Potential Investigation of Membrane Energy Recovery Ventilators for the Management of Building Air-Conditioning Loads

Hadeed Ashraf1,4, Muhammad Sultan1,4,*, Uzair Sajjad2, Muhammad Wakil Shahzad3, Muhammad Farooq4, Sobhy M. Ibrahim5, Muhammad Usman Khan6, Muhammad Ahmad Jamil1

1 Department of Agricultural Engineering, Faculty of Agricultural Sciences & Technology, Bahauddin Zakariya University, Multan 60800, Pakistan; hadedashraf15@gmail.com (H.A.); muhammad.sultan@bzu.edu.pk (M.S.)
2 Department of Energy and Refrigerating Air-Conditioning Engineering, National Taipei University of Technology, Taipei 10608, Taiwan; energyengineer01@gmail.com (U.S.)
3 Department of Mechanical and Construction Engineering, Northumbria University, Newcastle Upon Tyne, NE1 8ST, United Kingdom; muhammad.w.shahzad@northumbria.ac.uk (M.W.S.); muhammad2.ahmad@northumbria.ac.uk (M.A.I.)
4 Department of Mechanical Engineering, University of Engineering and Technology, Lahore 39161, Pakistan; engr.farooq@uet.edu.pk (M.F.)
5 Department of Biochemistry, College of Science, King Saud University, P.O. Box 2455, Riyadh 11451, Saudi Arabia; syakout@ksu.edu.sa (S.M.I.)
6 Department of Energy Systems Engineering, Faculty of Agricultural Engineering and Technology, University of Agriculture, Faisalabad, 38040, Punjab, Pakistan; usman.khan@uaf.edu.pk (M.U.K.)

* These authors contributed equally to this work.
† Correspondence: muhammad.sultan@bzu.edu.pk (M.S.); Tel: +92333-610-8888 (M.S.)

Abstract: The present study provides insights into the energy saving potential of membrane energy recovery ventilator (ERV) for the management of building air-conditioning loads. This study explores direct (DEC), Maisotsenko cycle (MEC) evaporative cooling, and vapor compression (VAC) systems with ERV. Therefore, this study aims to explore possible air-conditioning options in terms of temperature, relative humidity, human thermal comfort, wet bulb effectiveness, energy saving potential, and CO₂ emissions. Eight different combinations of the above-mentioned systems are proposed in this study i.e., DEC, MEC, VAC, MEC-VAC, and their possible combinations with and without ERVs. A building was modeled in DesignBuilder and simulated in EnergyPlus. The MEC-VAC system with ERV achieved highest temperature gradient, wet bulb effectiveness, energy saving potential, optimum relative humidity, and relatively lower CO₂ emissions i.e., 19.7 °C, 2.2, 49%, 48%, 499.2 kgCO₂/kWh, respectively. Thus, this study concludes the hybrid MEC-VAC system with ERV the optimum system for the management of building air-conditioning loads.

Keywords: Membrane energy recovery ventilator; energy recovery potential; Maisotsenko cycle; evaporative cooling; building air-conditioning; human thermal comfort; Pakistan

1. Introduction

1.1. Background

Energy consumption for domestic use / building sector has forever been soaring; gradually increasing up to 36% (for year 2021) of total global energy consumption [1]. Pakistan is among the countries with high energy consumption in building sector (including residential / commercial and public services) leading up to 65% (for year 2021) of its total energy consumption [2]. Whereas, the energy consumption in industry and agriculture / forestry sectors in Pakistan was 26% and 9% (for year 2021) of the total energy consumption [2]. In Pakistan, for year 2020, more than half (i.e., ~55%) of the total energy consumption...
consumption in residential / commercial and public services sector is consumed in space heating/ cooling [3]. This is due to the geophysical location of the country. Most of Pakistan’s area lies in the hot desert climate classification of the Köppen climate classification which leads to increased need of space heating/ cooling in winter/ summer [4]. Figure 1 shows the sector-wise energy consumption in Pakistan and energy consumption in buildings. According to Figure 1, residential / commercial and public service buildings consume 264,734 TJ (around 65% of total sector-wise energy consumption) out of which more than half (~55%) in consumed in space heating / cooling. In Pakistan, buildings are not built concerning energy saving or utilization. Generally, standalone vapor compression (VAC) systems are considered suitable for building air-conditioning in Pakistan which contribute to greenhouse gas emissions; ultimately leading to global warming and increased CO₂ in the atmosphere. Therefore, alternate building air-conditioning systems are fundamentally needed. Evaporative cooling systems could potentially prove to be an environment friendly building air-conditioning option. Moreover, energy in the form of conditioned air is wasted from the exhausts of buildings. This waste energy can be recovered using membrane energy recovery ventilators (ERVs). The ERVs can recover heat as well as humidity from the stale exhaust and exchange them with the outside fresh air.

![Figure 1. Energy consumption in Pakistan by sector and energy consumption in buildings (data source: IEA [5]).](image)

1.2. Multi-Stage Air-Conditioning Systems

Evaporative cooling systems coupled with standalone conventional vapor compression systems for the management of building air-conditioning loads and associated applications have been extensively studied in literature [6–15].

Chun et al. [16] thermodynamically analyzed an MEC system coupled with membrane-based dehumidification. The authors concluded that system performance directly correlated with outside temperature and humidity ratio. Kowalski et al. [17] studied the indirect evaporative cooling and the DEC systems in Poland. The authors concluded that the indirect evaporative cooling system outperformed the DEC. Additionally, the proposed system performed better in the dedicated outside air scenario compared to the recirculation air scenario. Da Veiga et al. [18] modeled an evaporative cooling system for building roofs and experimentally validated the results. The authors found strong correlation between performance of the proposed system and irradiation, outside temperature,
relative humidity, and windspeed. In a follow up study, da Veiga et al. [19] further studied the DEC system on a global level for building roofs. The results indicated that the DEC system is more likely to perform better in the cold semi-arid climate (BSk) and warm desert climate class (BW) of the Köppen climate classification areas [19]. Tewari et al. [20] experimented the DEC system for office building air-conditioning. According to the results, optimum relative humidity, temperature, and windspeed for human thermal comfort were 35-85%, 28.8 °C, and 0.75-1.5 m/s, respectively. Kim et al. [21] studied the integration of DEC and indirect evaporative cooling systems and compared with a conventional VAC system into an outdoor air-conditioning system. According to the results, multi-staging of evaporative cooling systems resulted in total energy consumption of 1.1 kWh compared to conventional VAC system (i.e., 2.1 kWh). Cui et al. [22] theoretically investigated an MEC system for air-conditioning application from the viewpoint of wet bulb (WBE) and dewpoint (DPE) effectiveness. According to the results, the proposed system achieved 1.2-1.3 WBE and 0.8-0.9 DPE under varying inlet temperature and relative humidity conditions. Gómez et al. [23] experimentally investigated two modes of air flow in a prototype polycarbonate indirect evaporative cooling system. According to the results, heat transfer, cooling capacity, and thermal effectiveness are improved in case of polycarbonate evaporative cooling system. Heidarinejad et al. [24] theoretically investigated an indirect evaporative cooling system and an MEC system. Numerical modeling was used to predict the performance of both the systems. According to the results, WBE performance of the MEC system comparatively increased by 60%. Cui et al. [25] used computation fluid dynamics for the performance prediction of the MEC system. Results from the study were within ±10% range to the actual experimental data. Moreover, the authors summarized that the MEC system could potentially achieve higher WBE and DPE for larger length-to-height ratio (at least 200 times), lower air velocity (< 1.5 m/s), and smaller channel height (< 10 mm). Moshari et al. [26] studied the performance of multi-stage evaporative cooling system for a variety of ambient conditions. According to the results, WBE of the multi-stage evaporative cooling system peaked at 0.9, whereas it was 0.6 in case of standalone indirect evaporative cooling system. According to the results, multi-staging of evaporative cooling systems can improve the performance at the expense of higher energy input. Cui et al. [27] investigated the performance of a multi-stage VAC and indirect evaporative cooling system. According to the results, the EC component pretreated the outside air, resulting in a ~47% drop in cooling load on compressor at the VAC stage which ultimately leads to an appreciable increase in energy saving potential. Numerical results from the study were within 9.7% range of actual experimental data. Campisi et al. [28] studied the energy efficiency in a case study of Italy. The authors concluded that the best energy saving technique was installation of solar thermal panels with heat pump for optimum energy saving and lesser CO2 emission. Obando et al. [29] investigated the effect of the temperature of water on the DEC system for livestock building air-conditioning. According to the experimental results, supply air temperature dropped 0.7 °C per °C drop in temperature, and supply air relative humidity increased by ~0.9%. Badiei et al. [30] numerically predicted the MEC performance. The authors concluded that the energy building model accurately predicted the performance of the MEC system as compared to numerical model. Nada et al. [31] analyzed the DEC with cellulose pads for the climatic conditions of Egypt. According to the results, the DEC system achieved maximum WBE of 0.85 at different ambient conditions. He et al. [32] experimentally studied solar operated dehumidification unit to treat outside air before entering evaporative cooling unit. According to the results, the proposed system could achieve supply temperature and relative humidity of 28 °C and 70% which satisfied required human thermal comfort levels. Boukhanouf et al. [33] designed and developed an MEC system for the management of building air-conditioning loads in arid climate. The study proposed porous ceramic and heat pipes for heat exchange purpose. According to the results, the proposed system achieved peak WBE, COP, and temperature gradient (i.e., referred to as the subtraction of outside and system outlet temperature) of 0.8, 11.43, and 14 °C, respectively. Zanchini et al. [34]
investigated the MEC-VAC system in terms of energy saving potential for the climatic conditions of North Italy. According to the results, the proposed system yielded 38% energy and electricity savings as compared to the conventional VAC system. Khandelwal et al. [35] studied the energy saving potential of the DEC and MEC systems coupled with water chiller. According to the results, the proposed systems yielded peak energy savings i.e., 12% and ~15.7%, respectively, whereas predicted mean vote (PMV) was between -1 and +1.

Results from these studies lead to general summarization that (i) multi-stage EC systems can potentially improve performance from the viewpoints of WBE, DPE, and system outlet humidity and temperature, and (ii) the MEC system can result in relatively higher performance for hot and dry climatic conditions.

1.3. Membrane Energy Recovery Ventilators

Gao et al. [38] studied membrane energy recovery ventilator (ERV) from the viewpoints of latent heat, sensible heat, and total energy exchange efficiency. According to the results, the developed model accurately predicted the performance of the ERV within ±7% of the actual experimental data for both summer and winter conditions. Abadi et al. [39] studied the condensation phenomenon in ERV core. According to the results, exhaust sensible effectiveness was increased due to condensation. However, in countries like Pakistan where most of the region lies in hot and dry area, condensation is not concerned to be a problematic factor. Huang et al. [40] experimentally investigated an indirect evaporative cooling system coupled with heat recovery ventilator in different regions of China. According to the results, performance of the proposed system increased in hot and humid
regions (i.e., Guangzhou). Additionally, the authors concluded that energy saving potential of vertical arrangement of the indirect evaporative cooling system was relatively more (~almost twice) compared to horizontal arrangement. Chen et al. [41] investigated the performance of an MEC system coupled with the ERV system for air-conditioning in wet markets of Hong Kong. The authors concluded that MEC based ERV system resulted in maximum energy saving potential (specifically in summer, up to 45% more) compared to standalone total energy or heat recovery. Qiu et al. [42] developed a regression model for the performance prediction of an ERV system. The authors declared that thermal properties of membrane in the ERV core were not a prerequisite. The developed numerical polynomial model accurately predicted results within ±8% of the experimental data. Zhong et al. [43] modeled the performance of an ERV system for building air-conditioning. Performance of the ERV was influenced by effectiveness, occupancy of the building, and outside air conditions. Moreover, peak yearly energy efficiency of the ERV in hybrid mode was 43%. Rasouli et al. [44] studied an ERV for ten storey building in four different climates of the USA. The authors concluded that peak energy saving during cooling mode in summer season was 20% under specified control conditions whereas it was 40% in heating mode in winter. Moreover, the authors declared that the proposed system yielded higher performance in humid climates with higher latent loads. Zhou et al. [45] modeled the performance of ERV system in Shanghai and Beijing. According to the results, the ERV performed better in Shanghai under winter conditions resulting in peak energy saving as compared to Beijing.

From the above discussion, to the best of authors’ knowledge, it can be stated that membrane energy recovery ventilators are not widely used in Pakistan. Therefore, this study provides a comprehensive assessment on the potential investigation of ERV systems for the management of building air-conditioning loads in Pakistan. According to Figure 2, Pakistan is represented by the warm desert climate (referred to as BWh) class of Köppen’s climate classification which imposes a need for air-conditioning. In this regard, this study explores combinations of direct (DEC), Maisotsenko cycle (MEC) evaporative cooling), and typical mechanical vapor compression (VAC) systems with membrane energy recovery ventilator in Pakistan.

2. Materials and Methods

2.1. Building Energy Simulation

A non-residential, office building (reported in authors’ previous work [6]) was used as a baseline for this study. Total area for the building was 3251.74 m² out of which 847.5 m² was conditioned with 2404.24 m² unconditioned building area. Figure 3 shows the proposed systems/ configurations for the management of building air-conditioning loads. All the proposed systems/ configurations presented in Figure 3 were designed in AHU module of DesignBuilder [46]. All the thermophysical properties of the baseline building were incorporated in the design in DesignBuilder, and simulated using EnergyPlus simulation engine [47]. Table 1 shows the details of design specifications of building construction and air-conditioning systems. In the present study, standalone direct evaporative cooling (DEC), Maisotsenko cycle evaporative cooling (MEC), conventional vapor compression (VAC), and hybrid MEC-VAC systems have been explored as possible alternative options for building air-conditioning coupled with two configurations i.e., with and without ERV & Recirculation. Figure 3 shows the proposed configurations and air-conditioning systems for energy recovery and building air-conditioning. Working phenomenon of each system/ configuration studied in this manuscript is given below:

- DEC system (Figure 3a) – This system humidifies and simultaneously cools the outside air, increasing the humidity of supply air in an isenthalpic manner.
- MEC system (Figure 3b) – This system provides two streams of air i.e., sensibly cooled air and humidified hot air. Ideally, this system can achieve below wet bulb temperature, i.e., dewpoint temperature.
• VAC system (Figure 3c) – This system is the conventional mechanical vapor compression system based on refrigerant cooling.

• MEC-VAC system (Figure 3d) – This system essentially behaves like a hybrid of the MEC and the VAC system. The MEC system pretreats the outside air (reducing its temperature) to reduce cooling coil loads in the VAC system.

• Air-conditioning system with ERV & Recirculation configuration (Figure 3) – This configuration allows the energy from the stale exhaust air to be recovered; exchanged into the supply air before exhaust. Additionally, recirculation mode is used in this configuration to divert/ mix a portion of the outside air depending upon thermal comfort requirement of inside conditions.

• Air-conditioning system without ERV & Recirculation configuration (Figure 3) – This configuration does not allow any sensible/ latent energy recovery from the stale air stream, essentially behaving like a simple air handling unit (AHU) consisting of the four proposed air-conditioning systems.

Table 1. Design specifications of the building construction and air-conditioning systems.

| Building construction information | Wall 1st layer | Wall 2nd layer | Wall 3rd layer | Wall 4th layer | Flat roof Layer 1 | Flat roof Layer 2 | Floor 1st layer | Floor 2nd layer | Window | Dimensions | Sill height | Panels |
|----------------------------------|----------------|----------------|----------------|----------------|------------------|-----------------|----------------|----------------|--------|------------|------------|--------|
| Type                             | Brickwork outer | Cement         | Brickwork inner | Cement         | Concrete at R 0.0625/in | Cement          | Concrete aggregate at R 0.0625/in | Cast concrete (dense) | Clear | W          | H          | 3      |
| Details                          | 4 in            | 0.5 in          | 4 in           | 0.5 in         | 0.5 in           | 0.5 in          | 2 in           | 5 in           |
| Properties                       |                |                |                |                |                  |                 |                |                |
| Area of the building             | 3251.74 m²      |                |                |                |                  |                 |                |                |
| Area of conditioned space        |                |                |                |                |                  |                 |                |                |
| Zones in conditioned space       | 24/47 (excluded zones include corridors, kitchen, and washrooms.) |                |                |                |                  |                 |                |                |
| Lighting power                   | Visible        | Radiant        |                |                |                  |                 |                |                |
| density fractions                | 0.2            | 0.7            |                |                |                  |                 |                |                |
| Population                       | Person population |                |                |                |                  |                 |                |                |
| Metabolic factor                 | 0.295 persons/conditioned area |                |                |                |                  |                 |                |                |
| Schedule                         | Workday schedule |                |                |                |                  |                 |                |                |
| On at:                           | 08:00          |                |                |                |                  |                 |                |                |
| Off at:                          | 16:00          |                |                |                |                  |                 |                |                |
| Workdays/week                    | 5              |                |                |                |                  |                 |                |                |
| Clothing                         | Winter         | Sumner         |                |                |                  |                 |                |                |
| Typical Pakistani wear           | 1.145 clo      | 0.775 clo      |                |                |                  |                 |                |                |
| [Shalwar Kameez] [48,49]         |                |                |                |                |                  |                 |                |                |
| Fan                              | Total efficiency |                |                |                |                  |                 |                |                |
| Motor efficiency                 | 75%            |                |                |                |                  |                 |                |                |
| Fan pressure                     | 85%            |                |                |                |                  |                 |                |                |
| Motor in air stream              | Yes            |                |                |                |                  |                 |                |                |
| (draw through system)            |                |                |                |                |                  |                 |                |                |
| AHU information                  |                |                |                |                |                  |                 |                |                |
| Type                             | Counterflow    |                |                |                |                  |                 |                |                |
| ERV                              | Design Sensile effectiveness | 0.75 |    |                |                  |                 |                |                |
| Silica-PE substrate permeability (at 50 °C, 50% RH | 6.2*10^-10 mol.m/m²/s/Pa | 105 μm |    |                |                  |                 |                |                |


Table 1. Properties of Peeling Polyurethane-ethanol Composite Coatings

| Property                        | Value          |
|--------------------------------|----------------|
| Silica-PE substrate density     | 600 kg/m³      |
| Silica-PE substrate thickness   | 105*10⁻⁶ m     |
| Silica-PE thermal conductivity  | 0.44 W/m/k     |
| PU-PEO coating film            |               |
| PU-PEO coating permeability     | 1.8*10⁻¹¹ mol/m²/s/Pa |
| PU-PEO coating density         | 1210 kg/m³     |
| PU-PEO coating thickness       | 2*10⁻⁶ m       |
| PU-PEO thermal conductivity    | 0.159 W/m/k    |

VAC Rated COP | 3
Coil Type     | Single speed
Condenser Type | Air cooled
Rated evaporator fan power per volume flow rate | 773.3 W/m³/s
Operation     | On sensible load

| Module Type         | Design wet bulb effectiveness | Water pump power sizing factor |
|---------------------|------------------------------|-------------------------------|
| DEC Direct research | 0.90                          | 90.0 W/m³/s                  |
| MEC Indirect research | 1.06                        | 90.0 W/m³/s                  |

Recirculation | Varies in zones based on cooling load requirement | 0.64 (average)
Thermostat    | 24 °C                                       |
Humidistat   | 60%                                         |

Figure 3. Proposed configurations and air-conditioning systems for energy recovery and building air-conditioning.
Temperature gradient, relative humidity, predicted mean vote (PMV), psychrometric profile, carbon dioxide (CO₂) emissions, predicted percentage of dissatisfied (PPD), wet bulb effectiveness, electricity consumption, and energy saving potential were used as performance indicators. Wet bulb effectiveness of the proposed systems was calculated using Equation 1.

\[
\epsilon_{wb} = \frac{T_{OA, DBT} - T_{SA, DBT}}{T_{OA, DBT} - T_{OA,WBT}}
\]  

(1)

where \( \epsilon_{wb} \) represents wet bulb effectiveness, \( T \) represents dry bulb temperature in (°C), the subscripts \( SA, OA, WBT, \) and \( DBT \) denote supply air, outside air, wet bulb, and dry bulb temperatures, respectively. Equation 2 was used to calculate cooling capacity of the proposed systems.

\[
Q = mC_p(\Delta T)
\]

(2)

where \( Q \) represents cooling capacity of the system (kW), \( m \) represents mass flow rate of air in the system (i.e., 14.5 kg/s for this study), \( C_p \) represents specific heat capacity, and \( \Delta T \) denotes the difference in system outlet temperatures between \( OA \) and \( SA \) (°C). Equations 3 – 6 were used to calculate cooling capacity of the VAC or hybrid VAC systems, considering latent heat transfer into account.

\[
m = \rho_{air}u
\]

(3)

\[
Q_{net} = m(h_{SA} - h_{OA})
\]

(4)

\[
Q_{sensible} = m(h_{SA} - h_{OA})x_{min}
\]

(5)

\[
Q_{latent} = Q_{net} - Q_{sensible}
\]

(6)

where \( \rho_{air}, u, h, x_{min}, Q_{net}, Q_{sensible}, \) and \( Q_{latent} \) represent density of air (kg/m³), volumetric flow rate (m³/s), total enthalpy of air (J/kg), minimum of the two humidity ratios at \( OA \) and \( SA \) (kg/kg), total cooling capacity, total sensible cooling capacity, and total latent cooling capacity (kW). Equation 7 was used to calculate average area of a human body to further facilitate the estimation of total heat and mass transfer from the human body.

\[
A_{hb} = 0.202M^{0.425}H^{0.725}
\]

(7)

where \( A, M, \) and \( H \) represent average area, mass, and height of a typical human body. Subscript \( hb \) represents the human body. Equations 8 – 17 were used to calculate heat gained from human body \( (Q_{hb}) \), sol-air temperature \( (T_{sa}) \), heat gained from exterior surfaces \( (Q_{ext}) \), heat gained from fans and motors \( (Q_m) \), heat gained from walls \( (Q_{wall}) \), heat gained from windows \( (Q_{glazing}) \), heat gained from floor \( (Q_{fp}) \), heat gains/losses from infiltration \( (ACH) \), latent load gains/losses through infiltration \( (Q_{i}) \), and sensible load gains/losses through infiltration \( (Q_{s,i}) \), respectively. Details of parameters can be found from cited literature [6].

\[
Q_{hb} = (Q_{sensible} + Q_{latent})_{skin} + (Q_{sensible} + Q_{latent})_{lungs}
\]

(8)

\[
T_{sa} = T_a + \frac{\alpha_{solar}q_{solar}}{h_o} - \frac{E\varphi(T_a^4 - T_{ext}^4)}{h_o}
\]

(9)

\[
Q_{ext} = h_oA_s(T_a - T_x) + \alpha_{solar}A_sq_{solar} - EA_s\varphi(T_a^4 - T_{ext}^4)
\]

(10)

\[
Q_m = \frac{P_f\cdot I_f}{\eta_m}
\]

(11)
\[ Q_{wall} = U_{wall}A_s(T_s - T_{in}) \]  \hfill (12)

\[ Q_{glazing} = Q_c + Q_e + Q_f = U_g A_g(T_{in} - T_{out}) \]  \hfill (13)

\[ Q_{sp} = U_{floor}P_{floor}(T_{in} - T_{out}) \]  \hfill (14)

\[ ACH = \frac{m_{in}}{V} \]  \hfill (15)

\[ Q_{li} = \rho_{air} h_{fg} ACH V(X_{in} - X_{out}) \]  \hfill (16)

\[ Q_{sl} = \rho_{air} c_p ACH V(T_{in} - T_{out}) \]  \hfill (17)

2.3. Human Thermal Comfort Indices

Comfort for human beings was assessed from the viewpoints of Fanger’s predicted mean vote (PMV) and predicted percentage of dissatisfied (PPD) [50,51]. Equations 18 – 22 were used to calculate PMV and PPD. Details of parameters can be found from cited literature [6].

\[ PMV = [0.303 e^{(-0.036MBR)} + 0.028](MBR - HL) \]
\[ - 3.05[5.73 - 0.007(MBR - HL) - P_{OA}] \]
\[ - 0.42[(MBR - HL) - 58.15] - 0.0173 MBR(5.87 - P_{OA}) \]
\[ - 0.0014 MBR(34 - T_{OA}) \]
\[ - 3.96 e^{-8} RCNB[(CT + 273)^4 - (MRT + 273)^4] \]
\[ - RCNB h_{conv}(CT - T_{OA}) \]  \hfill (18)

\[ CT = 35.7 - 0.0275(MBR - HL) \]
\[ - R_c[(MBR - HL) - 3.05[5.73 - 0.007(MBR - HL) - P_{OA}] \]
\[ - 0.42[(MBR - HL) - 58.15] - 0.0173 MBR(5.87 - P_{OA}) \]
\[ - 0.0014 MBR(34 - T_{OA})] \]  \hfill (19)

\[ h_{conv} = \begin{cases} 2.38(CT - T_{OA})^{0.25} \quad & \text{for} \quad 2.38(CT - T_{OA})^{0.25} > 12.1 \sqrt{u_{OA}} \\ 12.1 \sqrt{u_{OA}} \quad & \text{for} \quad 2.38(CT - T_{OA})^{0.25} < 12.1 \sqrt{u_{OA}} \end{cases} \]  \hfill (20)

\[ r_{cb} = \begin{cases} 1.0 + 0.2 CI \quad & \text{for} \quad CI < 0.5 \text{ clo} \\ 1.05 + 0.1 CI \quad & \text{for} \quad CI > 0.5 \text{ clo} \end{cases} \]  \hfill (21)

\[ PPD = 100 - 95 e^{-(-0.0335PMV^{4} - 0.2179PMV^{2})} \]  \hfill (22)

where \( MBR \) denotes metabolic rate in W m\(^{-2}\), \( HL \) denotes loss of heat from body in W m\(^{-2}\), \( T_{OA} \) denotes the room’s temperature in °C, \( P_{OA} \) denotes vapor pressure of outside air, \( RCNB \) denotes the cloth-naked-body ratio, \( CI \) denotes clothes’ insulation in clo, \( CT \) denotes clothes’ temperature in °C, \( h_{conv} \) denotes the convective heat transfer coefficient in W m\(^{-2}\) °C\(^{-1}\), \( MRT \) denotes the mean radiant temperature in °C, and \( u_{OA} \) denotes air flow velocity in m s\(^{-1}\), and.

3. Results & Discussion

3.1. Design Parameters

Effectiveness of a high-efficiency energy recovery ventilator (ERV) used as design effectiveness in DesignBuilder at varied design flow rate are presented in Figure 4. Experimental data for the effectiveness was obtained from literature [32]. This specific membrane ERV was selected for the study due to its low pressure drop at the supply air side, high effectiveness towards blocking of variety of gases, prevention of recirculation of
odors into the supply air, and smaller lead time. According to Figure 4, design effectiveness alpha represents the effectiveness at 57.7 ft/min active face velocity whereas design effectiveness beta represents the effectiveness at 107.5 ft/min active face velocity. Sensible design effectiveness at 75% heating and cooling flow rate was 0.75; whereas it was 0.70 at 100% heating and cooling flow rate. Latent design effectiveness at 75% heating and cooling flow rate was 0.65; whereas it was 0.60 at 100% heating and cooling flow rate. Figure 5 shows the numerical values of both wet bulb and dewpoint effectiveness of the experimental lab-scale prototypes of the DEC and MEC systems, respectively, for summer months, obtained from authors’ previous work [53]. The design values were used in simulation models developed in DesignBuilder. The design values used in DesignBuilder are presented in Table 1. The developed model was simulated for Multan, Pakistan in EnergyPlus.

![Figure 4](image1.png)

**Figure 4.** Membrane energy recovery ventilator design effectiveness for Designbuilder at varied flow rate, reproduced from literature [52].

![Figure 5](image2.png)

**Figure 5.** Design effectiveness of lab-scale evaporative cooling systems (i.e., MEC εwb, MEC εdp, and DEC εwb) for Designbuilder for summer in Multan [53].
3.2. Performance Profiles of the Systems

3.2.1. Temperature/Humidity

Results from the simulation are presented in Figures 6–7. Figure 6 shows the marginal distribution curves of temperature gradient of the proposed system configurations against ambient temperature for the summer months of the study area. According to Figure 6, the MEC-VAC system with ERV and Recirculation configuration achieved maximum temperature gradient of 19.8 °C (on June 16) with average 13.2 °C in summer months. MEC-VAC without ERV system achieved maximum temperature gradient of 16.6 °C average of 10.7 °C. It is worthy to mention that the distribution curves in Figure 6 represent the data height in terms of count rather than relative frequency or density of the data. DEC and MEC system could only achieve maximum temperature gradient of 9.2 °C and 10.8 °C, respectively, without ERV and Recirculation configuration with an average temperature gradient of 4.7 °C and 5.5 °C, respectively. It is worthy mentioning that the temperature gradient refers to subtraction of outside/ambient air and system outlet temperature. Meanwhile, both the standalone evaporative cooling systems achieved maximum temperature gradient of 5.9 °C and 10.4 °C, respectively, with ERV and Recirculation configuration in summer months average of 2.3 °C and 5.4 °C. Contrarily, the standalone VAC system achieved maximum temperature gradient of 13.4 °C and 19.7 °C, without and with ERV and Recirculation configurations, with an average temperature gradient of 9.3 °C and 13.2 °C, respectively. From these results, it can be deduced that the standalone VAC system with ERV configuration and the hybrid MEC-VAC system with ERV configuration performed best as compared to other systems. It could be argued that the VAC with ERV performed nearly equal to the hybrid MEC-VAC with ERV, however, the VAC with ERV system consumes more electricity as compared to the MEC-VAC with ERV system. According to the marginal distribution curves, the MEC-VAC with ERV system yielded overall smooth performance from the point of view of supply air temperature. The MEC-VAC with ERV system maintained an overall temperature of ~20–22 °C throughout the summer months. Similarly, the VAC with ERV system also maintained a similar profile of temperature throughout the summer months. Marginal distribution curves of the humidity of proposed system configurations against ambient relative humidity for the summer months of the study area is presented in Figure 7. According to Figure 7, maximum ambient air relative humidity for the summer months was 81% with an average relative humidity of 48%. It is worthy to mention that the distribution curves in Figure 7 represent the data height in terms of count rather than relative frequency or density of the data. Consequently, the standalone DEC system without and with ERV configuration achieved maximum relative humidity of 92% and 95%, with average relative humidity of 76% and 85%, respectively. Similarly, the standalone MEC system without and with ERV configuration achieved maximum relative humidity of 89% and 90%, with average relative humidity of 65% and 66%, respectively. Comprehensive results of the study are presented in Table 2.
Figure 6. Marginal distribution curves of the proposed system configurations’ temperature against the ambient temperature for the summer months of Multan (Pakistan).
Figure 7. Marginal distribution curves of the proposed system configurations’ relative humidity against the ambient relative humidity for the summer months of Multan (Pakistan).
On the other hand, the standalone VAC system without and with ERV configuration achieved maximum relative humidity of 86% and 60%, with an average relative humidity of 68% and 48%, respectively. Contrarily, the hybrid MEC-VAC system without and with ERV configuration achieved maximum relative humidity of 85% and 60%, with average relative humidity of 66% and 49%, respectively. According to these results, the standalone VAC system with ERV and Recirculation configuration, and the hybrid MEC-VAC system with ERV and Recirculation configuration achieved the desired average relative humidity level (i.e., 40% – 60% [54]) prescribed for human thermal comfort during the summer months of the study area. From Figure 6 and Figure 7, it can be concluded that the standalone VAC system with ERV and Recirculation configuration, and the hybrid MEC-VAC system with ERV and Recirculation configuration achieved the desired performance level in terms of humidity and temperature required for optimum human thermal comfort.

3.2.2. Mean Radiant Temperature

Figure 8 shows the psychrometric performance profile of the proposed system configurations correlating with mean radiant temperature and human thermal comfort. According to Figure 8, the standalone DEC system without and with ERV and Recirculation configuration achieved maximum mean radiant temperature of 36.1 °C and 36.9 °C, average MRT of 32.3 °C and 33.4 °C, respectively. However, according to color coding in Figure 8, the average MRT of this system should be <26 °C to achieve the optimum human thermal comfort. Similarly, the standalone MEC system without and with ERV and Recirculation configuration achieved maximum mean radiant temperature of 36.0 °C and 35.8 °C, with average mean radiant temperature of 32.0 °C and 32.5 °C, respectively. However, according to the color coding in Figure 8, the average MRT of this system should also be <26 °C to achieve the optimum human thermal comfort. Contrarily, the standalone VAC system without and with ERV and Recirculation configuration achieved maximum mean radiant temperature of 34.2 °C and 29.6, with average mean radiant temperature of 30.2 °C and 28.2 °C.

![Figure 8. Performance profile of the proposed system configurations correlating with mean radiant temperature and thermal comfort.](image)
respectively. However, according to the color coding in Figure 8, the average MRT of the VAC without ERV system should be <26 °C whereas in case of the VAC with ERV system should be 30.5 °C – 31.9 °C. Although the VAC system with ERV and Recirculation configuration achieves the desired temperature and relative humidity levels (as per Figure 6 and Figure 7), however, the system fails to achieve the required mean radiant temperature (as per Figure 8). On the other hand, the hybrid MEC-VAC system without and with ERV and Recirculation configuration achieved maximum mean radiant temperature of 33.5 °C and 31.9 °C, with average 29.5 °C and 29.6 °C MRT. According to the color coding in Figure 8, the average MRT for the MEC-VAC without ERV system should be 29.6 °C – 30.5 °C, whereas the MRT for MEC-VAC system with ERV system should be 29.6 °C – 31.9 °C, respectively. According to these results, the hybrid MEC-VAC system with ERV and Recirculation configuration achieved the desired temperature and relative humidity levels (as per Figure 9), however, the system fails to achieve the required mean radiant temperature.

3.2.3. Human Thermal Comfort

Profile of the proposed system/ configurations in terms of predicted percentage dissatisfied (PPD) and predicted mean vote (PMV) for the summer months of the study area is presented in Figure 9. According to Figure 9, the standalone DEC system without ERV and Recirculation configuration achieved PMV of -2.43 – 3.43. It is worthy to mention that the distribution curves in Figure 9 represent the data height in terms of count rather than relative frequency or density of the data. Similarly, the standalone DEC system with ERV and Recirculation configuration achieved a PMV of -0.89 – 3.0. Similarly, the standalone MEC system without ERV and Recirculation configuration achieved a PMV of -2.84 – 3.0. In addition, the standalone MEC system with ERV and Recirculation configuration achieved a PMV of -2.77 – 3.0. Additionally, the standalone VAC system without ERV and Recirculation configuration achieved a PMV of -3.0 to 1.39. On the other hand, the standalone VAC system with ERV and Recirculation configuration achieved a PMV of -2.28 – -3.0. Contrarily, the hybrid MEC-VAC system without ERV and Recirculation configuration achieved a PMV of 0.71 – -3.0. In addition, the hybrid MEC-VAC system with ERV and Recirculation configuration achieved a PMV of -2.2 – -3.0. From the predicted percentage of dissatisfied (PPD) point of view, according to Figure 9, both the standalone DEC system without and with ERV and Recirculation configurations achieved PPD of 17.6% – 96.7%, with an average of 50% PPD during the summer months of the study area. Additionally, the standalone MEC system without and with ERV and Recirculation configuration achieved PPD of 13.4% – 94.5% and 14.4% – 94.0% with average PPD of 46.3% and 45.7%, respectively. Moreover, the standalone VAC system without and with ERV and Recirculation configuration achieved PPD of 14.4% – 98.8% and 84.6% – 99.5% with average PPD of 54.0% and 98.7%, respectively. In case of the hybrid systems, the MEC-VAC system without and with ERV and Recirculation configuration achieved PPD of 9.4% – 99.3% and 83.2% – 99.5%, with average PPD of 67.2% and 98.7%, respectively. According to the results, the standalone VAC system, and the hybrid MEC-VAC system with ERV and Recirculation configuration achieved more than 98% PPD throughout the summer months which causes dissatisfaction among the human subjects. In case of MEC-VAC with ERV and Recirculation configuration, although high PMV and PPD correlate to discomfort under certain conditions, however it could be tackled by using an air-conditioning schedule, economiser, and time-to-time operation of the outside air mixing/ recirculation.
Figure 9. Variation in thermal comfort indices (i.e., PMV and PPD) of the proposed system configurations for summer months.
3.2.4. Carbon Dioxide Emissions

Figure 10 shows the annual carbon dioxide (CO$_2$) emissions per kWh electricity usage of the proposed system configurations. A CO$_2$ emission factor of 0.56 kgCO$_2$/kWh of electricity used in Pakistan [55]. According to Figure 10, the standalone DEC system without ERV and Recirculation configuration emitted 134.5 kgCO$_2$/kWh, closely followed by the standalone DEC system with ERV and Recirculation configuration which emitted 135.6 kgCO$_2$/kWh. Similarly, the standalone MEC system without ERV and Recirculation configuration emitted 159.2 kgCO$_2$/kWh. Similarly, the standalone MEC system with ERV and Recirculation configuration emitted 160.2 kgCO$_2$/kWh. In case of the standalone VAC system without ERV and Recirculation configuration, the CO$_2$ emissions were 878.5 kgCO$_2$/kWh whereas it was 538.1 kgCO$_2$/kWh in case of the VAC system with ERV and Recirculation configuration. On the other hand, the hybrid MEC-VAC system without ERV and Recirculation configuration emitted 749.5 kgCO$_2$/kWh whereas the MEC-VAC system with ERV and Recirculation configuration emitted 499.2 kgCO$_2$/kWh.

From these results, it can be safely concluded that although the CO$_2$ emissions of the standalone EC systems are relatively low however these systems fail to achieve the desired human thermal comfort and fail to provide optimum management of building air-conditioning loads. On the other hand, the standalone VAC system emits higher CO$_2$ but consumes high energy and fails to achieve the desired human thermal comfort and to provide optimum management of building air-conditioning loads. In contrast, the hybrid MEC-VAC system with ERV and Recirculation configuration emits relatively lower CO$_2$ per kWh and promises to deliver optimum thermal comfort as well as optimum management of building air-conditioning loads.

![Figure 10. CO$_2$ emissions per kWh electricity usage of the proposed system configurations.](image)

3.2.5. Wet Bulb Effectiveness

Profile of wet bulb effectiveness (WBE) of the proposed system configurations for summer months of the study area is presented in Figure 11. According to Figure 11, the hybrid MEC-VAC system with ERV and Recirculation configuration achieved maximum wet bulb effectiveness i.e., 2.2 in August. However, the MEC-VAC system without ERV and Recirculation configuration was the only system that achieved maximum WBE of 1.46 in August. Similarly, the standalone VAC system with ERV and Recirculation configuration also achieved maximum wet bulb effectiveness of 2.2 in August. However, the VAC
system without ERV and Recirculation configuration only achieved highest WBE of 1.27 in August. Contrarily, the standalone MEC system with ERV and Recirculation configuration achieved highest WBE of 0.64 in August. However, the MEC without ERV and Recirculation configuration achieved highest WBE of 0.65 in May. Similarly, the standalone DEC system without ERV and Recirculation configuration achieved maximum wet bulb effectiveness of 0.55 in June. On the other hand, the DEC system with ERV and Recirculation configuration achieved maximum wet bulb effectiveness of 0.31 in July. According to these results, the standalone VAC system, and the hybrid MEC-VAC system with ERV and Recirculation configuration achieved the maximum wet bulb effectiveness however the standalone VAC system with ERV and Recirculation was unable to achieve the desired mean radiant temperature (as per Figure 8), therefore unable to optimally manage the building air-conditioning loads. The hybrid MEC-VAC system, however, produced the best wet bulb effectiveness and was able to achieve the desired mean radiant temperature (as per Figure 8) thereby optimally managing the building air-conditioning loads.

![Figure 11](image_url)  
**Figure 11.** Monthly-averaged profile of wet bulb effectiveness of the proposed system configurations for summer months.

Evidently from Figure 11, the evaporative cooling systems were thermodynamically limited to the outside conditions of the study area therefore their performance was limited. However, for hybrid air-conditioning systems, systems’ output was beyond the psychrometric limits of EC.

### 3.2.6. Electricity Consumption

Annual electricity usage of proposed systems is presented in Figure 12. According to the results, the standalone DEC system without ERV and Recirculation configuration consumed maximum and minimum annual electricity of 281.6 kWh/day and 231.3 kWh/day with an average of 266.5 kWh/day annual electricity. Similarly, the DEC system with ERV and Recirculation configuration consumed maximum and minimum annual electricity of 281.5 kWh/day and 231.7 kWh/day with an average of 268.6 kWh/day annual electricity. On the other hand, the standalone MEC system without ERV and Recirculation
configuration consumed maximum and minimum annual electricity of 354.6 kWh/day and 231.3 kWh/day with an average of 315.3 kWh/day annual electricity. Similarly, the MEC system with ERV and Recirculation configuration consumed maximum and minimum annual electricity of 354.6 kWh/day and 232.4 kWh/day with an average of 317.4 kWh/day annual electricity. However, the standalone VAC system without ERV and Recirculation configuration consumed maximum and minimum annual electricity of 3018.6 kWh/day and 231.3 kWh/day with an average of 1739.7 kWh/day annual electricity. Similarly, the VAC system with ERV and Recirculation configuration consumed maximum and minimum annual electricity of 2176.6 kWh/day and 240.0 kWh/day with an average of 1065.7 kWh/day annual electricity. In contrast, the hybrid MEC-VAC without ERV and Recirculation configuration consumed maximum and minimum annual electricity of 3106.7 kWh/day and 231.3 kWh/day with an average of 1484.2 kWh/day annual electricity. However, the MEC-VAC system with ERV and Recirculation configuration consumed maximum and minimum annual electricity of 2176.6 kWh/day and 232.4 kWh/day with an average of 988.5 kWh/day annual electricity. Evidently, from the results, the standalone evaporative cooling systems were not feasible from the viewpoint of energy saving. However, the standalone VAC and the hybrid MEC-VAC systems with ERV and Recirculation configuration proved to be energy saving throughout the year.

![Figure 12. Annual electricity usage of the proposed system configurations.](image-url)

3.2.7. Energy Saving Potential
Correlation contours of energy saving potential (%) of membrane energy recovery ventilator & recirculation configuration of the DEC system in terms of outside humidity and temperature for the summer months is presented in Figure 13. According to Figure 13, energy saving potential of the standalone DEC system with ERV, and Recirculation configuration increased with increasing ambient temperature and relative humidity. According to the results, the standalone DEC system with ERV and Recirculation configuration achieved maximum and minimum energy saving potential of 47.8% and 29.1% with an average energy saving potential of 39.4%. Similarly, other systems with ERV and Recirculation configuration also saved energy as compared to their respective counterpart systems without ERV and Recirculation configuration.

**Figure 13.** Energy saving potential (%) of membrane energy recovery ventilator & recirculation configuration of the DEC system in terms of outside humidity and temperature for the summer months.
Table 2. Comprehensive results of the performance of proposed systems.

|                      | Temperature Gradient (°C) | Relative Humidity (%) | MRT (°C) | PMV (-)  | PPD (%) | CO₂ Emissions (kgCO₂/kWh) | WBE (-) | Electricity Consumption (kWh/day) |
|----------------------|---------------------------|------------------------|----------|----------|---------|---------------------------|---------|----------------------------------|
|                      | Max. | Avg. | Max. | Avg. | Max. | Avg. | Range | Avg. | Max. | Max. | Avg. |
| DEC w/o ERV          | 9.2  | 4.7  | 92   | 76   | 36.1 | 32.3 | -2.43 – 3.43 | 17.6 – 96.7 | 50 | 134.5 | 0.55 | 281.6 | 266.5 |
| DEC w/ ERV           | 5.9  | 2.3  | 95   | 85   | 36.9 | 33.4 | -0.89 – 3.0  | 17.6 – 96.7 | 50 | 135.6 | 0.31 | 281.5 | 268.6 |
| MEC w/o ERV          | 10.8 | 5.5  | 89   | 65   | 36.0 | 32.0 | -2.84 – 3.0  | 13.4 – 94.5 | 46.3 | 159.2 | 0.65 | 354.6 | 315.3 |
| MEC w/ ERV           | 10.4 | 5.4  | 90   | 66   | 35.8 | 32.5 | -2.77 – 3.0  | 14.4 – 94.0 | 45.7 | 160.2 | 0.64 | 354.6 | 317.4 |
| VAC w/o ERV          | 13.4 | 9.3  | 86   | 68   | 34.2 | 30.2 | -3.0 – 1.39   | 14.4 – 98.8 | 54.0 | 878.5 | 1.27 | 3018.6 | 1739.7 |
| VAC w/ ERV           | 19.7 | 13.2 | 60   | 48   | 29.6 | 28.2 | -2.28 – 3.0   | 84.6 – 99.5 | 98.7 | 538.1 | 2.2  | 2176.6 | 1065.7 |
| MEC-VAC w/o ERV      | 16.6 | 10.7 | 86   | 68   | 33.5 | 29.5 | 0.71 – 3.0   | 9.4 – 99.3 | 67.2 | 749.5 | 1.46 | 3106.7 | 1484.2 |
| MEC-VAC w/ ERV       | 19.8 | 13.2 | 60   | 48   | 31.9 | 29.6 | -2.2 – 3.0    | 83.2 – 99.5 | 98.7 | 499.2 | 2.2  | 2176.6 | 988.5 |
Being a developing country, it is extremely challenging for Pakistan to stop expanding energy interest. Therefore, it is crucial to investigate potential energy technologies in air-conditioning sector. Present research study is limited to numerical simulation which can only provide an approximate estimation of energy saving potential of ERV systems. However, in future research direction, the ERV systems could be experimentally investigated in commercial buildings of Pakistan. Moreover, experimental energy saving potential of such systems could be validated with the numerically simulated results presented in the current study. Being a cheaper source of air-conditioning, conventional air-conditioning systems coupled with ERV and Recirculation renders incredible possibilities for accomplishing energy security, independence to address energy issues, natural assurance and supportable monetary development Moreover, energy conservation, efficiency improvement of the current air-conditioning systems and mitigation measures can also be undertaken to mitigate CO₂ emissions.

4. Conclusions

The current study intended to explore possible alternative options i.e., standalone direct (DEC), Maisotsenko cycle (MEC) evaporative cooling systems, typical mechanical vapor compression (VAC), and hybrid MEC-VAC systems coupled with two configurations i.e., with and without membrane energy recovery ventilator (ERV) and recirculation, for the management of building air-conditioning loads in Multan (Pakistan). Commonly, the DEC and the VAC systems are used for building air-conditioning without any regard to waste of energy through building exhaust. Therefore, eight possible combinations of the above-mentioned systems are proposed in this study. Building model was developed and simulated in DesignBuilder and EnergyPlus. Essential conclusions of the study are:

- The MEC-VAC system with ERV and Recirculation configuration provided a temperature gradient of 19.7 °C with average relative humidity of 49%, whereas other systems failed to compete in terms of temperature gradient and relative humidity.
- All the systems except the MEC-VAC with ERV and Recirculation configuration failed to achieve required mean radiant temperature matching with their respective psychrometric performance.
- All the systems except standalone evaporative cooling systems achieved slightly cool to extremely cool PMV with 20% – 98% PPD.
- The VAC with ERV and Recirculation and MEC-VAC with ERV and Recirculation systems achieved maximum wet bulb effectiveness of 2.2 out of all the proposed systems.
- Among the studied systems, the standalone VAC system without ERV and Recirculation configuration resulted in highest CO₂ emissions i.e., 878.5 kgCO₂/kWh, whereas the MEC-VAC system with ERV and Recirculation configuration resulted in relatively lower CO₂ emissions i.e., 499.2 kgCO₂/kWh.

The hybrid MEC-VAC system with ERV and Recirculation configuration could achieve the desired results from the viewpoints of temperature gradient, relative humidity, wet bulb effectiveness, mean radiant temperature, and CO₂ emissions. Therefore, this study concludes the hybrid MEC-VAC system with ERV and Recirculation configuration the optimum feasible option for the management of building air-conditioning loads.

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