the deposition fractions based on the five different deposition mechanisms. Therefore, understanding of deposition gives an idea on how particles would interact with the membrane as they flow over it and are described briefly below.

2.2.5.1 Aerosol deposition due to interception

In interception, an aerosol particle that is following a gas streamline comes in contact with the edge of a fiber and gets attached to the fiber as shown Figure 2.4 [3].

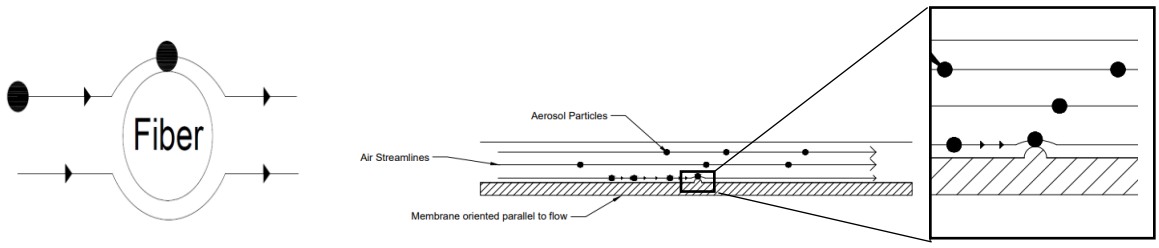

Figure 2.4: Illustration of deposition due to interception on a) a the fiber of a filter, flow through the filter perpendicular to the fiber and b) a membrane with flow parallel to the membrane

Interception is dependent on the ratio of the particle diameter (d_p) to the fiber diameter (d_f) represented using R as in Equation (2.5) [3].

$$R = \frac{d_p}{d_f} \tag{2.5}$$

As R increases or the aerosol particle size approaches the size of the fiber the likelihood of the aerosol particle getting intercepted by the fiber increases.

2.2.5.2 Aerosol deposition due to inertial impaction

Aerosol deposition due to inertial impaction is the most likely deposition mechanism for aerosols travelling in an air duct when they encounter obstacles like raised fibers on the surface of the membrane, and in cases when they encounter sharp 90° bends or elbows. Inertial impaction occur because some particles are unable to quickly change their direction of motion along with the flow streamlines and end up colliding with the fiber, as shown in Figure 2.5. Although the interception and inertial impaction appear similar there is a subtle distinction. In interception, the particle continues to follow the streamline when it is intercepted while in the case of inertial impaction it deviates from the streamline due to inertia when it attaches to the fiber.

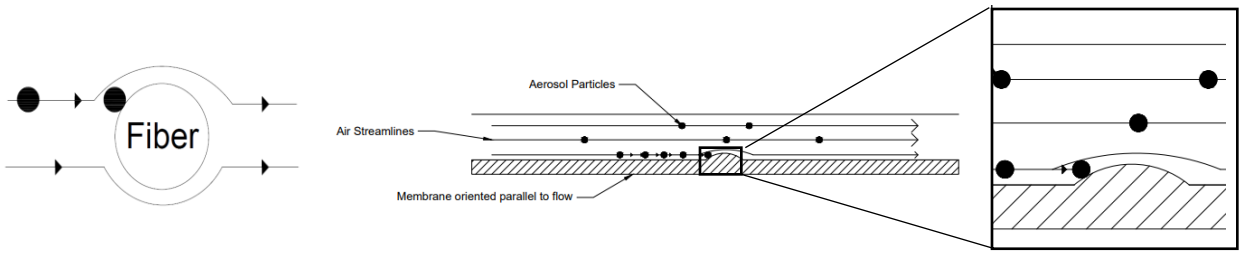

Figure 2.5: Illustration of deposition due to inertial impaction on a) a the fiber of a filter, flow through the filter perpendicular to the fiber and b) a membrane with flow parallel to the membrane

The likelihood of a particle impacting on a surface is directly proportional to the particle Stokes number. As the Stokes number increases due to higher velocity or size-based inertia, the stopping distance of the particle increases and thus it is less likely to make a sudden change in direction.

2.2.5.3 Aerosol deposition due to brownian motion or diffusion

Very small aerosol particles (< 1µm) randomly collide with air molecules and other aerosol particles undergoing Brownian motion. Brownian motion refers to the random wiggling motion of an aerosol particle in still air as gas and other molecules collide with it [3]. Thus, aerosol particles are likely to collide and stick to the membrane fibers even if they are travelling on a non-intercepting streamline as shown in Figure 2.6.

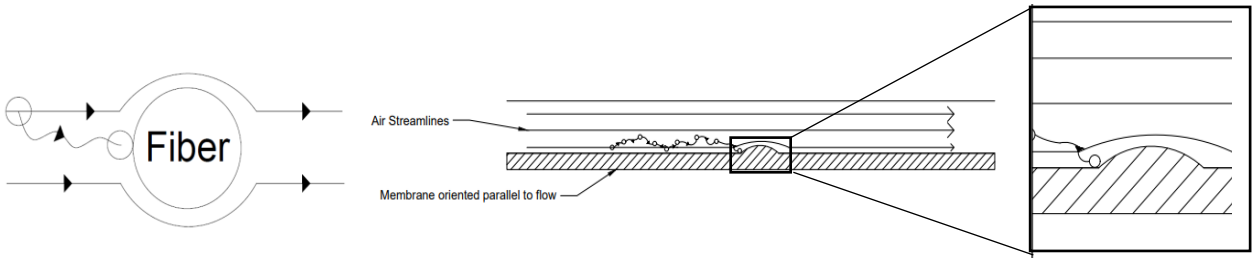

Figure 2.6: Illustration of deposition due to diffusion on a) a fiber of a filter with flow through the filter perpendicular to the fiber and b) a membrane with flow parallel to the membrane

The fraction of aerosol particles depositing on the membrane due to Brownian motion is dependent on the mass transfer (diffusion) Peclet number, which is inversely proportional to the particle diffusion coefficient in the air (D) [3]. The Peclet number can be calculated using Equation (2.6)

$$\mathrm{Pe_m} = \frac{v l_c}{D} \tag{2.6}$$

Where v the velocity of the particle is, l_c is the characteristic length of the channel and D is the mass diffusivity. A 0.1 μm standard density particle has a diffusion coefficient of $6.9 \times 10^{-10}\mathrm{m}^2/\mathrm{s}$ which is a hundred times larger than a 10 μm particle with a diffusion coefficient $2.4 \times 10^{-12}\mathrm{m}^2/\mathrm{s}$. The larger particle is therefore less effected by the Brownian motion compared to the smaller particle. The collection efficiency due to diffusion is inversely proportional to the Peclet number [3] and thus directly proportional to the diffusion coefficient. As the particle size decreases it can be expected more smaller particles will be collected by this mechanism of deposition compared to the larger particles.

2.2.5.4 Aerosol deposition due to gravitational settling

The aerosol deposition due to gravitational settling (G) represents the deposition of an airborne aerosol due to its own weight. G is dependent on particle size and directly proportional to the ratio of gas flow velocity (V_{fl}) to the terminal velocity (V_{TS}) as in Equation (2.7).

$$G = \frac{V_{TS}}{V_{fl}} = \frac{\rho_a d_p^2 Shp_s g}{18 \nu V_{fl}} \tag{2.7}$$

where ρ_a is the density of air, d_p is the particle size, Shp_s represents the shape correction factor, ν is the dynamic viscosity of air. Since G increases with particle size, deposition due to gravity also increases with particle size.

2.2.5.5 Aerosol deposition due to electrostatic forces

Aerosol particles may also deposit on the surface due to electrostatic forces between the aerosol particles and the surface. Electrostatic deposition is difficult to quantify, since it requires the precise charge on the aerosol particle be known. Qualitatively, the electrostatic deposition

increases as the charge on the particle or fiber increases. In addition, decreasing the face velocity can also increase the electrostatic deposition.

To summarize, it is important to understand that aerosol particles have a tendency to deposit on and stick to surfaces. Aerosol particles can be collected on a surface due to interception, impaction, Brownian motion, gravity and electrostatic forces. While analytical relationships are available for these deposition mechanisms on a single fiber for a case of perpendicular flow around the fiber, there are no relationships available for parallel flow over a membrane.

2.3 Water vapor and aerosol transfer in energy exchangers

While the transfer of aerosol particles in membrane energy exchanger has not been studied previously, water vapor transfer has been studied previously by many researchers [25, 26]. Thus as will be presented later, it is possible to calculate transfer of water vapor through these membranes both theoretically and experimentally but it is possible to measure the aerosol transfer, in particular the bio-aerosol transfer through the membranes experimentally.

The water vapor transfer is dependent on the airflow rate through the exchanger, the vapor transfer resistance properties of the membrane and the surface area of the membrane. Together these quantities can be combined and represented using a dimensionless parameter called the NTU (number of mass transfer units). The NTU_m can be calculated using Equation (2.8) [5, 27].

$$\mathrm{NTU}_m = \frac{U_m A}{\dot{m}_a} \tag{2.8}$$

where U_m is the convective mass transfer coefficient ($\mathrm{kg/(s.m^2)}$) that is dependent on the membrane vapor resistance and boundary layer resistance, the surface area of the membrane ($\mathrm{m^2}$) and $\dot{m}_a$ is the mass flow rate of the air [5].

Once NTU_m is determined, the water vapor transfer effectiveness ε_{latent} can be determined theoretically for a case of balanced flow, meaning the airflow rates in the return and outdoor air streams are equal using Equation (2.9) for a counterflow exchanger [27].

$$\varepsilon_{latent} = \frac{NTU_m}{1+NTU_m} \tag{2.9}$$

In addition, to the above theoretical relations, the amount of water vapor transfer can also be determined using the relations defined in ASHRAE Std. 84 as per Equation (2.10) [15]. For cases of balanced flow and a constant enthalpy of vaporisation ($h_{fg} = 254\ kJ/kg$), Equation (2.10) can be further simplified to Equation (2.11) for a case of balanced flow rates.

$$\varepsilon_{latent} = \frac{\dot{m}_2(h_{fg,1}W_1 - h_{fg,2}W_2)}{\dot{m}_{min}(h_{fg,1}W_1 - h_{fg,3}W_3)} \tag{2.10}$$

$$\varepsilon_{latent} = \frac{(W_1 - W_2)}{(W_1 - W_3)} \tag{2.11}$$

As shown in Figure 2.7, W_1 is the humidity ratio of the outdoor air (kg_w/kg_a) as it enters the membrane energy exchanger and W_2 is the humidity ratio of the outdoor air (kg_w/kg_a) as it leaves the membrane energy exchanger. The numerator in Equation (2.11) represents the amount of energy that the outdoor air gains or loses as it is humidified or dehumidified while passing through the exchanger. The denominator in Equation (2.11) represents the maximum possible energy transfer in the exchanger which is the difference between W_3, the humidity ratio at the return air stream and W_1, the humidity ratio at the outdoor air stream.

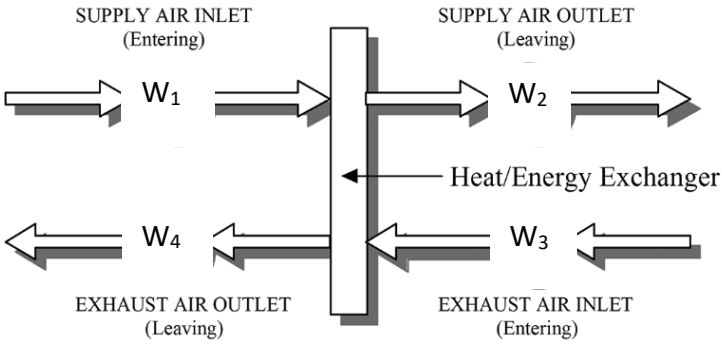

Figure 2.7: Schematic of the energy exchanger with the numbered entry and exit locations [15].

The treatment of contaminant transfer through a membrane is similar, but slightly different to the water vapour transfer. Equation (2.12) is used to calculate the exhaust contaminant transfer ratio (ECTR), which defines the amount of a contaminant that transfers through the membrane from the return air to the outdoor air. The ECTR was developed as a part of ASHRAE RP-1780 [28] to quantify gaseous contaminant transfer in membrane energy exchangers in a case of balanced flow

$$\text{ECTR} = \frac{(C_2 - C_1)}{(C_3 - C_1)} \tag{2.12}$$

Here C_1 is the concentration of gaseous contaminant in the outdoor air as it enters the exchanger and C_2 is the concentration of gaseous contaminant in the outdoor air at the exit of the exchanger. Together the numerator is the change in concentration of gases in the outdoor air (gain or loss) being supplied to the building. Similar to Equation (2.11) the denominator is the maximum possible gaseous contaminant transfer which is the difference in the gas concentration of the building return air C_3 and the concentration of gases in outdoor air C_1. This equation will be the basis for determining the amount of aerosols that transfer that transfer through the membrane in this thesis.

To determine the ECTR using experimental methods it is important to determine the test procedure using aerosols, such as generation and sampling methods. The following section presents a literature review of the existing research on generation and sampling instruments, test procedures and determines gaps that need to be addressed.

2.4 Review of aerosol test methods

A review of experimental bio-aerosol generation and sampling techniques has been presented by Annadurai et al. [4]. Liquid and solid generation techniques were identified as the two alternatives for bio-aerosol generation. However, the authors note the need for experiments to determine which generation mechanism is suitable for determining bio-aerosol transfer in energy exchangers. A variety of sampling techniques are identified, such as an optical spectrometer, solid impactors, liquid impingers, filters and a condensation growth tube. The applicability of the sampling method is dependent on the aerosol characteristics such as number of particles and size. More experimental research is needed to determine the suitability of the sampling and generation instruments with bio-aerosols for studying bio-transfer in membrane energy exchangers. In addition, the review is specific to techniques that can be used with MS2 phage particles as the challenge bio-aerosol. Limited review is provided for bacteria and fungi aerosol generation and sampling methods. Since bacteria are the common bio-aerosol in the ambient environment occupied by humans [10], more research on bacteria generation and sampling methods for determining bacteria aerosol transfer in membrane energy exchangers is needed.

Although research of aerosol transfer in membrane energy exchangers is limited, the interaction of ambient aerosols, including bio-aerosols with heating and cooling coils has been studied by Siegel et al.[29] and Wu et al. [30]. The authors identified aerosol deposition as a significant phenomenon especially on wet and cool surfaces [30]. The deposition was dictated by gravitational

settling, inertial impaction on leading edges and coil tubes, and particle deposition due to Brownian motion.

Engarnevis et al. [6] conducted extensive research on aerosol interaction with membrane energy exchangers to determine the effect of aerosol fouling on water-vapor and heat transfer in membrane energy exchangers. The aerosols were generated and sampled using test procedures outlined in ASHRAE Standard 52.2. The test method involves sampling aerosols upstream and downstream of the device using an optical particle counter and determining removal efficiency based on the difference in concentrations at these locations. The test method also specifies duct sizing, generation and injection mechanisms for challenge aerosols. Recently, the standard committee for ASHRAE Standard 52.2 also published an addendum C [31] to include a procedure to test using *Mycobacterium parafortuitum* (ATCC 19686) and *Aspergillus sydowii* (ATCC 365422) in case of bio-aerosols tests. In the research carried out by Engarnevis et al. [6] a customised aerosol generator was developed to output the aerosols and an optical spectrometer was used for sampling. Similar procedures to ASHRAE Standard 52.2 were used for dust aerosol tests in full-scale energy exchanger cores. It was concluded that the particle deposition was dependent on particle size and air speed. However, the particle deposition or aerosol fouling from coarse particles did not cause a significant change in the heat or water-vapor transfer. While the conclusion from the research by Engarnevis et. al [6] is important to determine whether fouling influences effectiveness, it does not answer the question whether the deposited aerosols could transfer through the membrane. In addition, no generation and sampling techniques are discussed for bio-aerosols.

Shirey et al. [32] recently carried out a bio-aerosol transfer study in an energy wheel in the Frederick Cancer Research Center using T1 *E.coli* phages and noted a cross over of less than 0.1% in the energy exchanger. The authors presented generation, sampling and testing methods suitable

to the T1 *E.coli* phage using liquid impingers and a glass nebulizer. The phages were sampled at 0.45 cfm (12.75 L/min) for a period of 2.5 min for a total collected sample volume of 31.8 L. However, the study does not include how long the aerosols were generated before taking the first sample and the order in which the samples were taken. In addition, no remarks are made whether similar sampling flow rates and sampling time can be used for other bio-aerosols. Detailed descriptions of phage preparation and assay techniques are presented, but limited information is provided on any standards followed for preparation, sampling or assaying techniques.

The NIOSH manual of analytical methods contains method 0800 [33] bio-aerosol sampling in indoor air and method 0801 [17] for aerobic bacteria measurement using gas chromatography. Andersen impactors are recommended as the samplers for bacteria sampling. A minimum sample volume of 50 L and maximum volume of 300 L at a flow rate of 28.3 L/min is recommended for collecting bacteria samples. Although method 0800 recommends a minimum time of 10 min for sampling, it is noted that in highly contaminated environments the sampling time might need to be adjusted. Thus, comparing the sampling time, and measurement method between methods 0800 and 0801 it can be observed that methods need to be tailored for the specific bio-aerosol or application situation.

Many studies have presented comparison of generation and sampling mechanisms for different bio-aerosols showing different sensitivity of generation and sampling devices [21, 34, 35] to different bio-aerosols. Therefore, more research is needed to integrate NIOSH, and ASHRAE methods to determine aerosol transfer, in particular bacteria aerosol transfer, in membrane energy exchangers.

2.5 Summary of theory and literature review

This chapter provides a review of the theory governing aerosols suspended in an airstream and reviews how this behaviour can be extended to aerosols that might transfer through a membrane energy exchanger. While the theory of water vapor transfer in membrane energy exchangers and the theory of aerosol behaviour in filters are well researched, it is challenging to relate the two, due to the geometrical differences between the membrane exchangers and the filters. For one, the filters are placed perpendicular to the airflow whereas the membrane is oriented parallel to the airflow. In addition, in numerical studies of aerosols it is computationally challenging to represent aerosols with different geometry and sizes. It is also not numerically possible to determine whether bio-aerosols remain active during transfer through a membrane energy exchanger. Therefore, experiments are needed to determine transfer of bio-aerosols through membranes used in these exchangers. While there are established methods for filter efficiency testing using aerosols and indoor air sampling of bio-aerosols, there is no standardised method for aerosol transfer in membrane energy exchangers. There have been two studies that have examined aerosol interaction with energy exchangers but some modifications were made to standard test methods for the specific applications. A detailed summary of the key outcomes of this chapter is provided below:

1) Particle size and shape are the two important factors that govern aerosol behaviour in an airstream. The particle Reynolds number and Stokes number can be used to understand the forces experienced by the particle and its behaviour with respect to obstacles. The relation of particle size with ECTR and particle size with Stokes number is explored but not rigorously examined in this thesis.
2) Analytical, numerical and experimental relations for water vapor transfer through membranes in energy exchangers are well developed but analytical and numerical relations

are not developed for aerosol transfer. Experimental relations will be used to calculate water vapor transfer and aerosol transfer through membranes.

3) Aerosol deposition mechanisms which govern filtration have well defined relations for flow perpendicular to fibers. However, in membrane energy exchangers the flow is parallel to the fibers and hence it is unsure if the analytical relations for flow perpendicular to fibers can be used. A discussion is presented based on experimental results in Chapter 3 whether these mechanisms are still in play in the case of aerosol transfer or deposition in the membrane.
4) Experiments can be used to determine aerosol transfer through membranes using a parameter called ECTR, which was developed in ASHRAE research project 1780 [28]. While ASHRAE RP-1780 developed a test method for gaseous contaminant transfer, there is limited research on test methods and protocols for aerosol transfer experiments. Test methods and protocols will be selected and developed in Chapter 3 and Chapter 4 to experimentally determine the aerosol transfer by calculating the ECTR.
5) ASHRAE Standard 52.2 method for testing air cleaning devices and NIOSH 0800, 0801 are the relevant test standards that can be used to guide aerosol generation and sampling methods. These standards will be used later in this thesis (Chapter 3 and Chapter 4) in the selection of test method and protocols and wherever applicable it will be noted when standard procedures are not followed.
6) Developed test methods, sampling and generation instruments work differently with different bio-aerosols and often test methods need to be modified to suit the particular bio-aerosol and application. More research is needed on bacteria aerosol transfer in membrane

energy exchangers as bacteria are amongst the common bio-aerosol indoors. Test methods for bacteria aerosol transfer will be determined in Chapter 3 and Chapter 4 of the thesis.

CHAPTER 3

TEST METHODOLOGY TO DETERMINE AEROSOL TRANSFER IN MEMBRANE ENERGY EXCHANGERS

3.1 Overview

This chapter addresses the first objective of the MSc research which is to develop a test method to quantify aerosol transfer in membrane energy exchangers and apply that method to measure aerosols transfer through a dense membrane. The aerosol choice and generation techniques are described. Sampling instrumentation and test procedures used to determine aerosol concentrations are documented alongside equations used to calculate the important parameters. Finally, aerosol transfer results for a dense membrane using the proposed test procedure are evaluated.

The paper presented in this chapter was accepted for the ASHRAE Winter Conference and was presented at the conference in Chicago, USA on Jan 22, 2024. Sections 3.3, 3.5, 3.6, 3.7, 3.8, 3.11 of the conference paper have been expanded in this thesis. New sections 3.4 and 3.10 documenting the membrane type used and pressure measurement procedure have been added. The introduction, acknowledgment sections have been removed. The procedures used for handling the bacteria aerosols are described in Appendix A of the thesis. The raw data for dust and bacteria concentration used to report results in the paper are provided in Appendix B of the thesis. During ongoing testing after the paper was complete, it was noted that the procedures outlined in this paper for bio-aerosol transfer did not work, so modifications were made. Since the paper was already published, it could not be changed. Comments are added to this chapter to identify the methods that did not work. The new methods developed for bio-aerosol testing are discussed in detail in Chapter 4.

The test facility used for these experiments was developed by a previous graduate student (Mr. Ashwin Matthews). The materials and methods proposed in this chapter were selected by the author of this thesis Tejvir Binepal in addition to preparing the manuscript and carrying out the experiments. Mr. Pezhman Zolfaghiri (PhD student) and Ms. Brooke Thompson (Laboratory manager) provided guidance for bio-aerosol selection, development of lab protocols to prepare, sample and culture the *E.coli* bio-aerosols and reviewed the manuscript. Dr. Melanie Fauchoux and Dr Albin Joseph critically reviewed the manuscript. Prof. Carey Simonson (supervisor) and Prof. Shelley Kirychuk (Advisory Committee Member) provided guidance, advice and feedback on the work.

Test methodology to determine aerosol transfer in membrane energy exchangers

Tejvir Singh Binepal, Pezhman Zolfaghiri, Brooke Thompson, Melanie Fauchoux, Albin Joseph, Carey Simonson, Shelley Kirychuk

3.2 Abstract

Ventilation systems are generally designed to meet occupant comfort and air quality requirements, but not for infectious disease control. However, by increasing the amount of clean fresh outdoor air, the concentration of bio-aerosols indoors can be reduced thereby reducing the chances of airborne transmission of diseases. Membrane energy exchangers are energy saving devices that can be used to precondition outdoor air by recovering energy from building exhaust air. A recent study has shown that aerosols deposit inside these exchangers [6]. These deposited aerosols could be transferred to the supply air into the building which would hinder the application of energy exchangers in some situations, such as during a pandemic. The ratio of the aerosols transferred from building exhaust air stream to the supply air stream can be defined as the exhaust contaminant transfer ratio (ECTR) and is an important parameter to quantify. ISO A-3 test dust and lab safe *E.coli* bacteria aerosols are used in this research to determine the ECTR in a small-scale experimental facility. A test method is proposed for lab-scale experiments and the method is applied to a dense membrane. Preliminary test results indicate no aerosol transfer for particles in the size range 0.3 µm – 10 µm (PM 2.5 and PM 10) and no transfer of *E.coli* through the tested membrane. Future work will use this test methodology with different porous membranes.

3.3 Aerosol choice and generation methods

Aerosols are solid or liquid particles suspended in a gas [3]. Aerosols found indoors can be referred to as particulate matter (PM) and are classified based on size. PM 2.5 (< 2.5 μm) and PM 10 (< 10 μm) are common size ranges and have a wide variety of geometries. In addition to particulate matter, aerosols of biological origin or bio-aerosols are also present indoors. Bacteria aerosols are the common aerosols present indoors [10]. Therefore, the selection of aerosols for this study was done to represent aerosols in ambient air.

3.3.1 Dust aerosols

To represent different PM size and shapes, ISO A-3 test dust is used [36]. The A-3 test powder has an average particle size of d_{50}= 14.73 μm and a density of 1025 kg/m^3 [6]. Figure 3.1 shows an SEM image of the dust powder. As the test dust has particles both in the PM 2.5 and PM 10 size ranges and different geometries it was chosen as the aerosol for testing. The dust is aerosolized using a solid aerosol generator [37].

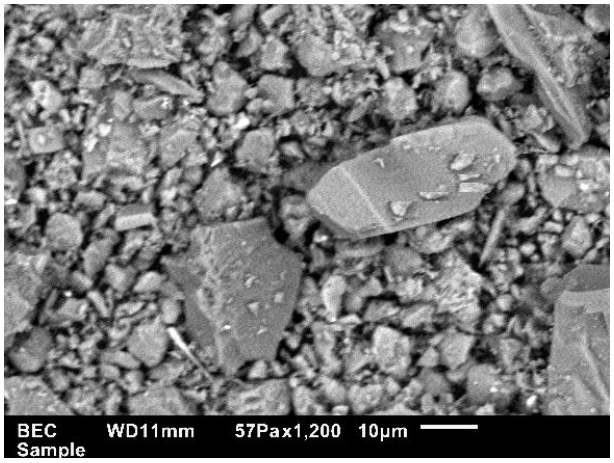

Figure 3.1: SEM image of the 12301-1 ISO A3 test dust. Image shows particles have different geometries and sizes.

Figure 3.2 shows a schematic of the solid aerosol generator from PALAS [37] used in this thesis to generate dust aerosols. To generate dust aerosols, the ISO A-3 dust powder is filled inside a reservoir and compacted to a density of 1.1 gm/cm^3. A motorized feed is used to push the powder into a rotating brush which feeds the powder into a compressed air stream. By controlling the feed rate, the amount of dust injected can be controlled. For all aerosol transfer experiments in this thesis the feed rate was set to 5 mm/h. This feed rate is the speed at which the piston travels to push out the dust in the reservoir.

Figure 3.2: Image of dust aerosol generator used for generation of dust aerosols

3.3.2 Bacteria aerosols

To represent bacteria aerosols indoors, *Escherichia Coli* (Migula) Castellani and Chalmers Strain (*E.coli*, ATCC 27325) is used. This is because it is safe to use (bio-safety level 1), easy to culture and *E.coli* has been used as the model organism for different bio-aerosol studies [35, 38]. Bacteria stocks are kept frozen in a 20% glycerol solution at -80°C (-112°F). Prior to testing, cultures are incubated in 40 mL Tryptic Soy Broth (TSB) (BD Difco, Missisauga, ON, Canada) overnight at 37°C (98.6°F). Two 40 mL solutions are prepared for aerosolization. The solutions are centrifuged

at 5000 rpm for 15 min at 22℃ (71.6℉) to pellet the bacteria. In a biosafety cabinet, the TSB is carefully removed and the pellet is re-suspended with 40 mL of sterile 1X Phosphate Buffered Saline (PBS) (Cytiva, HyClone Laboratories, Logan, Utah, USA) solution [39]. A total solution volume of 80 mL is aerosolized using a six-jet collison nebulizer (Pacwill Environmental, Beamsville, ON, Canada) [40].

Figure 3.3 below shows an image of the six-jet Collison nebulizer used for bacteria aerosol generation. A liquid solution consisting of the E-coli suspended in a phosphate buffer solution is filled inside the glass jar and the nebulizer base with jets is immersed 3/8 of an inch inside the solution. The base contains small capillary tubes to the jet. Compressed air is fed as the input which expands just before the jet creating a suction effect. As the liquid rises it is sheared into droplets which are then carried out of the nebulizer with the flow of air. Some of the generated droplets fall down and replenish the liquid. Since the liquid always exits the nebulizer, the aerosol output does not remain constant and continuously decreases with time.

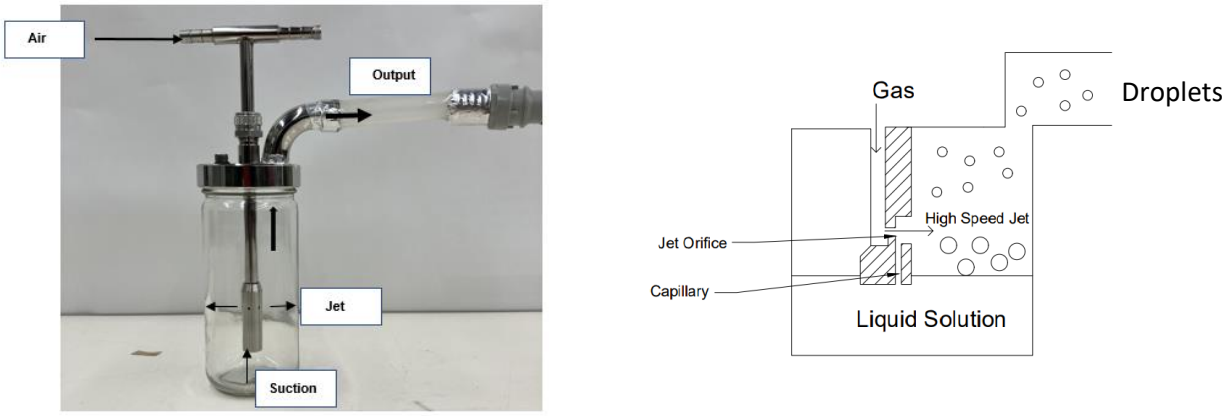

Figure 3.3: a) The six jet collison nebulizer used for generation of E-Coli aerosols and b) a schematic showing the generation mechanism adapted from [41]

Note to the reader: In addition to dust and bacteria aerosols, sodium chloride (NaCl) aerosols were also tested. Due to the limitation in the optical sensors inside the particle measurement device of

the maximum particle concentration and the flow rate limitations in the test setup a suitable dilution ratio could not be achieved that would give a readable NaCl size and particle concentration. In addition to the six-jet Collison nebulizer, a single jet Collison nebulizer was also used to find an appropriate injection flow rate and return air dilution rate that could give a readable measurement. However, the large number of droplets generated by the nebulizer overloaded the spectrometer sensors. Optical sensors with a high particle count (> 10^7 P/cm^3) tolerance with a customized dilution system is recommended to test NaCl.

3.4 Membrane sample used for testing

The membranes used in a membrane energy exchanger can be either a dense or a porous membrane as discussed previously. However, due to a concern of transferring contaminants such as gases [5], it is ideal to use a dense membrane which can selectively transfer water vapor over gaseous contaminant. A dense membrane is a composite of several layers, as shown in Figure 3.4 [13], [42]. The membrane used in the experiments has a dense polyamide layer coated on top of a porous polysulfone layer and supported additionally with a non-woven mechanical support. An SEM image of the membrane sample is shown in Figure 3.4 b) which shows that the membrane pore sizes are in the range of nm.

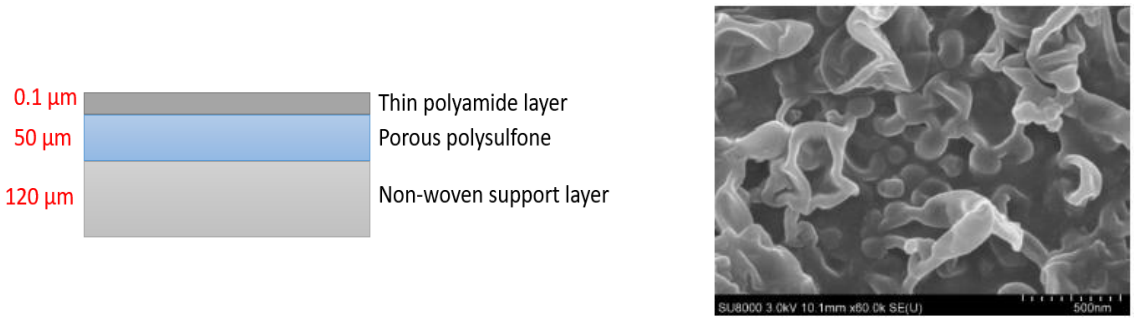

Figure 3.4:a) Schematic showing the dense membrane layers used in tests adapted from [42] *and b) SEM image of the top dense polyamide layer taken from* [5]

Table 3.1 summarizes the important characteristics of the membrane, the pore size and the vapor diffusion resistance. Since pore size is small it is expected that the membrane will have no transfer of micrometer sized aerosol particles.

Table 3.1: Characteristics of the dense membrane used for testing

Characteristic	Value	Reference
Pore Size (nm)	–	See SEM image above
Moisture transfer resistance (s/m)	301 ± 37	Lab Measurement [5]

3.5 Instrumentation and performance parameters

The test methodology proposed in this paper is used to evaluate aerosol transfer in a lab-scale membrane energy exchanger. The test facility used for this procedure was built and commissioned as a part of previous research to study gaseous contaminant transfer. The details of the test facility and commissioning are described in another publication [5]. The test facility, shown in Figure 3.5, is an annular energy exchanger consisting of three concentric pipes. The inner annulus has four slots, indicated by the four white rectangles, which are covered with membranes to separate the two air streams. The membrane pieces can be removed and replaced with new membrane samples for testing giving this test section the advantage of testing both the dense and porous membrane types. The test facility allows for test at room temperature conditions. The return air is humidified and injected with aerosols to simulate building exhaust air conditions. Figure 3.5 shows a schematic of the test section with the approximate locations of measurement instruments and aerosol injection. HEPA filters are placed at the exchanger outlets as shown in Figure 3.5 a). These HEPA filters protect the rotameters and make sure the air being exhausted out of the facility is free of the high concentration of aerosols used in testing for safety.

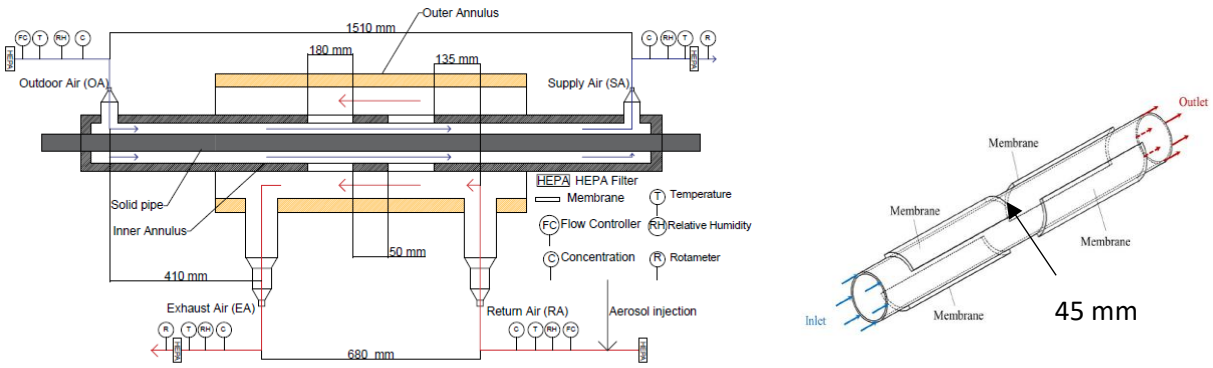

Figure 3.5: a) Cross-section of small-scale membrane energy exchanger with concentration measurement stations indicated and b)the location of membrane slots relative to each other [5]

The measured concentrations are used to calculate the ECTR as per Equation (3.1).

$$\text{ECTR} = \frac{c_{SA} - c_{OA}}{c_{RA} - c_{OA}} \tag{3.1}$$

A mass flow rate balance for the aerosols entering and leaving the system is done to check the conservation of mass using Equation (3.2) and verify the validity of experimental data. The volumetric flow rate at the inlets are measured using mass flow controllers and the flow at the outlets is measured using rotameters.

$$\dot{Q}_{OA} c_{OA} + \dot{Q}_{RA} c_{RA} = \dot{Q}_{EA} c_{EA} + \dot{Q}_{SA} c_{SA} + \dot{m}_{deposited} \tag{3.2}$$

Prior to injecting the aerosols, the dry air mass balance is checked using the criteria set by ASHRAE Standard 84 [15] using Equation (3.3).

$$\emptyset = \frac{|\dot{m}_{OA} - \dot{m}_{SA} + \dot{m}_{RA} - \dot{m}_{EA}|}{\min(\dot{m}_{OA}, \dot{m}_{RA})} < 0.05 \tag{3.3}$$

The steady state conditions for water vapor is checked using Equation (3.4) [15].

$$\frac{\delta W_{RA}}{|W_{OA}-W_{RA}|} < 0.1 \quad (3.4)$$

For the injected aerosols, steady state is checked using ASHRAE Standard 52.2 [16] criteria using Equation (3.5).

$$\frac{\delta c}{c_{mean}} < 0.15 \quad (3.5)$$

3.6 Concentration measurement for dust aerosols

The concentration of dust aerosols is determined using a PALAS 3000 optical spectrometer [43]. The WELAS 2300 sensors with a maximum particle count of 8000 P/cm^3 for low error and size range 0.2 µm – 40 µm are used. Prior to testing, the sensors are calibrated using MonoDust1500 supplied by the manufacturer. The uncertainty after sensor calibration is taken to be $\pm$ 20% and the uncertainty is primarily dominated by the coincidence error present during the particle measurement. The significant effect of coincidence error in uncertainty is explained in Appendix C of this thesis. The coincidence error is caused when multiple aerosol particles pass through the measurement volume but are assumed to be a single particle with a large size by the sensor. The density of the aerosol particle must be set in the instrument software to determine the mass of the particles and is set to the known density 1025 kg/m^3 of the ISO A-3 test dust. The test concentration is measured and reported in (mg/m^3) as PM 2.5, PM 10 threshold values used for air quality standards are often specified as daily maximum mass average (PM 2.5 35 µg/m^3; PM 10 150 µg/m^3) [44].

The spectrometer operates using the principle of light scattering. Assuming a single aerosol particle in the measurement volume, the amount of light scattered is used to measure particle size.

Based on the measured particle size, the sensor calculates the mass based concentration using Equation (3.6)

$$c_m = n_i . \frac{1}{6} . \pi . \rho_{particle} . \frac{1}{Volume_{meas}} \quad (3.6)$$

3.7 Concentration measurement for bacteria aerosols

Unlike dust particles, the ability of bacteria to cause diseases depends on the number of infectious aerosols rather than the mass concentration. Therefore, it is important to quantify the number of active bacteria aerosols in the airstream. In addition, using the spectrometer with the collison nebulizer requires a high amount of dilution [3, 35] to keep particle counts below the sensor maximum particle threshold. The dilution is challenging to obtain in a small-scale facility. Therefore, the concentration measurement of the *E.coli* aerosols is instead done using the polycarbonate filters [45]. The filters are placed shiny side up on a cellulose support and loaded into a sterile filter cassettes[45, 46]. The filter is capped to prevent contamination. All handling of the filters during preparation and after sample collection is done inside a biosafety cabinet.

After testing, the filters are transferred into a falcon tube containing 5 mL of sterile 1X PBS solution using sterile forceps. The contents of the tube are mixed on an orbital shaker at 500 rpm for 15 minutes to transfer the bacteria from the filter to the solution. 50 µL of the solution is added to 450 µL sterile 1X PBS and a dilution series ranging from 10^{-1} to 10^{-7} is done on the sample. From each dilution, 100 µL of the sample is plated on Tryptic Soy Agar (TSA) plates in triplicate using the standard spread plate method [47]. The concentration of the bacteria in colony forming units (CFU) is determined using Equation (3.7).

$$\frac{CFU}{ml} = \frac{\#\ of\ colonies\ counted}{10^{-\#\ of\ dilution} \times Volume\ of\ solution\ plated\ (ml)} \quad (3.7)$$

The concentration in the air can then be computed from this concentration using Equation (3.8).

$$\frac{CFU}{m^3} = \frac{C\left(\frac{cfu}{ml}\right) \times Volume\ of\ solution\ (ml)}{Sampling\ air\ flow\ rate\left(\frac{m^3}{s}\right) \times Sampling\ time\ (s)} \tag{3.8}$$

Note: The uncertainty in determining the bacteria concentration is presented as a discussion in Appendix C.

3.8 Test procedure and sampling methodology for dust aerosols

Each test is started by running the energy exchanger until steady state operating conditions as described in Equation (3.4) are reached (~30 min). The tests are run at room temperature conditions. The temperature, relative humidity and flow rates set points in the aerosol tests are summarized in Table 3.2. Once steady state is reached, the spectrometer is used to take the background aerosol counts at the exchanger inlets prior to any aerosol injection. The sampling flow rate of the device is fixed at 5 L/min (0.18 cfm) and the flow rate in the return air stream and aerosol injection is chosen to achieve an isokinetic sampling flow rate within ±15% of the sensor sampling flow rate.

The background sampling is done for a period of ~10 min at each inlet. After taking the background counts, the aerosols are injected using the dust aerosol generator into the return air stream at a flow rate of 9 L/min (0.32 cfm) to achieve the target return air flow rate. The flow rate at the outdoor air stream is increased to maintain a pressure differential that prevents membrane bulging. The return air inlet is sampled continuously until the aerosol mass concentration reaches a steady state as defined by Equation (3.5) (~ 10 min). Then a sample at the exhaust air station is taken for 5 min. The sampling time chosen exceeds the minimum 1 min sampling time recommended by ASHRAE Standard 52.2 [16]. Since the pipe size used has a 0.5 in (12.7 mm) OD, the area

(~1.27×10^2 mm^2/0.20 in^2) is much smaller than the minimum grid area recommended for one sample point (~4.13×10^4 mm^2/64 in^2), therefore only one grid measurement is done. After completing one sample of the exhaust air, the concentration upstream at the return air is again measured. A total of four concentration measurements are taken at both return air station and exhaust air station. Once four samples are collected (~40 min), the concentration in the supply air is measured. A time of (~ 60 min), which is twice as long as the time needed for the water vapor to reach steady state is allowed. After one sample at the supply air, another sample is taken at the return air station. A total of three concentration measurements are taken at the return air station and the supply air station. HEPA filters are placed at the exchanger outlets as shown in Figure 3.5 a). These filters collect all aerosol particles that have passed through the exchanger but are missed due to the non-continuous sampling procedure. These HEPA filters are used to verify if there was transfer of aerosols into the supply air by checking if the mass of the filters increases after testing.

There are a few limitations with the test methodology used. Since the sampling flow rate and aerosol injection flow rate is comparable to the mainstream flow rates, the steady state conditions of the exchanger are continuously disrupted. The time of the experiments is another limitation, since the diffusivity values of aerosols through the membranes are unknown, it's challenging to predict the time need to wait before taking readings at the supply air. Table 3.2 summarizes the test conditions used for dust aerosol tests

Table 3.2: Exchanger operating conditions during dust aerosol tests

Condition	Parameter	Outdoor Air	Return Air
Aerosol Transfer	Flow Rate L/min (cfm)	14, (0.5)	17, (0.6)
	Temperature ℃ , (℉)	$24 \pm 0.2, (75.2 \pm 3.6)$	$24 \pm 0.2, (75.2 \pm 3.6)$
	Relative Humidity (%)	6 ± 5	20 ± 5

Note to reader: The initial flow rates to allow isokinetic sampling flow rate in the return air stream were based on a nominal size of 0.5 in for the main duct and 0.25 in for the sampling tube. However, on physical measurements the actual pipe diameter was slightly larger than the nominal diameter and hence the flow rate calculated was corrected. The test flow rate required for sampling of bacteria is corrected in the revised method presented in Chapter 4. The test flow rate required for dust aerosols is higher than the maximum flow rate allowed for the rotameter (20 L/min) and hence could not be achieved. Even though the flow rate was matched, the velocity could not be matched as the test section did not have a sufficient volume to accommodate a manufacturer sampling probe inside the duct and hence isokinetic sampling was not achieved. However, based on Stokes number it is still expected that particles of 10 μm can be collected using the sampling port and the calculation is shown in Appendix D

3.9 Test procedure and sampling methodology for bacteria aerosols

The testing procedure for *E.coli* is different than dust aerosols to avoid contamination from ambient bio-aerosols during the spread plate counting. One day prior to running tests with bacteria, the system is disinfected by aerosolizing a solution of 70% ethanol using the collison nebulizer for a period of ~15 min. The system is then purged with dry air for ~2 hour. One sample is collected at each measurement station using the polycarbonate filters. The first dilution is then plated using the spread plate method to determine if any residual bacteria is present. The following day, the test is started by running the energy exchanger until steady state operating conditions, as described in Equation (3.4) are reached (~30 min). The test is run at room temperature conditions. Once steady operating conditions are reached, the bio-aerosols are injected into the system using a collison nebulizer at 8 L/min (0.28 cfm) with HEPA filtered air supplied using a compressed air source (20

psi/138 kPa). The temperature, relative humidity and flow rate set points during the test are summarized in Table 3.3. Information from the dust aerosol experiments is used to approximate the time needed for the aerosols to reach steady state (~ 10 min) before taking samples. Using separate tubing for each measurement station to prevent contamination, one sample is taken at outdoor air, return air, exhaust air and finally at the supply air. The sampling is done using a vacuum pump connected to a rotameter [48] and calibrated to sample at 4.5 L/min (0.16 cfm). Each sample is taken for a period of 5 min. The total running time of the experiment is ~ 1 hr.

The experiment time is reduced from the dust aerosol experiments to minimize the number of recirculations of the solution in the collison nebulizer because mechanical stresses imparted on the bacteria during aerosolization can inactivate the bacteria [35]. In addition, the number of samples at each station is reduced to one sample. This reduces the complexity for extraction and plating compared to the case where multiple concentration measurements as was the case for dust are taken at each station. All samples collected are plated on the same day they are collected. The experiment are repeated to compensate for the reduced number of samples.

Table 3.3: Exchanger operating conditions during bacteria aerosol transfer tests

Condition	**Parameter**	**Outdoor Air**	**Return Air**
Aerosol Transfer	Flow Rate L/min (cfm)	14, (0.5)	17, (0.6)
	Temperature ℃ , (°F)	$24 \pm 0.2, (75.2 \pm 3.6)$	$24 \pm 0.2, (75.2 \pm 3.6)$
	Relative Humidity (%)	6 ± 5	55 ± 5

Note: The method proposed above could be used to collect and measure the mass of bacteria on the filter but was not suitable for measuring active bacteria colonies. Changes to the sampling flow rate, sampling time and sampling measurement instrumentation were made to get active bacteria

colony samples. NIOSH method 0801 [17] recommends the minimum sampling volume and sampling instrument type for bacteria sampling. Recommendations from this NIOSH method are used to modify the bio-sampling method proposed here in Chapter 4 of the thesis.

3.10 Test procedure for pressure measurement

The static pressures in the energy exchanger were measured at the outdoor air (SP1), supply air (SP2), return air (SP3) and exhaust air (SP4) stations prior to testing using a Druck pressure calibrator [49]. The pressure measurement was done prior to testing as aerosols in the airstream could damage the pressure measurement equipment. In addition, during the testing aerosol particles are deposited inside the experimental facility ducts and also clog the HEPA filters which changes the pressure.

After reaching steady state (~ 30 min) the sampling port at the outdoor air (SP1) was opened for 1 min and the static pressure [kPa] was read directly off the pressure calibrator. Then the sampling port was closed, and the pressure measurement was allowed to drop to zero before taking the reading at the supply air (SP2) for 1 min. A similar procedure was followed to get the pressure reading at return air (SP3) and exhaust air streams (SP4).

To remove any extraneous couplings the trajectory of the pressure measurements was randomized and another set of measurements was taken beginning at the supply air station and moving through return air, exhaust air and outdoor air station. A total of four sets were taken each beginning at a different measurement station. The average of the four readings were used to determine the average value of the static pressure at outdoor air (SP1), supply air (SP2), return air (SP3) and exhaust air (SP4). According to practical guidance of the operation of ERV's during a pandemic [50], the pressure of the outdoor air must be higher than the return air to prevent any transfer from the return

air to the outdoor air. Pressure differential is defined as the difference between the static pressure of the leaving supply air flow (SP2) and the entering exhaust air flow/ return air (SP3) and can be calculated using Equation (3.9)

$$\Delta P_{static} = P_{SP2} - P_{SP3} \tag{3.9}$$

The practical guidance recommends a static pressure of +0.5 in W.C (water column) (125 Pa) with the outdoor air at a higher pressure than the return air stream. In case the return air stream has a higher static pressure difference, the static pressure differential is negative. In the aerosol transfer tests, the static pressure at the return air is maintained higher than the outdoor air (Δ P <0) to check for a worst-case scenario in which the pressure drives the transfer of aerosols through imperfect sealing or defects in the membrane slots.

3.11 Results and discussion

Three tests were done using the proposed dust transfer methodology for repeatability. No transfer of dust aerosols was detected, however there was a significant deposition of aerosol particles inside the exchanger as calculated using mass balance from Equation (3.2). This indicates a need to periodically replace the membranes. The fraction of the mass concentration deposited with respect to injected aerosol concentration is plotted as a function of particle size in Figure 3.6. The data markers represent the difference of the leaving aerosol concentration (exhaust) from the entering aerosol concentration (return) as a fraction of the entering concentration. The concentrations used are based on the average of the 5 minute average concentration measured at the return air stream and the exhaust air streams. The error bars represent both the systematic and the random error added using the root mean square method discussed in Appendix C of the thesis.

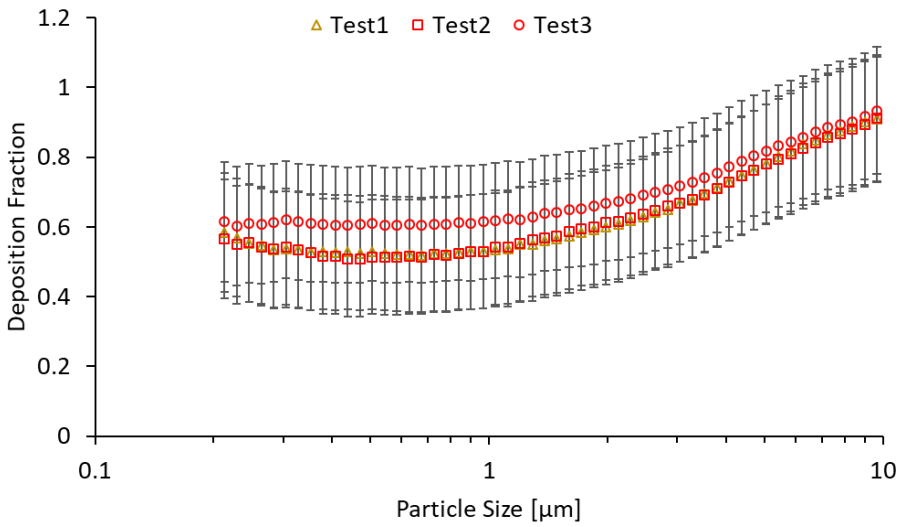

Figure 3.6: Deposition fraction of aerosols with respect to particle size.

The deposition of aerosols in the exchanger with no transfer through the membrane is consistent with the fact that the dense membrane tested (polyamide based reverse osmosis membrane) [42] had pore sizes on the order of nm, while the measured aerosols were in the size range of µm. The deposition of the aerosols with respect to particle size followed a similar trend as observed in the literature [6, 51]. For particle sizes > 1 µm, the deposition increased with particle size. Inertial impaction is the expected dominant mechanism for deposition. Since the exchanger used in the current study has 90° bends just before the inlets as shown in Figure 3.7, a large fraction of the aerosol particles likely impacted and got deposited on the wall of the pipe at the return air inlet. An image of the impaction point at the bend is shown in Figure 3.7 below.

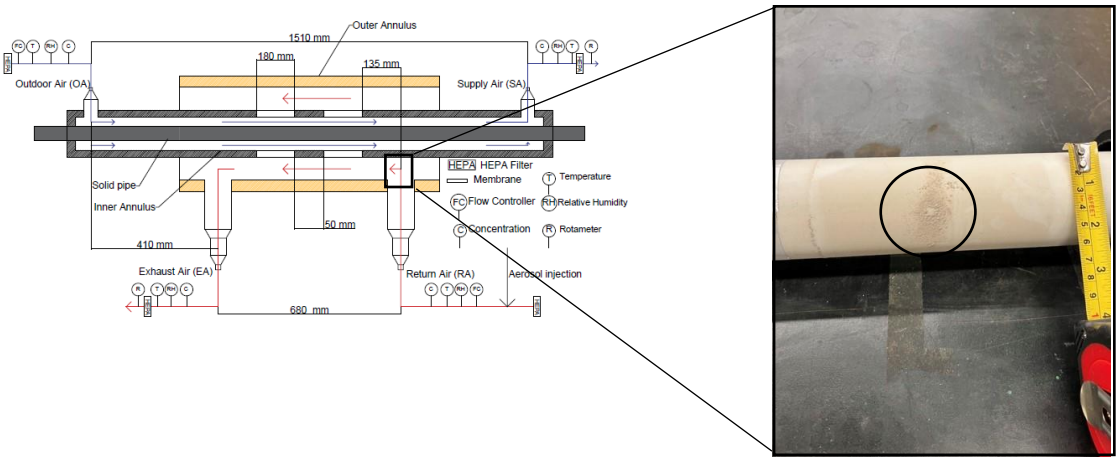

Figure 3.7: Image showing the impaction point for dust aerosols just before entering the exchanger

For particle sizes < 1 μm Brownian motion is the dominant deposition mechanism. The deposition of these particles increased with decrease in size. Since the travel length of aerosols through the exchanger and the piping is longer in the current test facility compared to the test facility used by Engarnevis et.al [6], a higher deposition for smaller aerosols is measured in this study.

A preliminary test was done using *E.coli* to compare results with dust aerosols. In this test, the mass of the bacteria deposited on the filter was used to determine the concentration. No transfer of bacteria was observed, and the deposition matched the dust aerosol deposition within experimental uncertainty as shown in Figure 3.8. The deposition of the bacteria is calculated based on the average concentrations at the return and exhaust air stream.

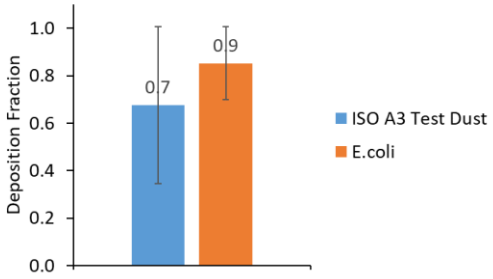

Figure 3.8: Comparison of the deposition of ISO A-3 test dust and E.coli aerosols

3.12 Conclusion and future work

A test methodology to determine aerosol transfer in membrane energy exchangers using a small-scale test facility was developed and applied to a dense membrane. Tests were done with aerosols representing PM 2.5 and PM 10 and an experiment was done with *E.coli* aerosols. The experiments detected no transfer indicating that membrane energy exchangers using a dense coating are not likely to transfer aerosols that could affect the air quality being delivered to an indoor space. However, a significant deposition of aerosols was measured. A limitation of the test methodology is the time of the experiments, it is probable that since the diffusivity of larger aerosol particles in air is much smaller than gases as discussed in Chapter 2, a longer period of time is needed for them to diffuse through the membrane. In addition, the instruments used for measurement of dust can only detect aerosols in the size range of 0.2 μm – 40 μm and cannot detect smaller aerosols. To verify whether there is no transfer through the membrane, or whether the measurement of no transfer is due to a systematic error in the test method or test facility, tests will be conducted using the same energy exchanger without a membrane and with a more permeable membrane in Chapter 4 of this thesis. More significant transfer is expected in these cases. In addition, more tests using bacteria will be completed using the proposed methodology to compare the results of the spectrometer-based dust aerosols transfer with the bio-sampling procedure based E-coli transfer tests.

CHAPTER 4

AEROSOL TRANSFER THROUGH POROUS MEMBRANES USED IN MEMBRANE ENERGY EXCHANGERS

4.1 Overview

The second objective of this MSc thesis is to quantify aerosol transfer in porous membranes. This chapter addresses this objective by applying the test methods developed for dust and *E.coli* aerosols in chapter 3 to a porous Tyvek® membrane. The method developed for determining bio-aerosol transfer is modified in this chapter. The Tyvek® membrane is chosen because it has pore sizes in the range of 2-15 μm [52], a high air permittivity and a low Darcy air flow resistance of (27/m) [14]. The test facility and method is verified using a case with no membrane separating the airstreams, where it is expected that there would be a large amount of aerosol transfer.

The paper presented in this chapter will be submitted to the journal "Science and Technology for the Built Environment". The experiments with dust and *E.coli* aerosols were conducted by Tejvir Binepal using the experimental facility built and commissioned by Mr. Ashwin Mathews. Ms. Brooke Thompson, a microbiologist from Canadian Center for Rural Agriculture and Health provided guidance to make sure lab protocols to determine active bacteria counts from collected samples were followed. Dr. Melanie Fauchoux and Dr. Albin Joseph provided guidance and support for the dust aerosol tests and critically reviewed the manuscript. Prof. Carey Simonson (supervisor) and Prof. Shelley Kirychuk (Advisory committee member) provided guidance, advice and feedback on the experiments.

Bio-aerosol transfer through porous membrane used in membrane energy exchangers

Tejvir Binepal, Brooke Thompson, Melanie Fauchoux, Albin Joseph, Shelley Kirychuk, Carey Simonson,

4.2 Abstract

ASHRAE and other public health authorities have recently introduced guidelines for control of infectious aerosols [53]. These guidelines recommend providing a larger quantity of fresh ventilation air and reduced recirculated air in building HVAC systems. At the same time, a reduction of building heating and cooling energy consumption to reduce greenhouse gas emissions has also become imperative. Membrane energy exchangers are one potential option to achieve both these competing objectives because of their ability to transfer heat and moisture from the building exhaust air to the outdoor ventilation air thus reducing the energy needed to condition the ventilation air to a comfortable temperature and humidity. Membrane energy exchangers use porous, semi-permeable membranes that can transfer heat and moisture well. But, because of their large pore sizes (in μm), might also transfer infectious aerosols, like bacteria, from the building exhaust air to the ventilation air. Currently, there is limited research on bacteria aerosol transfer in membrane energy exchangers and lack of test methods to determine aerosol transfer in membrane energy exchangers. In the first part of this study (chapter 3 of this thesis), a test method was developed to determine transfer of bacteria aerosols in membrane energy exchangers and applied to a dense membrane, which has smaller pore sizes. In this chapter, the proposed method is verified with a case of no membrane separating the air streams. In addition, some modifications are proposed to determine the concentration of active bacteria colonies in a collected sample, which

was not part of the original methodology. The modified method is then applied to a porous membrane. Negligible amount of active bacteria aerosol transfer is observed. The results are further verified by comparing them with dust aerosols, physically similar in size to the bacteria aerosols. Based on test results, it is concluded that membrane energy exchangers pose a very low risk of bacteria and dust aerosol transfer.

4.3 Introduction

This chapter builds on the first part of this study and verifies the method proposed by Binepal et al. [54], discussed in chapter 3 of the thesis. The method proposed is verified using a case of no membrane to check whether the method detects transfer of aerosols when there is no membrane to block the passage between air channels in the exchanger. The method is then applied to a porous membrane, to determine if there is transfer of *E.coli* bacteria aerosols in membrane energy exchangers. It is important to measure the concentration of aerosol particles to determine if there is transfer of aerosols. Unlike a small gaseous particle, the inertia of an aerosol particle is significant, and it is possible that some aerosols bypass the sampling port. This can cause an under representation of the particle concentration. The ability of a particle to react to an obstacle in flow can be quantified using the particle Stokes number (Stk). Therefore, experiments are conducted to compare the effect of sampling angle of the port using 45° and 90° ports and a discussion is presented on how the sampling angle affects the measurement.

The concentration of the active bacteria aerosols is sensitive to the type of sampling instrument. Although there is previous research comparing different types of bacteria aerosol samplers in an aerosol chamber [55] and in ambient air sampling [21] but they have not been evaluated with membrane energy exchangers. Therefore, two sampling measurement instruments for collection of bacteria aerosols, filters and liquid impingers, are compared. The verified test method is then

applied to a porous Tyvek® membrane to determine if active bacteria aerosols transfer through the membrane. The results of this study will determine if membrane energy exchangers pose a risk to the indoor air quality in a building due to transfer of bacteria aerosols.

4.4 Test methodology

An experimental approach is used to study the transfer of bio-aerosols and dust aerosols in a membrane energy exchanger. The detailed description of test methods and procedures were presented in chapter 3. An experimental method is chosen over numerical method because the experimental method allows testing with aerosol particles of different size and shapes and active bio-aerosol organisms. There are five major components of the experimental methods which are discussed: the choice of aerosol particles, the generation method for the particular aerosol type, the sampling instrumentation, test facility used for experiments, test procedures such as sampling sequence, sampling flow rates at different measurement locations and the equations used for calculation of important parameters. The aerosols and the methods used for testing are the same as chapter 3. Modifications are made for the testing flow rate of dust aerosols and bacteria and are discussed later in this chapter.

4.5 Test conditions for method verification

To verify the method, modifications are done to the test section discussed in chapter 3. The membranes on the inner annulus are removed such that there is no barrier separating the outdoor air stream and the return air stream. Figure 4.1 shows a schematic of the test facility with the modifications done for the experiments.

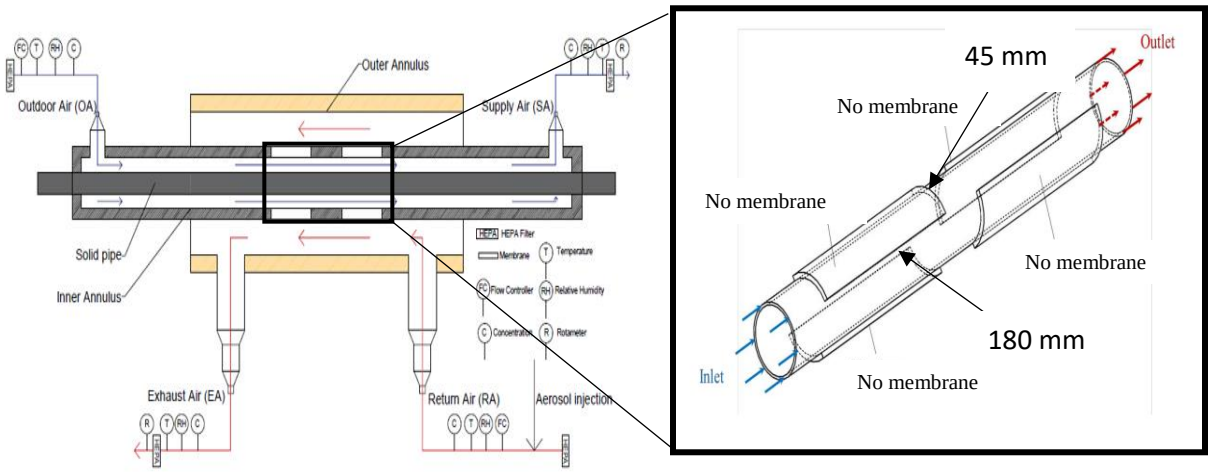

Figure 4.1 : A schematic showing the inner annulus pipe and the locations of the membranes [5]

The static pressure at the outdoor, supply, return and exhaust air stations is measured using a Druck pressure calibrator [49]. The static pressure is plotted with respect to the exchanger length to represent the pressure conditions and provide information on behavior of air flow with respect to pressure. As observed from Figure 4.2, the pressure difference at the return air stream is higher than the outdoor air for the initial portion of the exchanger and the pressure from the outdoor air becomes higher than the return air for the later portion of the exchanger. It is thus expected that some amount of return air will transfer to the outdoor air stream carrying the aerosols and some amount of outdoor air transfer into the return air stream diluting the concentration of exhaust aerosols due to the higher pressure.

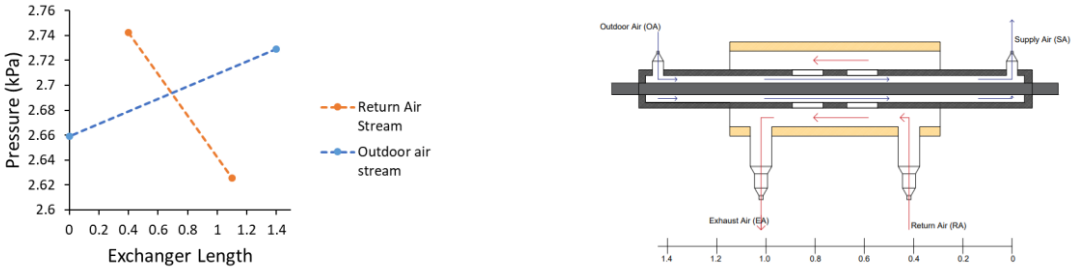

Figure 4.2: Schematic showing the (a) pressure drop along the length of the exchanger and (b) a close-up schematic of the exchanger (not to scale), used from [5].

The exchanger flow rate, temperature and humidity at the return air and outdoor air inlet during the pressure tests are summarized in Table 4.1. In the pressure tests the flow rate is the variable of interest not the temperature or RH.

Table 4.1: Operating conditions during the pressure tests with no membrane

Condition	Parameter	Outdoor Air	Return Air
No membrane	Flow Rate (L/min)	18.5 ± 0.1	18.5 ± 0.1
	Temperature (℃)	24 ± 0.2	23 ± 0.2
	Relative Humidity (%)	2 ± 5	14 ± 5

The flow rate is measured using mass flow controllers at the inlet of the exchanger and rotameters at the exit of the exchanger. The temperature is measured using T-type thermocouples and the relative humidity measured using Honeywell capacitive sensors. The instrumentation, uncertainty and calibration is described in [5] and summarized in Table 4.2 below.

Table 4.2: Measurement instrument uncertainty

Measurement Properties	Instrument	Operation range	Total Uncertainty
Temperature	Omega T- Type thermocouple	$-20℃ \; to \; 40℃$	$\pm 0.2℃$
Relative Humidity	Honeywell capacitive humidity sensor	$15 - 95\% \; at \; 23℃$	$\pm 1\%$ RH
Volume flow rate	MKC GE50A^{TM}	$0 - 30$ L/min	± 300 mL/min
	Flow controller (RBG)	$9 - 12$ L/min	± 600 mL/min

4.6 Verification of test method for transfer of dust aerosols

To determine whether PM 10 and PM 2.5 aerosols present in the building return air stream are transferred to the outdoor air stream, IS0 A-3 dust particles were used. The injected particles had a geometric mean diameter (stokes equivalent) of 1.3 µm with a geometric standard deviation of 2.5. This distribution covered all particle size ranges PM 1, PM 2.5 and PM10 with different particle geometries. Figure 4.3 shows the size distribution of the aerosol used for testing.

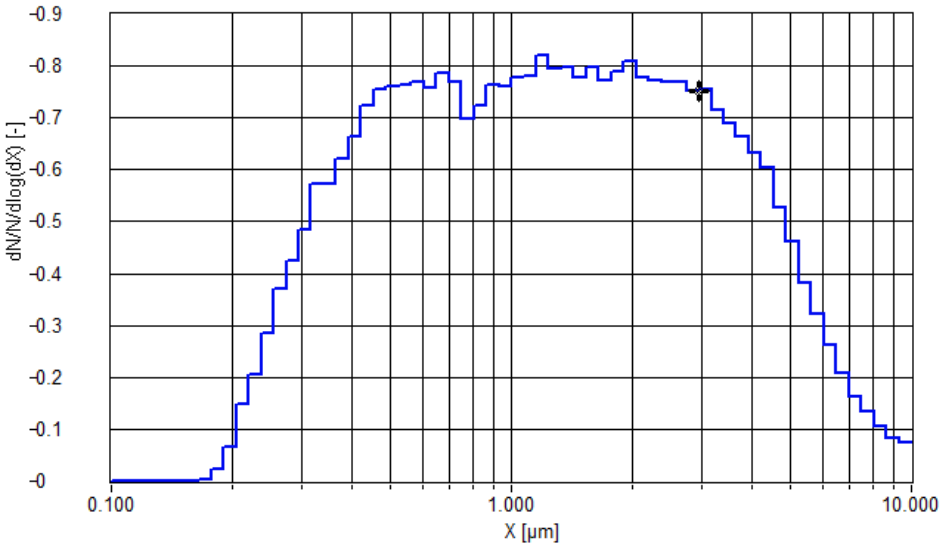

Figure 4.3: Size distribution of ISO A-3 test dust used for verifying method

The exchanger was allowed to run until it reached steady state, as described in chapter 3. The relative humidity and temperature measurements at the outdoor, supply air, return air and the exhaust air stations were collected. Then the background aerosol count was measured for 10 min at both return air and outdoor air inlet as per the procedure outlined in the chapter 3. After measuring the background aerosol count, dust aerosols were injected. Dust aerosols were injected in the return air stream at a flow rate of 8 L/min and mixed with return air at a flow rate of 10.5 L/min. After injecting the aerosols and waiting for a period of 10 min, the first sample was taken

at the return air station. The procedure for sampling followed is similar to that outlined in the method proposed in chapter 3. A total of four samples were taken at each station, with each sample containing 25 L of air (5 L/min x 5 min). The concentrations of dust aerosols based on average of the samples and the amount of water vapor in each stream is reported in Table 4.3. Using these values, the transfer percentages were calculated to be 88% for water vapor transfer (latent effectiveness) and 80% for dust aerosols (ECTR).

Table 4.3: Summary of dust aerosol concentration, water vapor content and transfer rate with no membrane

Condition	**Measurement Station**	**Water vapor (kg_w/kg_a), (RH %)**	**Dust Concentration (mg/m^3)**
No membrane	Outdoor Air	$4.4 \times 10^{-4} \pm 3.7 \times 10^{-4}, (2.5 \pm 1.8)$	0
	Return Air	$5.7 \times 10^{-3} \pm 0.3 \times 10^{-3}, (33.0 \pm 2.3)$	99 ± 6
	Exhaust Air	$5.5 \times 10^{-4} \pm 3.3 \times 10^{-4}, (3.2 \pm 1.7)$	2.2 ± 0.1
	Supply Air	$5.5 \times 10^{-3} \pm 0.4 \times 10^{-3}, (31.7 \pm 1.8)$	75 ± 8
	Latent Effectiveness/ ECTR	$88\% \pm 15\%$	$80\% \pm 20\%$

As summarized in Table 4.3, there was an appreciable amount of aerosol concentration measured at the supply air stream when there was no membrane between the air streams. The size distribution of the dust aerosol measured at the supply air station is shown in Figure 4.4. The geometric mean of the particles was 1.2 µm with a geometric standard deviation of 2.4. It can be seen the

distribution is similar to the distribution in Figure 4.3 of the injected aerosols indicating that most of these particles are transferred to the supply air stream.

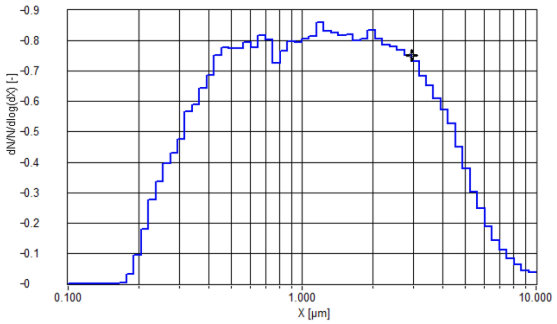

Figure 4.4: Size distribution of ISO A-3 test dust measured at the supply air station

As dust aerosol transfer was detected using the method proposed in chapter 3, it answers the question asked in chapter 3 and supports that the zero dust transfer measurement obtained was due to the dense membrane. The amount of transfer of dust aerosols ($80 \pm 20\%$) and water vapor ($88\% \pm 15\%$) is similar. This can be expected as the size of the open slot is many orders of magnitude larger than the size of aerosol particles (µm) and the water vapor particle (nm) and therefore there is no selective transfer of water vapor or dust.

As shown in Figure 4.5, a high transfer rate of smaller size particles in observed. As the particle size increases the transfer ratio decreases. This indicates that larger particles are more likely to accumulate in the test facility, a limitation of the current facility based on deposition principles. The data markers represent the average value of ECTR over the five minute sampling period and the error bars represent both the systematic and random error as discussed in Appendix D.

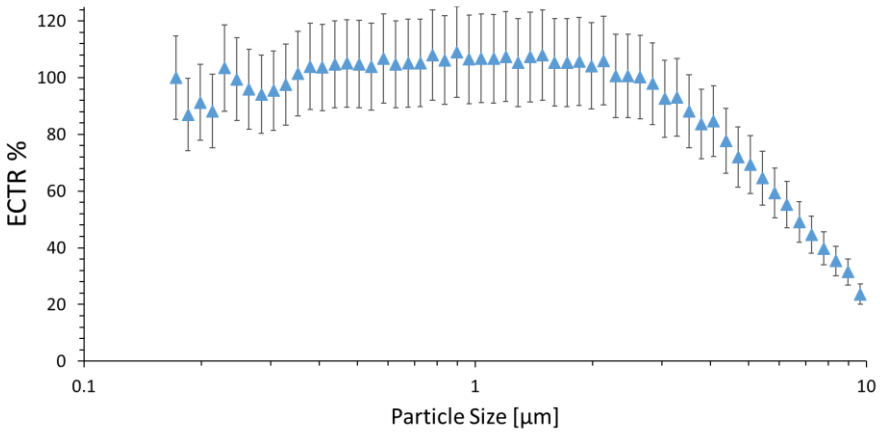

Figure 4.5: Variation of ECTR with particle size

4.7 Verification of test method for transfer of bacteria aerosols

Generation techniques and sampling instruments for measuring bacteria aerosols concentration for determining transfer in membrane energy exchanger is limited. In chapter 3 of the thesis, a test method was proposed which used a six jet Collison nebulizer for the generation of bacteria aerosols and a polycarbonate filter for sampling the aerosols. It was observed that the filters increased in mass after sampling indicating that they could capture some aerosol particles. However, the number of active *E.coli* colonies were not determined in the preliminary tests. To verify whether the test method proposed could be used to detect transfer of active *E.coli* colonies, the method was applied to the membrane energy exchanger with no membrane in place (i.e. in a case where transfer is expected). The test setup was cleaned by flushing fresh air through the setup for one hour. A blank sample containing the compressed air without injected aerosols was collected to determine the background bacteria count. No colonies were found during the background sampling. The test setup was disinfected using 70% ethanol aerosols for 15 min and was allowed to sit for 24 hours (1 day) before commencing testing.

Prior to beginning the testing, the exchanger was allowed to reach steady state, as defined previously. The aerosols were then injected into the return airstream using a Collison nebulizer and the first filter sample in the return air was collected after 10 min. Then a sample was taken using filters at the outdoor air, exhaust air and the supply air stations for a period of 5 min each. Only one sample was taken at each station to allow for same day culturing of the *E.coli* aerosols after testing because of limited people resources for culturing of the sample. The collected filter samples were immersed in 1X phosphate buffer solution (Cytiva, HyClone Laboratories, Logan, Utah, USA) and mixed to transfer the bacteria colonies into the sample. The procedure to transfer the bacteria colonies from the filter to the liquid solution was described in chapter 3. The measured concentration, water vapor and aerosol transfer rates are reported in Table 4.4. The active bacteria concentration is reported in CFU/m^3 (colony forming units/m^3). The concentration of the solution used for generating the bacteria aerosols using the nebulizer was 6.6×10^7 CFU/ml.

Table 4.4: Summary of measured bacteria concentration, calculated water vapor content and water vapor/aerosol transfer percentage with no membrane. Bacteria were sampled using a polycarbonate filter.

Condition	**Measurement Station**	**Water vapor (kg_w/kg_a). (RH%)**	**Bacteria Concentration (CFU/m^3)**
No membrane	Outdoor Air	$2.6 \times 10^{-4} \pm 1.8 \times 10^{-4}, (1.5 \pm 1.8\%)$	0
	Return Air	$7.7 \times 10^{-3} \pm 2.7 \times 10^{-4}, (48.2 \pm 2.3\%)$	0
	Exhaust Air	$9.9 \times 10^{-4} \pm 1.6 \times 10^{-4}, (6.0 \pm 1.7\%)$	0
	Supply Air	$8.0 \times 10^{-3} \pm 2.3 \times 10^{-4}, (48.2 \pm 1.8\%)$	0
	Latent Effectiveness/ ECTR	$97\% \pm 6\%$	0

As observed from Table 4.4, although a large amount of water vapor transfer was observed, there was no transfer of live bacteria aerosols. In addition, there was no countable colonies present in the return air stream, exhaust air stream or the supply air stream. This was not expected, and therefore the proposed method in chapter 3 could not detect active *E.coli* colonies. Based on observation from this test, polycarbonate filters should not be used for collection of E-coli. One difference between the collection of dust aerosol samples and the bacteria aerosol samples are the types of collected aerosols. The dust aerosol sample is not composed of inactive and active components, so the concentration measured in the optical spectrometer is the concentration that exists in the collected air sample. The bacteria aerosols generated by the Collison nebulizer, however, contain both active and inactive bacteria as well as droplets which contain no bacteria. These three types of droplets are randomly distributed in the collected sample. Figure 4.6 is used to illustrate this distinction between dust and bacteria aerosol collected sample.

While the filter method of sampling can capture the mass of the aerosols collected, it is not able to distinguish between active, inactive or empty aerosols. The mass change of the filter was recorded in the first test but in subsequent tests the mass change was not recorded. This was an oversight and it is recommended that the mass of the filters be recorded for future experiments. The method proposed in chapter 3 for transferring the collected colonies on the filter sample could not determine the active bacteria colonies in the collected sample. Therefore, while the mass of the filter is expected to change at each sampling location after collecting the sample, the proposed method is not able to determine if any active bacteria transfers through the membrane.

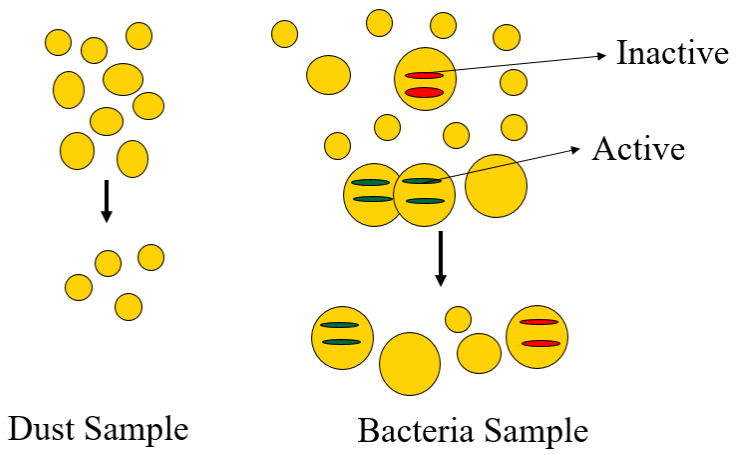

Figure 4.6: Illustration showing how a collected dust volume sample might differ from a collected bacteria sample.

It is proposed that there are three important aspects that influence whether the collected sample can yield countable bacteria colonies: sample volume, sampling angle and the sampling instrument.

Since the method presented could not detect transfer of active bacteria aerosols, each of these parameters was evaluated separately to determine what the error in the sampling methodology was and to propose modifications in the test method. NIOSH standards were used to evaluate the best collection volume, sampling flow rate and sampling time. The effect of sampling angle and instruments were determined experimentally. Conclusions from the analysis of the data were used to propose modifications in the test method. The modified test method was then first verified in the case with no membrane and then applied to determine transfer through a porous Tyvek® membrane.

4.7.1 Effect of sampling volume

NIOSH method 0801 [17] recommends a minimum sample volume of 50 L and maximum sample volume of 300 L, collected using an Andersen impactor to determine bacteria concentration using

gas chromatography. Using the method proposed, the collected sample volume was 25 L (5 L/min collected for 5 min) which was well less than the minimum sample volume recommended to be collected using an Andersen impactor. The initial volume was chosen as it was sufficient for determining the concentration of dust aerosols. Since the bacteria aerosols contain droplets, inactive and active bacteria a larger volume would offer a more probable chance of collecting the active bacteria. Appendix E shows a calculation of the minimum amount of time required to get countable results along with the assumptions made. A total time of 18 min at a flow rate of 2 L/min is needed (36 L sample volume). However, for the test 50 L is still chosen as it gives a more probable chance of collecting active bacteria.

In a study conducted by Li et al. [34] the effect of sampling time and sampling flow rate on the recovery of the sensitive *E.coli* aerosols using filtration and liquid impinger sampling techniques was examined. It was determined that the longer the sampling time, the lower the recovery of *E.coli*, because of the dehydration stress on the bacteria captured on the filter. The study shows that after 30 min less than 10% of the bacteria were viable therefore impingers would be a better method of collection than the filters. It is important to keep the sample time short while collecting a sample of bacteria so that they remain active and culturable. In order to keep the sample time short but collect a large volume, the sampling flow rate must be large. Although not as significant, the sampling flow rate also influences the bacteria survival as a larger flow rate (> 2 L/min) resulted in less colony survival for *E.coli*. The study showed that sampling at 2 L/min or lower had the highest colony survival for a high concentration of *E.coli*. Therefore, to collect a 50 L sample volume, the sampling time in the present study was chosen to be 25 min. The limitation of this method is that sampling time is longer than the minimum sampling time required of 18 min as determined in Appendix E, which may inactivate the bacteria.

4.7.2 Effect of sampling angle

Aerosol particles in an airstream often encounter obstacles which causes them to change their direction of motion. The chance whether an aerosol particle can rapidly change its direction of motion can be understood using the Stokes number (Stk). The Stokes number is the ratio of the stopping distance of the particle to the characteristic dimension of the obstacle it encounters. Stokes number plays an important role in determining which particle sizes can be sampled. The initial test method for collecting bacteria aerosol sample recommended 90° angle sampling ports to draw particles out of the airflow and into the spectrometer. However, unless Stk << 1, a sampling angle of 90° cannot give a representative sample as some particles cannot be drawn into the sampling probe due to inertia of the particles. It is thus possible that some of the larger particles (Stk >>1) that carry the active bacteria colonies were not collected while sampling and would be a probable reason as to why no active bacteria colonies were found in the sample. An experiment was conducted where the difference between concentrations obtained using sampling angles of 90° and 45° was determined. Figure 4.7 below shows the sampling ports used for experiment.

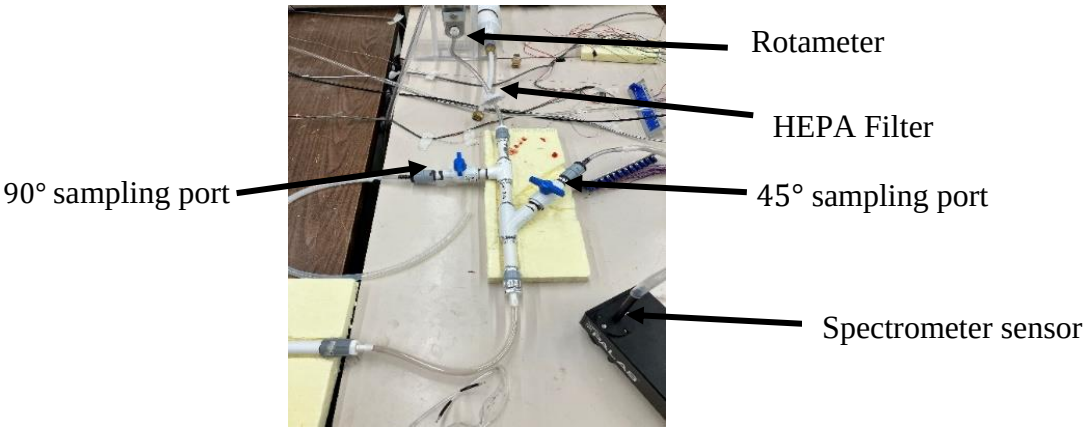

Figure 4.7: Sampling port used to determine concentration difference collected using a 90° *port and a* 45° *port using the optical spectrometer sensor.*

An experiment was conducted where dust was injected into the system at the test conditions reported in Table 4.1. A total of seven samples were collected at the return air station using the ports shown in Figure 4.7. The data markers represent the average concentration over the five minute sampling period and the error bars represent systematic and random error. Each sample was collected at flow rate of 5 L/min for five minutes and the measured concentrations were plotted with respect to time, shown in Figure 4.8. It was observed that the 45° sampling port collected a higher mass concentration compared to the 90° port. It is likely because larger size particles, which have more mass, can be collected using the 45° port.

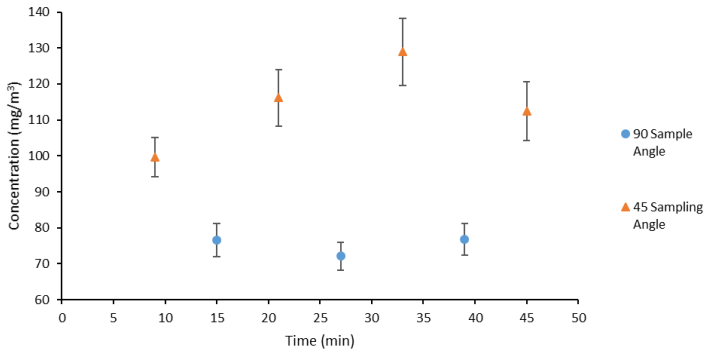

Figure 4.8: Plot of concentration vs time of the dust aerosol concentration measured at a sampling station using two different angles.

Figure 4.9 shows a particle size distribution plot comparing the normalized number fraction for a particular particle size collected using the 45° port shown in grey and 90° port shown in red. Although not significant, the 45° port has a higher concentration of particles for particles sized 1 µm and higher with a few exceptions. The 45° port however has a larger collection of particles in the size range 1 µm – 2 µm which is the interval containing the geometric mean particle size of 1.1µm. Thus the higher concentration measured at the 45° port is likely due to both larger particles and a large number of 1 µm – 2 µm collected.

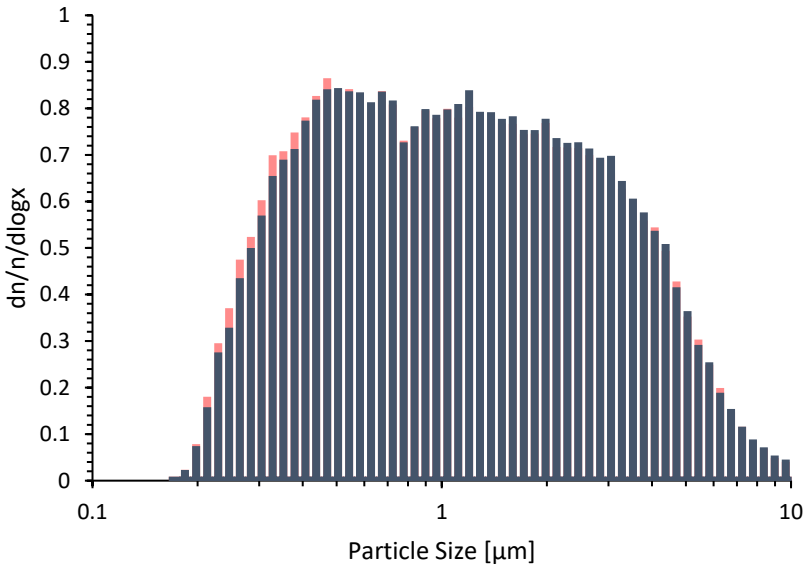

Figure 4.9: Plot comparing the fraction of particles (dn/n) normalized with the width of the logarithmic interval (dlogx) plotted with respect to particle size comparing particles collected using the 90° *port (red) and the* 45° *port (grey).*

After the experiment with dust aerosols, the same procedure was repeated for bacteria aerosols. Two samples were collected using two filters. One sample was collected using a 45° angle sampling port and one sample was collected using a 90° angle sampling port. The sample volume collected was more than the recommended 50 L minimum as shown in Table 4.5 which summarizes the sampling flow rate, collection time, volume and the collected colony count of the filters when challenged with a concentration of $1.6 \times 10^{10}\mathrm{CFU/m^3}$ *E.coli* aerosols.

Table 4.5: Summary of sampling flow rate, sampling time, collected sample volume and the counted colonies on the filter using 45° *and* 90° *sampling angles*

Sampling angle	**Sampling flow rate (L/min)**	**Sampling time (min)**	**Sample Volume (L)**	**Bacteria Concentration (CFU/m^3)**
45°	2.43 ± 0.05	25.1	61 ± 1	0
90°	2.79 ± 0.01	25.1	70.3 ± 0.3	0

As can be noted from Table 4.5, neither sample angles yielded any countable bacteria colonies even though the sample volume was increased to 50 L and ISO A-3 dust aerosols with a similar size magnitude to the bacteria aerosols (~1.2 µm) were detected using the optical spectrometer sensor on both sampling angles as shown in Figure 4.9. The bacteria aerosol measurements could not be done using the optical spectrometer as the number of bacteria ($\sim 10^{10}$) put the optical sensor in overload. This leads to the investigation of the third influencing factor which is the sampling instrument.

4.7.3 Effect of sampling instrument

In addition to dry collection methods such as filters, bacteria aerosols can also be collected using liquid collection instruments such as impingers. Liquid impingers have been shown to have a greater collection efficiency than the filter based method [34]. In the study conducted by Shirey et al. [32] for determining phage transfer in energy wheels, AGI glass impingers were used to collect phage aerosols. Therefore the effect of sampling instrument was studied using SKC liquid impingers [56] and SKC polycarbonate filters as proposed initially in the test method of chapter 3. Figure 4.10 shows an image of the experimental setup used with the impingers.

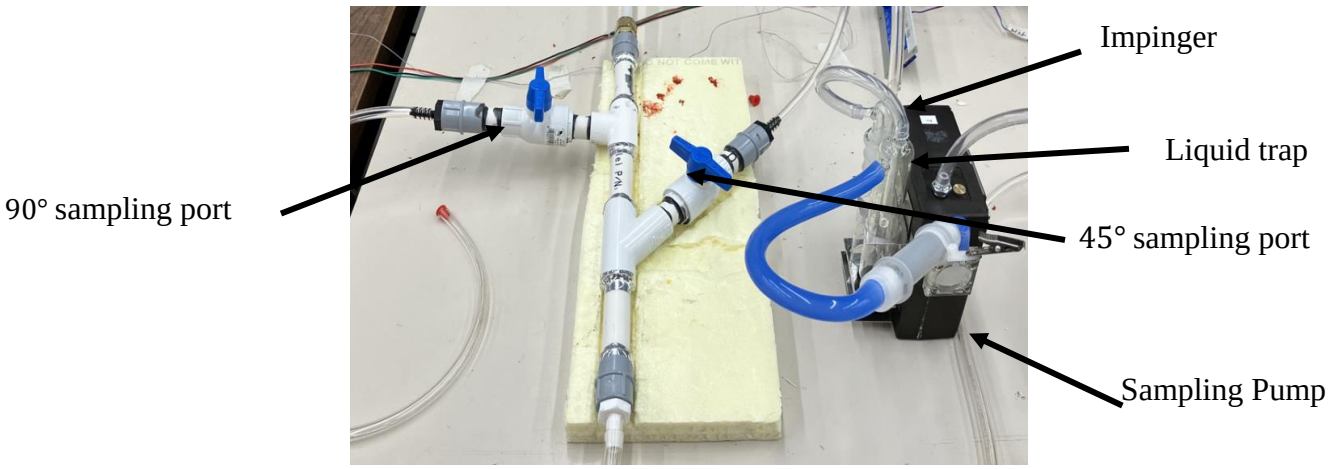

Figure 4.10: Sampling setup using a liquid collection method.

The system was challenged with 3.0×10^8 CFU/m^3 *E.coli* aerosols. The nebulizer was allowed to run for 10 min before samples were collected at the return air station. After 10 min, the first sample was collected using the 45° sampling port. Once the sample was collected, a brief pause of 2 min was allowed before the second sample was collected using the 90° sampling port. Table 4.6 summarizes the sampling flow rate, collection time, volume and the collected colony count of the impingers.

Table 4.6: Summary of sampling flow rate, sampling time, collected sample volume and the counted colonies on the impingers using 45° *and* 90° *sampling angles.*

Sampling angle	**Sampling flow rate (L/min)**	**Sampling time (min)**	**Sample Volume (L)**	**Bacteria Concentration (CFU/m^3)**
45°	2.12 ± 0.06	25.1	53 ± 2	2.9×10^8
90°	2.55 ± 0.05	25.1	64 ± 3	1.3×10^9

As reported in Table 4.6, collecting a minimum 50 L solution, the sample collected using a liquid impinger was able to obtain a countable number of bacteria colonies. Since the collected sample is in a liquid, 50 µl of the solution is withdrawn from the impinger and a series of seven dilutions was prepared [54]. 100 µl from each of these dilution is plated in triplicates using the spread plate technique as reported in chapter 3. These results show that the sampling instrument, in addition to the volume of the sample collected had a major influence on the measurement of bacteria aerosols. An Andersen impactor is the preferred method of collection as bacteria are impacted directly into agar plates which have nutrition for them. The Andersen impactor could not be used in this study as the sampling flow rate (28 L/min) was higher than the maximum flow rate in the test facility

(20 L/min). The second preferred method is using impingers as the phosphate buffer solution maintains a pH ideal for the bacteria. Filters should not be used for collection.

The measured colony count of $2.9 \times 10^8\ \mathrm{CFU/m^3}$ using the $45°$ port is a little less than the challenge concentration used. The sample collected with the $90°$ port is an order of magnitude higher than the challenge concentration. This is attributed to possible pre-existing bacteria in the impingers stem and better cleaning is needed. It was expected that the $45°$ sampling port would collect the larger droplets better as observed in Figure 4.9 and therefore a larger concentration compared to the $90°$ sampling port.

4.8 Method modifications proposed for determining bacteria aerosol concentration

Based on the experimental results discussed above, the following changes were proposed for improving the test procedure proposed in chapter 3, to determine active bacteria colonies in a collected sample

1) **Sample volume**: A minimum collected volume of 50 L is recommended with a sampling time of 25 min.
2) **Sampling angle:** A sampling angle of $45°$ is recommended for sampling of bacteria aerosols.
3) **Sampling instrument:** A liquid impinger sampling technique is recommended over the filter-based sampling technique.

With the new recommended changes another experiment was carried out to verify the method in the case of no membrane separating the air streams. It was expected that a transfer of active bacteria aerosols would be observed. However, mechanical stresses and deposition of aerosols in the test section would significantly reduce the collected active bacteria colony concentration at the supply air station, so the concentration in the supply air was not expected to be as high as the injected concentration in the return air.

The test setup was disinfected using 70% ethanol aerosols and a day before the experiment, a lab blank sample was taken at the return air station to determine the pre-existing bacteria count (if any) in the test section. In addition, the water vapor transfer effectiveness was also measured. During the experiment, the exchanger was allowed to run until it reached the steady state condition, before aerosols were injected. Aerosols were then injected using a Collison nebulizer for a period of 10 min before taking the first sample at the return air station. After taking the sample at the return air station, the sampling valve was closed and a period of 2 min was allowed to pass before taking the sample at the exhaust air stream. After completing the sampling at the exhaust air stream, the sampling valve was closed and a period of 2 min was allowed before taking a sample at the supply air stream. Table 4.7 shows a summary of the test results. For these tests, the challenge concentration injected was 1.3×10^{10} CFU/m^3. The pre-test background count was determined to be 2.9×10^3 CFU/m^3. Since the sampling flow rate was changed to 2 L/min, the testing flow rate was 12.5 L/min. The nebulizer output at 8 L/min was mixed with return air at 4.5 L/min.

Table 4.7: Summary of measured bacteria concentration, calculated water vapor content and water vapor/aerosol transfer percentage with no membrane at 12.5 L/min using an impinger method.

Condition	Measurement Station	Water vapor (kg_w/kg_a), (RH %)	Bacteria Concentration (CFU/m^3)
No membrane	Outdoor Air	$0.1 \times 10^{-3} \pm 0.4 \times 10^{-3}, (0.5 \pm 1.8\%)$	0
	Return Air	$8.3 \times 10^{-3} \pm 0.6 \times 10^{-3}, (41.7 \pm 2.3\%)$	$9.6 \times 10^{8} \pm 1.0 \times 10^{8}$
	Exhaust Air	$1.6 \times 10^{-3} \pm 0.4 \times 10^{-3}, (7.9 \pm 1.7\%)$	$5.7 \times 10^{5} \pm 3.4 \times 10^{4}$
	Supply Air	$8.6 \times 10^{-3} \pm 0.4 \times 10^{-3}, (42.8 \pm 1.8\%)$	$2.2 \times 10^{7} \pm 1.6 \times 10^{6}$
	Latent Effectiveness/ ECTR	$84\% \pm 10\%$	$2.4\% \pm 0.3\%$

With the changes to the sampling volume, sampling instrument and sampling angle proposed, the sampling method was successfully able to detect transfer when no membrane was present. As expected, there was a large amount of water vapor transfer. However, there was still only a small percentage of *E.coli* aerosols transfer observed. It should be noted that this transfer percentage was only a measure of the active colonies, and a large number of inactive colonies would be excluded even if they were present. The *E.coli* bacteria are very sensitive to changes in RH [57] and extreme change in RH from 100% to 50% can drop the survival rate to 20%. Since there is a great difference in RH between the return air and the outdoor air it is probable that the stress caused by the change in humidity would have resulted in the low count of active bacteria. In addition, the shear stress during mixing could also have damaged the cell wall of the bacteria. To confirm the effect of these factors a test can be done where RH in both air streams is kept constant and see whether the shear stress results in a low concentration of active bacteria.

Figure 4.11 shows a schematic which compares the expected versus measured concentration at different measurement station and gives the percentage recovery value. When a concentration of $1.3 \times 10^{10}\ \mathrm{CFU/m^3}$was injected using the nebulizer only a small concentration $9.6 \times 10^{8}\ \mathrm{CFU/m^3}$ was recovered downstream at the return air station after mixing. Thus, a concentration of $2.2 \times 10^{7}\ \mathrm{CFU/m^3}$ at the supply air, which is many orders of magnitude higher than the background count of $2.9 \times 10^{3}\ \mathrm{CFU/m^3}$ but small percentage of the return air is a reasonable measurement as the return air is diluted with the clean outdoor air. It is expected that mechanical stresses and deposition along the airline are the reason for loss of other bacteria aerosols.

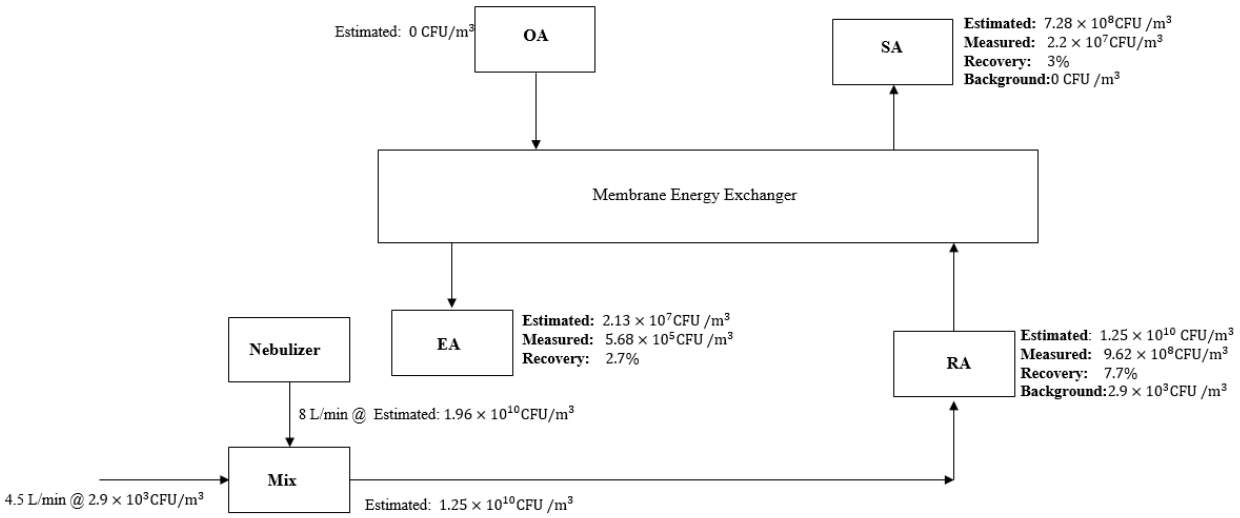

Figure 4.11: Schematic of the test results discussed above showing the recovered E.coli aerosols at different sampling locations

The overall conclusion is that with the modifications, the method can be verified as it can detect a small amount of transfer in case of an expected transfer (i.e. no membrane on the exchanger). However comparing the expected concentration based on the dust aerosol test results versus measured values it can be seen that there is a low recovery (<10%) of the active bacteria colonies in the test facility. Since the RH conditions in an actual exchanger will be similar i.e. return air is

humid and the outdoor air is dry, there would be a very low transfer of E.coli as most of the bacteria might be inactivated due to change in RH.

4.9 Limitations of method to detect transfer of dust aerosols

A small amount of transfer was detected for *E.coli* aerosols for a case of a no membrane compared to the large amount of transfer of dust aerosols with no membrane present. To determine the lower end of the range of measurable dust aerosol transfer, an experiment was carried out where three of the membrane slots were covered with impermeable material and one slot was covered with a semi-permeable Tyvek® membrane. Eight small defects were punctured into the membrane with a drill bit to allow for a small amount of transfer and a pressure difference was maintained such that the return air stream had a higher pressure than the outdoor air. Figure 4.12 shows an image of the membrane with an approximate location of the defects.

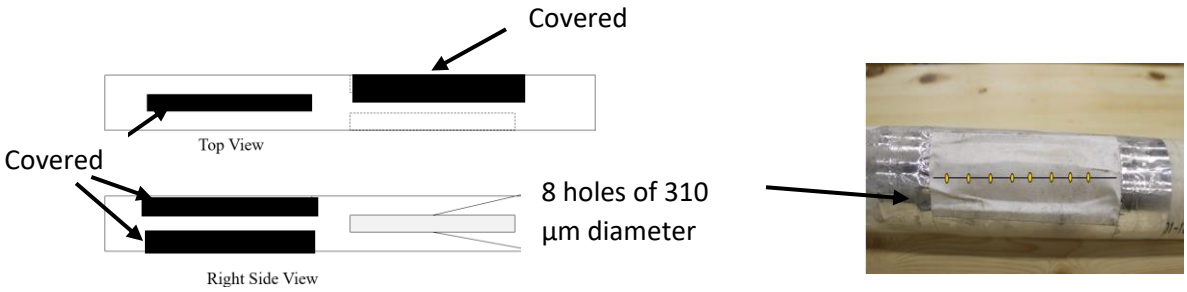

Figure 4.12: A schematic of the modification done (i.e. covering three slots of the membrane and puncturing 8 holes in the membrane exposed) to the inner annulus pipe to measure a small amount of dust aerosol transfer

As shown in Figure 4.12 three of the slots were covered with an impermeable cover, with only one slot having the membrane over it. The membrane was then challenged with dust aerosols and water vapor and the amount of dust and water vapor transfer percentage was determined. Table 4.8 shows a summary of the results. The static pressure differential between the air streams was maintained such that the return air pressure was higher. The background dust concentration was 0.002 mg/m^3.

Table 4.8: Summary of measured dust concentration, calculated water vapor content and water vapor/aerosol transfer percentage with one membrane and defects at 18.5 L/min.

Condition	**Measurement Station**	**Water vapor (kg_w/kg_a)**	**Concentration (mg/m^3)**
Membrane with defects	Outdoor Air	$0.5 \times 10^{-4} \pm 0.3 \times 10^{-4}$	0
	Return Air	$7.1 \times 10^{-3} \pm 0.5 \times 10^{-3}$	101 ± 12
	Exhaust Air	$6.9 \times 10^{-3} \pm 0.3 \times 10^{-3}$	29 ± 2
	Supply Air	$5.5 \times 10^{-3} \pm 0.4 \times 10^{-3}$	$18 \times 10^{-3} \pm 1 \times 10^{-3}$
	Latent Effectiveness/ECTR	$21\% \pm 8\%$	$0.015\% \pm 0.006\%$

A very small amount of dust aerosol transfer was measured using this sampling procedure. This indicates that a small amount of concentration of dust aerosols (18 $\mu g/m^3$), one order of magnitude higher than the background concentration could be measured using the method and the spectrometer. In addition, the amount of water vapor transfer is still many orders of magnitude higher than the amount of dust aerosol transfer indicating that the membrane can selectively transfer water vapor compared to the dust aerosols.

The ECTR with respect to time is plotted in Figure 4.13. The data markers represent the average value for the five minute interval. The error bar represent both the systematic and random error. As observed, the initial amount of ECTR is higher and then decreases with time. In addition to dust aerosols, bacteria aerosols were also injected in a different test however the concentration was not recorded.

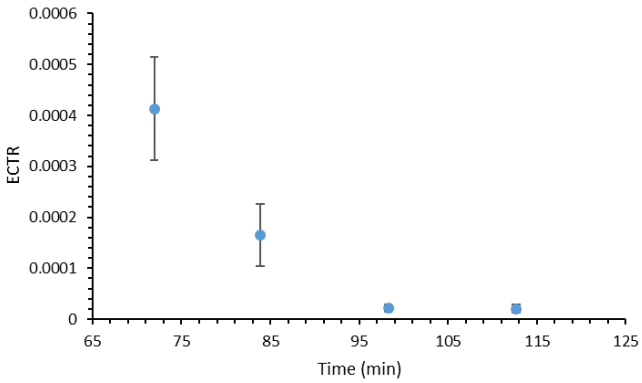

Figure 4.13: The ECTR in case of a membrane with defects represented a function of time.

The ECTR decreases with time because the particles deposit on the membrane and then agglomerate together. As the particles agglomerate together, they become larger in size and block the pores of the membrane preventing other particles from passing through. The ECTR is plotted with respect to size in Figure 4.14 showing a large amount of small particles transfer but not larger particles. The data markers represent the average value for each size bin during the test and the error bars represent both systematic and random error.

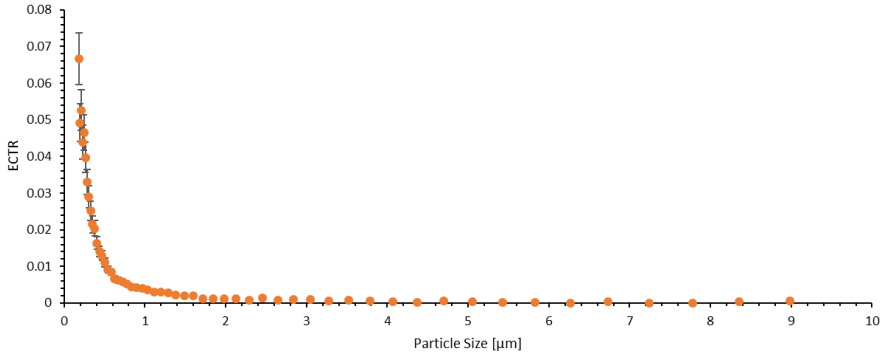

Figure 4.14: ECTR as a function of particle size for the membrane with defects

Figure 4.15 shows an SEM image of the membrane with defects after testing with dust and bacteria aerosols. As shown in the image, large agglomerates of particles are observed.

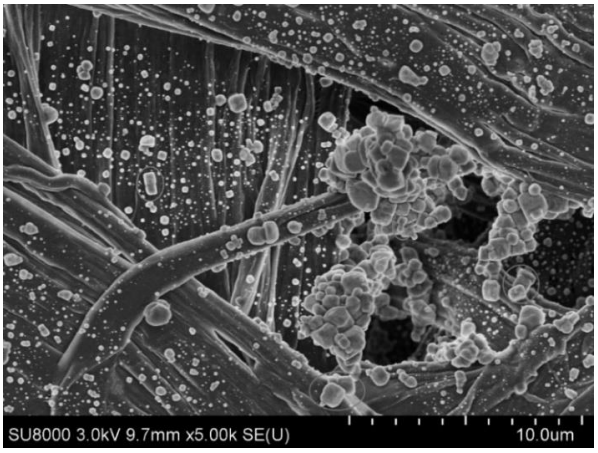

Figure 4.15: An SEM image of a small portion of Tyvek® membrane loaded with dust and bacteria aerosols.

4.10 Transfer of dust aerosols and bacteria aerosols in Tyvek® membrane

Porous membranes used in membrane energy exchangers often have small pores and are paper or polymer based. The polymer-based membranes are common due to their economic cost, mechanical strength and ability to be produced easily. Polyvinyl alcohol (PVA), polypropylene (PP), ethylene cellulose (EC), polyethylene (PE) and polydimethylsiloxane (PDMS) are common polymeric membranes out of which PVA offers the best selectivity to volatile organic compounds (VOC's) and high moisture permeation [58]. Polyethylene (PE) performs the least effective as it has low moisture permeation and also has a low selectivity for gaseous contaminants such as N_2. The aim of this study is to determine if porous membranes used in membrane energy exchangers can transfer aerosols therefore a Tyvek® membrane consisting of high density (PE) is chosen. Pore size and porosity are important properties of a membrane affecting selectivity and moisture permeation. The Tyvek® membrane used has pore sizes in the range of 2-15µm, a porosity of 45% and a high air permeability [14, 52]. Table 4.9 summarizes the important membrane properties of the Tyvek membrane used.

Table 4.9: Characteristics of the porous membrane used for testing

Characteristic	Value	Reference
Pore Size (nm)	$2 - 15$ μm	[52]
Moisture transfer resistance (s/m)	409 ± 80	[52]

The high air permittivity of the membrane is expected to increase transfer of aerosols if it is the case. An SEM image of the membrane is shown in Figure 4.16. As seen in the SEM image the membrane has a fibrous structure with large distances (pores) between the two fibers in the range of 2-15 μm.

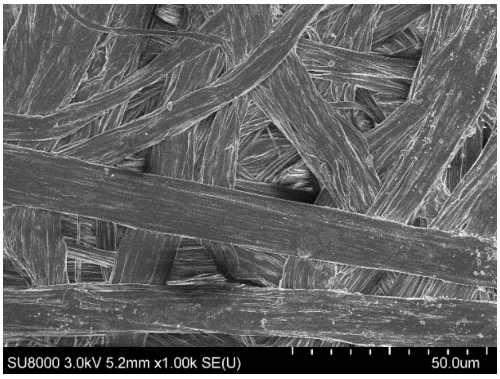

Figure 4.16: SEM image of the Tyvek® membrane used to determine the aerosol transfer with pore sizes in the range 2 – 15 μm.

4.10.1 Transfer of ISO A-3 dust aerosols in Tyvek® membrane

The transfer of dust aerosols through the Tyvek® membrane was experimentally determined using the test procedure proposed in chapter 3 and verified earlier in this chapter. No concentration of dust aerosols was measured in the supply air stream. The aerosols used for testing had a geometric mean size of 1.09 μm and geometric standard deviation of 2.55. Table 4.10 shows a summary of the test results for each of the two tests. The flow rate during the aerosol transfer tests was 18.5 L/min ($Re < 2300$) indicating a laminar flow. The static pressure difference for the test was

maintained such that the return air stream was at a higher pressure. Background aerosol count was 2.4×10^{-4} mg/m^3. The latent effectiveness at 10.5 L/ min was $30 \pm 8\%$.

Table 4.10: Summary of dust aerosol transfer experiments in the porous Tyvek® (PE) membrane.

Aerosol Type	**Measurement Station**	**Test 1 Dust Concentration (mg/m^3)**	**Dust Concentration (mg/m^3)**
ISO A-3 test dust	Outdoor Air	0	0
	Return Air	72 ± 5	87 ± 6
	Exhaust Air	12.1 ± 0.3	32 ± 1
	Supply Air	0	0
	ECTR	0%	0%

As summarized in the Table 4.10, no transfer of dust aerosols from the return air to the supply air was detected; even though the porous membrane has pore sizes in the same order of magnitude as the aerosol particles. Although the particles did not transfer through the membrane, the outlet exhaust concentration is not equal to the inlet air concentration, indicating that a significant number of particles deposit on the membrane and in the energy exchanger. Particle deposition occurs due to interception, inertial impaction, diffusion, gravitational settling and electrostatic forces mechanisms which govern the interaction between the aerosol particles and the membrane as described in chapter 2 [3]. Since the Tyvek® membrane has a fibrous structure, inertial impaction, diffusion, interception and electrostatic forces would have prevented transfer of dust aerosols. To confirm whether sampling using a $45°$ angle would change the ECTR, the test was repeated with a $45°$ sampling port. The ECTR calculated was negligible (10^{-5}). Table 4.11 shows the

concentration measured during the test. The background aerosol count was 9.2×10^{-3} mg/m^3. The water vapor transfer rate was $15 \pm 9\%$

Table 4.11: Summary of dust aerosol transfer experiments in the porous Tyvek® (PE) membrane using a $45°$ sampling port.

Aerosol Type	Measurement Station	Water vapor (kg_w/kg_a)	Test 2 Dust Concentration (mg/m^3)
ISO A-3 test dust	Outdoor Air	$9.0 \times 10^{-4} \pm 4.0 \times 10^{-4}$	0
	Return Air	$7.4 \times 10^{-3} \pm 5.0 \times 10^{-4}$	44 ± 2
	Exhaust Air	$7.0 \times 10^{-3} \pm 4.0 \times 10^{-4}$	17 ± 1
	Supply Air	$2.0 \times 10^{-3} \pm 4.0 \times 10^{-4}$	$5.0 \times 10^{-4} \pm 2.0 \times 10^{-4}$
	Latent Effectiveness/ ECTR	$15 \pm 9\%$	0% (10^{-5})

4.10.2 Transfer of *E.coli* aerosols through Tyvek® membrane

The modified method to determine *E.coli* aerosol transfer proposed and verified earlier is applied to the Tyvek® membrane to determine bio-aerosol transfer through the membrane. It is expected that the transfer of *E.coli* aerosols would be negligible due to the aerosols being similar in size to the dust aerosols, which did not transfer through the membrane. Two repetitions of the experiment were conducted to confirm this assumption. Table 4.12 shows a summary of test results. The flow rate for transfer tests was 12.5 L/min ($Re < 2300$). The static pressure differential during the tests was maintained such that there was a higher pressure at the return air than the outdoor air. The latent effectiveness at 12.5 L/min was $23 \pm 8\%$. The background aerosol count was 2.2 x 10^4 CFU/m^3.

Table 4.12: Summary of E.coli aerosol transfer experiments in the Tyvek® membrane.

Aerosol Type	**Measurement Station**	**Test 1 Concentration (CFU/m^3)**	**Test 2 Concentration (CFU/m^3)**
E.coli	Nebulizer	3.8×10^{10}	1.5×10^{10}
	Outdoor Air	0	0
	Return Air	$1.1 \times 10^{9} \pm 2.0 \times 10^{8}$	$8.8 \times 10^{8} \pm 1.6 \times 10^{8}$
	Exhaust Air	$2.5 \times 10^{8} \pm 4.0 \times 10^{7}$	$8.7 \times 10^{7} \pm 9.0 \times 10^{6}$
	Supply Air	$5.8 \times 10^{4} \pm 1.2 \times 10^{4}$	$2.6 \times 10^{5} \pm 4.0 \times 10^{4}$
	ECTR	0% (10^{-5})	0% (10^{-4})

As expected, there is a negligible transfer of *E.coli* aerosols in both tests as shown in Table 4.12. It can also be observed that the concentration of aerosols in the exhaust air is much less than the injected *E.coli* aerosols at the return air stream. Particle deposition on the membrane and ducts are the two factors that play a role in the lower concentration at the exhaust air. Figure 4.17 shows SEM images of the deposits on the membrane with energy dispersive spectrometry (EDS) used to show *E.coli* particles (carbon-based compounds). Both *E.coli* and particles of the phosphorus buffer saline solution are pictured deposited on the fibers. The *E.coli* are circled with a black boundary for identification. EDS shows that these regions have carbon content along with particles from the phosphate buffer solution that was used for nebulization. The PBS contains phosphorus, sodium, chloride and potassium.

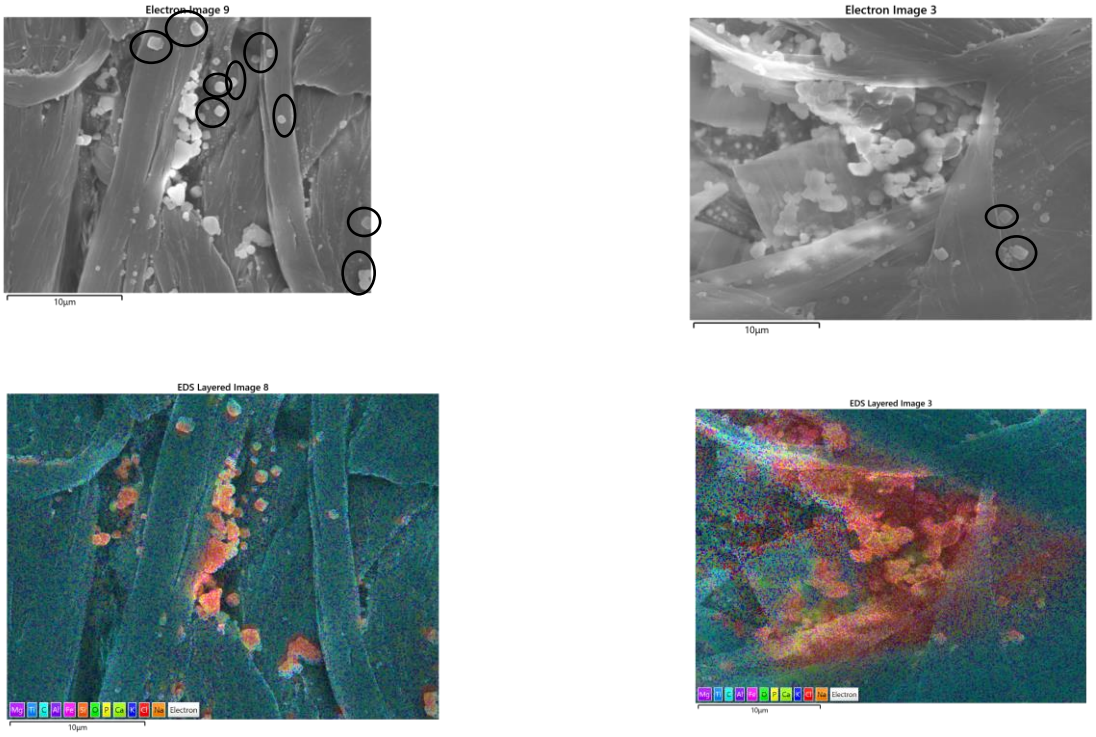

Figure 4.17: SEM images showing single bacteria particles (rod like structures) deposited on the fiber surfaces.

At the tested flow rate of 12.5 L/min there was a large water vapor transfer of $23 \pm 8\%$. Compared to the water vapor transfer there was a negligible amount of *E.coli* aerosols transferred 10^{-5} %. Thus, these test results demonstrate that porous polymeric membranes like Tyvek® (PE), even with its low selectivity for gaseous contaminants such as N_2, can selectively transfer water vapor over aerosols. These membranes used in membrane energy exchangers can therefore be used with little risk of affecting the indoor air quality as they do not transfer significant amounts of particulate matter to the ventilation air.

4.11 Summary and Conclusions

The motivation of this study was to determine whether membrane energy exchangers could affect the indoor air quality due to transfer of bio-aerosols such as *E.coli* aerosols. Limited research is present on standard test procedures to evaluate transfer of *E.coli* aerosols in membrane energy

exchangers. The method and instruments proposed in chapter 3 were used to determine transfer of aerosols through membranes and verified with a case of no membrane where transfer of aerosols is expected due to mixing of the return and outdoor air streams. In a separate test to evaluate different sampling instruments for *E.coli* aerosols, polycarbonate filters and liquid impinger sampling methods were compared. In this test comparing the two sampling instruments, it was concluded that the liquid impinger sampling method was best suited for collection of the *E.coli* aerosols as no active bacteria colonies were collected using the filter samples.

Overall, a negligible amount of bacteria aerosol transfer (ECTR = 10^{-5} %) was detected when a membrane was placed to separate the air streams compared to the case when there is no membrane present (ECTR = 2.4%). ISO A-3 dust particles with a similar geometric mean diameter (1.2 µm) to the *E.coli* (2 µm) were used to further verify the test results as no transfer of dust aerosols was seen through the Tyvek membrane. Compared to the *E.coli* aerosol particles, the amount of water vapor transfer $23 \pm 8\%$ was many order of magnitudes higher indicating that the membrane could selectively transfer water vapor more than the bacteria aerosol.

The concentration of *E.coli* used for testing $\sim 10^{10}\ \mathrm{CFU/m^3}$ is many folds higher than the typical concentration is found in an office building $14\ \mathrm{CFU/m^3} - 494\ \mathrm{CFU/m^3}$ [21]. With a transfer rate of 10^{-5}% it is expected that less than $1\ \mathrm{CFU/m^3}$ would end up in the supply air, indicating that membrane energy exchangers possess a very low risk to the indoor air quality due to transfer of bacteria aerosols.

In the verification tests, a very low recovery of bacteria aerosols was measured. It is therefore proposed that the test facility be redesigned free of sharp corners that can reduce the aerosol accumulation of large particles in the test facility. A significant parameter that changes in indoor spaces is the relative humidity which also affects the survival of *E.coli* [57]. In the future,

experiments are recommended with low, moderate and high relativity humidity to determine if there is an effect on the bacteria concentration in the membrane energy exchanger. In addition, experiments are recommended with *B. subtilis* spores [34] that are less sensitive than *E.coli* to compare the results of the *E.coli* transfer obtained using the proposed method above.

CHAPTER 5

SUMMARY, CONTRIBUTIONS AND FUTURE WORK

This chapter provides a summary of the thesis based on tests conducted on measuring dust and E-coli aerosol transfer through dense and porous membranes used in membrane energy exchangers. Based on the summary of experiments, important conclusions are drawn which are used to address the research question as to whether membrane energy exchangers can be used to pre-condition ventilation air by transferring heat and moisture from the building exhaust air without transferring aerosols. Future work is recommended to improve the experimental facility and method, and to better understand if operating conditions, such as relative humidity of the air, plays a role in the transfer of active *E.coli*.

5.1 Summary

The main aim of this thesis was to determine if membrane energy exchangers affect the indoor air quality by transferring bio-aerosols from the building exhaust air to the ventilation air based on the type of membrane used. To achieve this aim, a literature review was conducted to review numerical and experimental research on aerosol transfer in membrane energy exchangers. Previous research has focused on particulate fouling in membrane energy exchangers, aerosolized bacteriophage transfer in energy wheels, and aerosol generation and sampling methods for aerosol transfer experiments. However, it was determined that there is no directly applicable test method available for determining aerosol transfer through membranes. In addition, bio-aerosols such as bacteria aerosols are sensitive to generation and sampling techniques but there are no standard test methods on which instrumentation should be used for to generate and sample active bacteria aerosols to determine their transfer in membrane energy exchangers. There were two objectives

that were formed to address this gap i) develop a test method to quantify aerosol transfer in membrane energy exchangers and apply the method to a dense membrane and ii) quantify aerosol transfer in porous membranes. A total of 51 experiments were conducted to meet the objectives and all tests are summarized in Appendix F.

Objective 1: Develop a test method to quantify aerosol transfer in membrane energy exchangers and apply it to a dense membrane:

On reviewing literature for water vapor and aerosol transfer in membrane exchangers, it was determined that water vapor and gaseous contaminant transfer in membrane energy exchangers is well researched. Theoretical models and experimental data are available to evaluate the transfer of water vapor and gaseous contaminants in membrane energy exchangers. However, there are limited theoretical relations or experimental data available for determining aerosol transfer in membrane energy exchangers. Aerosols have a particle size that is much larger than the gaseous contaminants. In addition, aerosols have different size and shape distribution than gases, which makes theoretical and numerical studies challenging. Thus, experiments were selected to study aerosol transfer.

A recently published literature review provides an evaluation on generation and sampling mechanisms for bio-aerosols specifically for bacteriophages, a safe substitute for viruses [4]. However, no study evaluated the suitability of the sampling mechanisms and a generation technique for bacteria bio-aerosols which are amongst the most common bio-aerosols indoors. Therefore, this objective also addresses the development of a sampling test procedure and evaluation of different sampling instruments, using a six jet Collison nebulizer for sample generation, which can be used to determine bacteria aerosol transfer in membrane energy exchangers. The main findings of objective 1 are summarized below:

- The aerosol particle behavior is dependent on its size. An aerosol moves much slower than a gas molecule and has a lower diffusivity in air than other gases like nitrogen. Aerosols have an affinity for deposition on surfaces. Aerosol deposition can be explained through five mechanisms interception, inertial impaction, diffusion, gravitational settling and electrostatic attraction. Particles smaller than 1μm are likely to deposit due to Brownian motion or diffusion and particles greater than 1μm are likely to deposit due to gravitational settling.
- A test method was proposed to determine aerosol transfer in membrane energy exchangers using IS0 A-3 test dust generated using a dry aerosol generator and sampled using an optical spectrometer. Sampling flow rate, sampling time, number of samples and sampling sequence were identified as important parameters in this developed test method. The test facility and the method were verified in a case of an exchanger with no membrane where a large amount of transfer is detected. On applying the developed procedure to a dense membrane, no transfer of dust aerosols was detected but a significant deposition was observed. Compared to dust aerosol transfer, water vapor transfer through the dense membrane is much larger, indicating that a dense membrane can selectively transfer moisture without aerosols.
- A test method was developed for determining *E.coli* transfer in membrane energy exchangers using a six jet Collison nebulizer for generation, and impinger sampling mechanisms. The method was verified with a case of an exchanger with no membrane, to confirm that the test method proposed can detect transfer. It should be noted that in this test there was a very low recovery of the active bacteria aerosols. The same test method was used for an exchanger with a dense membrane, and no transfer of *E.coli* was detected.

- The transfer of water vapor and dusts is much larger than the transfer of *E.coli* aerosols in tests with no membrane separating the airstreams. It is likely that the temperature, and relative humidity of the air, and other physical conditions, like mixing of the air puts stress on the bacteria, causing a lower recovery of active bacteria in the collected sample.
- The required sample volume needed to determine the concentration of bacteria is much larger than that required for dust aerosols. Thus, it is necessary to develop test methods for bio-aerosol transfer using bio-aerosols which are safe to experiment with, and cannot be assumed to be similar to other aerosols with the same physical size such as dust.
- Aerosols in the ambient environment occur both in dry solid form (PM) and liquid droplets (bio-aerosols). Both liquid and dry aerosols were used for testing and the transfer through the membrane for both aerosol types was very low. Thus the membrane energy exchangers pose a very low risk for aerosol transfer.

Objective 2: Quantify aerosol transfer in porous membranes

A porous Tyvek® membrane was chosen instead of other porous membranes as it has a variety of pore sizes which means one porous membrane could be tested instead of multiple porous membranes with limited pore sizes. In addition the Tyvek® membrane has a low airflow resistance, leading to more air transferring through the membrane, and in general a poor selectivity for gaseous contaminants such as N_2 over water vapor. Aerosol transfer through a Tyvek® membrane is expected to be larger than a dense membrane due to higher pore sizes, low selectivity and low airflow resistance. The key findings of this objective are given below:

- Applying the test method for dust aerosols it was determined that, even with a low selectivity and airflow resistance, the Tyvek® membrane is an effective barrier for

preventing aerosol transfer in a membrane energy exchanger. No transfer of dust aerosols, based on testing with ISO A-3 test dust with a geometric mean size of 1.09 µm and a size distribution of 0.97 µm-10 µm, was observed.

- A Tyvek® membrane with artificially punctured holes was tested to determine the lower amount of dust aerosol transfer that could be measured with the proposed test method. It was observed that the amount of aerosol transferred through the membrane was three orders of magnitude lower in mass concentration than the aerosol challenge concentration used at the return air station. This indicates that the membrane is an effective barrier against aerosol transfer, even with small defects. In addition, it was observed in this case the particles agglomerate on the membrane, increasing in size and blocking the transfer of other aerosol particles, decreasing the concentration of aerosols transferred over time.
- Applying the test method for bio-aerosol transfer, it was determined a negligible amount of *E.coli* aerosols were transferred from the building exhaust air to the building supply air. A large challenge concentration of bacteria aerosols was used for testing (10^{10} CFU/m^3) which is unlikely to arise in an indoor space where the typical concentration would be 14 CFU/m^3 – 494 CFU/m^3. The small amount of transfer would lead to a concentration of less than 1 CFU/m^3 thus posing a very low risk of infection.

5.2 Contributions

This thesis has one major contribution to the literature: A test method was developed for determining transfer of active *E.coli* aerosols through membranes used in membrane energy exchangers. Using this method it was determined that the transfer is negligible. Two sampling techniques (liquid and dry) for bacteria aerosols were compared and the liquid sampling technique using impingers was determined as a better way to collect *E.coli*, compared to the filter collection

method. A six jet Collison nebulizer was determined to be a suitable generation technique for generation of *E.coli* aerosols and a 50 L minimum collected sample volume was determined to be an important parameter in the proposed test method.

5.3 Future Work

Based on the experiments, there are two items recommended for future work:

- As reported in Chapter 3 & 4 during verification of the test facility a large number of aerosols were deposited at the 90° turns, along the length of the exchanger and during injection and mixing. In addition due to the small scale size of the test facility a probe could not be inserted into the pipe for sampling. Therefore, it is recommended to redesign the test facility to address these issues for future work. ASHRAE Standard 52.2 can be used for redesign of ducts and injection methods.
- All tests conducted in this study were at a set air temperature and relative humidity conditions. Future investigation of these parameters is recommended, as temperature and humidity affect the survival of air borne *E.coli*. This could affect the collected concentration of *E.coli* at the return air, supply air and exhaust air.

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APPENDIX A

BACTERIA HANDLING PROCEDURES

The *E.coli* used for the research are sensitive to the storage, preparation and transportation procedures. This appendix describes the procedure used for preparation, storage of *E.coli* and preparation of media to culture the bacteria.

A brief description of the procedure:

This procedure is intended to provide the steps necessary to prepare a known concentration of *E.coli* and phosphate buffer solution for testing using the Collison Nebulizer, transporting the collected filter and impinger samples and determining the bacteria concentration (CFU/ml) in these filters and impingers using plating. Finally, instructions on safe disposal are provided. The testing is a multi-day procedure

Potential hazards that might occur during the use of the facility (e.g., physical hazards, environmental concerns, chemical hazards, biological hazards).

BIOLOGICAL HAZARD: All procedures that involve handling of the bacteria when not enclosed in a leak and drop resistant plastic container can lead to the bacteria inhalation and must be done inside the approved bio-safety cabinets.These procedures include transferring bacteria from one solution to another, dilution of the collected solution for plating and spreading the solution on the plate for incubation. The bacteria are level 1 and pose minimum risk for infection.

EQUIPMENT HANDLING: All procedures that involve transportation of bacteria must be done in a leak and drop proof container. While handling the nebulizer make sure the lid is securely

closed and the hose ends are plugged. The nebulizer must be transported within a plastic container that has appropriate Styrofoam padding to prevent it from moving within the container

Personal Protective Equipment (PPE) and hygiene practices while operating the procedure (e.g., gloves, dust mask, lab coat).

Wear gloves and knit cut sleeve lab-coat while using the bio-safety cabinet. Make sure handling happens closer to the back of the cabinet rather than at the front edge of the cabinet

After entering and leaving a lab space wash your hands with soap thoroughly and disinfect the external surfaces of all containers being used with disinfecting wipes or 70% Ethanol solution

Wearing a surgical mask with eye protection is recommended while testing bio-aerosols

1. **Preparing a known concentration of bacteria solution, growth medium and buffer solutions (1 month to 1 week in advance of testing)**
    a. Preparation of Tryptic soy broth/TSB
        i. Materials needed:
            1. Tryptic Soy Broth powder (BD Difco, Fisher Scientific, Cat# DF0370-17-3)
            2. Distilled water
            3. Top loading balance (Mettler Toledo)
            4. Weigh boats
            5. 1 L Nalgene bottle or 500 ml Nalgene bottle
            6. Spatula
            7. Stirring rods (if available)
            8. Gloves

ii. Preparation

1. Weigh out 15 g of TSB powder using a top loading balance and place into a 1 L Nalgene bottle **(wear gloves).**
2. Dissolve the TSB powder in 500 ml of distilled water.
3. If the smaller glassware is available dissolve 7.5 g of TSB in 250 ml distilled water, making sure that the solution fills no more than half of the bottle volume.
4. Unscrew the lid on the bottle so it is loose, cover the lid with tin foil and put a piece of autoclave tape with:
    a. Media type (TSB)
    b. Date
    c. Lab #
5. Put the bottles of media in a solid container and place on cart for autoclaving.
6. Autoclaving pickups are scheduled for 10:00 AM and 1:00 PM and the procedure above is expected to take 30-45 min. Begin the procedure ideally an hour before pickup time.
7. Solution should last for one month's testing time and can be stored in the fridge in 2D10.

b. Preparation of TSA Plates (Done 2 weeks before testing)

i. Materials needed:

1. Tryptic Soy Broth powder (BD Difco, Fisher Scientific, Cat# DF0370-17-3)

2. Granulated agar (BD Difco, Fisher Scientific, Fisher Scientific, Cat#DF0145-17-0)
3. Distilled water
4. Top loading balance (Mettler Toledo)
5. Weigh boats
6. 1 L Nalgene or 500 ml Nalgene bottle
7. Thermo-scientific petri-plates

ii. Preparation

1. Weigh out 4.5 g of granulated agar and 9 g of TSB powder using a top loading balance. Place both into the same 1L Nalgene bottle.
2. Dissolve the powder into 300 ml of distilled water.
3. Unscrew the lid on the bottle so it is loose, cover the lid with tin foil and put a piece of autoclave tape with:
    a. Media type (TSA)
    b. Date
    c. Lab #
4. Put the bottles in a solid container and place it on the cart for autoclaving.
5. The TSA has a working life of 1-2 hours and solidifies if it reaches the room temperature. Pouring of the plates should be done within this time frame.
6. If needed, agar can be heated in a water bath to 65℃. Do not use microwave to heat up solidified agar

7. In the bio-safety cabinet, pour agar into petri-dishes covering at least ¾ of the plate. Close the lids to the plates and swirl gently to distribute the agar across the petri plate.
8. Allow the plates to solidify. Store the plates upside down at 4℃ if not being used immediately. (Storing plates upside down allows water droplets to accumulate on the cover and prevents contamination).
9. Fresh plates are better and in an ideal case plate are no older than 2 weeks.

c. Preparation of *E.coli* after receiving from supplier

i. Materials needed

1. ATCC 27325 *Escherichia coli* (Migula) Castellani and Chalmers Strain W3110
2. Sterile Tryptic Soy Broth
3. Pipettes, 1000 uL volume (sterile)
4. Pipette, 1000 uL volume (sterile)
5. 20% glycerol solution
6. 37°C Incubator

ii. Preparation of 20% glycerol solution

1. In a clean, sterile Nalgene bottle prepare the 20% glycerol solution according to the volume you need from the table below:
2.

Volume of 20% Glycerol Wanted (FINAL VOLUME)	Volume of 100% Glycerol to Add (ml)	Volume of ddH20 to add (ml)
150 mL	30	120
100 mL	20	80
50 mL	10	40

3. Keep the bottle cap loose, cover the cap with tin foil put a piece of autoclave tape with:
    a. 20% glycerol
    b. Date
    c. Lab #
4. Put the bottle in a solid container and place it on the shelf for autoclaving.
5. After autoclaving, 20% glycerol can be stored in the fridge.

iii. Preparation of *E.coli* culture

1. In the bio-safety cabinet, open the vial according to the manufacturer's instructions.
2. Add 0.5 ml to 1 ml TSB to the tube containing the pellet using a pipette.
3. Mix the contents of the tube by pipetting up and down gently.
4. Aseptically transfer this aliquot to a tube containing TSB (5 to 6 mL) and mix well.
5. Incubate the tube at 37℃ overnight.
6. If time is within an hour after end of incubation period (i.e. 25 hr), specimen is still valid.

iv. Preparation of glycerol stocks (Done day after preparing culture)

1. Label cryovials with *E.coli* strain and date.
2. To the labelled cryovials, add 1 ml of 20% glycerol and 1 mL of the E.coli culture from the day before.
3. Place the cryovials in the -80℃ fridge.

d. Subculturing *E.coli* from glycerol stocks

i. Materials needed

1. Sterile TSB- 40 ml for each aerosolization
2. 50 ml conical tubes
3. *E.coli* W3310 glycerol stock
4. 15 ml conical tubes
5. Pipettes, 1000 uL volume (sterile)
6. Pipette tips, 1000 uL volume (sterile)
7. 37°C Incubator

ii. Preparation

1. Take *E.coli* W3110 glycerol stock out of the -80°C freezer.
2. Pipette up and down in the glycerol stock to mix contents.
3. Transfer the *E.coli* W3110 to 40 mL of Sterile TSB in a 50 mL conical tube. Swirl the tube gently to mix the contents. (Prepare two tubes).
4. The bio-safety cabinet should be booked for an hour for this procedure.

5. Disinfect the external surfaces of all containers using 70% ethanol wipes.
6. Incubate the culture at 37°C overnight in the incubator.
7. The following day, take the solution for storage
8. This solution is used for testing for a week and a sample of this solution is used to prepare known concentrations of the *E.coli* solution to test.
9. Alternatively prepare a fresh sample each day before test if storage is not available.

2. Preparation of a known concentration of bacteria solution for nebulizer (Morning during day of testing)

a. Determining the concentration of the solution using UV-Vis Spectrophotometer

i. Materials needed

1. Small sized Kim wipes
2. Sterile Tryptic Soy Broth (used as blank)
3. Cuvettes
4. UV-Vis Spectrophotometer
5. 1000 uL pipettes
6. 1000 uL pipette tips

ii. Procedure

1. In the biosafety cabinet, transfer 1 mL of culture and put it into a plastic cuvette and 1 mL of TSB into another plastic cuvette.

2. Recap the falcon tube containing the culture and the bottle containing the sterile TSB.
3. Wipe down the outside of of the cuvette with a Kim wipe to remove any thing that could interfere with the OD reading.
4. Use the single wavelength mode of UV-Vis spectrophotometer measures the absorbance of 1 ml incubated TSB medium at 600 nm (TSB as blank).
5. The calculation of concentration of: $E.coli\left(\frac{cfu}{ml}\right) = Optical\ density \times 10^9$.
6. Record the reading and plate the solution using the plating procedure described in the SOP.
7. Set aside 80 mL of the solution for pouring into the nebulizer

b. Transferring the solution into the nebulizer

i. Materials needed

1. Nebulizer
2. 80 mL PBS Solution
3. Centrifuge
4. 80 mL TSB & *E.coli* solution
5. Hose plugs

ii. Procedure

1. Take two falcon tubes containing TSB+*E.coli* solution and use a centrifuge with 5000 rpm to separate the bacteria and the TSB. The mass difference between the tubes should be less than 0.01g.

a. Hazard: Make sure tubes are conical. Ensure lids are tight, you have to flip the bottle to weigh it. This step is prone to leaks if lid is not securely close or manufacturing defects in lid. To be safe use dark blue colored cap tubes

2. In the bio-safety cabinet pour out the TSB solutions and transfer the PBS solution into the falcon tubes with the bacteria pellets.
3. Close the caps and swirl the tubes to mix PBS and the bacteria.
4. Once mixed, carefully pour the solution into the nebulizer glass jar and screw the lid.
5. Plug in the hose end and put a kink in the hose to prevent any air flow during transportation.
6. Disinfect the outside of the container using 70% ethanol wipes.

c. Preparing the liquid impingers for sample collection

i. Materials needed

1. Liquid Impinger
2. 15 ml PBS Solution
3. Pippettes (5000 µL)
4. Pippette tip
5. Hose Plugs

ii. Procedure

1. The day before testing ensure the impinger has been disinfected with 70% ethanol (especially the foam at the impinger tip) and dried using an oven

2. Remove the impinger top piece and carefully using a pipette add 5 ml of PBS solution to the tube.
3. Repeat the step above till the collection volume is 10 mL – 15 mL. Record the volume
4. The impinger is bound to have some overflow so the collection volume needs to be adjusted according to the application to minimize fluid lost to the liquid trap.
5. Immerse the impinger top into the collection liquid and plug the inlet and outlet with a hose clap before carrying it to the sampling pump assembly.

d. Connecting the nebulizer to the test facility
    i. Once transported to the lab, take out the nebulizer from the plastic container
    ii. Remove the cap, connect the nebulizer to the injection port and then remove the kink in the hose.

e. Disposing of the nebulizer solution
    i. Once testing is complete, pour 20% bleach by volume in the remainder of the solution and allow it to stay for 24 minutes to disinfect the active bacteria.
    ii. Pour the solution down the drain with a lot of water.
    iii. In the event of any leaks while connecting nebulizer, paper towels should be used clean the leak area from outside to inside (wear gloves).
    iv. Once cleaned, disinfect the paper towel with 70 % ethanol and allow it to dry before throwing it in the garbage.

3. **Transporting and incubating samples for counting (Done immediately after testing is complete)**
    a. Transporting the collected samples
        i. Once testing is complete put a kink in the filter/Impinger hoses and disconnect the hose from the pump and sampling port.
        ii. Plug in the ends of the hoses and place the filters/ Impingers in a plastic container.
        iii. Disinfect the external surfaces of the container and transport it to the bio-safety cabinet for counting.
        iv. In the bio-safety cabinet, extract a small sample from the filters/ impingers to be used for counting the concentration as per the procedure below.
4. **Determining the concentration of the collected sample (Done immediately after testing)**
    a. Plating liquid samples- Spread plate method
        i. Materials needed
            1. Tryptic Soy Agar Plates
            2. 1.5 mL micro centrifuge tubes
            3. Pipettors
            4. Pipette tips
            5. T-shaped cell spreaders
            6. Phosphate buffer solution
        ii. Procedure

1. In the bio-safety cabinet, prepare your microcentrifuge for dilutions of the samples. Label tubes 10^{-1} to 10^{-8}.
2. Add 450 uL of 1X Phosphate Buffer Solution to each of the tubes.
3. Add 50 uL of your collected solution to the first tube (10^{-1}). Pipette up and down 3 to 5 times to mix.
4. Take 50 uL of your solution from the first tube and add it to the second tube (10^{-2}). Pipette up and down 3 to 5 times to mix. Repeat this till you reach the 10^{-8}.
5. From the respective dilution, take 100 uL and pipette it onto the surface of the TSA plate. Be careful not to generate any aerosol, each solution will be plated in a triplicate.
6. Repeat the procedure for all four concentration stations (return air, exhaust air, supply air).
7. Allow the plates to dry in the cabinet for 45 min – 1 hr or until you can no longer see liquid on the surface of the agar.
8. Once dry, place the plates side up in the incubator for one night.
9. The following day, count the number of colonies on the plate.
10. To determine the number of colonies, use the following equation:

$$\frac{CFU}{mL} = \frac{\#\ of\ colonies\ counted}{dilution\ counted\ x\ vol.of\ diluted\ sample\ added}$$

5. Waste management guidelines

a. If there is a leak in the test faculty, spray leak area with 70% ethanol and allow the aerosols to settle for 5 min. Then throw the paper towels in the garbage.

b. To disinfect the plates, pour bleach on the plate and let it stand for 24 hr before throwing them in the garbage. The bleach is poured down the drain.
c. Any bio-waste generated during procedures carried out in 2D10 must be disposed in the gray bio-waste bins.
d. To disinfect the test facility, use the Collison nebulizer to run 70% ethanol solution through the test facility after testing is complete for 4 hours.
e. To disinfect the nebulizer, heat in oven for 24 hours after running the disinfection test.

APPENDIX B

RESULTS FOR DENSE MEMBRANE TRANSFER TESTS

This appendix provides the concentration data used to calculate the overall deposition rate of dust aerosols presented in Figure 3.5 presented in chapter 3. Three repetitions of the experiment were conducted (test 1, test 2, test 3). The deposition fraction which is the fraction of the entering aerosols not leaving the exchanger was calculated for each test with the uncertainty. The average value of this deposition fraction was used for comparison with the *E.coli* deposition fraction. There are two main observations from the raw concentration data. The major observation recorded was that the concentration of the aerosols in the exhaust air is significantly lower than the injected concentration due to deposition inside pipes, turns and membrane surfaces. This is to be expected for aerosol tests in membrane energy exchangers. Second, the coefficient of variation of concentration proposed to be 15% for steady state is not always achievable at each sampled measurement. For example CV > 0.15 for return air sample measurements 1,2,3,4 in the first repetition. This is due to the fact that aerosols often deposit and re-suspend back in the air inside the small test section.

Table B.1: Test results from the first repetition of dust aerosol transfer in a dense membrane

Return Air

Intv	Dur. (min)	Conc (mg/m^3)	Dev.	CV.
1	6.0	229.3	49.4	0.22
2	6.0	230.2	41.7	0.18
3	5.7	217.0	41.3	0.19
4	5.3	224.1	38.6	0.17
5	5.6	217.2	33.9	0.16
6	5.4	221.1	35.1	0.16
	Avg	223.1		
	Uncert.	29.3		

Exhaust Air

Intv	Dur. (min)	Conc (mg/m^3)	Dev.	CV.
1	6.6	58.6	7.3	0.12
2	5.6	65.8	6.8	0.10
3	5.0	70.2	7.0	0.09
4	5.8	72.3	7.2	0.09
	Avg	66.7		
	Uncert.	9.0		

Supply Air

Intv	Dur. (min)	Conc (mg/m^3)	Dev.	CV.
1	5.6	0.003	-	-
2	5.8	0.006	-	-

Table B.2: Overall fraction of aerosols deposited inside the test section (n=1)

Deposition Fraction	Uncertainty
0.70	0.33

Table B.3: Test results from the second repetition of dust aerosol transfer in a dense membrane

Return Air

Intv	Dur. (min)	Conc (mg/m^3)	Dev.	CV.
1	32.8	148.3	21.3	0.14
2	5.0	158.4	20.9	0.13
3	5.0	159.9	23.0	0.14
4	5.0	153.9	20.1	0.13
5	4.9	159.8	19.5	0.12
6	5.5	159.6	18.6	0.12
	Avg	156.7		
	Uncert.	21.0		

Exhaust Air

Intv	Dur. (min)	Conc (mg/m^3)	Dev.	CV.
1	5.4	48.0	5.5	0.11
2	5.0	53.3	5.1	0.09
3	4.9	55.6	4.7	0.08
4	5.1	54.8	4.9	0.09
	Avg	52.9		
	Uncert.	7.1		

Supply Air

Intv	Dur. (min)	Conc (mg/m^3)	Dev.	CV.
1	5.0	0.02	-	-
2	4.6	0.001	-	-

Table B.4: Overall fraction of dust aerosols deposited inside the test facility (n=2)

Deposition Fraction	Uncertainty
0.66	0.33

Table B.5: Test results from the third repetition of dust aerosol transfer in a dense membrane

Return Air

Intv	Dur. (min)	Conc (mg/m^3)	Dev.	CV.
1	33.2	178.7	23.0	0.13
2	4.8	186.5	21.1	0.11
3	4.9	185.7	19.5	0.11
4	5.8	184.4	23.4	0.13
5	5.1	194.3	23.4	0.12
6	5.5	189.6	20.3	0.11
7	4.4	206.3	37.2	0.18
	Avg	189.4		
	Uncert.	25.4		

Exhaust Air

Intv	Dur. (min)	Conc (mg/m^3)	Dev.	CV.
1	5.3	58.4	6.4	0.11
2	4.9	63.1	6.4	0.09
3	4.9	64.2	5.7	0.08
4	5.2	64.0	5.5	0.09
	Avg	62.4		
	Uncert.	8.4		

Supply Air

Intv	Dur. (min)	Conc (mg/m^3)	Dev.	CV.
1	4.9	0.00	-	-
2	5.4	0.00	-	-
3	6.0	0.0	-	-

Table B.6: Overall fraction of aerosols deposited inside the test facility (n=3)

Deposition Fraction	Uncertainty
0.67	0.33

Table B.7: Mass and volume data used to calculate E.coli deposition fraction

Return Air Filter

Mass pre-test (g)	Mass post-test (g)
14.3676	14.3690
14.3676	14.3693
14.3678	14.3694
14.3673	14.3693
14.3676	14.3694
Net Change	0.0017
Uncertainty	0.0002
Samp. Volume (m^3)	1.22×10^{-2}
Conc (mg/m^3)	139 ± 16

Exhaust Air Filter

Mass pre-test (g)	Mass post-test (g)
13.1620	13.1716
13.1624	13.1714
13.1623	13.1715
13.1620	13.1716
13.1621	13.1715
Net Change	0.0094
Uncertainty	0.0002
Samp. Volume (m^3)	4.57×10^{-1}
Conc (mg/m^3)	20.5 ± 0.4

Table B.8: Overall deposition fraction of E-coli deposited inside test facility

Deposition Fraction	Uncertainty
0.85	0.15

APPENDIX C

UNCERTAINTY IN CONCENTRATION AND CALCULATED QUANTITIES

This appendix provides a description of the procedure through which the uncertainty in concentration of dust aerosols, latent effectiveness (water vapor transfer percentage) and the uncertainty in ECTR for bio-aerosols is calculated.

C.1 Concentration measured using spectrometer

The spectrometer classifies the size of the aerosol particle based on a known calibration curve and places it in a size range/bins. The number of aerosols is also counted during the procedure of sizing. The concentration can then be determined using equation (C1.1) and (C1.2) provided below from the manufacturer.

$$c_m = n_i \times \frac{1}{6} \times \pi \times d_i^3 \times \rho_i \times \frac{1}{Volume_{meas}} \quad \text{(C1.1)}$$

$$Volume_{meas} = V_p \times A_{meas} \times t_{meas} \quad \text{(C1.2)}$$

Here c_m represents the mass concentration of aerosol (mg/m^3 or µg/m^3), n_i is the number of aerosols, d_i represents the size of aerosol, ρ_i is the density of the aerosol (kg/m^3), $Volume_{meas}$ is the measurement volume (m^3) that can be calculated using Equation (C1.2). V_p represents the particle velocity (m/s) and t_{meas} is the measurement time (s). The uncertainty in the concentration of the dust aerosols can be calculated using the Equation (C1.3) below

$$\frac{U_{c_m}}{c_m} = \sqrt{\left(\frac{U_{n_i}}{n_i}\right)^2 + 3\left(\frac{U_{d_i}}{d_i}\right)^2 + \left(\frac{U_{\rho_i}}{\rho_i}\right)^2 + \left(\frac{U_{Volume_{meas}}}{Volume_{meas}}\right)^2} \quad \text{(C1.3)}$$

The relative uncertainty in number of particles $\frac{U_{n_i}}{n_i}$ is the coincidence error read from the machine display. The uncertainty in particle size D_i varies with particle size and is $\pm 0.5\ size\ bins$. For a conservative estimate, the particle size error is approximated to be based on the size bin with the largest relative size error (4%). The uncertainty in measured volume is approximated to be 10% as it is difficult to find the uncertainty in particle velocity. The density of ISO A-3 test dust is available in literature and hence the uncertainty in density is neglected.

The uncertainty in the measured concentration based on Equation (C1.4) is

$$\frac{U_{c_m}}{c_m} = \sqrt{(0.20)^2 + 3 \times (0.04)^2 + (0)^2 + (0.10)^2} \approx 0.23\ or\ 23\% \quad \text{(C1.4)}$$

Based on the calculation above the coincidence error is the dominant factor in uncertainty. The errors in velocity and particle size are challenging to quantify and hence the error in the concentration is based relative to the coincidence error during the sampling interval.

In addition to the systematic error due to coincidence, a random error due to standard deviation of the values during the five-minute interval. The systematic/ Type A error and the random error can be added to get the net uncertainty in the concentration as per Equation (C1.5). The uncertainty is multiplied by a coverage factor of two to report the 95% confidence interval.

$$\frac{U_{c_m}}{c_m} = 2 \times \sqrt{\left(\frac{U_{n_i}}{n_i \times \sqrt{3}}\right)^2 + \left(\frac{stdev}{\sqrt{n}}\right)^2} \quad \text{(C1.5)}$$

The reported concentration values for the supply air (c_{SA}), outdoor air (c_{OA}), return air (c_{RA}) are based on an average of four values. The overall uncertainty is thus the root mean square of the uncertainties in the concentration value as shown in Equation (C1.6)

$$U_{c_m} = \sqrt{\left(\frac{U_{c_{RA,1}}^2 + U_{c_{RA,2}}^2 + U_{c_{RA,3}}^2 + U_{c_{RA,4}}^2}{4}\right)} \quad \text{(C1.6)}$$

C.2 Concentration of bacteria measured using the spread plate method

The concentration of bacteria aerosols is determined using Equations (C1.7) and Equation (C1.8) given below:

$$\frac{CFU}{ml} = \frac{\#\ of\ colonies\ counted}{10^{-\#\ of\ dilution} \times Volume\ of\ solution\ plated\ (ml)} \tag{C1.7}$$

$$\frac{CFU}{m^3} = \frac{Conc\left(\frac{cfu}{ml}\right) \times Volume\ of\ solution\ (ml)}{Sampling\ air\ flow\left(\frac{m^3}{s}\right) \times Sampling\ time\ (s)} \tag{C1.8}$$

The error in the counted colonies is determined from the standard deviation of the replicates of the dilution plated. The standard deviation is converted into a Type A error by dividing the standard deviation by the square root of the number of observations *n*. The resulting concentration is multiplied with the volume of the solution to get the error in total CFU. The final reported value is multiplied by coverage factor of 2.

Example: The following images shows the bacteria colonies in dilution 4 of an imaginary return air sample. The error in total concentration is reported for a solution volume of 7.5 ml

Plate 1 colonies: 31

Plate 2 colonies: 36

Plate 3 Colonies: 32

Average number of colonies $= \frac{31+36+32}{3} = 33$

Stdev colonies $= \frac{2.516}{\sqrt{3}} = 1.45$

Uncertainity in colony count $= \frac{1.45}{10^{-4}\times10^{-1}} = 1.45 \times 10^5 \frac{\text{cfu}}{\text{ml}} \times 7.5\text{ml} = 1.0 \times 10^6$ CFU

Collected volume = Sampling flow rate $\left(\frac{\text{m}^3}{\text{s}}\right) \times$ Sampling time (s)

Let $\dot{Q}_{Sample}$ represent the sampling flow rate and t_{sample} the sampling time, the collected volume is V_{sample}, then the uncertainty in the collected volume can be calculated using Equation (C1.9).

$$U_{V_{SAMPLE}} = \sqrt{\left(\frac{U_{Q_{sample}}}{Q_{sample}}\right)^2 + \left(\frac{U_{t_{sample}}}{t_{sample}}\right)^2} \times V_{sample} \quad \text{(C1.9)}$$

Once the uncertainty in the collected volume and the total colony counts can be determined, the uncertainty in Equation (C1.8) can be calculated as follows

$$\frac{CFU}{m^3} = \frac{Conc\left(\frac{cfu}{ml}\right)\times Volume\ of\ solution\ (ml)}{Sampling\ air\ flow\left(\frac{m^3}{s}\right)\times Sampling\ time\ (s)} = \frac{Total\ number\ of\ colonies}{Collected\ volume} = \frac{Num}{Den}$$

If C_{E-coli} represents the concentration of *E.coli* in CFU/m^3 then the uncertainty in this this quantity can be determined using the equation below

$$U_{E-Coli} = \sqrt{\left(\frac{U_{Num}}{Num}\right)^2 + \left(\frac{U_{Den}}{Den}\right)^2} \times C_{E-Coli} \times 2 \quad \text{(C1.10)}$$

Where the uncertainty in the numerator is the uncertainty in the total colony count and the numerator is the total colony count. Similarly, the uncertainty in denominator is the uncertainty in collected volume and the den is the collected sample volume. The concentration is multiplied by a coverage factor of two to report the 95% confidence value.

C.3 Uncertainty in the calculated ECTR

Once the concentration of the aerosols and the uncertainty in the concentration has been determined, the net uncertainty in the ECTR can be calculated using a similar method

$$\text{ECTR} = \frac{c_{SA}-c_{OA}}{c_{RA}-c_{OA}} = \frac{Num}{Den} \tag{C1.11}$$

Then the uncertainty in the ECTR can be expressed using the uncertainties of the numerator and denominator

$$U_{Num} = \sqrt{\left(U_{C_{SA}}\right)^2 + \left(U_{C_{OA}}\right)^2} \tag{C1.12}$$

$$U_{DEN} = \sqrt{\left(U_{C_{RA}}\right)^2 + \left(U_{C_{OA}}\right)^2} \tag{C1.13}$$

$$U_{ECTR} = \sqrt{\left(\frac{U_{Num}}{Num}\right)^2 + \left(\frac{U_{Den}}{Den}\right)^2} \times ECTR \tag{C1.14}$$

C.4 Uncertainty in the calculated latent effectiveness

The uncertainty in latent effectiveness can be derived similar to the uncertainty in the ECTR using mathematical relations provided below

$$\varepsilon_{latent} = \frac{(W_1-W_2)}{(W_1-W_3)} \tag{C1.15}$$

The amount of water vapor per unit dry air (kg_w/kg_a) is determined from the measured relative humidity (RH) and temperature (T°C) using the relation given below:

$$W = \frac{10^6 \times \text{RH}}{e^{5294/(T+273)} - 1.61 \times 10^6 \times \text{RH}} \tag{C1.16}$$

Then the uncertainty in the calculated value of W because of measured temperature and relative humidity is determined using

$$U_w = \sqrt{\left(\frac{\partial W}{\partial RH} U_{RH}\right)^2 + \left(\frac{\partial W}{\partial T} U_T\right)^2} \tag{C1.17}$$

Where $U_{RH}$the uncertainty in relative humidity is, U_T is the relative uncertainty in temperature and $\frac{\partial W}{\partial RH}$ is the sensitivity coefficient for U_{RH} and $\frac{\partial W}{\partial T}$ is the sensitivity coefficient for temperature and the expression to evaluate are provided below

$$\frac{\partial W}{\partial RH} = \frac{10^6\left(e^{\frac{5294}{T+273.15}} - 1.61\times10^6(RH)\right) - 10^6(RH)(0 - 1.61\times10^6)}{\left(e^{\frac{5294}{T+273.15}} - 1.61\times10^6(RH)\right)^2} \tag{C1.18}$$

$$\frac{\partial W}{\partial T} = \frac{0\times\left(e^{\frac{5294}{T+273.15}} - 1.61\times10^6(RH)\right) - 10^6(RH)(e^{\frac{5294}{T+273.15}}\times\frac{-5294}{(T+273.15)^2} - 0)}{\left(e^{\frac{5294}{T+273.15}} - 1.61\times10^6(RH)\right)^2} \tag{C1.19}$$

Once the uncertainty in W_1, W_2, W_3, W_4, has been evaluated using equation (C1.17) the uncertainty in latent effectiveness can be evaluated using Equation (C1.20) once the sensitivity coefficients for W_1, W_2, W_3, W_4, are determined

$$U_{\varepsilon_{latent}} = \sqrt{\left(\frac{\partial \varepsilon_{latent}}{\partial W_1} U_{W_1}\right)^2 + \left(\frac{\partial \varepsilon_{latent}}{\partial W_2} U_{W_2}\right)^2 + \left(\frac{\partial \varepsilon_{latent}}{\partial W_3} U_{W_3}\right)^2} \tag{C1.20}$$

And the sensitivity coefficients for W_1 $\frac{\partial \varepsilon_{latent}}{\partial W_1}$, W_2 $\frac{\partial \varepsilon_{latent}}{\partial W_2}$, W_3 $\frac{\partial \varepsilon_{latent}}{\partial W_3}$ can be evaluated using expressions below:

$$\frac{\partial \varepsilon_{latent}}{\partial W_1} = \frac{(W_2 - W_3)}{(W_1 - W_3)^2} \tag{C1.21}$$

$$\frac{\partial \varepsilon_{latent}}{\partial W_2} = \frac{-1}{(W_1 - W_3)} \tag{C1.22}$$

$$\frac{\partial \varepsilon_{latent}}{\partial W_3} = \frac{(W_1 - W_2)}{(W_1 - W_3)^2} \tag{C1.23}$$

APPENDIX D

CALCULATION OF STOKES NUMBER BASED ON GEOMETRIC MEAN DIAMETER

D.1 Stokes number for dust aerosol particles

The Stokes number of a particle reflects the particles ability to react to changes in the flow and is a ratio of its stopping distance to the characteristic dimension of the obstacle in the flow. As long as the Stokes number is much less than 1, it can be assumed most of the particles in the flow will enter the sampling probe even though it might not be perfectly aligned. In the tests with the aerosols the geometric mean diameter of the aerosol particles ranges from 1.09 μm-1.3 μm. The largest particle sampled reported is 10 μm. The flow rate in the duct is maintained at 18.5 L/min during the tests and the sampling flow rate of the spectrometer is 5 L/min. The diameter of the pipe at the sampling port is 15 mm and the sampling duct is 6.15 mm. Then, to calculate the Stokes number first the velocity of the particle is determined assuming it to be the same as the duct air velocity.

$$v_p = \frac{\dot{Q}}{A} = \frac{18.5\ \text{L/ min}\times(\frac{10^{-3}m^3}{1\text{L}})\times(\frac{1\ \text{min}}{60\ s})}{(\frac{\pi}{4})\times(15\times10^{-3}\ m)^2} = 1.74\ m/s \quad \text{(D.1)}$$

$$Stk = \frac{\tau\times v_p}{l_{probe}} \quad \text{(D.2)}$$

Here the stopping distance is represented as a product of relaxation time and particle velocity v_p and can be calculated after the relaxation time for the largest particle size is determined:

$$\tau = \frac{\rho_{particle}\times d_{particle}^2}{18\ (\eta)} = \frac{1025\times\left(10\times10^{-6}\right)^2}{18\ (18.03\times10^{-6})} = 3.15\times10^{-4}s \quad \text{(D.3)}$$

$$Stk = \frac{\tau\times v_p}{l_{probe}} = \frac{3.15\times10^{-4}\times1.74}{(6.15\times10^{-3})} = 8.9\times10^{-2} \ll 1 \quad \text{(D.4)}$$

Since Stk<<1, therefore as seen in Figure 4.9 particles upto 10µm can be sampled using the 90° port.

In addition to the Stokes number with respect to the sampling port inlet diameter, the Stokes number is also plotted with respect to the case of a no membrane (a) and a membrane with holes (b) in the figures below. For the case with no membrane it can be observed that Stk<<1 however for the case of membrane with holes Stk >1 for certain particle sizes.

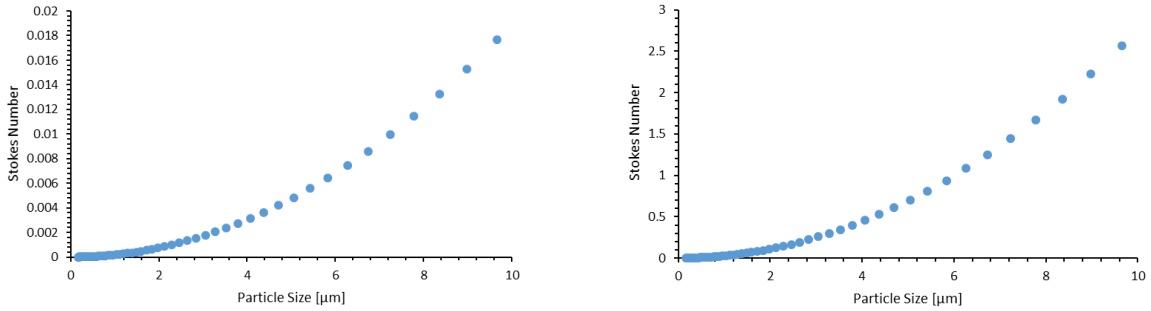

Figure D.1: (a) Stk number for a case of no membrane calculated using a characteristic obstacle length of 45 mm and b) Stk number for a case of membrane with holes calculated using a characteristic obstacle length of hole size 310 µm.

APPENDIX E

ESTIMATION OF BACTERIA SAMPLING TIME

This appendix contains the calculation for estimating the minimum amount of sampling time required to obtain a countable number of the bacteria from the air sample. Equations (3.7) and (3.8) from Chapter 3 are used for the calculations. In the actual experiment however, a sampling time larger than calculated here is used to get more probability of getting active bacteria colonies.

Estimated amount of bacteria at start: 10^{10} $\mathrm{CFU/m^3}$

The amount of bacteria colonies must be greater than the background count and ideally between 30 and 300. Assuming for the minimum sampling time we collect an amount that can be counted in the first dilution, then:

$$\frac{CFU}{ml} = \frac{\#\ of\ colonies\ counted}{10^{-\#\ of\ dilution} \times Volume\ of\ solution\ plated\ (ml)} \tag{E.1}$$

Assuming the number of colonies to be 30, the first dilution

$$\frac{CFU}{ml} = \frac{30}{10^{-1} \times 0.1} = 3000\ \mathrm{CFU/ml}$$

The amount of collection volume used in the impinger is 12 ml, therefore the concentration in $\mathrm{CFU/m^3}$ can be determined using the Equation (E.2) below:

$$\frac{CFU}{m^3} = \frac{C\left(\frac{cfu}{ml}\right) \times Volume\ of\ solution\ (ml)}{Sampling\ air\ flow\ rate\left(\frac{m^3}{s}\right) \times Sampling\ time\ (s)} \tag{E.2}$$

$$\frac{CFU}{m^3} = \frac{3000\left(\frac{cfu}{ml}\right) \times 12\ (ml)}{Sampling\ air\ flow\ rate\left(\frac{m^3}{s}\right) \times Sampling\ time\ (s)}$$

Assuming a 1% recovery of bacteria after mixing with the air stream and a 1% recovery from the collection medium (impinger) the concentration to be collected:

$$Estimated\ collected\ amount: 0.01 * 0.01 * 10^{10}\ \frac{\text{CFU}}{\text{m}^3} = 10^6\ \text{CFU/m}^3$$

The impinger sampling flow rate is fixed at 2L/min which can be converted into m^3/s

$$Sampling\ rate: \frac{2\ L}{min} \times \frac{10^{-3} m^3}{1\ L} \times \frac{1\ min}{60\ s} = 3.333 \times 10^{-5}\ \text{m}^3/\text{s}$$

Therefore the sampling time required can be obtained by using Equation (E.2)

$$10^6\ \frac{CFU}{m^3} = \frac{3000\left(\frac{cfu}{ml}\right) \times 12\ (ml)}{3.333 \times 10^{-5}\left(\frac{m^3}{s}\right) \times Sampling\ time\ (s)} \qquad \text{(E.2)}$$

$$\text{Sampling time (s)} = \frac{3000\left(\frac{cfu}{ml}\right) \times 12\ (ml)}{3.333 \times 10^{-5}\left(\frac{m^3}{s}\right) \times 10^6 \text{CFU/m}^3}$$

$$\text{Sampling time (s)} \approx 1080\ s \sim 18\ \text{min}$$

With a sampling flow rate of 2 L/min and the collection time of 18 min this would be a collected sample volume of 36 L which would be less than the 50 L recommended.

APPENDIX F

SUMMARY OF EXPERIMENTS CONDUCTED

F.1 Summary of experiments

Table D.1 provides a summary of experiments conducted to determine transfer of NaCl, dust and *E.coli* aerosols in dense and porous membranes. The aim and outcome of each test are summarized. A total of 51 experiments were conducted to achieve the objectives. The purpose of this summary is to give an insight on lessons learned while selecting aerosol injection rate, dilution rate and choice of sampling methods. The reader can then make an informed choice while determining improved experimental methodologies.

Table D.1: Experiments conducted to evaluate transfer of aerosols in dense and porous membranes used in membrane energy exchangers.

Test Number	Experiment Aim	Experiment Outcome
1.	Commissioning of test facility with dense membrane and determining water vapor transfer at 6.5 L/min, 9 L/min, 13 L/min, 16 L/min, 19.5 L/min	Test facility meets ASHRAE Std. 84 dry air and water vapor mass balance for 9 L/min – 19.5 L/min. Water vapor transfer was highest at 6.5 L/min at $52.8 \pm 4.7\%$
2.	Measure the aerosol concentration output from the nebulizer using NaCl aerosols (5% by mass solution) and an optical spectrometer sensor	A large coincidence error (> 20%) was present, and a higher dilution rate was needed.

3.	Determine background ambient aerosol concentration in outdoor and return air stream filtered using the HEPA filters inside the test facility.	The background concentration was measured to be 0.00 mg/m^3
4.	Determine the dilution rate of return air and aerosol injection rate of the collison nebulizer such that the optical spectrometer had a low coincidence error (< 20%) and could read NaCl aerosols.	At an aerosol injection rate of 6.0 L/min, three air flow rates 12 L/min, 16.5 L/min, 19.5 L/min were tested. 19.5 L/min was the ideal flow rate where coincidence was (< 20%). However, there was a leak detected in the nebulizer output tube which reduced the aerosol output as aerosols were lost to the environment.
5.	Determine error in mass concentration measured by optical spectrometer for dust aerosols by comparing it to the concentration obtained using a HEPA filter downstream of the sensor at a flow rate of 15 L/min.	The mass measured by integrating the concentration measured by the spectrometer with time was 3.2 ± 0.2 mg whereas the mass collected on the filter was 4.4 ± 0.4 mg. Assuming the mass collected on the filter to be the reference

		value, the error is 28.5%. The outcome is used to estimate the uncertainty in mass concentration.
6.	Determine the background aerosols in the compressor air without HEPA filters and determine if transfer of these aerosols was possible at a low flow rate (8 L/min) forcing most of the air through the sampling sensor (5 L/min). In addition, check if the compressed air has a PM limit of 12 $\mu g/m^3$ that can be used for testing.	The inlet concentration of PM1 particles was 0.005 $\mu g/m^3$. In addition, it was observed that a small number of these particles were seen at the supply air station 0.20 P/cm^3 ; after a period of 55 min. Thus, the period of time of experiment is an important parameter.
7.	Verify the six jet Collison nebulizer is free of leaks and that the steady state output using NaCl aerosols could be read using an optical spectrometer sensor. Determine steady state conditions	Although the dry air mass balance was verified the spectrometer read zero number and mass concentration of NaCl aerosols at the return air station.
8.	Repetition two: Verifying test #7 above. Tested three aerosol injection rates 10 L/min, 11 L/min, 12 L/min	Even with a higher injection rate, the optical sensors read zero number and mass concentration of NaCl aerosols at the return air station. A high

		coincidence error (> 95% was noted)
9.	Verify that the single jet Collison nebulizer is free of leaks and can inject NaCl aerosols at a concentration that can be read using the optical spectrometer sensor.	Even with lower injection rate (2 L/min) and higher dilution rate (8 L/min) the spectrometer sensor read zero aerosols at the return air inlet. Intermittent spikes are seen indicating aerosols are likely present but not readable due to overload.
10.	Determine test concentration of NaCl aerosols at the return air inlet for determine test conditions for membrane tests using single jet Collison nebulizer	Test was unsuccessful, no NaCl aerosols were detected at the return air station but aerosol with a high coincidence error were detected downstream at the exhaust air stream. In addition, the HEPA filter near the exhaust air outlet had a significant increase in mass indicating NaCl aerosols had deposited on the filters but weren't being read by the

		sensor due to higher coincidence error.
11.	Determine test concentration of dust aerosols at the return air inlet to determine test conditions for membrane tests using the dust aerosol generator	The dust generator was allowed to run for three hours while the output was monitored. The concentration of aerosols increased with time. The average was 46.5 mg/m^3 and the coefficient of variation from the mean value was $< 15\%$. This was assumed to be the inlet concentration for the next day tests.
12.	Dust aerosol transfer in dense membrane at 17.5-L/min; laminar flow conditions	No transfer of aerosols observed but a significant difference in the aerosol concentration collected at the exhaust air. The concentration at the exhaust air station was higher than the assumed inlet condition from the previous day
13.	Monitor the concentration at the return air station using 70% ethanol aerosols generated	The particle count on the display would increase and then

	using the single jet nebulizer at 1 L/min diluted with 9 L/min return air using optical particle sensors	go to zero. On increasing the dilution rate the aerosols were readable again. This means the generated aerosols were shown as zero because the coincidence error is large (>99%)
14.	Dust aerosol transfer in dense membrane at 17.5 L/min/ laminar flow conditions (n=1)	No transfer of dust aerosols was observed
15.	Dust aerosol transfer in dense membrane at 17.5 L/min/ laminar flow conditions (n=2)	No transfer of dust aerosols was observed
16.	Dust aerosol transfer in dense membrane at 17.5 L/min/ laminar flow conditions (n=3)	No transfer of dust aerosols was observed
17.	Monitor the concentration at return air station of 30% NaCl solution (by mass) generated using a single jet nebulizer using the optical particle sensor	No countable aerosols are observed as the coincidence error is greater (>99%)
18.	Measure static pressure difference between the supply air and return air to determine which way the air leaks through the membrane due to defects and improper sealing	The pressure at return air stream is higher than the outdoor air stream. Air is likely to transfer from the return air stream to the outdoor air.

19.	Collect lab blanks from disinfected test setup to determine background bacteria count in the compressed air stream	No bacteria are collected in the background sample
20.	Transfer of *E.coli* aerosols in a dense membrane based on filter sampling using a 2 min sample time (Sampling flow rate $5.0 \pm 0.3\ L/\text{min}$)	No change in mass of filter collecting *E.coli* samples in the supply air stream (No transfer). A similar deposition to the dust aerosols is observed
21.	Measure static pressure differential after E-coli test to determine which way the air would leak through the membrane.	The return air stream was at a higher pressure than the outdoor air.
22.	Transfer of *E.coli* aerosols in a dense membrane based on filter sampling using a 5 min sample time (Sampling flow rate $4.5 \pm 0.3\ L/\text{min}$)	No active *E.coli* colonies were extracted from the filters at supply air stream (i.e. no transferred aerosols), however even the collected samples from the building exhaust air stream had no active colonies.
23.	Measuring static pressure in an open exchanger configuration (i.e. no membrane) for verifying whether proposed method can detect transfer in a case of transfer	Static pressure difference was higher at the return air inlet compared to the supply air outlet indicating some air would leak into the outdoor air stream.

		Static pressure at the outdoor air inlet was higher than the exhaust air outlet indicating some air would leak from the outdoor air stream to the exhaust air stream
24.	Measuring the transfer of dust aerosols in an open exchanger (n=1)	Method detects transfer of aerosols from the return air stream to the outdoor air stream
25.	Measuring the transfer of dust aerosols in an open exchanger (n=2)	On repeating the experiment, the method again detects transfer of aerosols from the return air stream to the outdoor air stream
26.	Collect lab blanks from open exchanger to determine background bacteria count in the compressed air stream	No countable bacteria colonies were found in the return air stream or the outdoor air stream
27.	Measure the transfer of *E.coli* aerosols in an open exchanger (n=1), 5 min sampling time (Sampling flow rate $5.0 \pm 0.3\ L/\text{min}$)	No active bacteria colonies were found in the supply air station, return air station, and exhaust air station indicating the method proposed for

		determining *E.coli* transfer needs to be modified.
28.	Commissioning of test facility with porous membrane and determining water vapor transfer at 8 L/min, 13 L/min, 14 L/min	Observed a large amount of air leaking from return air stream to outdoor air stream and dry air mass balance did not meet Standard 84 limits of 5%, however water vapor mass conservation criteria was met (< 20%) and even on restricting the rotameter the amount of air imbalance remained constant indicating no high pressure leaks to the outside.
29.	Transfer of dust aerosols in porous Tyvek® membrane (n=1).	No transfer of dust aerosols observed
30.	Measure static pressure difference between return air stream and outdoor air stream with a Tyvek® membrane and re-verify dry air mass balance. Adjusted rotameters restriction to balance air flow in both air streams	Return air stream was at a higher pressure than the outdoor air stream. The rotameters were swapped to get rid of random error and the dry air mass balance meets standard 84 mass balance limit of 5%

31.	Transfer of dust aerosols in porous Tyvek® membrane (n=2)	No transfer of aerosols was detected at the supply air stream
32.	Compare bio-aerosol sampling techniques to determine if sampling instrument, angle and location had an effect on collection of active *E.coli* aerosols in the aerosol. The filter sample was collected immediately after the nebulizer and the liquid impinger sample was collected at the return air station at a 45° angle. The sampling time was 25 min, and the target sampling flow rate is $(2 - 2.5\ \mathrm{L/min})$ (n=1)	No *E.coli* colonies were extracted from the filter sample however *E.coli* colonies were collected downstream from the liquid impinger sample.
33.	Measure if a 45° collection angle collects a larger concentration of dust aerosols compared to 90° collection angle at the return air station	The 45° collection angle collected a larger concentration of dust aerosols compared to the 90° angle as collected larger particles
34.	Transfer of dust aerosols in a defective Tyvek® membrane using artificially constructed holes of 310µm. The sampling in this case was directly started at the supply air stream 10 min after the aerosols were injected	A very small amount of dust aerosols are transferred through the eight punctured holes.

35.	Measure static pressure difference between return air stream and outdoor air stream for a defective Tyvek® membrane with holes	The return air stream was at a higher pressure than the outdoor air stream.
36.	Transfer of dust aerosols in a defective Tyvek® membrane using artificially constructed holes of 310µm. The developed test method for transfer of dust aerosols was used in this experiment	A small amount of dust aerosol transfer is observed. The measured transferred concentration of dust aerosols is three orders of magnitudes ($\mu g/m^3$) lower than the challenge concentration (mg/m^3)
37.	Repetition two: Compare bio-aerosol sampling techniques to determine if sampling instrument, angle and location had an effect on collection of active *E.coli* aerosols in the aerosol. The filter sample was collected immediately after the nebulizer and the liquid impinger sample was collected at the return air station at an 45° angle. The sampling time was 25 min, and the target sampling flow rate is $(2 - 2.5\ L/min)$ (n=2)	The impinger was able to collect active *E.coli* aerosols at the return air stream whereas there were no active *E.coli* colonies on the filter.
38.	Measure static pressure difference between the return air stream and outdoor airstream with a new sample of Tyvek® membrane to determine	The return air stream was at a higher static pressure than the outdoor air stream

	transfer of bacteria aerosols through a porous membrane with large pore size and high air permittivity	
39.	Collect lab blanks from membrane exchanger to determine background bacteria count in the compressed air stream (n=1)	A small number of bacteria colonies are found in the supply and return air stream and recorded
40.	Transfer of *E.coli* aerosols in porous Tyvek® membrane (n=1)	A small number of additional colonies are collected in the supply air stream (transferred aerosols) but they are a negligible amount of the injected aerosols.
41.	Collect lab blanks from membrane exchanger to determine background bacteria count in the compressed air stream after disinfection (n=2)	A small number of bacteria colonies are found in the supply and return air stream and recorded
42.	Transfer of *E.coli* aerosols in porous Tyvek® membrane (n=2)	A small number of additional colonies are collected in the supply air stream (transferred aerosols) but they are a negligible amount of the injected aerosols.

43.	Determine transfer of water vapor in Tyvek® membrane at the aerosol transfer test flow rate (12.5 L/min)	A large amount of water vapor transfer is observed compared to aerosol transfer amount
44.	Measure static pressure difference between the return air stream and the exhaust air stream for an open exchanger configuration for method verification test	The return air stream was at a higher static pressure than the outdoor air stream
45.	Collect lab blanks from open membrane exchanger to determine background bacteria count in the compressed air stream after disinfection	A small number of bacteria colonies are found in the supply and return air stream and recorded
46.	Transfer of *E.coli* aerosols in an open exchanger configuration to verify the proposed method for determining bio-aerosol transfer in membrane energy exchanger	The method detects transfer of *E.coli* aerosols from the return air stream to the outdoor air stream. In addition, the colony count at return air station, exhaust air station is non-zero
47.	Transfer of water vapor in the open exchanger configuration	A large amount of water vapor transfer from the return air stream to the outdoor air stream is observed when there is no membrane barrier separating the air streams

48.	Determine if the sampling angle of 45° or 90° has an effect on collection of active *E.coli* colonies from filter samples collected from these angles.	No active *E.coli* colonies are found indicating the filter-based sampling mechanism is not suitable for use
49.	Determine the water vapor transfer rate in Tyvek membrane at 6.5 L/min, 9 L/min, 13 L/min, 16 L/min, 18.5 L/min and verify dry air mass balance, water vapor mass balance as per ASHRAE Std. 84	Water vapor transfer decreases with increase in flow rate. Facility does not meet ASHRAE Std. 84 criteria for 9 L/min
50.	Determine transfer of dust aerosols in Tyvek membrane using dust aerosols and a 45° sampling angle	Changing the sampling angle from 90°to 45°did not change the ECTR. The ECTR remains negligible.
51.	Compare the concentration readings using two sampling angles 45° and 90° with a 2mm probe inside the duct.	The probe underestimates the mass concentration of the aerosol.