DESIGN, FABRICATION AND TESTING OF A MEMBRANE-BASED ENERGY RECOVERY VENTILATOR

Thesis submitted for the undergraduate degree in Mechanical Engineering

at the

University of Central Punjab

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Session 2019-2023

Department of Mechanical Engineering,
University of Central Punjab, Lahore Pakistan

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ABSTRACT

Thirty percent of the total energy used by society is consumed by air conditioning. In hot and humid locations, 20–40% of the entire energy load for air conditioning is used to cool and dehumidify new ventilation air. These days, recovering heat and moisture from ventilation air has become a popular topic for reducing building energy use. Also, the majority of human activities in today's "indoor generation" are carried out in enclosed spaces with complicated and diversified chemical air quality. To cut down on the energy needed to condition ventilation air, energy recovery ventilators (ERVs) transfer energy between the air evacuated from buildings and the outdoor supply air. Increased ventilation rates enhance indoor air quality by reducing contaminants like VOCs and airborne particulates. A viable alternative among the numerous heat-and-moisture recovery systems is the membrane-based complete heat exchanger. The next generation of HVAC (heating, ventilation, and air conditioning) systems is thought to be largely comprised of air-to-air membrane enthalpy exchangers (MEEs). By preconditioning the incoming air using the exhaust air, MEEs are a green way to lower building energy use. MEEs use semi-permeable membranes to divide the air streams and recover heat from one air stream to the next in both sensible and latent forms. Fabrication of a membrane-based energy recovery ventilator was conducted to see the overall effect on the air quality and energy usage of HVAC equipment in a room. Calculations were done for the given design conditions and the room load which varies for different number of people. Selection of membrane and metal conducted resulted in the change in the effectiveness of the system. This study resulted in the decrease of HVAC loads as well as improving the air quality of the given space which was the main concern of this research.

ACKNOWLEDGEMENTS

First and foremost, we would like to sincerely express our gratitude to our advisor, Sir Ahmed Zohaib Zaidi, for his constant support throughout the entirety of our project. His assistance has been instrumental in guiding us through various crucial phases, including research, modeling, fabrication, and testing. We feel incredibly fortunate to have been under the mentorship of such an exceptional and dedicated advisor for our project

We would also like to extend our heartfelt thanks to our Co-Advisor, Sir Umer Hayat, for his invaluable assistance in both the thesis writing and presentation stages. His support and expertise have significantly enhanced the quality and presentation of our work.

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Lastly, we would like to wholeheartedly express our gratitude to Allah for guiding us through the myriad challenges we encountered along this arduous journey. Your divine guidance has been evident each day, and we humbly recognize that it is through your benevolence and support that we have been able to successfully complete our degree.

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LIST OF ABBREVIATIONS AND ACRONYMS

AQC	Air Quality Categories
BMS	Building Management System
CAD	Computer-Aided Design
CEP	Complex Engineering Problem
CFM	Cubic Feet per Minute
ERV	Energy Recovery Ventilator
HRV	Heat Recovery Ventilator
HVAC	Heating, Ventilation, and Air Conditioning
LMTD	Log Mean Temperature Difference
MDR	Moisture Diffusion Resistance
MEEs	Membrane Enthalpy Exchangers
SDGs	Sustainable Development Goals
UN	United Nations

CHAPTER ONE: INTRODUCTION

This chapter includes the concerning issue regarding the decreasing air quality and increasing energy consumption which are two of the major issues which ERV solves. It also talks about the basics and fundamentals of an ERV system. This includes the working, types, advantages, and how it differentiates from an HRV system. Its importance on air quality and energy saving is also elaborated. It also contains the UN SDGs, CEP attributes, and Gantt chart.

1.1 Project Background

Air-to-air energy recovery is the process of transferring heat and moisture between two airstreams that are at different temperatures and humidity levels. This procedure is crucial for maintaining good indoor air quality while lowering energy expenses, consuming less energy overall, and emitting less carbon dioxide. This application makes advantage of ERV systems. Energy recovery ventilation (ERV) is a technique used in residential and commercial HVAC systems to recover energy by treating (preconditioning) incoming outdoor ventilation air with energy from typically exhausted air from a building or climate-controlled space.

1.2 Problem Statement

In modern day life, individuals spend on average about 90% of their time indoors, whether it be in homes, cafes, or class rooms, which usually have inadequate/poor ventilation due to which indoor air quality is compromised and can negatively affect human health and wellbeing. Also in normal ventilation systems, non-preconditioned supply air can increase the overall load on air conditioning system which leads to increased energy consumption for heating and cooling. Therefore, an energy efficient ventilation device needs to be installed in indoor spaces to improve air quality in relation to health, productivity and wellbeing while also reducing air conditioning loads.

1.3 Proposed Solution

We aim to design and fabricate an easy to install Energy Recovery Ventilator (ERV) which will not only fulfill the ventilation requirements by providing us with quality air but also saves energy by transferring sensible (heat) and latent (moisture) energy from outgoing exhaust air to incoming outdoor air. The energy lost during cooling and heating is recovered by the ERV, and humidity is controlled without combining the two air streams. The key to this method is the moisture-permeable membranes placed in the core, which allow humidity to be exchanged between indoor and outdoor airstreams.

1.4 HRV or ERV

A heat recovery ventilator (HRV) is an energy recovery ventilation device that utilizes two air sources with various temperatures (HRV). Buildings can use less energy for heating and cooling by recovering heat from existing energy sources. Before the fresh air enters the room or the air cooler of the air conditioning unit performs heat and moisture treatment, the fresh air fed into the air conditioning system is preheated (precooled) and the fresh air enthalpy is increased (decreased). This is done by extracting the remaining heat from the exhaust gas.

ERV stands for Energy Recovery Ventilator, and it consists of two fans and a heat exchanger that makes it possible to transfer heat and moisture between the two air streams. They pull fresh, clean air into the building and take out stale/unclean air.

HRVs and ERVs are similar since they both recover energy from exhausted air and transfer it to fresh air. The primary distinction between the two is that an ERV also transfers moisture in addition to heat, whereas an HRV just transfers heat [1].

1.5 Types of ERV

ERVs come in a number of types for diverse uses. In an ERV, there are typically four options; rotary heat exchangers (wheel), plate heat exchangers (fixed core), heat-pipe heat exchangers (refrigerant), and runaround coils (water).

1.5.1 Rotary Heat Exchanger (Wheel)

A wheel is a rotating device made of metal or plastic that moves between the outside and exhaust air streams. It transfers heat from one air stream to the other by absorbing it from the first.

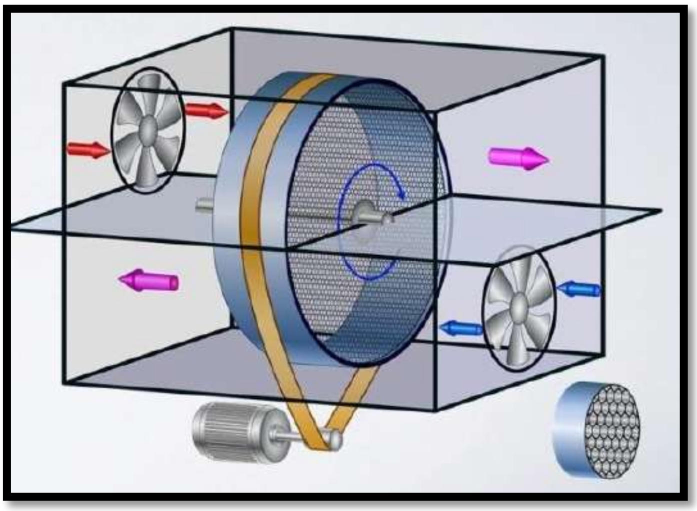


Figure 1.1 Rotary heat exchanger (wheel) [2]

1.5.2 Plate Heat Exchanger (Fixed Core)

Since fixed-core plates don't have any moving elements, they can be used in locations like hospitals where a wheel might not be permitted by code. Instead of a wheel rotating back and forth to transfer energy, the air streams travel by each other through a network of channels, heating or cooling the material between the channels.

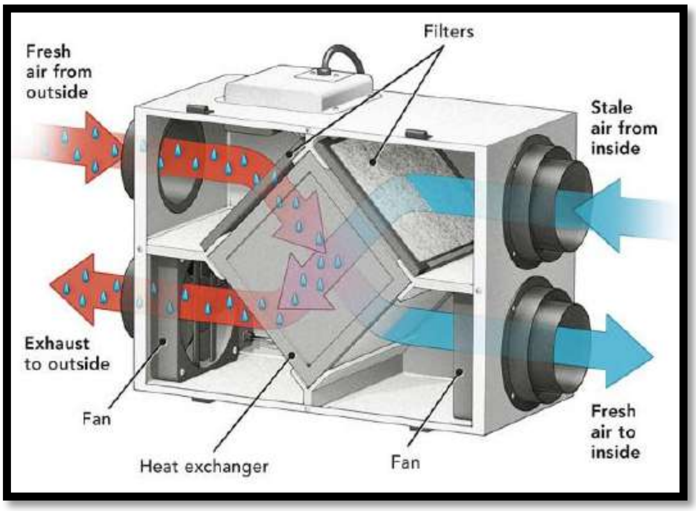


Figure 1.2 Plate heat exchanger (fixed core) [3]

1.5.3 Heat-Pipe Heat Exchanger (Refrigerant)

Heat pipes are copper tubes that contain refrigerant. The tubes are present in the middle of two air streams (exhaust and outside air). The refrigerant in the tube is heated by one air stream, which causes it to evaporate, which then moves down the pipe to the other air stream. The refrigerant condenses as that other air stream cools the pipe, warming the cooler air stream in the process. The newly cooled refrigerant then returns to the stream of warmer air.

Figure 1.3 Heat-pipe heat exchanger (refrigerant) [4]

1.5.4 Runaround Coils (Water)

Runaround coils and heat pipes have certain similarities; however runaround coils are typically used when the exhaust and external airflows are separated by a great distance. Installing two water coils, one in the exhaust air stream and the other in the entering outdoor air stream, is necessary for this kind of system [1].

Figure 1.4 Runaround coils (water) [5]

1.6 Working Principle of a Membrane-Based Plate Type ERV

Basically a plate type ERV is a cross flow heat exchanger in which there is transfer of sensible (heat) and latent (moisture) energy between the exhaust and outdoor airs by using a membrane based core. The membrane is a desiccant material which is used to transfer moisture. It purifies the outdoor air as well by using filters behind the fans.

In the summer, an ERV transfers the moisture from the incoming outdoor air to the exhaust air, keeping it outside the building. However, because an ERV eliminates moisture, it also makes it possible for the air conditioner to operate cooler air much more effectively.

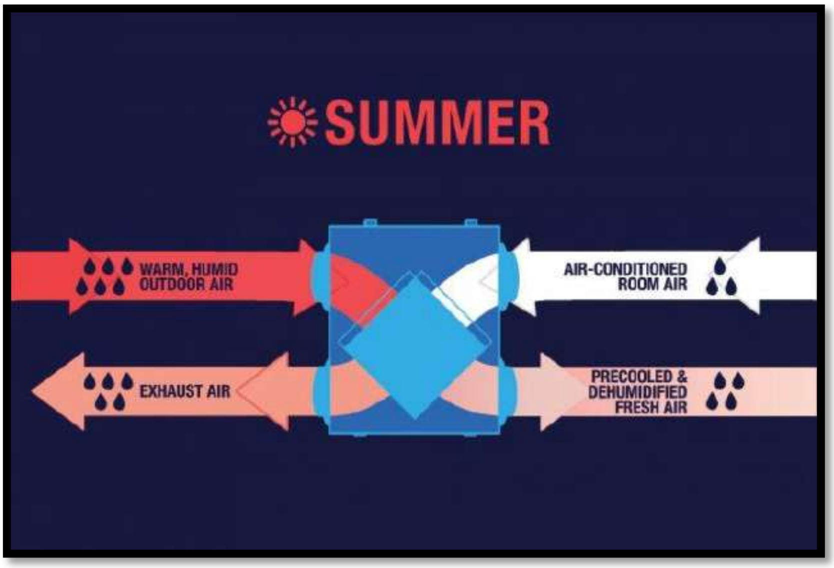


Figure 1.5 Working during summer [6]

In the winter, humidifiers are not necessary because an ERV distributes humidity from the exhaust air to the outdoor ventilation air. By doing this, householders can avoid getting dry skin and throat irritation from the cooler, less humid air in the atmosphere.

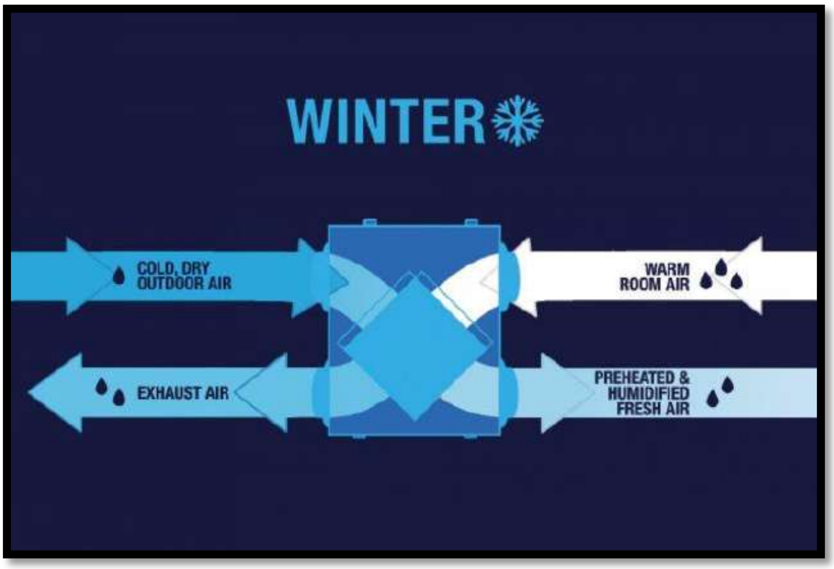


Figure 1.6 Working during winter [6]

In short, an ERV humidifies throughout the winter and dehumidifies during the summer.

1.7 Advantages of an ERV

Some of the major benefits of installing an ERV in a house or office include:

- The HVAC equipment used to condition the spaces is shrunk due to the reduction in heating and cooling load brought on by using an ERV system.
- Improved indoor air quality and better humidity control.
- The preconditioning of the outdoor air lowers the demand for electricity.
- Filtering and elimination of formaldehydes, allergens, and other toxins from the inside spaces, and provision of fresh air in a room
- Improving the quality and energy efficiency of the home or office.
- Uses a silent system and has little maintenance and upkeep requirements.
- Extending the HVAC system's life span [7].

1.8 Effects of ERV on Air quality

Air quality refers to the amount of air that is pure enough for humans and the environment. Good air quality means the air is free of harmful pollutants. The level of pollution in the air is measured using air quality categories (AQC), which rank the amounts of contaminants in the air. The higher the AQC rating, the worse the air quality is.

An ERV can help regulate airflow by ensuring that low-quality and stale air rising in the indoor environment is exhausted outdoors. The ERV's fans filter the air, eliminating dust, pathogens, and pollutants from inside your home. This feature is nothing less than a lifesaver for asthmatics or those individuals with seasonal allergies, as it helps ensure a safe and healthy indoor environment. Moreover, an energy recovery ventilator also helps to expel and eliminate any odors present or materialize in the house. Some of the major pollutants are;

- Carbon Monoxide
- Carbon Dioxide
- Lead
- Nitrogen Dioxide
- Volatile Organic Compounds
- Particle Pollution
- Sulfur Dioxide

1.9 Installation and Airflow Representation

Figure 1.7 shows the representation of air flow in a room with the ERV system installed above the false ceiling and how it carries the old stale air from the room and brings in the new fresh air.

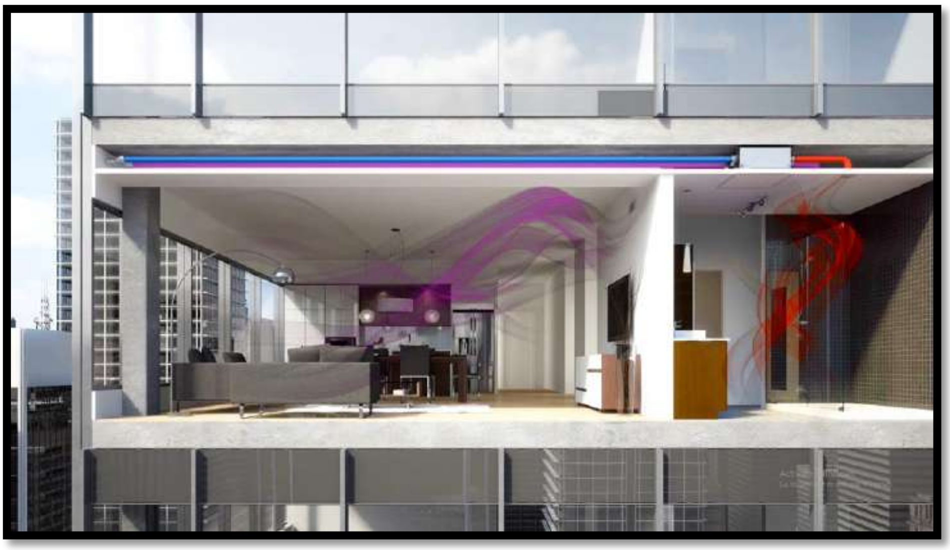


Figure 1.7 Installation and air flow representation [8]

1.10 Scope of the Project

The scope of the project basically tells us the about the work that needs to be done to complete the project. It consists of 4 phases, which are;

- Research and Data Collection – Here we will consult various research articles and books related to ERV to gather the necessary information such as theory, equations, and calculations etc.

- Design and Modeling - In this portion we will be designing and modeling our 3D model by using CAD software's.
- Fabrication – Here we will survey the market and purchase all the required material and items. This phase will also begin the assembling of the project.
- Testing - Here we will be performing all the experiments needed to calculate the efficiencies of various variables as well as the effect on various factors mainly air quality and power consumption.

1.11 Mapping with Complex Engineering Problem Attributes

Table 1.1 shows the list of CEP attributes which lines up with our project. Following is the explanation of how these attributes relate to our project;

- **"Depth of knowledge"** refers to a comprehensive understanding and expertise in fluid dynamics, thermodynamics, and heat and mass transfer. It involves optimizing airflow patterns, pressure differentials, and heat transfer efficiency. It also entails selecting suitable membrane materials and components, and employing precise fabrication methods. Additionally, it requires expertise in control systems and automation for seamless integration into HVAC systems. This deep knowledge ensures the design, construction, and optimization of efficient and reliable ERVs that enhance indoor air quality and reduce energy consumption.
- **"Range of conflicting requirements"** refers to the surveying of the market and finding the local available material as well as its cost.
- **"Consequences"** refers to understanding the impacts of design choices. Professionals assess consequences on energy efficiency, indoor air quality, system reliability, and cost-effectiveness.. By considering these consequences, professionals ensure informed decision-making and successful implementation of efficient and effective ERV systems.

Table 1.1
CEP Attributes (ERV)

CEP Attributes (ERV)		
WP1	Depth of knowledge	WK3 – Engineering Fundamentals WK4 - Engineering Specialist Knowledge WK5 - Engineering Design WK6 - Engineering Practice (Modern tools) WK8 - Research Literature
WP2	Range of conflicting requirements	Use of only locally available material Cost
EP1	Consequences (Professional Competency)	Testing (Effect of ERV on cooling load and power consumption)

1.12 Mapping with UN SDGs

1.12.1 Good Health and Well-Being

Ensure healthy lives and promote well-being for all at all ages [9] - The primary health benefits of installing an ERV is improved, safer, and healthier air conditions. Currently Lahore is one of the top most polluted cities in the world, so by using ERV we can filter out the harmful pollutant's making the room safer.

Figure 1.8 Third UN SDG [10]

1.12.2 Responsible Consumption and Production

Ensure sustainable consumption and production patterns [9] - By using an ERV system, not only will the overall HVAC loads decrease since the warm and humid air entering into the ERV turns into preconditioned and dehumidified fresh air that would decrease the overall temperature of the entering air but it will also reduce the sizing of HVAC units required for the given space due to decreased loads.

Figure 1.9 Twelfth UN SDG [11]

CHAPTER TWO: LITERATURE REVIEW

This chapter includes a review of recent literature articles relevant to ERVs from the basics such as the type of the ERV to the material selection of the core. This chapter also talks about various different conditions and their effects on the performance such as weather and humidity. It also contains the formulae and values regarding the design calculations. Optimization factors for better effectiveness of the ERV were also given here.

2.1 Importance of ERVs

Awareness regarding the indoor air quality has become a major concern in the recent years [12]. Proper ventilation of fresh air is required for the health of the residents. One of the ways to fulfill that requirement is to opening windows to let fresh air in; however conservation of energy is also important. The latent and sensible load of incoming fresh air is quite high. It accounts to 20-40% of the load of air conditioning system in humid, hot areas. Hence, in the summer, is important to recuperate the dryness and coldness of the exhaust air stream [13].

A significant portion of the energy consumed to cool and dehumidify new air could be recovered by using heat and moisture recovery systems, also known as complete heat exchangers. In fact, it has been observed that 70-90% of the energy can be saved that is required recondition and purify the fresh air. An existing HVAC system's efficiency can be raised using heat and moisture recovered. The cause is that the typical method of dehumidifying fresh air involves condensation on cooling coils followed by energy-intensive re-heating operations. However, if equipment is built to lower the dehumidification load, such as heat and moisture recovery systems, this portion of energy can be saved [14].

The increase in population, urbanization, economy, and improved indoor thermal comfort are all contributing to a constant rise in the electricity needed for HVAC systems and the corresponding greenhouse gas emissions [15]. In order to lower building energy consumption, engineers and designers are prioritizing the development of energy-efficient HVAC systems.

Because of their ability to reduce the energy consumption as well as the related emissions of greenhouse gases, ERVs are gaining popularity [16]. It has been claimed that when an ERV unit is integrated into an HVAC system, the energy needed to condition the fresh air can be lowered by 70–90% [17].

Enthalpy wheel, air-to-liquid membrane enthalpy exchanger, and air-to-air membrane enthalpy exchanger (MEE) are some of the types of ERVs used in building applications [18]. Air-to-air MEE is one of these and is frequently used in buildings due to its high effectiveness, small footprint, simple design, and low cross-contamination [19].

Semi-permeable membranes are used in air-to-air MEE to separate the supply air from the exhaust air. Heat and moisture can be transferred between the two air streams thanks to the membranes [20]. The membranes may be arranged inside MEEs as parallel plates or hollow fibers. The large pressure drops and irregularity of the flow distribution, however, limit the uses of the hollow fibers MEE [21].

MEEs have been thoroughly investigated over the past few decades from a variety of study angles. To enhance the performance of MEEs, novel membranes have been created and used [22,23]. It was discovered that by utilizing these membranes, the latent heat transfer effectiveness may increase to 70% [24]. On the other hand, significant efforts were also made to improve the performance of MEEs by suitable flow channel design [25] and flow configuration optimization [26].

2.2 Types of Membranes used in MEEs

Membranes are the layers that permit specific mixture constituents to move back and forth between the membrane's surfaces; the driving force determines the direction of the transport. The MEE's most crucial component is the membranes. Due to the difference in moisture content and temperature on the membrane sides, semi-permeable membranes employed in MEEs can let both heat and moisture to flow between the air streams. The following subsections cover many significant characteristics of the membranes used in MEEs [27].

2.3 Properties of Membranes used in MEEs

The qualities of the chosen membranes affect how well a MEE performs. The key properties of the membranes used in MEEs are their pore size, porosity, moisture diffusivity, selectivity, and modulus of elasticity. For membrane characterization, however, factors like tortuosity factor and thermal conductivity are less significant [27].

2.3.1 Pore Size

The supposed diameter of the membrane pores is referred to as the "pore size" in most cases. The structure of the membrane is influenced by pore size, which also affects how moisture is transferred across the membrane [28]. Based on the size of the pores, they can be divided into 2 types which are dense and porous membranes. The pore size of porous membranes is typically approximately 0.1 m, whereas that of dense membranes is typically in the range of 0.1 nm [29]. A membrane's capacity to exchange moisture might be improved by bigger pores. However, as the pore size grows, so does the chance of transmitting other undesirable gases and contaminants.

As a result, MEEs need membranes with the appropriate pore diameters.

2.3.2 Porosity

The volume of the pores in relation to the overall volume of the membrane is known as the membrane porosity ratio [30]. According to a report, membrane porosity has a significant impact on the thermal efficiency and the flux that is transferred across the membrane. An increase in moisture flux and a decrease in conductive heat dissipation would be brought on by a larger porosity. However, the greater porosity may have a negative impact on the membrane's mechanical characteristics [31].

2.3.3 Moisture Diffusivity

The most crucial characteristic of the membranes employed in MEEs is moisture diffusivity, or permeability. It shows how much moisture diffuses through a membrane's surface area in a given amount of time. Water vapor can permeate more quickly through membranes with high moisture diffusivity compared to the membranes with low moisture diffusivity. The reciprocal of moisture diffusivity is moisture diffusion resistance (MDR) [32]. MDR is a measure of how well a membrane can withstand water vapor permeating through it. About 65 to 90 percent of the total moisture transfer resistance is made up of MDR. It is possible to calculate the moisture diffusivity using a variety of tools and methods [33].

2.3.4 Selectivity

Selectivity of membrane is it capacity to transport water vapor while excluding other elements of the air. A high selectivity suggests less cross-contamination of undesirable gases, and the membrane mostly permits the passage of water vapor. Reduced membrane selectivity can occur when the pore size is increased [34]. High water vapor selectivity membranes are crucial for MEEs because their purpose is to not only recover energy but also to maintain the quality of indoor air at a reasonable level.

2.3.5 Modulus of Elasticity

In the regime of elastic deformation, the modulus of elasticity is the ratio of stress change to strain change. A crucial factor in the MEE design to lessen membrane deflection is the membrane's modulus of elasticity. According to [35], membrane elasticity has a significant impact on the pressure drop in MEE channels. The difference pressure between the two neighboring channels may cause membrane displacement.

2.3.6 Thermal conductivity

The ability of the membrane to conduct heat is indicated by its membrane thermal conductivity. The materials utilized to make the membranes for MEEs typically have modest thermal conductivities of 0.12 to 0.33W/m.K [36]. In contrast to the MDR, less than 0.5% of the MEE's overall heat transfer resistance makes up the thermal resistance of the membrane makes up less than and may therefore be disregarded.

2.3.7 Tortuosity factor

The ratio of the length of the water vapor diffusion pathway through the porous membrane to the length of the straight pathway is known as the tortuosity factor. Higher water vapor flux would be produced by a lower tortuosity factor. The pore geometry affects the tortuosity factor.

The porous membranes' pore geometry can take on a variety of shapes. However, it is generally considered that the tortuosity factor has a value of 2.0 [37].

2.4 Membrane Materials

The performance of MEEs will be directly impacted by the membrane materials employed in them. Membrane characteristics such as moisture diffusivity, water vapor selectivity, and mechanical qualities have a significant impact on a MEE's performance. This article looked into possible membrane materials that could be employed for MEEs. In addition to the structural characteristics, the membrane's cost, hardness, and durability should be taken into account while choosing it [38]. A variety of materials may be used in MEEs. However, the membranes for MEEs are often constructed using just two materials, namely paper and polymer.

2.4.1 Paper membranes

The most prevalent type of hydrophilic fiber membranes is paper. Both heat and moisture have been successfully transferred between two air streams using them [39]. Paper membranes feature low hardness and thermal conductivity, as well as a relatively high surface wettability. Paper membranes can have a dense or porous structure.

The majority of fiber materials used to make paper membranes have poor mechanical qualities, especially after getting wet. This reduces the membrane's resistance to deformation and its lifetime. However, as most paper membranes are reasonably inexpensive, membrane lifetime can be overcome by replacing the membranes after a while [40].

2.4.2 Polymeric membrane

The most popular semi-permeable surfaces utilized in MEEs for heat and moisture transport are polymeric membranes. This kind of membrane is strong mechanically and has cheap cost and reproducibility. The most crucial determining criteria when choosing polymeric membranes for MEEs are membrane permeability and water vapor selectivity over the air. Several polymeric membranes that are frequently employed for water vapor transport applications are shown in the figure below in terms of their selectivity and permeability [41].

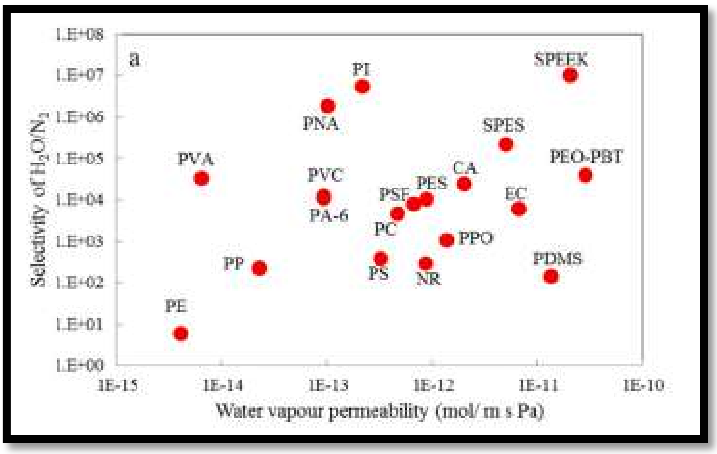


Figure 2.1 Variation of selectivity of H_2O/N_2 with water vapor permeability [42]

2.5 Membrane Spacing

Membrane spacing also plays a crucial role in the effectiveness of an ERV system. It has been proven that all the properties such as total heat rate transfer, enthalpy effectiveness, latent-to-sensible heat ratio and airflow rate vary with the change in membrane spacing. The variation of each property can be seen in the figures below;

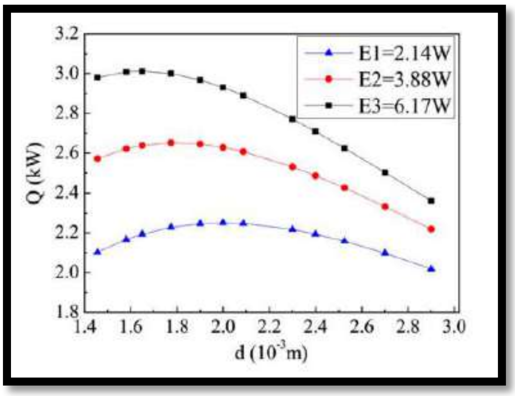


Figure 2.2 Variation of total heat transfer rate with membrane spacing [43]

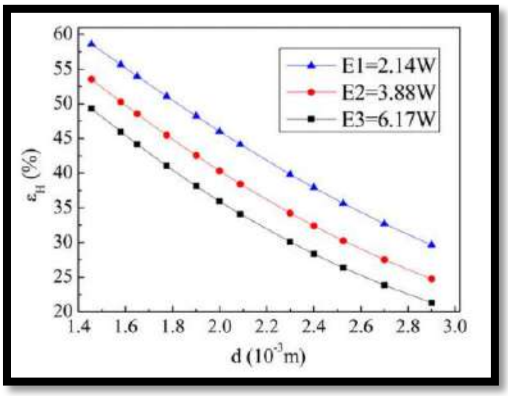


Figure 2.3 Variation of enthalpy effectiveness with membrane spacing [43]

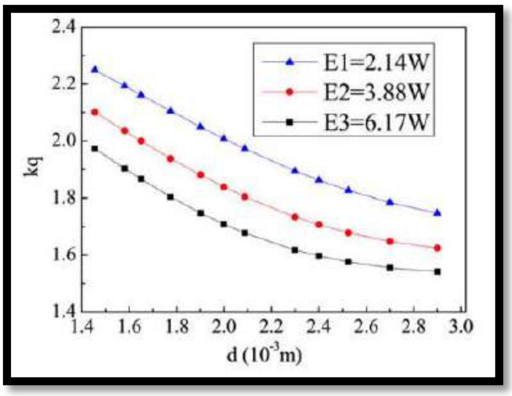


Figure 2.4 Variation of latent-to-sensible heat ratio with membrane spacing [43]

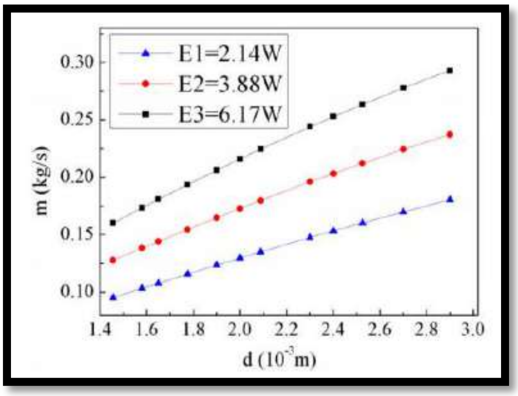


Figure 2.5 Variation of airflow rate with membrane spacing [43]

2.6 Membrane Thickness

Membrane thickness also plays a crucial role in the effectiveness of an ERV system. The figures below demonstrate how increasing membrane thickness causes an increase in thermal, moisture, and airflow resistances, which lowers the overall heat transfer rate, enthalpy effectiveness, latent-to-sensible heat ratio and airflow rate. Therefore, a thin membrane can be used to achieve a satisfactory performance for a membrane-based energy recovery ventilator.

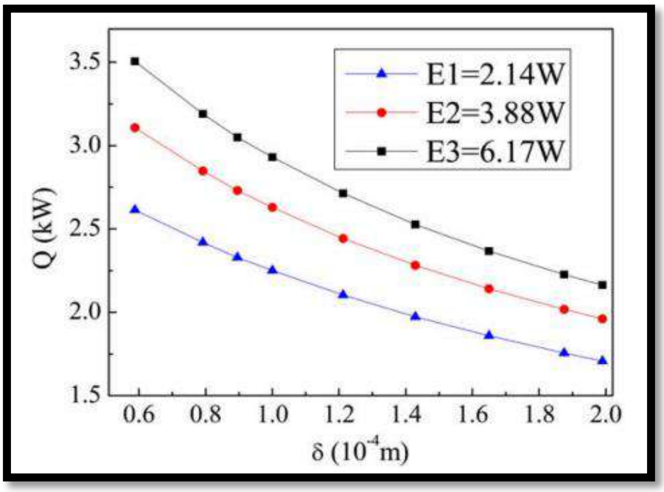


Figure 2.6 Variation of total heat transfer rate with membrane thickness [43]

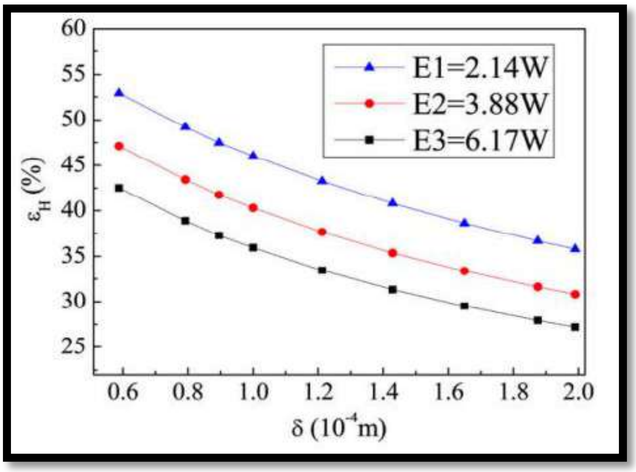


Figure 2.7 Variation of enthalpy effectiveness with membrane thickness [43]

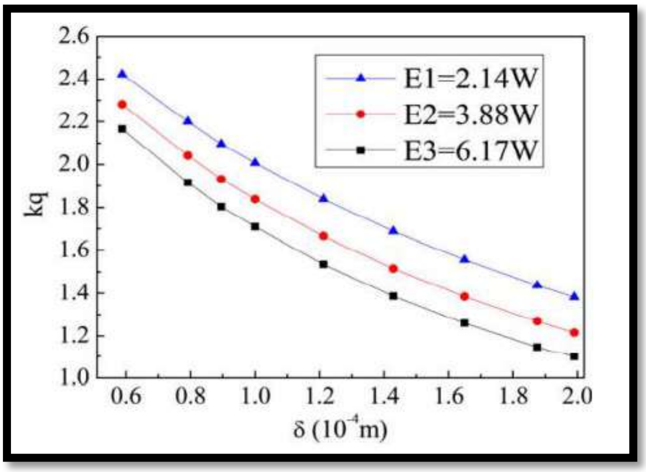


Figure 2.8 Variation of latent-to-sensible heat ratio with membrane thickness [43]

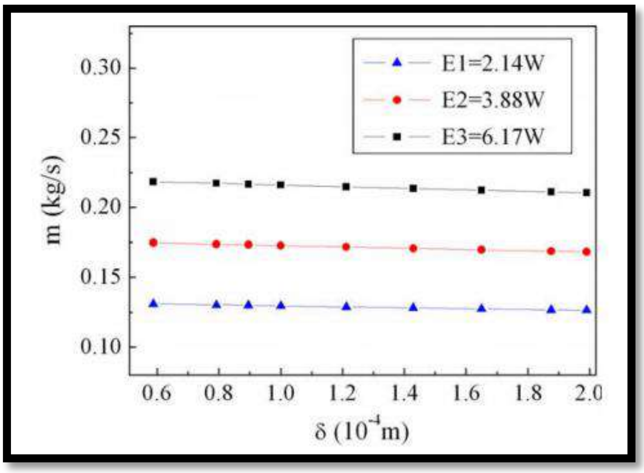


Figure 2.9 Variation of airflow rate with membrane thickness [43]

CHAPTER THREE: DESIGN CALCULATIONS AND MODELING

This chapter deals with the design parameters which are required for the design of our project. It also has calculations for our ERV design such as CFM, area of one layer, and dimensions of core are also given. It also includes the models of the core, casing, and final assembled model.

3.1 Design Parameters

The design parameters required for our project is CFM which will tell us the amount of volume flow rate needed for our room. Next is the size of core, the core is the most important part of our project, so we need to calculate its size and number of layers in it. Lastly is the amount of fan power needed to meet our chosen CFM.

3.2 Design Calculations

3.2.1 CFM Calculation

The amount of air that passes by a stationary place in one minute, or cubic feet per minute (CFM), is a measurement of airflow volume. Table 3.1 was taken from ASHRAE 62.1 to get the values for air rates.

Table 3.1

Minimum Ventilation Rates in Breathing Zone [44]

Occupancy Category	People Outdoor Air Rate R_p		Area Outdoor Air Rate R_a		Default Values Occupant Density	Air Class	OS (6.2.6.1.4)
	cfm/ person	L/s· person	cfm/ft^2	L/s·m^2	#/1000 ft^2 or #/100 m^2		
Educational Facilities (continued)							
University/college laboratories	10	5	0.18	0.9	25	2	

HMT Lab Area = A_z = 20ft x 38ft = 760 ft^2

Zone Population = P_z = 20people

Outdoor Air Flow Rate = R_p = 10 $\frac{\text{cfm}}{person}$

Outdoor Air Flow Rate = R_a = 0.18 $\frac{cfm}{ft^2}$

$$\dot{V} = R_p \times P_z + R_a \times A_z \qquad (1)$$

$$\dot{V} = (10 \times 20) + (0.18 \times 760)$$

$$\dot{V} = 336.8cfm = 158.9\frac{L}{s} = 0.1589\frac{m^3}{s}$$

Equation (1) was taken from ASHRAE 62.1 (Eq 6-1) and it was used to calculate the CFM required for HMT Lab which is the room under consideration.

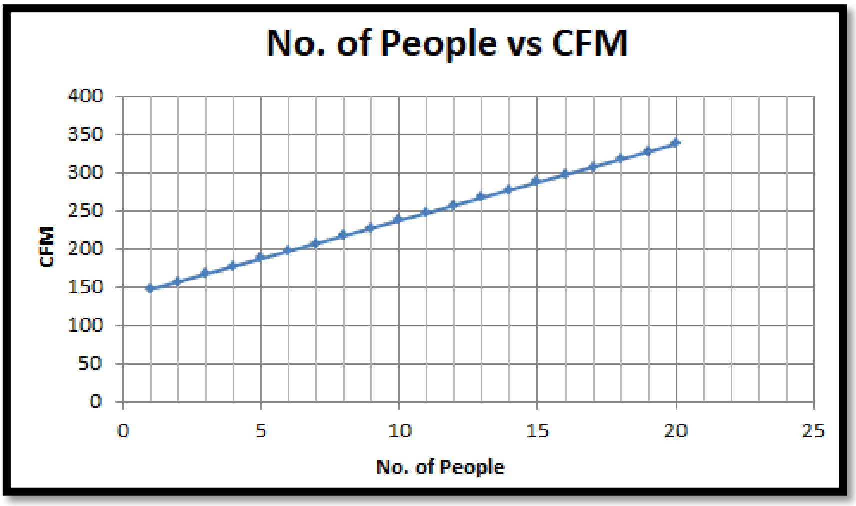


Figure 3.1 Variation of CFM with no. of people

3.2.2 Outdoor Design Conditions

The outdoor design conditions for Lahore, Pakistan were taken from ASHRAE Handbook. Our testing phase will be done during summer seasons, hence we have taken the values for cooling 2% (summer).

Table 3.2

Extreme weather conditions of Lahore [45]

Meaning of acronyms:
DB: Dry-bulb temperature, °C *WB: Wet-bulb temperature, °C*
MCWB: Mean coincident wet-bulb temperature, °C
Lat: Latitude, °
DP: Dew-point temperature, °C
MCDB: Mean coincident dry-bulb temperature, °C
Long: Longitude, °
HR: Humidity ratio, g of moisture per kg of dry air
HDD and CDD 18.3: Annual heating and cooling degree-days, base 18.3°C, °C-day
Elev: Elevation, m
WS: Wind speed, m/s

Station	Lat	Long	Elev	Heating DB		Cooling DB/MCWB						Evaporation WB/MCDB				Dehumidification DP/HR/MCDB						Extreme Annual WS			Heat./Cool. Degree-Days	
						0.4%		1%		2%		0.4%		1%		0.4%			1%							
				99.6%	99%	DB	MCWB	DB	MCWB	DB	MCWB	WB	MCDB	WB	MCDB	DP	HR	MCDB	DP	HR	MCDB	1%	2.5%	5%	HDD	CDD 18.3
AMSTERDAM SCHIPHOL	52.309N	4.764E	-3	-6.2	-4.2	27.8	19.8	25.6	19.0	23.7	18.0	20.7	25.9	19.7	24.2	19.0	13.8	22.8	18.1	13.0	21.6	13.5	11.8	10.3	2929	71
HOEK VAN HOLLAND	51.983N	4.100E	14	-5.2	-3.3	27.2	19.3	24.7	18.4	22.8	18.0	20.6	25.0	19.6	23.2	19.1	13.9	22.2	18.2	13.2	21.1	16.0	14.4	13.1	2757	70
IJMUIDEN	52.467N	4.567E	4	-6.4	-4.1	25.6	18.7	23.6	17.8	21.8	17.6	20.0	23.3	19.2	21.5	19.0	13.8	21.1	18.4	13.3	20.2	18.6	16.4	15.0	2921	51
ROTTERDAM THE HAGUE	51.957N	4.437E	-5	-6.2	-4.1	28.1	19.9	25.8	19.1	24.0	18.1	20.9	26.2	19.8	24.4	19.1	13.9	23.0	18.1	13.0	21.8	12.1	10.5	9.3	2902	71
VALKENBURG	52.167N	4.433E	1	-6.3	-4.2	27.1	19.6	24.8	18.7	22.9	17.8	20.6	25.2	19.5	23.4	19.0	13.7	22.5	18.0	13.0	21.2	13.1	11.6	10.3	2941	56
WOENSDRECHT AB	51.449N	4.342E	19	-7.6	-5.2	29.1	19.8	26.7	19.1	24.8	18.2	21.0	26.7	20.0	25.0	19.1	13.9	22.9	18.1	13.1	22.0	9.7	8.4	7.4	2963	78
New Zealand																										*4 sites, 35 more on CD-ROM*
AUCKLAND AERO AWS	37.000S	174.800E	7	4.4	5.6	25.2	19.7	24.3	19.2	23.5	18.8	21.2	23.4	20.5	22.8	20.4	15.1	22.4	19.6	14.4	21.9	12.6	11.1	9.9	1222	157
AUCKLAND INTL	37.008S	174.792E	7	4.0	5.2	25.7	19.9	24.8	19.4	23.8	18.9	21.4	23.8	20.6	23.0	20.8	15.4	22.8	19.9	14.6	22.0	12.6	11.3	10.1	1218	172
CHRISTCHURCH AP AWS	43.483S	172.517E	37	-2.4	-1.4	27.6	16.6	25.5	15.8	23.5	15.2	18.1	24.1	17.2	22.5	16.2	11.6	19.1	15.5	11.0	18.4	11.4	10.1	9.0	2597	49
CHRISTCHURCH INTL	43.489S	172.532E	38	-2.8	-1.9	28.0	16.9	25.9	16.0	23.9	15.4	18.3	24.5	17.5	22.9	16.2	11.5	19.4	15.4	11.0	18.5	11.3	10.0	9.0	2619	56
Nicaragua																										*1 site, 0 more on CD-ROM*
MANAGUA INTL	12.141N	86.168W	59	20.0	20.9	36.0	24.3	35.1	24.2	34.8	24.1	26.6	31.4	26.2	31.1	25.2	20.5	28.4	25.1	20.3	28.3	8.3	7.4	6.5	0	3479
Niger																										*1 site, 12 more on CD-ROM*
NIAMEY DIORI HAMANI INTL	13.482N	2.184E	223	15.9	17.0	42.3	20.5	41.8	20.4	40.9	20.5	27.1	33.0	26.5	32.6	25.9	21.8	29.3	25.1	20.8	29.1	9.3	8.0	7.0	0	4249
Norway																										*2 sites, 117 more on CD-ROM*
HAKADAL	60.117N	10.833E	170	-19.1	-16.1	26.5	17.6	24.8	16.9	23.0	15.9	19.2	23.5	18.1	22.8	17.8	13.0	20.6	16.3	11.9	19.3	8.0	6.7	5.7	4513	44
OSLO-BLINDERN	59.942N	10.720E	97	-14.3	-12.1	26.7	17.3	24.8	16.6	23.1	15.7	18.6	23.7	17.7	22.7	16.8	12.1	20.2	15.9	11.4	19.4	8.0	6.9	6.0	4182	54
Oman																										*1 site, 20 more on CD-ROM*
AL BURAIMI	24.233N	55.783E	299	9.8	11.2	45.1	21.5	44.1	21.3	43.1	21.2	27.4	33.3	26.6	33.9	26.1	22.3	30.7	24.8	20.5	31.1	8.2	7.1	6.3	71	3756
Pakistan																										*3 sites, 25 more on CD-ROM*
BENAZIR BHUTTO INTL	33.617N	73.099E	508	2.1	3.2	41.1	22.7	39.4	22.8	38.0	22.7	28.0	34.2	27.5	33.4	26.5	23.4	31.3	26.0	22.8	31.0	13.0	10.4	9.3	639	2044
JINNAH INTL	24.907N	67.161E	31	10.1	11.8	38.9	22.7	37.1	23.1	36.0	23.5	28.2	33.3	27.8	32.7	27.1	22.9	30.9	26.6	22.3	30.7	9.7	8.5	7.7	24	3248
LAHORE ALLAMA IQBAL INTL	31.522N	74.404E	217	3.0	4.8	43.2	23.4	41.9	23.3	40.1	23.3	29.2	34.5	28.6	33.7	28.1	24.9	32.2	27.2	23.6	31.5	8.0	6.4	5.4	444	2608

The outdoor conditions selected from Table 3.2 are dry bulb temperature, T_{Db}= 40.1°C, wet bulb temperature, T_{Wb}= 23.3°C, and wind speed, v= 8m/s.

3.2.3 Indoor Design Conditions

The indoor design conditions were also taken from ASHRAE Handbook, which shows the ranges for comfort zones during summer and winter. We have taken the average value for summer.

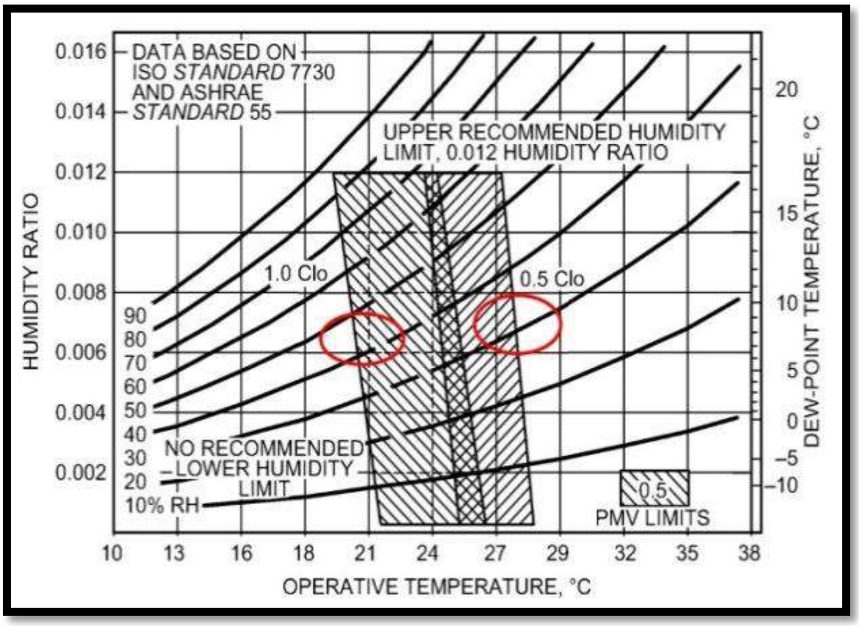


Figure 3.2 Summer and winter comfort zones [45]

The indoor conditions selected from Figure 3.2 are dry bulb temperature, T_{Db}= 26°C and humidity ratio, W_i= 0.008kg/kg.

3.2.4 Area of One Layer

$Volume\ Flow\ Rate\ of\ Air = \dot{V} = 0.1589\, m^3/s$

$Density\ of\ Air = \rho_{Air} = 1.293\ \ kg/m^3$

$Cp_{Air} = 1\ \ kJ/kg.k$

$$\dot{m} = \dot{V}\rho_{Air} \tag{2}$$

$$\dot{m} = 0.1589 \times 1.293$$

$$\dot{m} = 0.205\frac{kg}{s}$$

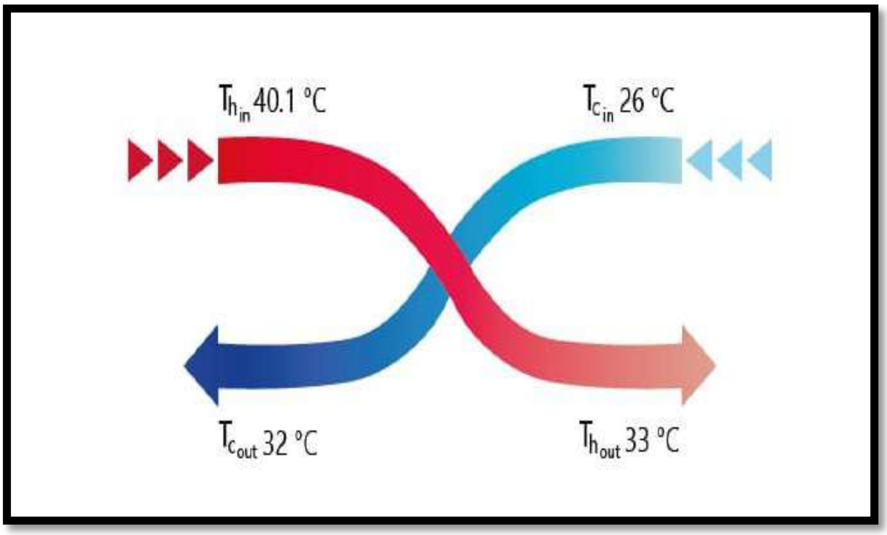


Figure 3.3 Selected design temperatures

$$q_c = m_c \times C_{p_c}(T_{c_{out}} - T_{c_{in}}) \quad (3)$$

$$q_c = 0.205 \times 1000 \times (32 - 26)$$

$$q_c = 1230W$$

$$q_h = m_h \times C_{p_h}(T_{h_{in}} - T_{h_{out}}) \quad (4)$$

$$q_h = 0.205 \times 1000 \times (40.1 - 33)$$

$$q_h = 1455W$$

$$\Delta T_1 = T_{h_{in}} - T_{c_{out}} \quad (5)$$

$$= 40.1 - 32$$

$$= 8.1°C$$

$$\Delta T_2 = T_{h_{out}} - T_{c_{in}} \quad (6)$$

$$= 33 - 26$$

$$= 7°C$$

$$LMTD = \frac{\Delta T_1 - \Delta T_2}{Ln\left(\frac{\Delta T_1}{\Delta T_2}\right)} \quad (7)$$

$$LMTD = \frac{8.1 - 7}{Ln\left(\frac{8.1}{7}\right)}$$

$$= 7.54°C$$

$$Thickness = t_{Al} = 0.1mm = 0.0001m$$

$$Thermal\ Conductivity = k_{Al} = 201\ W/m.k$$

$$Heat\ Transfer\ Coefficient = h_c$$

$$h_c = 12.12 - 1.16(v) + 11.6(v)^{\frac{1}{2}} \quad (8)$$

$$h_c = 12.12 - 1.16(8) + 11.6(8)^{\frac{1}{2}}$$

$$h_c = 35.6\frac{W}{m^2.K}$$

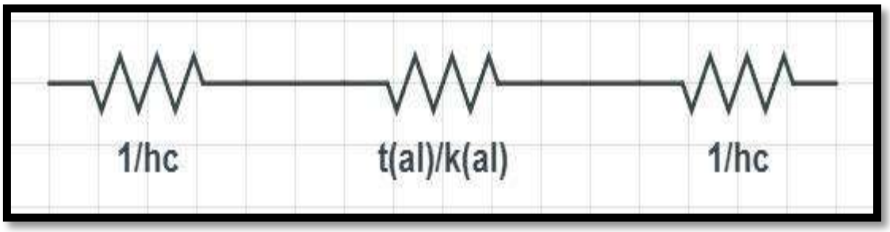


Figure 3.4 Thermal equivalent circuit

$$R_{Total} = \frac{1}{h_c} + \frac{t_{Al}}{k_{Al}} + \frac{1}{h_c} \quad (9)$$

$$R_{Total} = \frac{1}{35.6} + \frac{0.0001}{201} + \frac{1}{35.6}$$

$$R_{Total} = 0.0561\frac{m^2.K}{W}$$

$$Total\ Heat\ Transfer\ Coefficient = U = \frac{1}{R_{Total}} \quad (10)$$

$$U = \frac{1}{0.0561}$$

$$\mathrm{U} = 17.8\frac{W}{m^2.K}$$

$$q_{max} = UA_{One\ layer}LMTD \quad (11)$$

$$A_{One\ layer} = \frac{q_{max}}{ULMTD}$$

$$A_{One\ layer} = \frac{1455}{17.8 \times 7.54}$$

$$A_{One\ layer} = 10.8m^2$$

Equation (2) was used to get the mass flow rate of the air. Equation (3) calculates the heat transfer of cold air while (4) is concerned with the hot air. Equations (5) and (6) were used to calculate the temperature difference for counter flow configuration which is then further used to calculate LMTD in (7). Equation (8) was used to calculate the heat transfer coefficient. Equation (9) was used to calculate the total heat resistance which is then further used to calculate the total heat transfer coefficient in (10). Finally equation (11) is used to calculate the total area required for one layer.

3.2.5 Size of Core

The following code was made using C++ software which was used for the iterations to find size of cube of our core.

It starts by calculating the area of cube by using starting value of length and width of 0.1, which is then used to find the total number of layers by dividing the area of a single layer by the area of the cube, which is then multiplied by the thickness of a single layer to get the total thickness of our cube. The thickness of single layer consists of two air spaces with thickness of 2mm (constant), one sheet of membrane with thickness of 0.1mm (constant), and one sheet of aluminum with variable thicknesses. Finally, it repeats the program for multiple iterations until the final answer ensures that the length and width is equal to the total height.

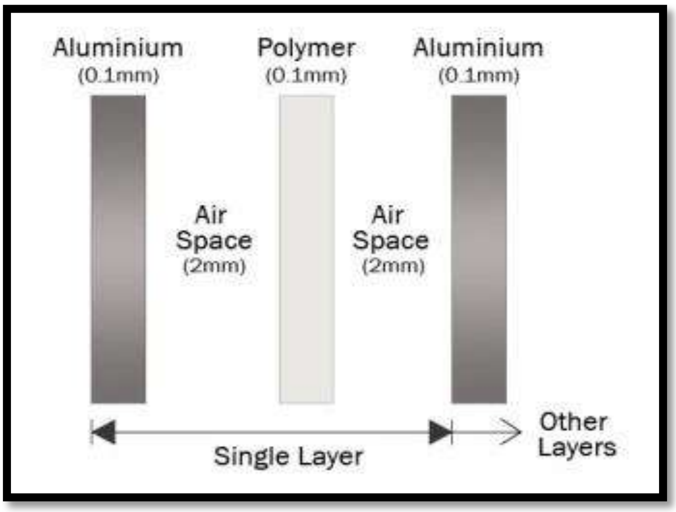


Figure 3.5 Single layer representation

Nomenclature

SLA Single Layer Area
L Length of Cube
W Width of Cube
T Thickness of Cube
A Area of Cube
t Single layer thickness
TL Total number of layers

```
#include <iostream>
#include <cmath>
using namespace std;
double round_to(double value, double prec )
{
   double precision = pow(10,prec);
   return std::round(value * precision) / precision;
}
int main()
{
   float SLA = 0;
   float L = 0;
   float W = 0;
   float A = 0;
   float t = 0;
   float TL = 0;
   float T = 0;
   cout << "Enter the value of L: ";     //input value of L and W (L=W) starting from 0.1
   cin >> L;
   cout << "Enter the value of W: ";
   cin >> W;
   cout << "Enter the value of t: ";
   cin >> t;
   for (int i = 1; i <= 1000000; i++)
   {
      SLA = 17;
      if ((L == W) && (L != T))
      {
         A = L * W;
         TL = SLA / A;
         T = TL * t;
         if (round_to(L, 2) == round_to(T, 2))
         {
            goto stop;

         }
         else
         {
            L += 0.001;                // Equivalent to L=L+0.001
            W += 0.001;
         }
      }
   }
stop:
   cout << "Value of L: " << L << endl;
   cout << "Value of W: " << W << endl;
   cout << "Value of T: " << T << endl;
   return 0;
}
```

Table 3.3

Comparison between different thicknesses of Aluminum

Thickness of Aluminum [mm]	Thickness of Single Layer [mm]	Total Number of Layers	Length of Cube (L=W=H) [cm]	Diagonal Length [cm]
0.02 (Food grade foil)	4.12	88	35	49.5
0.1 (Industrial foil)	4.2	83	36	50.9
1.0 (Sheet)	5.1	75	38	53.7

Table 3.3 shows the results of our program found using different thicknesses of aluminum which changes the overall thickness of a single layer, hence changing the total number of layers required and the dimensions of our cube/core.

3.2.6 Fan Power

$\rho_{Air} = \text{Air density} = 1.164\ kg/m^3 \quad @30°\text{C}$

$v = Air\ velocity\ inside\ core = 8.0\ m/s$

$\mu = Viscosity\ of\ air = 1.872 \times 10^{-5}\ kg/ms \quad @30°\text{C}$

$K_c = Entrance\ loss\ coefficient = 0.5\ (square\ edged)$

$K_e = Exit\ loss\ coefficient = 1.0$

$d = Membrane\ spacing = 2mm = 0.002m$

$d_h = \text{Hydraulic diameter} = 2\text{d} = 0.004\text{m}$

$\delta = Membrane\ thickness = 0.1mm = 0.0001m$

$n = Number\ of\ channels = 83$

$\Delta P = Air\ pressure\ drop\ across\ core\ (Pa)$

$A = total\ heat\ transfer\ area\ (m^2)$

$A_c = minimum\ freeflow\ area\ (m^2)$

$x_f = Channel\ length = 36cm = 0.36m$

$y_f = Channel\ width = 36cm = 0.36m$

$$\alpha = Channel\ aspect\ ratio = \frac{x_f}{d} \tag{12}$$

$$\alpha = \frac{0.36}{0.002}$$

$$\alpha = 180$$

$$Reynolds\ no. = Re = \frac{\rho v d_h}{\mu} \tag{13}$$

$$Re = \frac{1.164 \times 8 \times 0.004}{1.872 \times 10^{-5}}$$

$$Re = 1990$$

$$f = \frac{\frac{-28.3}{\alpha} + 24}{R_e} \tag{14}$$

$$f = \frac{\frac{-28.3}{180} + 24}{1990}$$

$$f = 0.0120$$

$$\frac{A}{A_c} = \frac{x_f y_f}{x_f d} \tag{15}$$

$$\frac{A}{A_c} = \frac{0.36 \times 0.36}{0.36 \times 0.002} = 180$$

$$\Delta P = \frac{1}{2} \rho v^2 \left(K_c + K_e + f \frac{A}{A_c}\right) \tag{16}$$

$$\Delta P = \frac{1}{2} \times 1.164 \times (8)^2 \times [0.5 + 1 + (0.0120 \times 180)]$$

$$\Delta P = 136 Pa$$

$$Fan\ power = E = n x_f\ d v \Delta P \tag{17}$$

$$E = 83 \times 0.36 \times 0.002 \times 8 \times 136$$

$$E = 65W$$

All the parameters in 3.2.6 and equations (12) to (17) [43] were used to calculate the fan power required for our project to achieve the required CFM as calculated in (1).

3.3 Modeling in SOLIDWORKS

Following are the pictures of our ERV model designed using SOLIDWORKS which is a computer-aided design (CAD) software used for creation of 3D models.

3.3.1 *Air to Air Heat Exchanger Core*

The heat exchanger core is the location where the transfer of latent and sensible energy takes place between the outdoor and exhaust air. The model we have created is by using the industrial foil (0.1mm thick), which results in the core dimensions as shown by Table 3.3. It consists of multiple layers of aluminum, membrane, and air gap. It also shows how the two different airs (outdoor and exhaust) cannot mix with other since there is a blockage at each successive entrance. Some of the commands used in SOLIDWORKS to make the core are extrude, line, and rectangle.

Figure 3.6 Single layer thickness (millimeters)

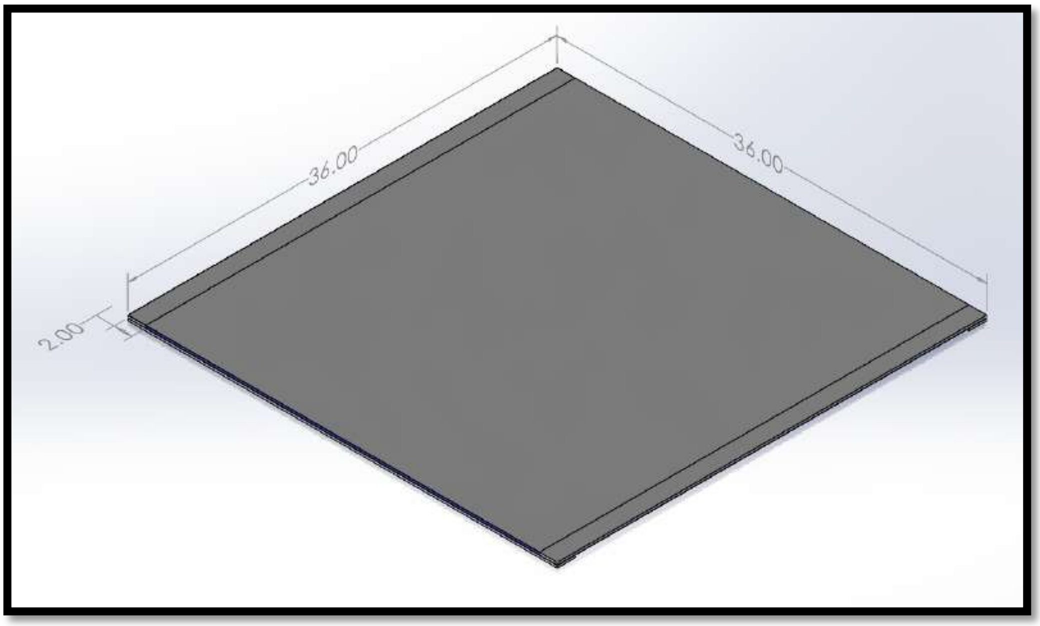


Figure 3.7 Isometric view of single layer (centimeters)

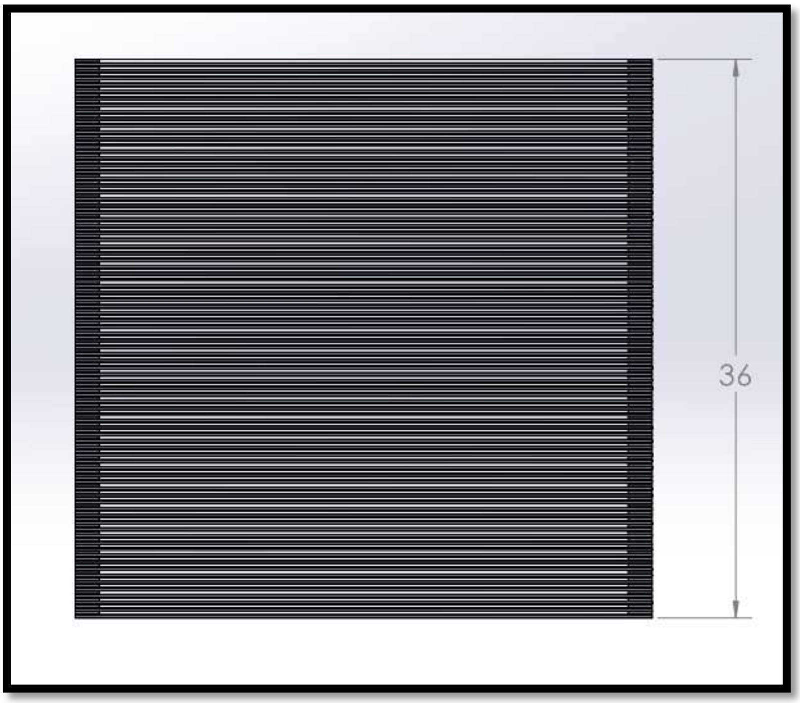


Figure 3.8 Front view of core (centimeters)

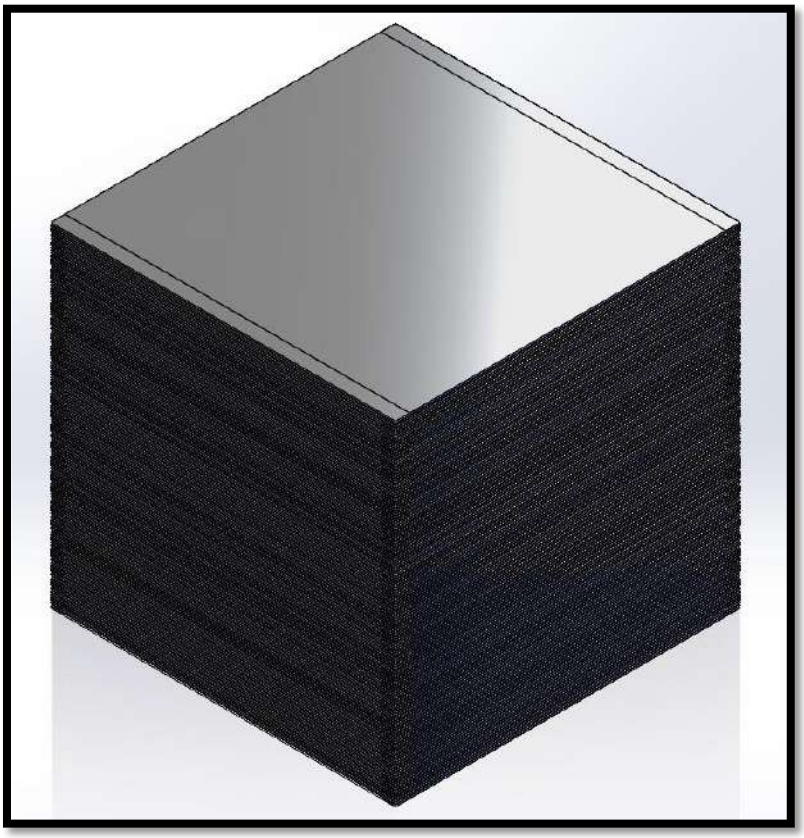


Figure 3.9 Isometric view of core

3.3.2 Body

The body is in the main box which will house all the components like core, fans, and filters. It is made up of 19-gauge galvanized steel (1mm thickness). Some of the commands used in SOLIDWORKS to make the body are hole, extrude line, and rectangle.

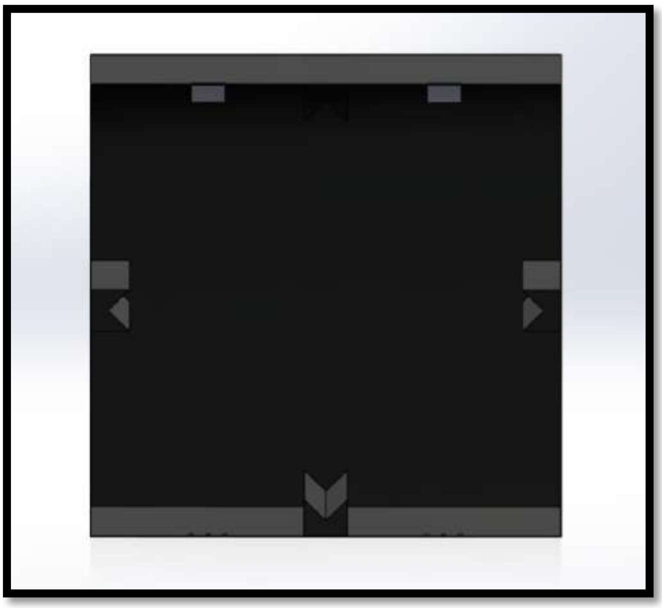


Figure 3.10 Front view of body

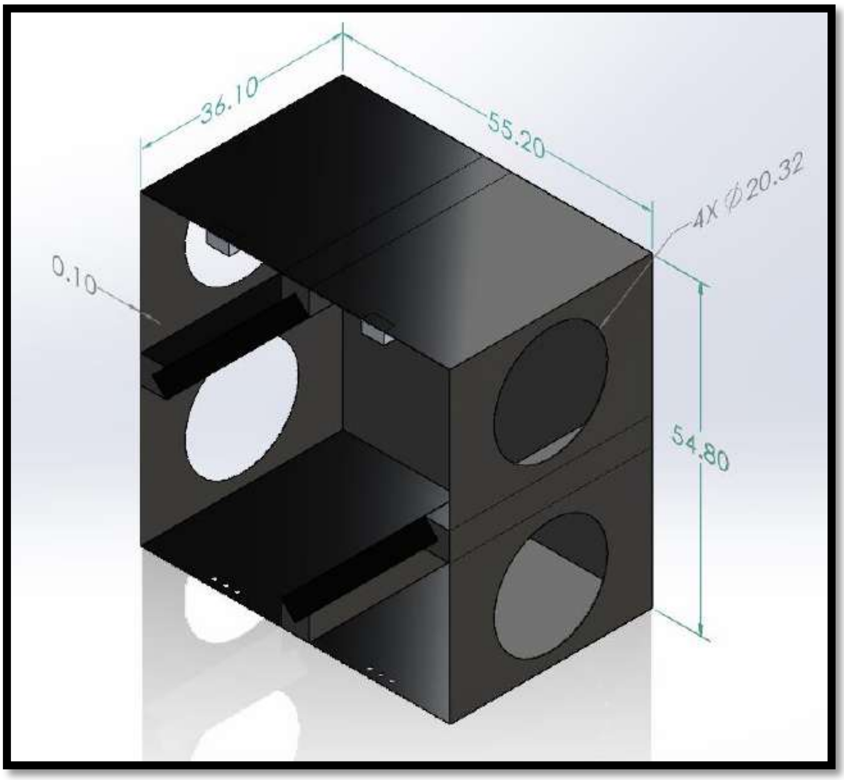


Figure 3.11 Isometric view of body (centimeters)

3.3.3 Air Ducts

Air ducts are responsible for the direction of air flow, and also increases the air pressure due to the decrease in the cross section area (from 8inch to 6inch diameter). Some of the commands used in SOLIDWORKS to make the air ducts are circle, revolve, and mirror.

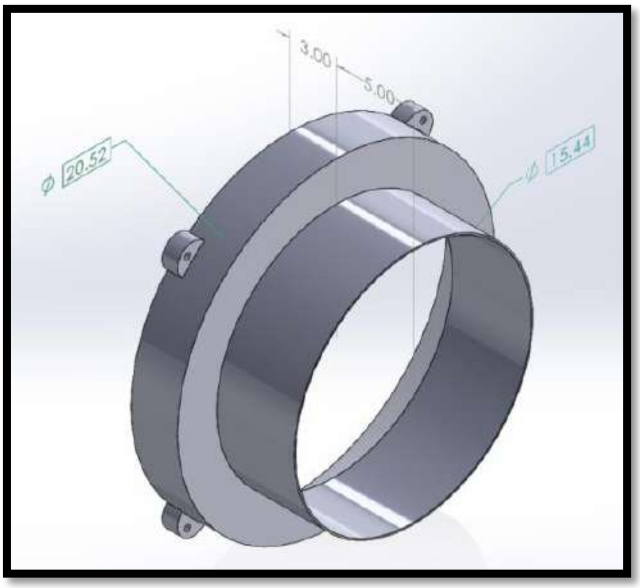


Figure 3.12 Isometric view of air duct (centimeters)

3.3.4 Core Brackets

Core brackets are basically a support with a 90° angle to coincide with the borders of the core. Four of them will be attached on each of the four walls of the core to centrally align and hold our core in place. Some of the commands used in SOLIDWORKS to make the core brackets are line and extrude.

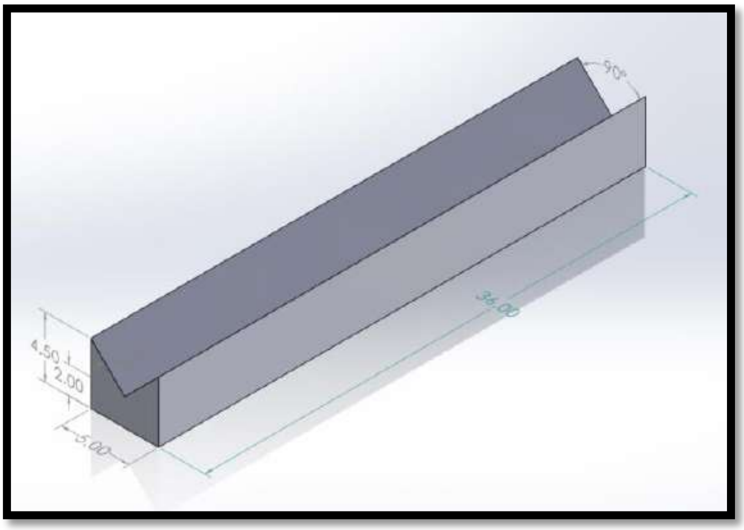


Figure 3.13 Isometric view of core bracket (centimeters)

3.3.5 Final Assembly

The final assembly is the complete model consisting of all the components.

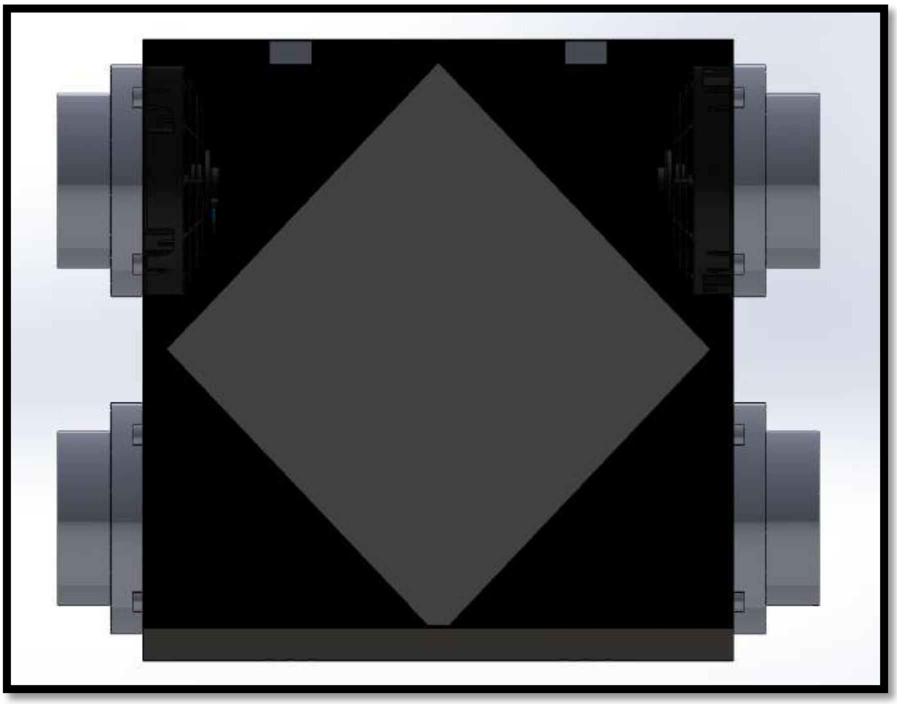


Figure 3.14 Front view of final assembly

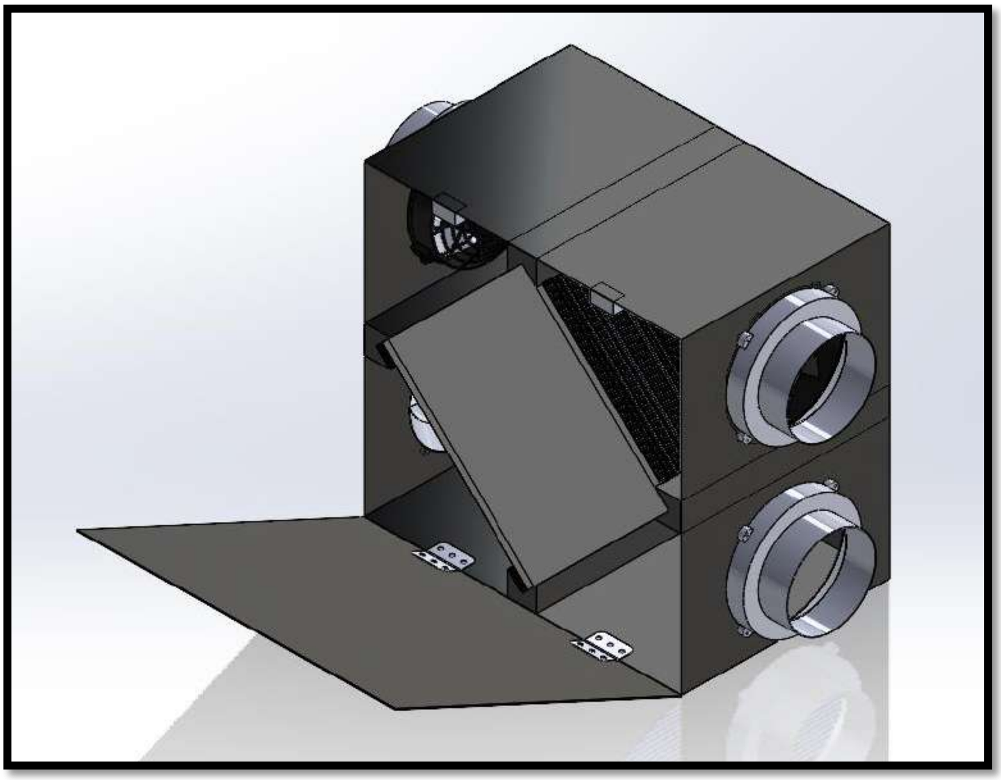


Figure 3.15 Isometric view of final assembly

CHAPTER FOUR: MATERIAL SELECTION, FABRICATION AND TESTING

This chapter encompasses selection of materials and items used and the methodology employed for the fabrication all of which play a crucial role in the project. It also provides an in-depth overview of the processes involved to fabricate each component. It also contains the Arduino coding, Arduino circuit. Furthermore, it delves into a comprehensive analysis of the project's overall cost.

4.1 Materials/Items Selected for ERV

4.1.1 Metal Selection for Core

After consulting various different research articles, we have observed that majority of them have fabricated their metal portion of core using aluminum while some have used steel. So we chose aluminum due to the following reasons;

- Economical
- No need of galvanization
- Higher thermal conductivity (201W/m.K versus 22W/m.K)

The three types of aluminum are; food grade aluminum foil (0.02mm thickness), industrial foil (0.1mm thickness), and aluminum sheet (1mm). The food grade aluminum foil is the best option since it has the highest thermal transfer but is more complex to fabricate due to its minute thickness, while aluminum sheet will be easier to fabricate but lower thermal transfer.

The metal selected for our core is industrial foil (0.1mm thick), a roll was cut into sheets of size 36x36cm, and obtained the requirement of 83 sheets (as shown in Table 3.3), with a few spare sheets.

Figure 4.1 Industrial foil (0.1mm thick)

4.1.2 Membrane Selection for Core

After consulting various articles regarding membrane selection and how membrane can change the effectiveness of an ERV system. Membrane sheets can be made either from polymers or papers. We have narrowed down a few polymers and papers membranes based on various different properties such as;

- **Pore size** - The nominal diameter of the membrane pores is referred to as the "pore size" in most cases. The structure of the membrane is influenced by the size of the pores, which has an impact on how moisture moves through the membrane.
- **Diffusivity/Permeability** – The most crucial aspect of the membranes is moisture diffusivity, or permeability. It shows how much moisture diffuses through a membrane's surface area in a unit of time.
- **Selectivity** - A membrane's capacity to transport water vapor over other air constituents is known as selectivity.

Table 4.1
Properties of paper membranes used in MEEs [42]

Membrane	Thickness (μm)	Porosity	MDR ($m^2.s/kg$)[a]	Moisture diffusivity (m^2/s)	Thermal conductivity (W/m K)
Kraft paper 45 gsm	78	0.0027	95868Δw+42	–	–
Kraft paper 60 gsm	98	0.0029	84988Δw+38.388	–	0.12
Kraft paper 70 gsm	130	–	4168.3Δw	–	–
ER paper	96	–	–	1.78×10^{-7}	0.31
Treated paper	–	–	–	5×10^{-7}	0.18
Plate-paper	100	–	–	3.5×10^{-11}	0.44
LiCl treated paper	42	–	11489.36[b]	3.0×10^{-11}- 3.8×10^{-11}	0.13
Paper membrane	55		–	6.08×10^{-12}	0.44

Table 4.2
Properties of polymer membranes used in MEEs [42]

Membrane	Pore size (μm)	Surface function	Diffusivity (m^2/s)	Thickness (μm)	Porosity	Density (kg/m^3)	Conductivity (W/m K)
Cellulose acetate, AC	–	Hydrophilic	1.05×10^{-11}	5	–	760	0.41
	–	–	3.2×10^{-11}	100	–	836	–
	0.45	–	3.77×10^{-6}		0.75	–	0.127
Polyvinylidene fluoride, PVDF	0.22	–	1.65×10^{-6}	81.6	–	–	–
	0.22	Hydrophilic	1.59×10^{-6}	100	–	–	–
	0.45	Hydrophilic	1.91×10^{-6}	100	–	–	–
Polyethersulfone, PES	0.22	–	6.11×10^{-7}	94.8	–	–	–
	0.1	Hydrophilic	1.57×10^{-6}	100	–	–	–
Cellulose	0.22	–	6.72×10^{-7}	114.6	–	–	–
Polypropylene, PP	–	Hydrophobic	1.6×10^{-12}	32	0.41	370	0.16
	0.156 ± 0.008	–	–	32 ± 2	–	–	–
Polydimethylsiloxane, PDMS		–	–	55	–	–	–
Polyethylene, PE	0.068 ± 0.006	–	–	105 ± 4	–	–	–
Nylon	0.1	Hydrophilic	1.41×10^{-6}	100	–	–	–
	0.45	Hydrophilic	1.50×10^{-6}	100	–	–	–

The two polymers which we have decided are Polyethersulfone (PES) and Cellulose due to their higher diffusivity and selectivity. We have also selected paper membrane as an alternate selection in case there are any ambiguities in the availability of the mentioned polymer-membranes or the lack of funds for the project.

From section 2.6 we have concluded that for our design we have selected a membrane thickness of 0.1mm.

The membrane material selected for our core is kraft paper 60gsm (0.1mm thick) (as shown in Table 4.2**)**, a large sheet was cut into sheets of size 36x36cm, and obtained the requirement of 83 sheets, with a few spare sheets.

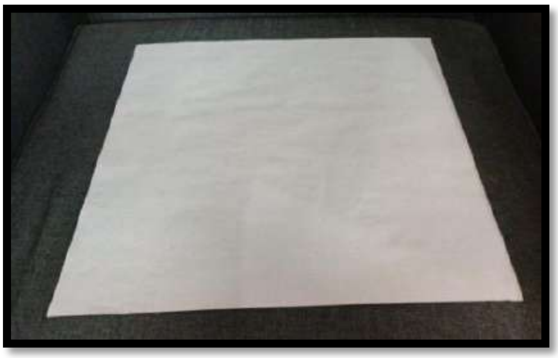


Figure 4.2 Kraft paper 60gsm (0.1mm thick)

4.1.3 Metal Selection for Casing (Body)

Majority of the global companies are using galvanized steel for their construction of the body. Galvanizing is the process in which a coating of zinc is applied on a metal like steel to provide protection, increase toughness and prevent rust. It is usually done by dipping the steel into molten zinc. Galvanized steel is used due to the many benefits offered by it; hence the metal we selected for our body is galvanized steel.

Galvanized steel comes in various different gauges (thickness) and the one we have selected is 19-gauge galvanized steel by taking the ERV product of Venmar as a reference. Venmar is a Canadian manufacturing company making various ventilation products.

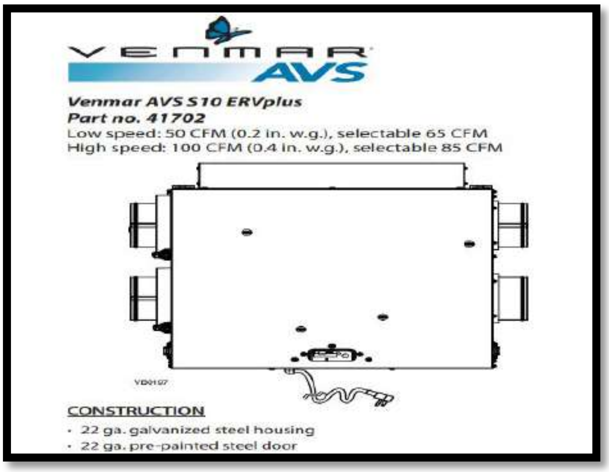


Figure 4.3 Venmar ERV [46]

The material selected for our body is 22 gauge galvanized steel (0.7mm thick), a large sheet of was cut into sheets of our required size.

Figure 4.4 22 Gauge galvanized steel

4.1.4 Acrylic

From section 2.5 we concluded that to keep a balance for all of the effects we have taken a membrane spacing of 2mm for our design.

Acrylic (2mm thick) was used to build the gap of 2mm between a layer of foil and membrane. A 50sq.ft sheet was cut into 540 strips of size 2x36cm, of which 498 fulfilled our requirement (83layers x 6strips per layer), remaining were spare pieces.

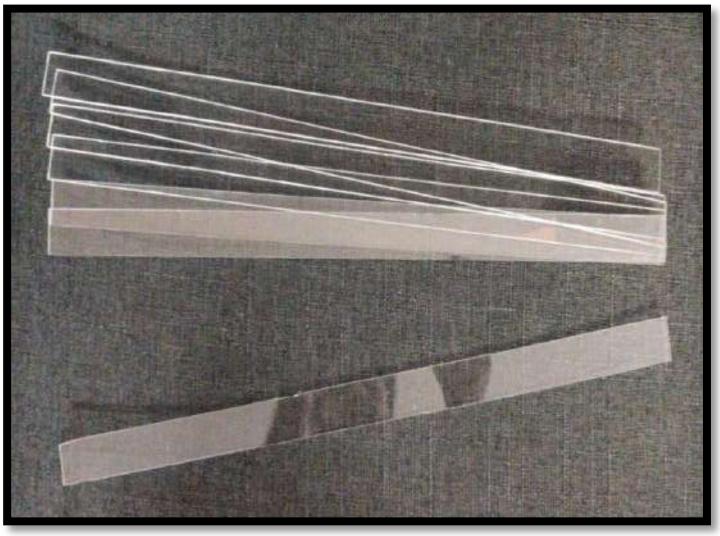


Figure 4.5 Acrylic strips

4.1.5 Fan

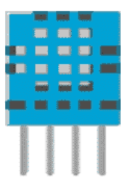
As calculated in 3.2.6 the fan power we needed to meet our CFM requirement was 65W. The diameter of the fan is 8 inch.

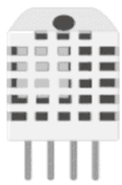
Figure 4.6 65W Fan

4.1.6 Temperature and Humidity Sensor

Temperature and humidity can be measured simultaneously by using a DHT sensor. DHT stands for Digital Humidity and Temperature. The DHT sensor is a low-cost digital temperature and humidity sensor. This sensor is readily interfaced with any microcontroller, such as Arduino and can monitor humidity and temperature in real time. The DHT sensor has two versions; DHT11 and DHT22 [47].

The temperature and humidity sensor that we have selected is DHT11 since its ranges fall in between our requirements of temperature and humidity, and it is cheaper.





	DHT11	DHT22
Operating Voltage	3 to 5V	3 to 5V
Max Operating Current	2.5mA max	2.5mA max
Temperature Range	0-50°C / ± 2°C	-40 to 80°C / ± 0.5°C
Humidity Range	20-80% / 5%	0-100% / 2-5%
Sampling Rate	1 Hz (reading every second)	0.5 Hz (reading every 2 seconds)
Advantage	low cost	More Accurate

Figure 4.7 Characteristics of DHT sensor [47]

4.1.7 Arduino UNO R3

The Arduino Uno R3 is a microcontroller board that is built on a detachable dual-inline-package (DIP) ATmega328 AVR microprocessor. It features 20 digital I/O pins (six of which can be used as PWM outputs and six as analogue inputs). It may be programmed using the simple Arduino computer programme.

Figure 4.8 Arduino UNO R3 [48]

4.1.8 SD Card Module

SD card module can be connected with Arduino UNO R3 which will be used as a data logger. Its purpose would be to store data our sensors data over a long period of time.

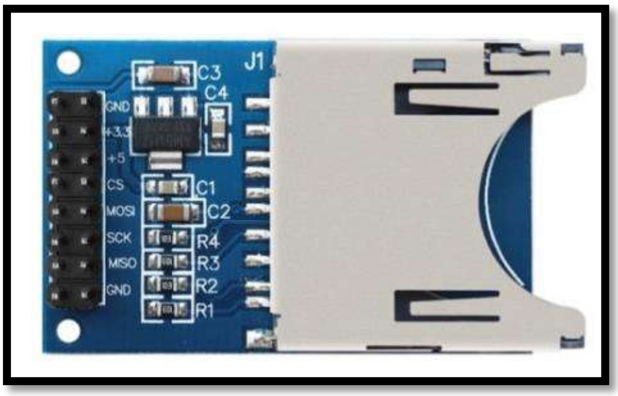


Figure 4.9 SD card module [49]

4.2 Fabrication

By using the final assembly modeled in 3.3.5 as a reference and after selecting all the required items/materials we advanced to the fabrication stage, here we will be discussing the fabrication process as well as the techniques and processes that are used to fabricate.

4.2.1 Core

The core is the most important piece of the ERV, so it had to be made layer by layer with extreme care and delicacy. The core will act as a cross flow heat exchanger. So for the fabrication of the core the following steps were followed;

- **Step 1:** To make a single layer of the core, first start by sticking 3 strips (two on the edges and one at the center of the sheet) of acrylic on a sheet of industrial foil as shown in the following figure.

Figure 4.10 Step 1 of core fabrication

- **Step 2:** Then stick a sheet of kraft paper membrane on the acrylic as shown in the following figure.

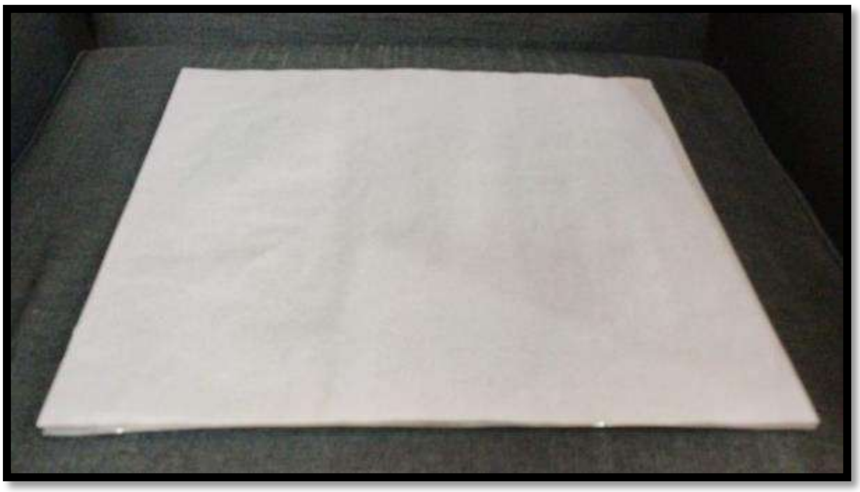


Figure 4.11 Step 2 of core fabrication

- **Step 3:** Then rotate the piece by 90° to make the alternate layer since it's a cross flow heat exchanger, exhaust air and fresh air are not supposed to mix together, so each alternate layer is blocked by acrylic strip. Then stick 3 strips of acrylic (two on the edges and one at the center of the sheet) on the sheet of kraft paper membrane, this completes a single layer as shown in the following figure.

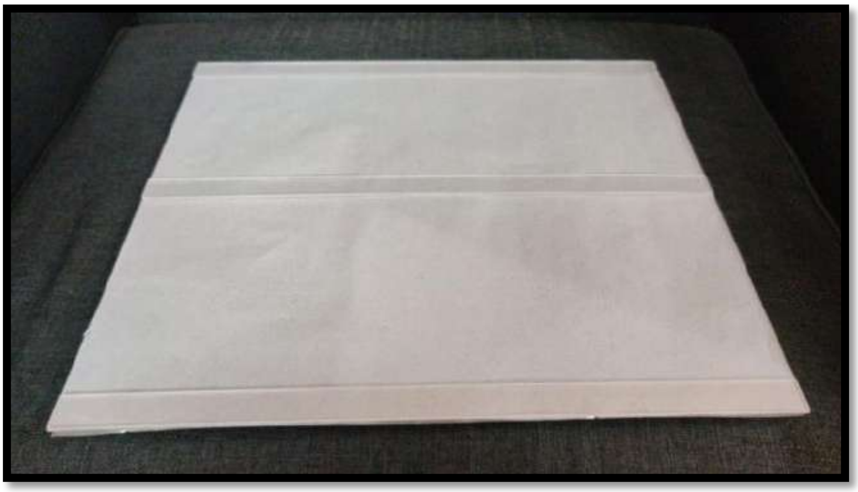


Figure 4.12 Step 3 of core fabrication

- **Step 4:** Further repeat this process 83 times and then stick the individual layers together to make our complete core as shown in the following figure.

Figure 4.13 Step 4 of core fabrication

Figure 4.14 Isometric view of fabricated core

4.2.2 Body

The body is made of galvanized sheets. Each sheet of galvanized steel was folded from the edges so that it can overlap with the fold of another sheet to form the box. Finally, four holes of 8inch diameter were cut on the sides of the box.

Figure 4.15 Folded edges

Figure 4.16 8inch holes

Figure 4.17 Front view of fabricated body

Figure 4.18 Isometric view of fabricated body

4.2.3 Core Brackets

The core brackets are made of galvanized steel and were simply made by bending a small strip of the metal in the middle until an angle of 90° is achieved. They are used to hold the core together in place in the main body.

Figure 4.19 Core brackets

4.2.4 Air Ducts

3D printer was used for the fabrication of the air ducts, since it allows more precise dimensions and also allows us to make amendments according to our requirements in the design. The air ducts were printed in separate parts due to their excessive time required to print and also due to load shedding. These pieces at the end are glued together using elfy. The following pictures show us the mass and time required to print each piece.

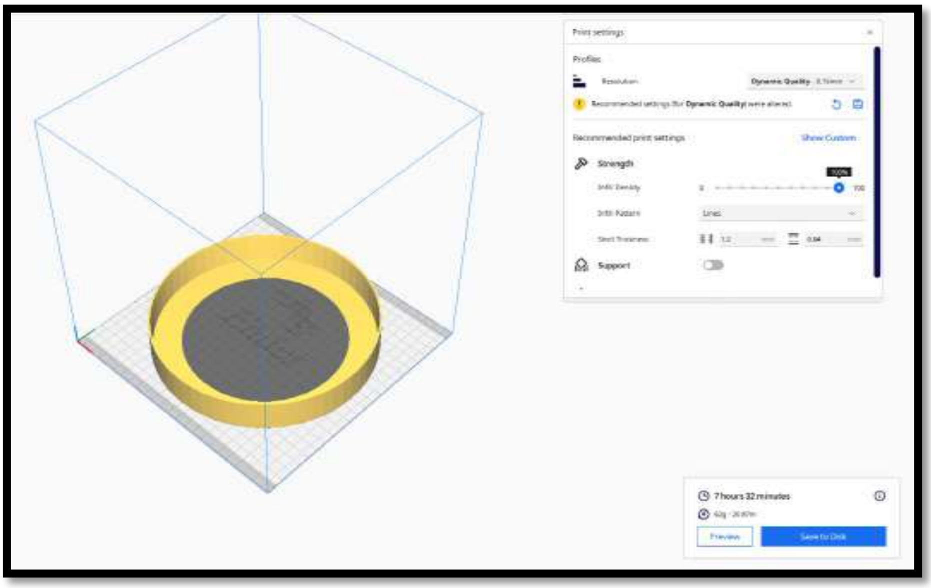


Figure 4.20 Mass and time required to print 8inch duct

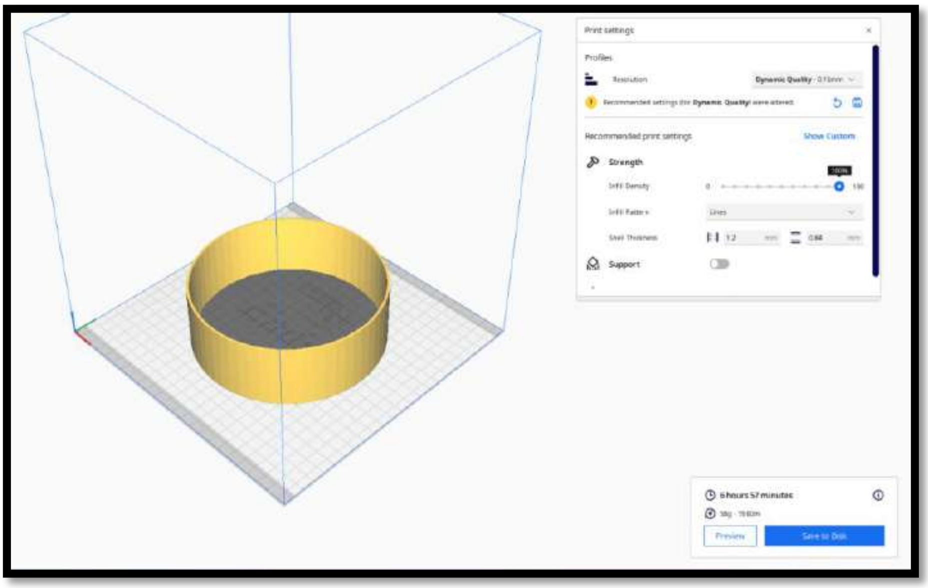


Figure 4.21 Mass and time required to print 6inch duct

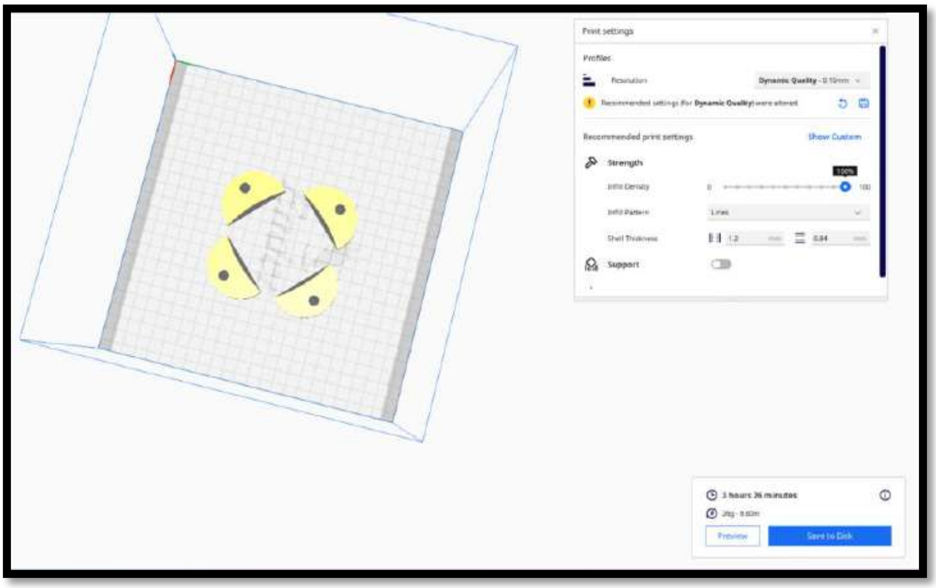


Figure 4.22 Mass and time required to print screw holders

Figure 4.23 3D printed air duct

4.2.5 Final Assembly

The final assembly of the entire Energy Recovery Ventilation (ERV) system involved the meticulous integration of various components. The first component is the core, which functions as a cross-flow heat exchanger between indoor and outdoor airflows. Core brackets were utilized to securely position and align the core in place. Air ducts were incorporated to ensure optimal airflow throughout the system. A bulb was employed as a heating element to simulate the effect of hot outdoor air. Additionally, temperature and humidity sensors were integrated into the system. To achieve an airtight enclosure, a rubber sheet and silicon were utilized to construct a sealed box. Lastly, the system was enclosed within a body that houses all of these aforementioned parts.

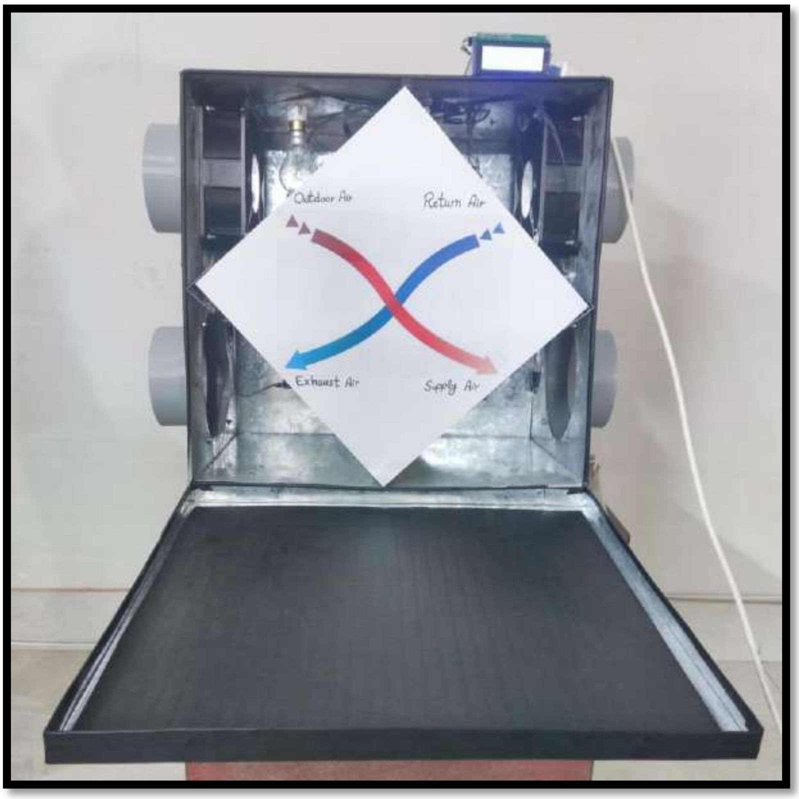


Figure 4.24 Front view of fabricated ERV

Figure 4.25 Isometric view of fabricated ERV

4.3 Testing

For the testing phase, we tested our fabricated ERV in a room by placing it in a partially opened window while covering the top of the opened window using thermopore sheets to close the gap. Various sensors were placed at each of the four ducts of ERV such as temperature and humidity sensor, which were coded and connected with Arduino. Some of the parameters to be tested are latent and sensible heat efficiency, and heat exchanger efficiency.

4.3.1 Arduino Code

The Arduino code required for testing and data logging was done using Arduino 1.8.19. This program stores the temperature and relative humidity readings of our sensors every ten minutes and displays them as well.

```
#include <SPI.h>
#include <SD.h>
#include "DHT.h"
#include <Wire.h>
#include <LiquidCrystal_I2C.h>

#define DHTPIN0 2
#define DHTPIN1 3
#define DHTPIN2 4
#define DHTPIN3 5

#define DHTTYPE DHT11 //or//DHT22

DHT dht0(DHTPIN0, DHTTYPE);
DHT dht1(DHTPIN1, DHTTYPE);
DHT dht2(DHTPIN2, DHTTYPE);
DHT dht3(DHTPIN3, DHTTYPE);

const int chipSelect = 10;  // Chip select pin for the SD card module
File dataFile;  // File object to handle the data file

LiquidCrystal_I2C lcd(0x27, 20, 4); // CHANGE THE 0X27 ADDRESS TO YOUR
SCREEN ADDRESS IF NEEDED

void setup() {
  Serial.begin(9600);
  dht0.begin(); // initialize the sensor
  dht1.begin(); // initialize the sensor
  dht2.begin(); // initialize the sensor
  dht3.begin(); // initialize the sensor

  pinMode(0, INPUT);
  pinMode(1, INPUT);
  // Initialize SD card
  if (!SD.begin(chipSelect)) {
```

```
    Serial.println("SD card initialization failed!");
    return;
  }
  Serial.println("SD card initialized.");
  // Open a new file for writing
  dataFile = SD.open("data.txt", FILE_WRITE);

  // Check if the file opened successfully
  if (!dataFile) {
    Serial.println("Error opening file!");
    return;
  }
  Serial.println("File opened successfully.");
  lcd.init();
  lcd.backlight();
}
void loop() {
  // Write data to the file
  //dataFile.println("Hello, SD card!");
    float humi[4];
    float tempC[4];
    float tempF[4];

  // read humidity
  humi[0]  = dht0.readHumidity();
  // read temperature as Celsius
  tempC[0] = dht0.readTemperature();
  // read temperature as Fahrenheit
  tempF[0] = dht0.readTemperature(true);
// read humidity
  humi[1]  = dht1.readHumidity();
  // read temperature as Celsius
  tempC[1] = dht1.readTemperature();
  // read temperature as Fahrenheit
  tempF[1] = dht1.readTemperature(true);
  // read humidity
  humi[2]  = dht2.readHumidity();
  // read temperature as Celsius
  tempC[2] = dht2.readTemperature();
  // read temperature as Fahrenheit
  tempF[2] = dht2.readTemperature(true);
  // read humidity
  humi[3]  = dht3.readHumidity();
  // read temperature as Celsius
  tempC[3] = dht3.readTemperature();
  // read temperature as Fahrenheit
  tempF[3] = dht3.readTemperature(true);

  // check if any reads failed
  for(int i=0;i<4;i++)
```

```
  {
    if (isnan(humi[i]) || isnan(tempC[i]) || isnan(tempF[i])) {
      Serial.println("Failed to read from DHT sensor!");
    } else {
      if(i==0)
      {
        Serial.println(" Outdoor Air ");
        dataFile.println(" Outdoor Air ");
      }
      else if(i==1)
      {
        Serial.println(" Supply Air ");
        dataFile.println(" Supply Air ");
      }
      else if(i==2)
      {
        Serial.println(" Return Air ");
        dataFile.println(" Return Air ");
      }
      else if(i==3)
      {
        Serial.println(" Exhaust Air ");
        dataFile.println(" Exhaust Air ");
      }

     // Serial.print(" Sensor#");
      //Serial.println(i+1);
      Serial.print("Humidity: ");
      Serial.print(humi[i]);
      Serial.print("%");
      Serial.print("  |  ");
      Serial.print("Temperature: ");
      Serial.print(tempC[i]);
      Serial.print("°C  ");
      Serial.println(""); //to go to next line
//      Serial.print(tempF[i]);
//      Serial.println("°F");
      //dataFile.print(" Sensor#");
      //dataFile.println(i+1);
      dataFile.print("Humidity: ");
      dataFile.print(humi[i]);
      dataFile.print("%");
      dataFile.print("  |  ");
      dataFile.print("Temperature: ");
      dataFile.print(tempC[i]);
      dataFile.print("°C  ");
      dataFile.println(""); //to go to next line
//      dataFile.print(tempF[i]);
//      dataFile.println("°F");
    }
```

```
}

lcd.backlight();
lcd.setCursor(0,0);
lcd.print("Outdoor Air: ");
lcd.setCursor(12,0);
lcd.print(tempC[0]);
lcd.setCursor(14,0);
lcd.print("C");
lcd.setCursor(15,0);
lcd.print(",");
lcd.setCursor(16,0);
lcd.print(humi[0]);
lcd.setCursor(18,0);
lcd.print("% ");
lcd.setCursor(0,1);
lcd.print(" Supply Air:");
lcd.print(tempC[1]);
lcd.setCursor(14,1);
lcd.print("C");
lcd.setCursor(15,1);
lcd.print(",");
lcd.setCursor(16,1);
lcd.print(humi[1]);
lcd.setCursor(18,1);
lcd.print("% ");
lcd.setCursor(0,2);
lcd.print("Return  Air:");
lcd.print(tempC[2]);
lcd.setCursor(14,2);
lcd.print("C");
lcd.setCursor(15,2);
lcd.print(",");
lcd.setCursor(16,2);
lcd.print(humi[2]);
lcd.setCursor(18,2);
lcd.print("% ");
lcd.setCursor(0,3);
lcd.print("Exhaust Air:");
lcd.print(tempC[3]);
lcd.setCursor(14,3);
lcd.print("C");
lcd.setCursor(15,3);
lcd.print(",");
lcd.setCursor(16,3);
lcd.print(humi[3]);
lcd.setCursor(18,3);
lcd.print("% ");

// Flush the data to the card
```

```
  dataFile.flush();

  // Print a message to the serial monitor
  Serial.println("Data written to file.");

  // Wait for 10min
  delay(600000);

}
```

4.3.2 Arduino Circuit Board

The following figure shows the whole circuitry of our project. The major components are Arduino UNO, breadboard, jumper wires, and LCD display.

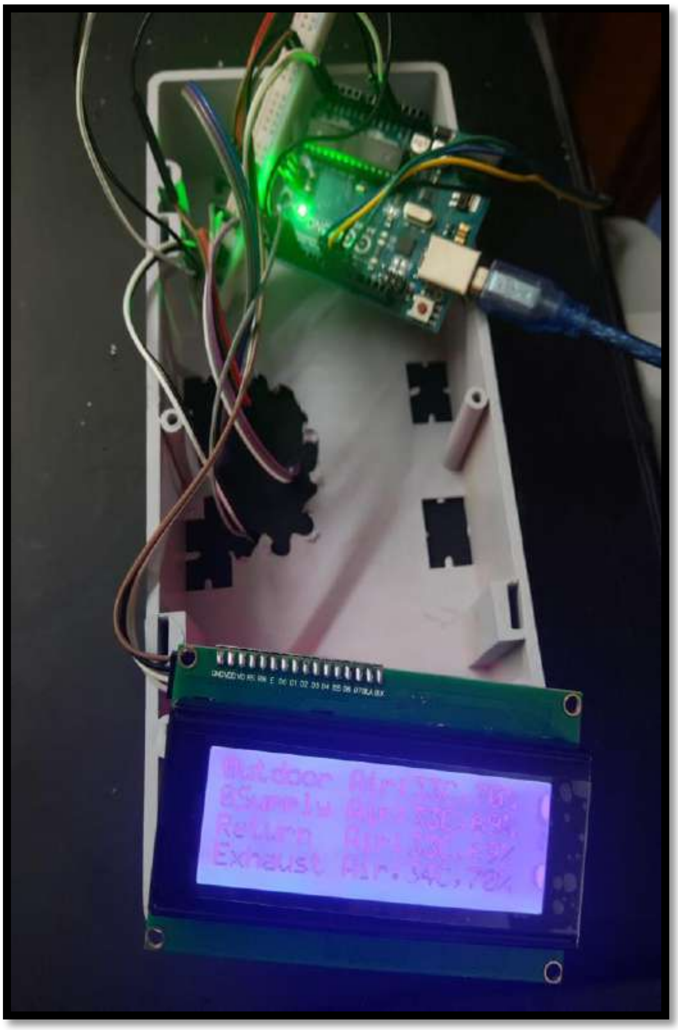


Figure 4.26 Arduino circuit with display

4.4 Costing

Table 4.3 shows all of the details regarding the costing of our project.

Table 4.3

Costing of our project

Sr. No.	Item/Material Name	Per Unit Cost (Rs)	No. of Units	Total (Rs)
1.	Industrial foil (0.1mm thick)	700 Rs/kg	5.5 kg	3,850
2.	Industrial foil cutting	-	90 sheets	1,450
3.	Membrane	300 Rs/kg	1 kg	300
4.	Membrane cutting	-	90 sheets	300
5.	Acrylic	160 Rs/sq.ft	50 sq.ft	8,000
6.	Acrylic cutting	-	540 pieces	800
7.	Galvanized steel (22gauge)	610 Rs/kg	9 kg	5,500
8.	Body fabrication	-	-	2,000
9.	Rubber sheet	600 Rs/sq.ft	2 sq.ft	1,200
10.	3D printer PLA filament	3000 Rs/kg	1 kg	3,000
11.	Black wrap	-	-	2,700
12.	Samad Bond	400 Rs/can	10 cans	4,000
13.	Sand Paper	250	2	500
14.	65W Fan	3800	2	7,600
15.	Temperature and humidity sensor (DHT-11)	230	4	920
16.	Dimmer	250	1	250
17.	Jumper wires	150 Rs/wire	4	450
18.	Breadboard	220	1	200
19.	Arduini UNO R3	1850	1	1,850
20.	SD card module	120	1	120
21.	9 volt 1 ampere adapter	200	1	200
22.	Display (I2C – 4x20)	900	1	900
23.	Convertor LCD 16 to 4	220	1	220
24.	Miscellaneous items	-	-	2,000
25.	Travelling costs	-	-	5,000
26.	Thesis printing and binding	-	-	10,000
			Total (Rs)	**63,310**

CHAPTER FIVE: RESULTS AND DISCUSSION

Within this chapter, we present the data concerning the testing process and engage in a thorough discussion of the results obtained for various parameters. Moreover, we address the limitations encountered during the course of our project, providing an analysis of the challenges faced. This section aims to offer a comprehensive overview of the experimental outcomes, fostering a deeper understanding of the project's performance and highlighting the boundaries and constraints that influenced our research.

5.1 Results

5.1.1 Acquired CFM

We used anemometer to measure the air speed which was further used to calculate CFM. It was observed that the acquired CFM is approximately equal to the CFM which was calculated in our designing phase.

Figure 5.1 Acquired air speed (m/s)

Equation (18) was used to find the CFM using our acquired air speed.

$$CFM = Air\ speed\left(\frac{ft}{min}\right) \times Duct\ area\ (ft^2) \tag{18}$$

$$CFM = 4.84 \times 196.85 \times \pi \times \left(\frac{4}{12}\right)^2$$

$$CFM = \dot{V} = 332.6\frac{ft^3}{min}$$

5.1.2 Data Obtained and Calculations

Following is the data that was obtained through data logging as shown in Table 5.1 which was obtained during the testing phase of the project. This data was used to calculate the efficiencies as well as their graphs.

Equations (19) to (25) were taken from a research article [50].

Table 5.1

Results of testing day 1

Day 1								
	Regions							
	Outdoor Air		Supply Air		Return Air		Exhaust Air	
Time(min)	Temperature (C°) t_{out}	Relative Humidity (%) h_{out}	Temperature (C°) t_{sup}	Relative Humidity (%) h_{sup}	Temperature (C°) t_{ret}	Relative Humidity (%) h_{ret}	Temperature (C°) t_{exh}	Relative Humidity (%) h_{exh}
0	42.1	45.6	32.7	55.8	28.8	63.6	32.2	55.0
10	42.4	46.0	32.3	55.5	28.2	63.9	32.4	55.6
20	42.0	46.0	32.7	55.3	28.8	63.2	32.5	55.6
30	42.3	45.7	32.6	55.1	28.5	63.3	32.4	55.9
40	43.0	45.8	33.0	55.9	28.0	63.6	32.5	55.3
50	42.5	45.6	32.8	56.0	28.1	63.3	32.9	55.3
60	42.9	46.0	32.7	55.1	28.4	63.3	32.5	55.8
70	42.7	46.0	32.9	55.7	28.9	63.7	32.0	55.7
80	42.6	45.9	32.8	55.1	28.6	63.0	32.9	55.1
90	42.9	45.6	32.3	54.4	28.5	63.2	32.2	55.2
100	42.4	45.7	32.7	55.2	27.9	63.2	31.9	55.1
110	42.7	45.8	32.4	55.7	28.5	63.6	32.1	55.1
120	42.7	45.6	32.8	55.0	28.8	63.7	32.9	55.0
130	42.5	45.7	32.4	55.7	27.8	63.6	32.3	55.4
140	42.7	45.8	32.8	54.7	29.0	63.6	31.9	55.1
150	42.8	45.7	32.8	54.4	28.8	63.9	31.9	55.4
160	42.8	45.6	32.3	54.4	28.4	63.6	32.9	55.0
170	42.9	45.9	32.4	55.5	28.7	63.4	32.7	56.0
180	42.9	45.6	32.9	54.8	27.6	63.7	32.9	55.1
Mean =	**42.6**	**45.8**	**32.7**	**55.2**	**28.4**	**63.5**	**32.4**	**55.4**
Humidity Ratio W = (kg/kg)	**0.0248**		**0.0172**		**0.0155**		**0.0170**	
Energy consumption without ERV system = Q =			**18**	**kW**				
Fresh air volume = $\dot{V}$ =			**332.60 cfm =**	**156.96 L/s**				
Sensible heat exchange efficiency = η_S =			**70.21**	**%**				
Latent heat exchange efficiency = η_L =			**53.35**	**%**				
Overall heat exchanger efficiency = η_{ERV} =			**61.78**	**%**				
Sensible load = q_S =			**1.92**	**kW**				
Latent load = q_L =			**3.58**	**kW**				
Total load = ΔQ_{ERV} =			**5.50**	**kW**				
Energy saving percentage = Δ% =			**30.57**	**%**				

$$\eta_t = \frac{(t_{out} - t_{sup})}{(t_{out} - t_{ret})} \times 100\% \tag{19}$$

$$\eta_t = \frac{(42.6 - 32.7)}{(42.6 - 28.4)} \times 100\%$$

$$\eta_t = 70.21\%$$

$$\eta_h = \frac{(h_{out} - h_{sup})}{(h_{out} - h_{ret})} \times 100\% \tag{20}$$

$$\eta_h = \frac{(45.8 - 55.2)}{(45.8 - 63.5)} \times 100\%$$

$$\eta_h = 53.35\%$$

$$\eta_{ERV} = \frac{\eta_t + \eta_h}{2} \times 100\% \tag{21}$$

$$\eta_{ERV} = \frac{70.21 + 53.35}{2} \times 100\%$$

$$\eta_{ERV} = 61.78\%$$

$$q_S = 1.23\dot{V}(\,t_{out} - t_{sup}) \tag{22}$$

$$q_S = 1.23 \times 156.96(\,42.6 - 32.7)$$

$$q_S = 1.92kW$$

$$q_L = 3000\dot{V}(\,W_{out} - W_{sup}) \tag{23}$$

$$q_L = 1.23 \times 156.96(\,0.0248 - 0.0172)$$

$$q_L = 3.58kW$$

$$\Delta Q_{ERV} = q_S + q_L \tag{24}$$

$$\Delta Q_{ERV} = 1.92 + 3.58$$

$$\Delta Q_{ERV} = 5.50kW$$

$$\Delta\% = \frac{\Delta Q_{ERV}}{Q} \tag{25}$$

$$\Delta\% = \frac{5.50}{18} \times 100\%$$

$$\Delta\% = 30.57\%$$

Same process was repeated for days 2–5 and the results are shown in Table 5.2.

Table 5.2
Results of ERV testing

Parameters	Day 1	Day 2	Day 3	Day 4	Day 5
Mean t_{out} (°C)	42.6	43.3	42.0	39.7	40.0
Mean h_{out} (%)	45.8	44.7	47.7	48.7	48.8
Mean t_{sup} (°C)	32.7	32.3	32.6	32.1	32.1
Mean h_{sup} (%)	55.2	55.3	55.6	55.5	55.7
Mean t_{ret} (°C)	28.4	28.3	28.3	28.2	28.2
Mean h_{ret} (%)	63.5	63.5	63.5	63.6	63.4
Mean t_{exh} (°C)	32.4	31.1	31.3	31.4	31.5
Mean h_{exh} (%)	55.4	57.5	56.5	56.4	56.5
Sensible heat exchange efficiency η_S (%)	70.21	73.12	68.25	66.04	67.42
Latent heat exchange efficiency η_L (%)	53.35	56.15	50.12	45.89	47.22
Overall heat exchanger efficiency η_{ERV} (%)	61.78	64.63	59.19	55.97	57.32
Sensible load q_S (kW)	1.92	2.21	1.81	1.46	1.54
Latent load q_L (kW)	3.58	3.86	3.63	3.11	3.39
Total load ΔQ_{ERV} (kW)	5.50	5.98	5.44	4.57	4.93
Energy saving percentage Δ%	30.57	33.23	30.21	25.38	27.39

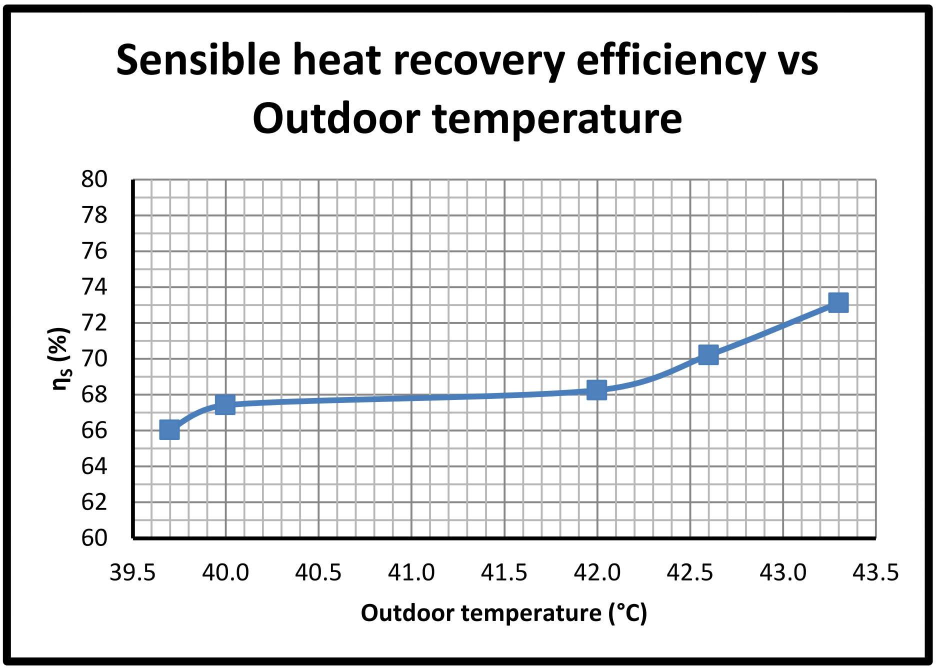


Figure 5.2 Sensible heat recovery efficiency under different outdoor temperatures when indoor temperature is 26 °C

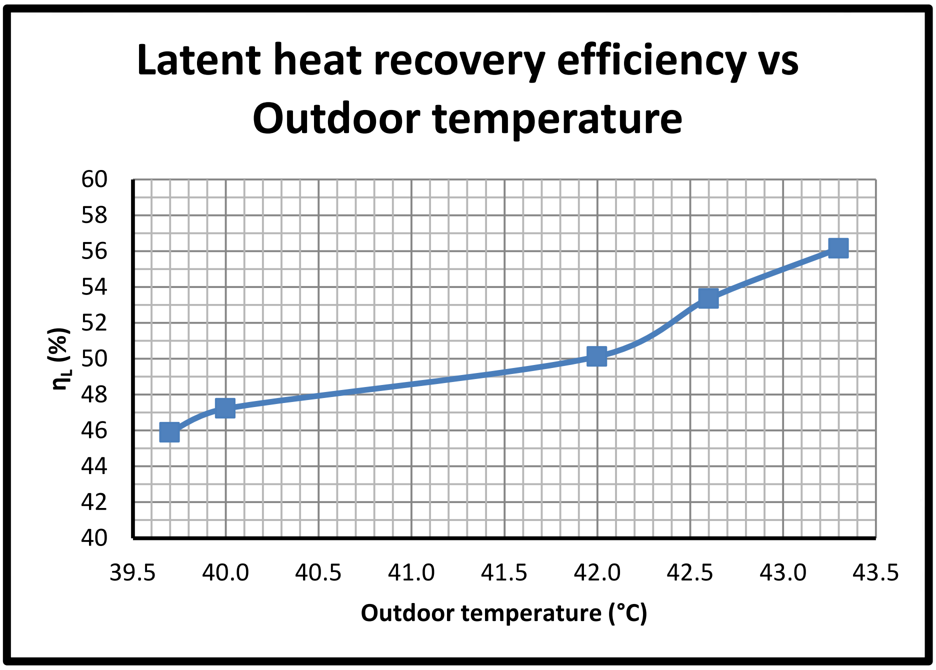


Figure 5.3 Latent heat recovery efficiency under different outdoor temperatures when indoor temperature is 26 °C

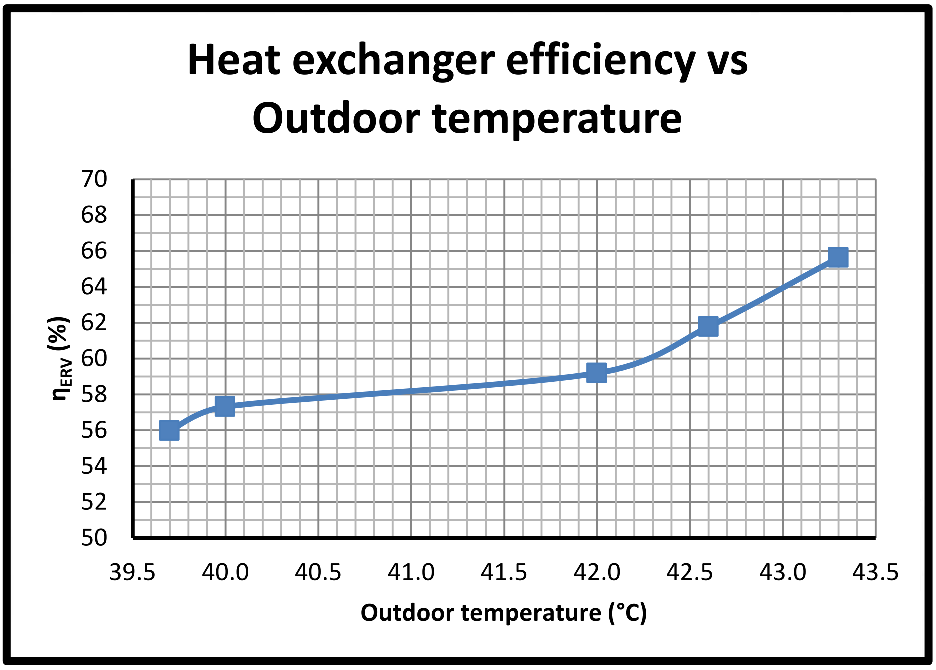


Figure 5.4 Heat exchanger efficiency under different outdoor temperatures when indoor temperature is 26 °C

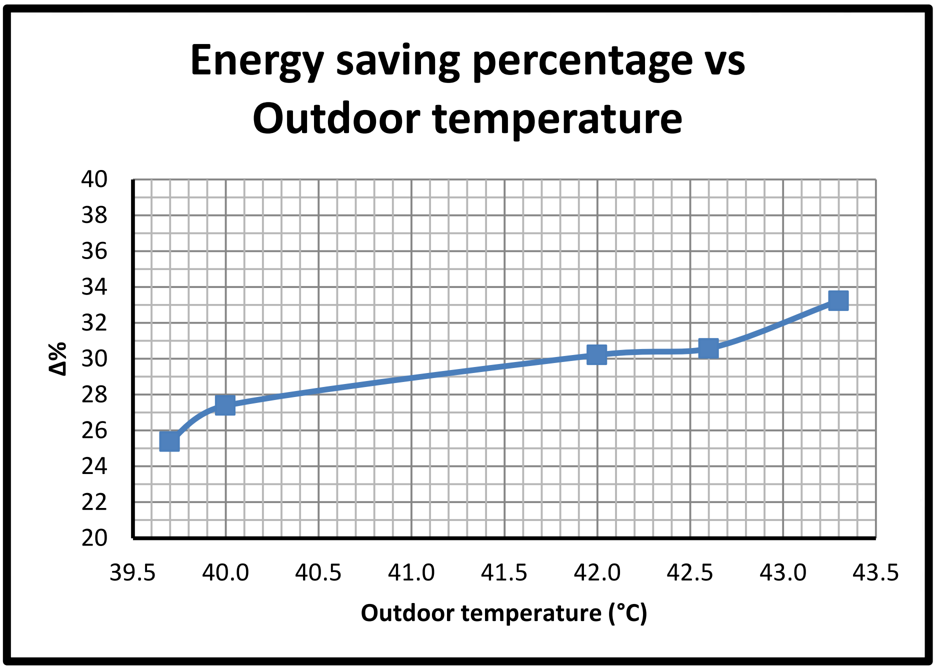


Figure 5.5 Energy saving percentage under different outdoor temperatures when indoor temperature is 26 °C

5.2 Discussion

When the indoor temperature in an Energy Recovery Ventilator (ERV) is kept constant and the outdoor temperature increases, several factors come into play that can lead to increased latent efficiency, sensible efficiency, overall efficiency, and energy savings.

- **Acquired CFM:** During our designing phase we calculated the CFM required for a room with 20 people, and our project was able to achieve approximately the same CFM as calculated. From equation (18) we concluded that our calculated CFM was $336.8\frac{ft^3}{min}$ and our acquired CFM was $332.6\frac{ft^3}{min}$.
- **Latent Efficiency:** Latent efficiency refers to the ability of an ERV to transfer moisture or humidity between the incoming and outgoing air streams. As the outdoor temperature rises, the ERV's latent efficiency increases. This is because warmer outdoor air typically holds more moisture, and when it passes through the ERV, the moisture is transferred to the cooler outgoing air stream. By transferring moisture, the ERV helps maintain a more comfortable indoor humidity level, reducing the load on the cooling system and potentially saving energy. From Figure 5.2 we concluded that our ERV system was able to achieve a latent efficiency ranging from 45-55% depending on the varying weather conditions.
- **Sensible Efficiency:** Sensible efficiency refers to the ability of an ERV to transfer heat between the incoming and outgoing air streams without any moisture exchange. When the outdoor temperature increases, the sensible efficiency of an ERV also tends to improve. This is because there is a greater temperature difference between the warm outdoor air and the cooler indoor air. As a result, the ERV can recover more heat from the outgoing air and transfer it to the incoming air. This helps reduce the load on the heating or cooling system, leading to energy savings. From Figure 5.3 we concluded that our ERV system was able to achieve a sensible efficiency ranging from 65-70% depending on the varying weather conditions.
- **Heat Exchanger Efficiency:** The overall efficiency of an ERV is a combination of the latent and sensible efficiencies. As both latent and sensible efficiencies increase with rising outdoor temperatures, the overall efficiency of the ERV improves as well. This means that the ERV is better at recovering both heat and moisture from the outgoing air, resulting in greater energy savings and improved indoor comfort. From Figure 5.4 we concluded that our ERV system was able to achieve an overall efficiency ranging from 57-62% depending on the varying weather conditions.
- **Energy Savings:** When an ERV operates with higher latent and sensible efficiencies, it helps reduce the load on the heating, ventilation, and air conditioning (HVAC) system. By transferring heat and moisture between the incoming and outgoing air streams more effectively, the ERV reduces the demand for heating or cooling energy. This leads to energy savings since the HVAC system doesn't have to work as hard to maintain the desired indoor temperature. Consequently, lower energy consumption translates into reduced utility costs. From Figure 5.5 we concluded that our ERV

system was able to achieve a latent efficiency ranging from 27-31% depending on the varying weather conditions.

In summary, when the indoor temperature in an ERV is kept constant and the outdoor temperature increases, the latent efficiency, sensible efficiency, overall efficiency, and energy savings all tend to improve. The ERV effectively transfers both heat and moisture between the incoming and outgoing air streams, reducing the load on the HVAC system and promoting energy-efficient operation.

5.3 Limitations

Following are the limitations that were faced by us during this project. It compromises of various factors ranging of unavailability of materials to proper required processes or technology;

- **Unavailability and high cost of polymer membranes in Pakistan:** A significant challenge we faced was the unavailability and high cost of polymer membranes, leading us to opt for paper membranes instead. While paper membranes are inexpensive and readily available, they have a shorter lifespan, necessitating the replacement of the core on an annual basis. To overcome this limitation, it is crucial to explore alternative sources or suppliers for polymer membranes. Additionally, efforts should be made to establish local manufacturing capabilities to reduce costs and improve accessibility. By incorporating durable and long-lasting polymer membranes into the ERV system, we can enhance its efficiency and reduce maintenance requirements.
- **Lack of proper cutting machinery or process:** Another limitation we encountered was the lack of proper cutting machinery or processes, resulting in deviations in the overall sizes of layers and other project-related objects. This lack of precision and accuracy in cutting can have a significant impact on the overall performance and functionality of the ERV system. To address this limitation, it is imperative to invest in advanced cutting technology that can achieve the required dimensions with higher precision and accuracies. Collaborations with industry partners or research institutions specializing in manufacturing processes can provide valuable insights and expertise in this regard.
- **Immobility of the core due to silicone sealing:** The utilization of silicone for creating a vacuum seal inside the ERV system led to the immobility of the core. This restriction made it challenging to replace the core when necessary, potentially affecting the overall maintenance and functionality of the system. To mitigate this limitation, an alternative sealing solution should be explored. One potential approach could be to incorporate rubber lining on the sides of the layers, ensuring a tight seal that prevents air intermixing while allowing for the mobility of the core. This modification would significantly enhance the ease of maintenance and facilitate core replacements, thereby improving the longevity and efficiency of the ERV system.

- **Fragility of kraft paper and the need for additional acrylic:** The fragility of the kraft paper used in our project required the attachment of additional acrylic in the center of each layer to maintain the air gap necessary for airflow. However, this resulted in a decrease in the volume available for air flow. To overcome this limitation, it is crucial to explore the use of higher-quality kraft paper with enhanced structural integrity. By utilizing sturdier kraft paper, we can eliminate the need for additional acrylic, thereby increasing the volume available for air flow and improving the ventilation efficiency of the ERV system.
- **Unavailability of '3-Layer Filter':** An important aspect of ensuring better health and well-being is filtering the incoming fresh air before it enters the room. Unfortunately, the unavailability of '3-Layer Filters' in Pakistan prevented us from implementing such filters in our project. To address this limitation, efforts should be made to establish local manufacturing or distribution channels for '3-Layer Filters' or suitable alternatives. Collaborations with air filtration companies or researchers specializing in indoor air quality can aid in identifying or developing appropriate filters that can effectively remove pollutants, allergens, and contaminants from the incoming fresh air, thereby significantly enhancing indoor air quality.

Basically, the limitations encountered during the development and implementation of the ERV system in our thesis project serve as valuable learning experiences and provide clear directions for future improvements. Addressing the unavailability and high cost of polymer membranes, investing in advanced cutting technology, exploring alternative sealing solutions, utilizing higher-quality kraft paper, and establishing local manufacturing or distribution channels for air filters are critical steps for enhancing the performance, durability, and efficiency of ERV systems. By overcoming these limitations, we can contribute to better indoor air quality, energy conservation, and overall well-being. Future research should focus on these areas to unlock the full potential of ERV systems and promote sustainable and healthy environments.

CHAPTER SIX: CONCLUSION AND FUTURE DIRECTION

This chapter focuses on the conclusions drawn from our project, highlighting the key findings and insights gained. Additionally, it explores potential future directions for enhancing overall efficiencies and introducing automation. These future directions may involve implementing technologies such as automated human detection to dynamically adjust fan speeds. By presenting these possibilities, we aim to provide a roadmap for further advancements in the field, aiming for improved performance and increased functionality in the system.

6.1 Conclusion

In conclusion, the design, production, and testing of a membrane-based energy recovery ventilator (ERV) were the main focuses of this thesis project. The major goal was to create an innovative system that could reuse and recover energy from exhaust air streams, enhancing indoor air quality while consuming less energy.

During the testing phase, a thorough evaluation of performance under different operating conditions was conducted. Impressive heat and moisture transfer abilities were displayed by the ERV, which successfully recovered energy from the exhaust air stream and transferred it to the entering fresh air. The trial findings revealed considerable improvements in indoor air quality together with a concurrent decrease in energy use, resulting in more sustainable and effective building operations. Our ERV system was able to achieve a latent efficiency ranging from 45-55%, sensible efficiency of 65-70%, overall efficiency of 57-62% and energy saving of 27-31% depending on the varying weather conditions.

The ERV design can be improved in the future to increase efficiency even more. Other research options include examining other membrane materials and configurations as well as possible integration with renewable energy sources. To enable the system's wide adoption and application in various building types and climates, it should also be evaluated for scalability and cost-effectiveness.

Overall, the understanding and practical use of membrane-based energy recovery ventilators have improved as a result of this thesis study. The designed ERV system has the ability to significantly improve sustainable building practices and people's health by tackling the crucial issues of energy efficiency and indoor air quality in buildings.

6.2 Future Direction

Following are the areas where there is room for improvement as well as new technologies that can be implemented in an ERV system.

- **Using more efficient materials for thermal transfer:** To increase the overall efficiency of the ERV system, it is essential to explore the use of advanced materials that offer superior thermal transfer properties. Instead of relying solely on traditional polymer or paper membranes, we recommend investigating innovative materials such as advanced ceramics or metal alloys. These materials possess enhanced heat transfer capabilities, enabling more efficient energy recovery and increasing the air conditioning loads of conditioned spaces. Rigorous testing and careful selection of suitable materials will be crucial to ensure their compatibility, durability, and effectiveness within the ERV system.

- **Implementation of automation in the ERV system:** The integration of automation technologies can significantly enhance the performance and efficiency of the ERV system. By incorporating sensors and controls into the system, real-time monitoring and control can be achieved, ensuring optimal operation. A Building Management System (BMS) can be utilized to collect data on temperature, humidity, and air quality, facilitating intelligent decision-making and optimization of the ERV system's performance. For instance, the installation of laser detection systems at building entrances and exits can enable the ERV system to detect occupancy levels and dynamically adjust its parameters, such as fan speed and ventilation rates, accordingly. This adaptive approach maximizes energy efficiency while maintaining optimal indoor air quality.
- **Corrugated membranes for increased efficiency:** To optimize heat and moisture transfer, we suggest utilizing corrugated membranes in the core of the ERV system instead of flat or straight membranes. The corrugated design offers a larger surface area for air to come into contact with the layers, facilitating improved transfer of sensible and latent heat. Moreover, the inherent turbulence created within the core by the corrugated membranes allows for a longer residence time of the air, further enhancing the transmission of heat. By incorporating corrugated membranes, the overall efficiency of the ERV system can be significantly improved, resulting in enhanced energy recovery and reduced operating costs.

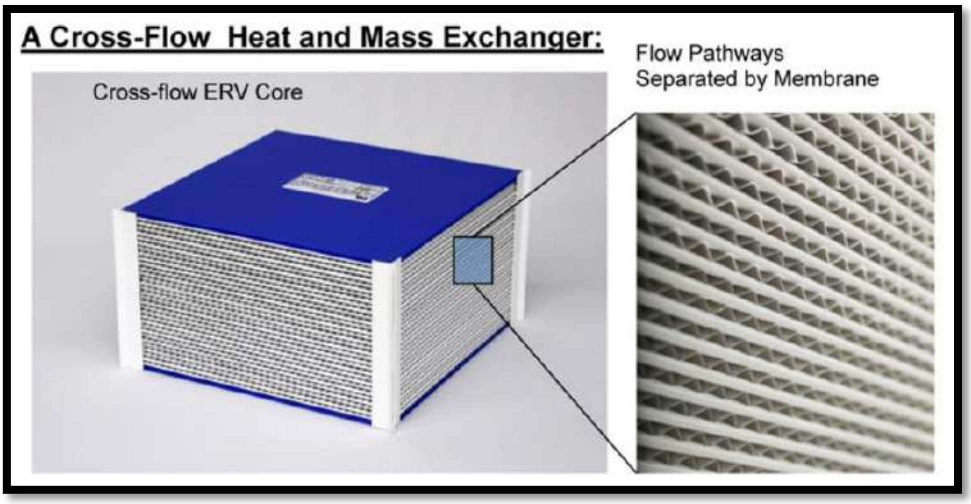


Figure 6.1 Corrugated membranes [51]

- **Introduction of new fabrication methods and efficiency enhancement techniques:** As ERV technology continues to evolve, it is imperative to embrace new fabrication methods and techniques that can further enhance system efficiency and performance. This can involve the development of innovative manufacturing processes, novel heat exchanger designs, and advanced control algorithms. Collaboration with experts in the field and staying up to date with the latest research and advancements will be essential in exploring and implementing these cutting-edge approaches. By continuously innovating and refining ERV fabrication and efficiency enhancement techniques, we can unlock the full potential of the technology and drive its adoption on a larger scale.

- **Alternative bonding methods for core fabrication:** While our project utilized glue for core layer fabrication, we acknowledge the need to explore alternative bonding methods that are more practical for mass production and long-term durability. Welding or utilizing frames to house all the layers present promising options. These alternative bonding methods offer enhanced structural integrity, minimizing maintenance requirements and facilitating scalable production of ERV systems. By ensuring robust and reliable core fabrication, the performance and longevity of the ERV system can be greatly improved.
- **Usage of better filters for improved air quality:** As the focus on health and indoor air quality intensifies, it is crucial to implement advanced filtration methods and employ high-quality filters in the ERV system. The incorporation of efficient air filters capable of capturing a wide range of pollutants, allergens, and contaminants is essential. Additionally, exploring innovative air purification technologies, such as UV-C germicidal lamps or electrostatic precipitators, can further enhance the air quality provided by the ERV system. This multi-layered filtration approach ensures the delivery of clean and healthy indoor air, promoting occupant well-being and comfort.

In short, our thesis project has provided valuable insights into the limitations and potential improvements of ERV systems. By focusing on the usage of efficient materials, implementing automation technologies, enhancing air filtration methods, utilizing corrugated membranes, exploring alternative bonding methods, and fostering innovation in fabrication and efficiency enhancement, we can contribute to the continued advancement and widespread adoption of ERV technology. These future directions open up numerous research opportunities and hold the potential to significantly improve energy efficiency, indoor air quality, and occupant comfort in buildings. The ongoing pursuit of these areas will drive progress in the field and lead to sustainable and healthier built environments.

REFERENCES

[1] Ryan-R-Hoger. (2009, July 31). The facts about energy recovery ventilators. Architect. Retrieved January 27, 2023, from https://www.architectmagazine.com/technology/products/the-facts-about-energy-recovery-ventilators_o.

[2] T., C. (2020, March 28). Types of energy recovery ventilation system. https://www.linkedin.com/pulse/types-energy-recovery-ventilation-system-cici-tau/

[3] Ponschok, D. (2018, August 2). Heat Recovery Ventilator(HRV) vs Energy Recovery Ventilator(ERV): What's the Right Unit for Your Home? EP Sales Inc. https://www.epsalesinc.com/heat-recovery-ventilator-hrv-vs-energy-recovery-ventilator-erv-whats-right-unit-home/

[4] Heat pipe heat exchangers. https://www.holtop.com/. Retrieved January 27, 2023, from https://www.holtop.com/heat-pipe-heat-exchangers.html

[5] Davidson. (n.d.). Finned tube coil heat exchangers - UK Exchangers Ltd - Heat Transfer Specialists. http://www.uk-exchangers.com/. Retrieved January 27, 2023, from https://www.uk-exchangers.com/heat-exchange-products/finned-tube-coil-heat-exchangers/

[6] Gibson, S. (2022, October 10). Balanced Ventilation with HRVs and ERVs. GreenBuildingAdvisor. https://www.greenbuildingadvisor.com/article/balanced-ventilation-with-hrvs-and-ervs

[7] Team, L. (2021, January 11). Energy Recovery Ventilator (ERV): Installation, Types & Advantages | Linquip. Industrial Manufacturing Blog | Linquip. https://www.linquip.com/blog/energy-recovery-ventilator/

[8] Venmar. (2014, April 8). Venmar AVS - S Series (S10 ERV and S10 ERV Plus) [Video]. YouTube. https://www.youtube.com/watch?v=ELxSE2_fIWY

[9] THE 17 GOALS | Sustainable Development. (n.d.). https://sdgs.un.org/goals

[10] Wikipedia contributors. (2022, December 11). Sustainable Development Goal 3. Wikipedia. https://en.wikipedia.org/wiki/Sustainable_Development_Goal_3

[11] Wikipedia contributors. (2022a, December 2). Sustainable Development Goal 12. Wikipedia. https://en.wikipedia.org/wiki/Sustainable_Development_Goal_12

[12] Liu, X., Li, Z., Jiang, Y., & Lin, B. (2006). Annual performance of liquid desiccant based independent humidity control HVAC system. Applied Thermal Engineering, 26(11-12), 1198-1207

[13] Zhang, L. Z., & Jiang, Y. (1999). Heat and mass transfer in a membrane-based energy recovery ventilator. Journal of Membrane Science, 163(1), 29-38.

[14] Zhang, Y., Jiang, Y., Zhang, L. Z., Deng, Y., & Jin, Z. (2000). Analysis of thermal performance and energy savings of membrane based heat recovery ventilator. Energy, 25(6), 515-527.

[15] Ürge-Vorsatz, D., Cabeza, L. F., Serrano, S., Barreneche, C., & Petrichenko, K. (2015). Heating and cooling energy trends and drivers in buildings. Renewable and Sustainable Energy Reviews, 41, 85-98.

[16] Cuce, P. M., & Riffat, S. (2015). A comprehensive review of heat recovery systems for building applications. Renewable and Sustainable Energy Reviews, 47, 665-682.

[17] Zhang, L. Z. (2012). Progress on heat and moisture recovery with membranes: From fundamentals to engineering applications. Energy Conversion and Management, 63, 173-195.

[18] Alonso, M. J., Liu, P., Mathisen, H. M., Ge, G., & Simonson, C. (2015). Review of heat/energy recovery exchangers for use in ZEBs in cold climate countries. Building and Environment, 84, 228-237.

[19] Engarnevis, A., Huizing, R., Green, S., & Rogak, S. (2018). Heat and mass transfer modeling in enthalpy exchangers using asymmetric composite membranes. Journal of Membrane Science, 556, 248-262.

[20] O'Connor, D., Calautit, J. K. S., & Hughes, B. R. (2016). A review of heat recovery technology for passive ventilation applications. Renewable and Sustainable Energy Reviews, 54, 1481-1493.

[21] Qu, M., Abdelaziz, O., Gao, Z., & Yin, H. (2018). Isothermal membrane-based air dehumidification: A comprehensive review. Renewable and Sustainable Energy Reviews, 82, 4060-4069.

[22] Zhang, X. R., Zhang, L. Z., Liu, H. M., & Pei, L. X. (2011). One-step fabrication and analysis of an asymmetric cellulose acetate membrane for heat and moisture recovery. Journal of Membrane Science, 366(1-2), 158-165.

[23] Min, J., & Su, M. (2010). Performance analysis of a membrane-based enthalpy exchanger: Effects of the membrane properties on the exchanger performance. Journal of Membrane Science, 348(1-2), 376-382.

[24] Zhang, L. Z. (2016). A reliability-based optimization of membrane-type total heat exchangers under uncertain design parameters. Energy, 101, 390-401.

[25] Sabek, S., Tiss, F., Chouikh, R., & Guizani, A. (2016). Numerical investigation of membrane based heat exchanger with partially blocked channels. Applied Thermal Engineering, 104, 203-211.

[26] Zhang, L. Z. (2010). Heat and mass transfer in a quasi-counter flow membrane-based total heat exchanger. International Journal of Heat and Mass Transfer, 53(23-24), 5478-5486.

[27] Liu, X., Qu, M., Liu, X., & Wang, L. (2019). Membrane-based liquid desiccant air dehumidification: A comprehensive review on materials, components, systems and performances. Renewable and Sustainable Energy Reviews, 110, 444-466.

[28] Alkhudhiri, A., Darwish, N., & Hilal, N. (2012). Membrane distillation: A comprehensive review. Desalination, 287, 2-18.

[29] Liu, P., Alonso, M. J., Mathisen, H. M., & Simonson, C. (2016). Performance of a quasi-counter-flow air-to-air membrane energy exchanger in cold climates. Energy and buildings, 119, 129-142.

[30] Abdel-Salam, M. R., Ge, G., Fauchoux, M., Besant, R. W., & Simonson, C. J. (2014). State-of-the-art in liquid-to-air membrane energy exchangers (LAMEEs): A comprehensive review. Renewable and Sustainable Energy Reviews, 39, 700-728.

[31] Al-Turki, Y. A., Mebarek-Oudina, F., Ahmadian, A., & Baleanu, D. (2021). Flat sheet direct contact membrane distillation desalination system using temperature-dependent correlations: thermal efficiency via a multi-parameter sensitivity analysis based on Monte Carlo method. Journal of Thermal Analysis and Calorimetry, 144(6), 2641-2652.

[32] Huang, J. (2008). A device for characterizing water vapor permeability of polymer membranes. International Journal of Polymer Analysis and Characterization, 13(1), 37-48.

[33] Ge, G., Mahmood, G. I., Moghaddam, D. G., Simonson, C. J., Besant, R. W., Hanson, S., ... & Gibson, P. W. (2014). Material properties and measurements for semi-permeable membranes used in energy exchangers. Journal of membrane science, 453, 328-336.

[34] Woods, J. (2014). Membrane processes for heating, ventilation, and air conditioning. Renewable and Sustainable Energy Reviews, 33, 290-304.

[35] Alonso, M. J., Mathisen, H. M., Aarnes, S., & Liu, P. (2017). Performance of a lab-scale membrane-based energy exchanger. Applied Thermal Engineering, 111, 1244-1254.

[36] Al-Waked, R., Nasif, M. S., & Mostafa, D. B. (2018). Enhancing the performance of energy recovery ventilators. Energy Conversion and Management, 171, 196-210.

[37] El-Bourawi, M. S., Ding, Z., Ma, R., & Khayet, M. (2006). A framework for better understanding membrane distillation separation process. Journal of membrane science, 285(1-2), 4-29.

[38] Liu, S., Zhao, X., Riffat, S., & Yuan, Y. (2009). Comparative study of hydrophilic materials for air-to-air heat/mass exchanger. International Journal of Low-Carbon Technologies, 4(2), 120-130.

[39] Nasif, M. S. (2015). Effect of utilizing different permeable material in air-to-air fixed plate energy recovery heat exchangeron energy saving. ARPN Journal of Engineering and Applied Sciences, 10(21), 10153-10158.

[40] Fend, T., Hoffschmidt, B., Pitz-Paal, R., Reutter, O., & Rietbrock, P. (2004). Porous materials as open volumetric solar receivers: experimental determination of thermophysical and heat transfer properties. Energy, 29(5-6), 823-833.

[41] Metz, S. J., Van de Ven, W. J. C., Potreck, J., Mulder, M. H. V., & Wessling, M. (2005). Transport of water vapor and inert gas mixtures through highly selective and highly permeable polymer membranes. Journal of Membrane Science, 251(1-2), 29-41.

[42] Albdoor, A. K., Ma, Z., Al-Ghazzawi, F., & Arıcı, M. (2022). Study on recent progress and advances in air-to-air membrane enthalpy exchangers: Materials selection, performance improvement, design optimisation and effects of operating conditions. Renewable and Sustainable Energy Reviews, 156, 111941.

[43] Min, J., & Su, M. (2010). Performance analysis of a membrane-based energy recovery ventilator: Effects of membrane spacing and thickness on the ventilator performance. Applied Thermal Engineering, 30(8-9), 991-997.

[44] Refrigerating and Air-Conditioning Engineers American Society of Heating, Heating, R. A. C. E. A. S., & American National Standards Institute. (2016). Ventilation for Acceptable Indoor Air Quality: ANSI/ASHRAE Standard 62.1-2016. ANSI/ASHRAE.

[45] American Society of Heating, & Engineers, R. A. A. (2016). 2016 ASHRAE Handbook -- HVAC Systems and Equipment (I-P) - (includes CD in I-P and SI editions) (Har/Cdr). American Society of Heating, Refrigerating and Air-Conditioning Engineers.

[46] Air Exchangers: S10 ERVplus. (n.d.). Venmar. https://www.venmar.ca/101-air-exchangers-s10-ervplus.html

[47] Kalaburgi, N. (2021). Working of DHT sensor – DHT11 and DHT22. NerdyElectronics. https://nerdyelectronics.com/working-of-dht-sensor-dht11-and-dht22/

[48] City ElectronicsPK. (2023, May 16). *Arduino Uno R3 SMD - City ElectronicsPK*. https://cityelectronics.pk/product/arduino-uno-r3-smd/

[49] *SD Card Module Slot Socket Reader for Arduino UNO R3 Mega 2560 Nano*. (n.d.). Keyestudio. https://www.keyestudio.com/free-shipping-sd-card-module-slot-socket-reader-for-arduino-uno-r3-mega-2560-nano-p0450.html

[50] Yang, P., Li, L., Wang, J., Huang, G., & Peng, J. (2015b). Testing for Energy Recovery Ventilators and Energy Saving Analysis with Air-Conditioning Systems. Procedia Engineering, 121, 438-445. https://doi.org/10.1016/j.proeng.2015.08.1090

[51] Huizing, R. N., Chen, H., & Wong, F. (2015). Contaminant transport in membrane based energy recovery ventilators. *Science and Technology for the Built Environment*, *21*(1), 54–66. https://doi.org/10.1080/10789669.2014.969171