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Novel concept for a portable personalized ventilator with embedded air treatment system to disinfect, dehumidify, cool, and capture carbon at low energy (A)

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Abstract— A personalized stationery air treatment unit is proposed in this work to provide acceptable breathable air quality and adequate thermal comfort in in poorly ventilated spaces. The system consists of a coaxial personalized ventilation system integrated with an antibacterial filter and a metal organic framework-coated thermoelectric cooling unit. Validated mathematical models were developed to minimize the system size while maintaining thermally comfortable conditions. The system was simulated to determine its operative conditions and its required energy consumption. The supplied air conditions at the user's breathing zone were met by the system ensuring acceptable air quality and thermal comfort levels. The system needed a total of 60 g of Nb-OFFIVE-1-Ni adsorbent with 130 W of electrical energy to properly operate the cooling unit and the fans.

Keywords— personalized ventilation, disinfection, carbon capture, desiccant dehumidification

I. INTRODUCTION

The indoor environment in occupied non-ventilated spaces suffers from high levels of CO_2, humidity, and pathogenic germs as well as a thermally non-comfortable environment. Thus, for the well-being of occupants, outdoor air is usually treated by reducing the CO_2 and H_2O concentrations to acceptable levels, exempting it from contaminants, and cooling the resulting clean air before supplying it to the indoor space. It follows that providing clean and cool air to the entire indoor environment using the renowned total volume ventilation techniques intensifies the energy burden, as it requires the **treatment of large air flowrates**. Thus, there is a need for an easily-integrated compact ventilator supplying **small treated airflow rates** to provide acceptable air quality and comfort levels at reduced energy consumption.

A growing interest in "occupant-focused" ventilation strategies has been mushrooming in the last decade. Such techniques target the microclimate of occupants, providing them with clean and cool air [1-5]. These systems – known as personalized ventilation (PV) systems – enable the treatment of **small amount** of air that would be supplied to the occupant's breathing zone (BZ), while relaxing the macroclimate environment in terms of temperature and air quality. PV systems are usually served by their own air-handling unit to provide cool air. However, for ease of retrofitting and practicality, light has been shed on **ductless PV** systems that extract the cool room air and supply it to the microenvironment of occupants [6]. However, such systems lack the potential to treat the PV-supplied air. On this matter, there are new techniques arising in the research field that rely on using desiccant material – such **as metal organic frameworks** (MOFs) [7], for **dehumidification**, **decarbonization** and **disinfection** of air. When implemented in PV system operating at **low flowrates**, such desiccant systems are expected to be **compact in size**. Consequently, implementing MOF-based desiccant techniques within ductless PV systems results in a clean, dehumidified and decarbonized air supplied to the PV user. The burden of cooling the PV-supplied air and the regeneration energy of the desiccant system requires a novel implementation of a cooling system which is the addition of thermoelectric cooling (TEC). When electric power is applied to a TEC module, heat is transferred from one side of the device to another through the Peltier effect, causing the cooling effect on one side and heating effect on the other [8]. The simultaneous cooling/heating merit fulfils the need for the localized PV air treatment. The treatment thus consists of dehumidification, carbon removal, disinfection as well as cooling, all **combined within one compact portable unit**. Furthermore, the regeneration of the desiccant is achieved by the heating effect of the TEC module. This renders the proposed system **an inclusive strategy** that consists of a holistic operation, resulting in comfortable and clean microenvironment at minimal energy cost since the macroenvironment (room air) conditions can be relaxed. However and in order to reduce the risk of entrainment of the relaxed macroenvironment air into the clean PV jet, a low-mixing coaxial nozzle can be used [9]. Such configuration consists of a primary nozzle supplying the clean cool air, surrounded by a coaxial secondary nozzle delivering recirculated room air at the same velocity [10]. By minimizing the shear stress at the boundary of the primary clean jet, this configuration ensures the effective clean air delivery to the BZ of the user at **minimal flowrate of the treated air**. This leads to the reduction in the overall system size (cost) and energy consumption [10].

Subsequently, the novelty of the work resides in the **multi-feature proposed system** that decontaminates, dehumidifies, decarbonizes and cools the air to be supplied locally to the user via ductless coaxial PV system, providing enhanced air quality and thermal comfort levels at reduced system size and energy cost. Such system has not been proposed in previous literature work, which renders it worthy of investigation for feasible applicability.

Therefore, this research proposes a novel portable PV system consisting of a ductless coaxial PV extracting room air, treating it using MOF-based system with TEC, and supplying it to the microenvironment of the occupant. Implementing these air treatment techniques with ductless coaxial PV systems using low airflow supply is a ***win-win strategy*** where the air treatment system within the primary PV jet allows the supply of **cool decontaminated air at low CO_2/H_2O levels** at reduced energy consumption and system size. An integrated mathematical model depicting the proposed system is developed and validated with experimentally published data. The model is then used to adequately size and operate the system for typical relaxed room air conditions.

II. SYSTEM DESCRIPTION

The proposed personalized ventilation system, shown in **Fig. 1**, consists of a stationery coaxial PV system that extracts the room air, disinfects it from bacterial agents, treats it for water vapor and CO_2 removal using MOFs while simultaneously cooling using TEC unit, and supplying it to the occupant' BZ. Two important advantages of TEC encourage its use in this application: it provides simultaneously the cooling and heating loads required for the air dehumidification/cooling and regeneration of the MOFs. Furthermore, it can easily switch between cooling/heating modes simply by alternating the supplied current direction [11]. Such system is easily integrated within poorly ventilated spaces suffering from contaminated room air.

For air disinfection, Mortada et al. [12] developed new antimicrobial agent systems based on metal organic frameworks (MOFs). Highly stable MOFs structures were used as platforms for the post-metalation with silver cation employed as ***antimicrobial agents***. Thus, a cellulose filter loaded with such MOFs is used for the disinfection of both PV primary and secondary airflow jets. Note that the disinfection of the total PV-supplied air is crucial, as the air supplied to the BZ of the user from both primary and secondary jets should be exempt from contaminants for protection. The disinfected room air is, then divided into two airstreams: the primary stream passes over the cold TEC side to be cooled while the water vapor and CO_2 are simultaneously adsorbed by the MOFs coated on the fins of the TEC unit (**Fig. 1**). The resulting treated air is supplied from the PV primary jet to the occupant at breathing level, while the secondary air stream consisting of disinfected room air is supplied via the coaxial PV nozzle (**Fig. 1**). To regenerate the MOFs, another airstream, extracted from the room, passes over the hot TEC side, desorbing thereby the species (CO_2, H_2O) that are purged into the airstream (**Fig. 1**). This regeneration exhaust air is then discharged upwards away from the occupant.

Having the PV coaxial configuration consisting of small primary and higher secondary PV jets ensures a reduced system size as only the primary jet is to be dehumidified, decarbonized and cooled. This results in a low MOFs mass, reducing thus the system overall size and cost. Moreover, the MOFs-coated TEC unit ensures a continuous operation by rotating the finned plate and simultaneously switching the electric current direction, to constantly provide cooling, dehumidification and decarbonization for the primary PV jet. Note that the different fans needed for the system operation, as well as the TEC can be run using a power supply source (batteries and/or plug-in socket).

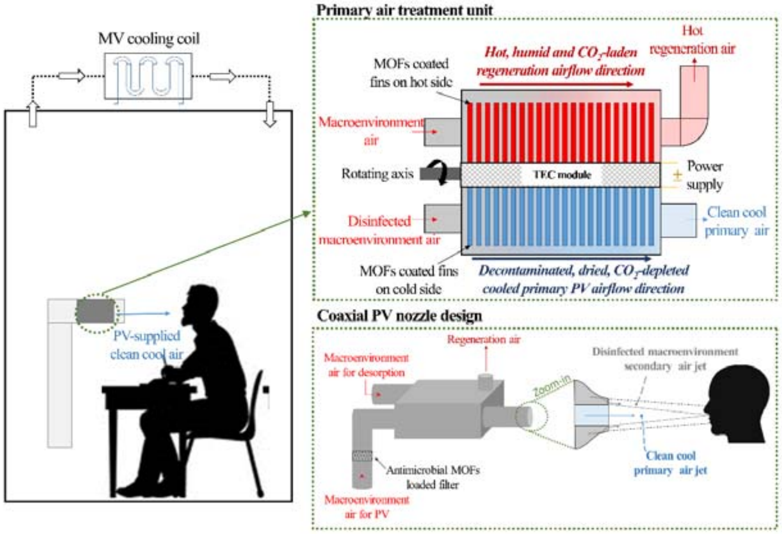

Fig. 1. Schematic of the localized air-conditioning system for the coaxial PV supply outlets using the TEC compact unit.

III. METHODOLOGY

The performance of the PV treatment unit is evaluated through its ability in generating clean cool air at minimal investment and operation costs. The latter consists of the needed electrical energy to operate the PV fans and the TEC unit. This is achieved using validated numerical models of the heat and mass balances of the adsorption process using MOFs and the Peltier effect of the TEC unit. These models are used to size the air treatment unit and determine its energy consumption to provide the supply air conditions.

A. *Adsorption model*

In this system, the MOFs adsorbent is coated on the fins of the TEC unit to enhance the heat transfer on both hot and cold sides. Such configuration offers higher heat and mass transfer area compared to packed beds as well as lower pressure drop on the airflow. Since there is interest in predicting the H_2O and CO_2 concentrations in the air at the outlet of the PV unit, a lumped transient adsorption model is adopted in this study [13]. The model considers coupled heat and mass transfers in the adsorbent assumed at uniform conditions throughout the unit. This is possible due to the small coating thickness, small unit size and fast sorption kinetics of the MOFs. Moreover, the model uses the linear driving force (LDF) assumption to simulate the solid side diffusion of water vapor and CO_2. In this assumption, the adsorption rate of species "i" is proportional to the difference between its equilibrium concentration q_i^* (kg/kg) and the volume-averaged adsorbed concentration $\bar{q}_i$ (kg/kg): The proportionality constant, k_{LDF} (s^{-1}), of this model combines all three mass transfer resistances taking place in the adsorbent: i) the external mass transfer in the fluid film, ii) the intraparticle diffusion in the mesopores, and iii) the interparticle diffusion micropores [14-17]. Based on the above, the macroscale mass conservation of each species is given by:

$$\dot{V}_a\left(C_{in,i} - C_{out,o}\right) + M_s\frac{\partial \bar{q}_i}{\partial t} = 0 \qquad (1)$$

where (1) indicates that the change between inlet and outlet of the PV airflow's species concentration is equivalent to the amount adsorbed by the MOFs. $\dot{V}_a$ (m^3) is the flowrate of the primary air jet, $\frac{\partial \bar{q}_i}{\partial t}$ (kg/kg·s) is the average adsorption rate of species i in the gas phases with inlet and outlet concentrations of $C_{in,i}$ (kg/m^3) and $C_{out,i}$ (kg/m^3), respectively. M_s (kg) is the coated adsorbent mass. The adsorption rate ($\frac{\partial \bar{q}_i}{\partial t}$) is given by the LDF assumption as follows:

$$\frac{\partial \bar{q}_i}{\partial t} = k_{LDF,i}(q_i^* - \bar{q}_i) \qquad (2)$$

The LDF constant and equilibrium uptake of the adsorbent depend on the air and solid temperatures, hence energy balances are needed for both phases.

For the air side, the energy balance considers the change in the PV airflow caused by the heat transfer with the MOFs-coated fins of the TEC unit as given by:

$$\rho_a C_{p,a}\dot{V}_a\left(T_{a,in} - T_{a,out}\right) = h_a A(T_s - \bar{T}_a) \qquad (3)$$

where ρ_a (kg/m^3), $C_{p.a}$ (J/kg·K) and $\bar{T}_a$ (K) are the density, specific heat capacity and average temperature of the air in the PV airflow, $T_{a,in}$ (K) and $T_{a,out}$ (K) are the air inlet and outlet temperatures to the unit. T_s (K) is the adsorbent temperature. h_a (W/m^2·K) is the convective heat transfer coefficient and A (m^2) is the total heat exchange area.

To solve these equations, the adsorbent temperature (T_s) should be known. Hence, an equivalent RC- circuit is used as shown in **Fig. 2**. It should be noted that the heat of adsorption (P_s) is considered as a heat input to the thermal RC- circuit, which is added to the interface between the solid and the fins (**Fig. 2**). Such analysis has been adopted from the experimentally validated model of Li et al. [13].

To simulate the above model, the following inputs are needed: i) Thermos-physical parameters and isotherms of the adsorbent; ii) Inlet air conditions of temperature, species (H_2O, CO_2) concentrations and flowrate; and iii) Heat fluxes from the TEC unit.

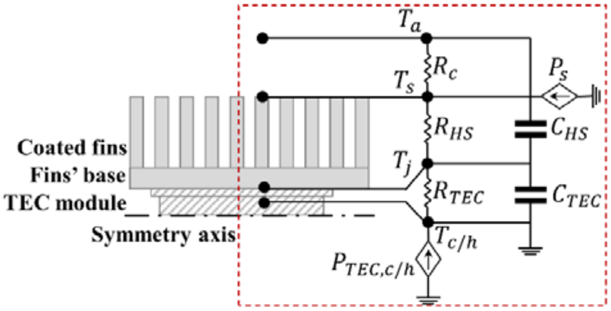

Fig. 2. Equivalent RC-circuit of the TEC unit and its heat sink..

B. *Thermoelectric cooling model*

In the analysis of the RC-circuit previously mentioned, it is required to determine the heat fluxes provided by the TEC unit: when the electrical current is passed in the semi-conductor, a Peltier effect is observed where the heat fluxes on both cold ($P_{TEC,c}$) and hot ($P_{TEC,h}$) sides are given by [18]:

$$P_{TEC,c/h} = \alpha I_{TEC} T_{c/h} \qquad (4)$$

where α (V/K) is the Seebeck coefficient of TEC unit, $T_{c/h}$ (K) is the temperature of the cold or hot side. Due to the internal resistance of the unit, heating by Joule effect is also present and considered, whereas the Thomson effect is neglected in comparison with the Peltier and Joule effects. To solve the model, the supplied electrical current and thermos-physical properties of the TEC unit are needed.

C. *Numerical solution*

The heat and mass transfer equations are solved using the finite volume method with implicit scheme along with Kirchhoff's law and Laplace transformation for the RC-circuit analysis. A time-step independence test is performed to determine the time-step that yields accurate results at acceptable computational time. The convergence of the different mass and energy balances is reached when the residuals of the calculated parameters are less than 10^{-6}. These numerical models are integrated among each other through the RC-circuit analysis [13].

D. *Sizing appraoch*

It is necessary to determine the adsorbent mass needed for effective capture of the water vapor and CO_2 from the primary PV airflow jet. This mass is determined to capture either water vapor or CO_2 separately, and the largest amount is used for the unit design. The captured amount of each adsorbate depends on the PV flowrate to be treated, the specific humidity and CO_2 level of the air at the inlet and outlet of the PV unit as well as the regeneration temperature and cycle time. The flowrate and supply air conditions (temperature, H_2O, and CO_2 concentration) adopted for the sizing must ensure the provision of needed air quality and thermal comfort for the user. The regeneration temperature of the adsorbent is fixed at the minimum desorption temperature that ensures the complete regeneration of the adsorbent using the macroclimate air.

For the cycle time (flipping frequency of the TEC unit), it is fixed to simplify the control and operation of the proposed system. For large flipping frequencies (short cycle period), the needed adsorbent mass decreases, which reduces the system size. However, frequent flipping increases the fluctuations in the supply air temperature to the user, compromising thus their local thermal comfort at the BZ level. Hence, the optimal cycle time should be determined to reduce the adsorbent mass while ensuring thermal comfort for the user. Such optimization problem involves complex physics that combines both the adsorption mechanism in the system and the thermoregulation of the human body. For this reason, genetic algorithm is chosen due to its robustness in finding near optimal solutions for non-linear problems by searching the solution domain. An objective function is set for the minimization of the adsorbent mass. The function is subjected to constraints of meeting the user's thermal comfort requirements. This constraint is integrated into the objective function as presented by Zangwill [19] as follows:

$$J = M_s + \delta_{pen}(4 - CL) \tag{5}$$

where J (kg) is the objective function and CL (-) is the comfort level of the user at the face, which is determined from the comfort model developed by Zhang et al. [20]. This model evaluates the comfort level based on a 9-points scale ranging from −4 (very uncomfortable) to +4 (very comfortable). The model requires the facial skin temperature of the user, its transient change rate as well as the core temperature change rate. To determine these different parameters, bioheat model developed by Karaki et al. [21] is used. δ_{pen} (kg) is a virtual conversion factor for the penalty term of the constraint, which enables the penalty to have similar contribution to the overall objective function. The population size of variable to be optimized (M_s) is set to 20 with a maximum generation number of 50. The crossover fraction, mutation factor and function tolerance were set to 0.8, 0.1 and 10^{-14}, respectively [22]. For the obtained optimal mass, the required number of TEC modules is determined to ensure that the regeneration air heating and primary PV air cooling needs are met at the needed desorption and supply temperatures.

IV. SYSTEM SPECIFICATIONS AND PERFORMANCE

The performance of the proposed PV air treatment unit is assessed in providing the user with acceptable air conditions at their BZ at minimal energy consumption. Typical relaxed macroenvironment conditions are adopted: a temperature of 26 °C, a relative humidity of 65 %, CO_2 concentration of 1500 ppm [23], and a concentration of 10^5 CFU/m^3 of airborne bacteria (*E. coli*) [24]. Acceptable air quality and thermal comfort are ensured when the PV treatment unit supplies clean cool air at a typical primary air flowrate of 2.5 L/s [10], with the following conditions: 23 °C, 55 % relative humidity (i.e., 9.67 g/kg specific humidity), 400 ppm CO_2 concentration (ambient CO_2 level) and exempted from bacterial agents [3]. Note that a secondary air flowrate of 8 L/s for the coaxial PV is adopted.

For the dehumidification and CO_2 capture, Nb-OFFIVE-1-Ni, developed by Bhatt et al. [25] is selected as it exhibits exceptional carbon capture capacities from dilute and humid airstreams with capacities reaching 2.1 mmol/g at ambient CO_2 levels. Additionally, it showed good water vapor uptake capacities of 7 mmol/g and a regeneration temperature of 75 °C, which makes it a great candidate for this application. For the bacteria removal, conventional glass fiber medium filter of 0.3 ± 0.05 mm thickness is used. The filter is doped with 3 % of the media weight with Ag/MIL-101(Cr)/IMI. Such filter proved to have a filtration efficiency > 99.99 % and a bacteria deactivation efficiency of 100 % (completely inactivate retained bioaerosols) [26]. The number and power of the TEC model to be used should cover both cooling and regeneration needs of the PV treatment unit. A proper design of the heat sink (fins) is necessary to provide the required heat dissipation rate on the TEC hot side and ensure proper operation at the desired temperature levels. For this reason, the fins' number, thickness, length and width are determined to ensure the minimum thermal resistance (R_{HS}) capable of releasing the heat on the TEC hot side.

V. RESULTS AND DISCUSSION

The integrated model had been simulated with the optimization algorithm to determine the optimal switching time able to provide the adequate local comfort at minimal system size. A switching time of 10 min ensured the highest comfort level close to 0.9 (comfortable) as presented in **Fig. 3**. For this switching time, the needed mass of the adsorbent was 60 g to remove the needed amounts of CO_2 and H_2O to meet the supply air conditions in species concentrations. Note that this mass was mainly dictated by the H_2O capture requirements. The adsorbent regeneration temperature was provided by the TEC module along with the needed cooling power for the primary PV airflow. For the current application, two TEC units with cooling power of 30 W each were used, which also provide a temperature difference of 55 °C [27]. For effective heat dissipation at the hot side of the TEC, the units were equipped with a heat dissipation sink formed of 19 extruded fins with the following dimensions (110 mm × 50 mm × 1 m) and 3 mm spacing. The needed 60 g of MOFs were coated with a thickness of 0.15 mm.

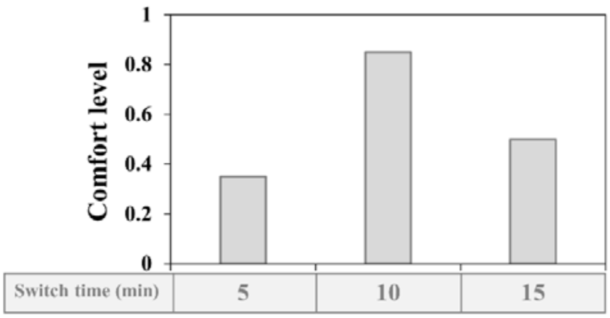

Fig. 3. The obtained comfort level at different switching times.

The system operation was simulated using the developed model and the resulting air conditions at the PV and regeneration air jets outlet are shown in **Fig. 4**. A cyclic steady state was clearly reached in terms of outlet air conditions at both air jet of the proposed unit. For the PV air temperature, it increased at the beginning of the cycle to 27.2 °C due to the heated fins from the previous cycle (**Fig. 4.a**). However, the air temperature decreased and was maintained at 23 °C for the majority of the cycle time, which highlights the validity of the selected optimal time. For the supply air species, both water vapor and CO_2 witnessed a high concentration at the beginning of each cycle caused by the high temperature of the adsorbent, which reduced its capture capacity. However, as the adsorbent was cooled by the TEC, its capacity was restored, and the target supply concentration was maintained throughout most of the cycle time (> 8.5 min). Note that the supply CO_2 level was around 250 ppm, lower than the design value of 400 ppm. This is due to adopting the greater MOFs mass needed for water vapor adsorption.

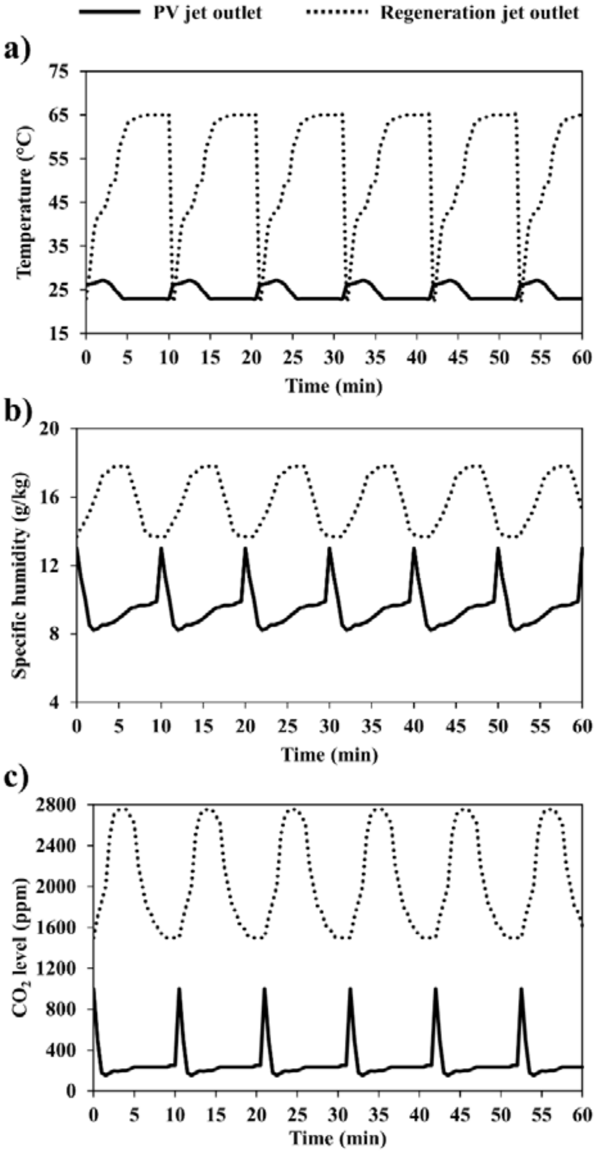

Fig. 4. The variation of a) temperature, b) specific humidity, and c) CO_2 level at the outlet of the PV and regeneration air jets.

The operation of this system required electrical energy to operate the TEC and the fans. The TEC units necessitated 19 V with a current of 6.1 A, resulting in 116 W energy consumption. The fans were used to drive the PV primary and secondary airflows through the filters as well as to drive the primary and regeneration airflows over the TEC unit. These fans required thus 14 W, resulting in a total of 130 W for the overall system operation.

VI. CONCLUSION

This work proposed a personalized stationery air treatment unit consisting of a coaxial PV system integrated with an antibacterial filter and a MOFs-coated TEC unit. This system is used to provide the user with acceptable breathable air quality and adequate thermal comfort in poorly ventilated space. Experimentally validated mathematical models were adopted to minimize the system size while maintaining thermally comfortable conditions. The models were also used to simulate the system operation and determine its energy consumption. It was found that the system required a total of 60 g of adsorbent with 130 W of electrical energy to properly operate. Future work is necessary to assess the impact of implementing this system on the energy consumption of the background room air conditioning system.

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REFERENCES

1. Al Assaad, D., et al., *Evaluation of different personalized ventilation air terminal devices: Inhalation vs. clothing-mediated exposures.* Building and Environment, 2021. **192**: p. 107637.
2. Cermak, R., et al., *Performance of personalized ventilation in conjunction with mixing and displacement ventilation.* Hvac&R Research, 2006. **12**(2): p. 295-311.
3. Katramiz, E., et al., *Effect of individually controlled personalized ventilation on cross-contamination due to respiratory activities.* Building and Environment, 2021. **194**: p. 107719.
4. Melikov, A.K., R. Cermak, and M. Majer, *Personalized ventilation: evaluation of different air terminal devices.* Energy and buildings, 2002. **34**(8): p. 829-836.
5. Pantelic, J., et al., *Personalized ventilation as a control measure for airborne transmissible disease spread.* Journal of the Royal Society Interface, 2009. **6**(suppl_6): p. S715-S726.
6. Liu, J., et al. *Performance analysis of a ductless personalized ventilation combined with radiant floor cooling system and displacement ventilation*. in *Building Simulation*. 2019. Tsinghua University Press.
7. Harrouz, J.P., et al., *Feasibility of MOF-based carbon capture from indoor spaces as air revitalization system.* Energy and Buildings, 2022. **255**: p. 111666.
8. Attavane, P., et al. *Solar powered portable food warmer and cooler based on peltier effect*. in *2017*

2nd IEEE International Conference on Recent Trends in Electronics, Information & Communication Technology (RTEICT). 2017. IEEE.

9. Makhoul, A., K. Ghali, and N. Ghaddar, *Low-mixing coaxial nozzle for effective personalized ventilation.* Indoor and Built Environment, 2015. **24**(2): p. 225-243.
10. Khalifa, H.E., M.I. Janos, and J.F. Dannenhoffer III, *Experimental investigation of reduced-mixing personal ventilation jets.* Building and Environment, 2009. **44**(8): p. 1551-1558.
11. Sarbu, I. and A. Dorca, *A comprehensive review of solar thermoelectric cooling systems.* International Journal of Energy Research, 2018. **42**(2): p. 395-415.
12. Mortada, B., et al., *Postmetalated zirconium metal organic frameworks as a highly potent bactericide.* Inorganic chemistry, 2017. **56**(8): p. 4739-4744.
13. Li, B., et al., *A full-solid-state humidity pump for localized humidity control.* Joule, 2019. **3**(6): p. 1427-1436.
14. Yang, R.T., *Gas separation by adsorption processes*. 2013: Butterworth-Heinemann.
15. Tien, C., *Introduction to adsorption: Basics, analysis, and applications*. 2018: Elsevier.
16. Shafeeyan, M.S., W.M.A.W. Daud, and A. Shamiri, *A review of mathematical modeling of fixed-bed columns for carbon dioxide adsorption.* Chemical engineering research and design, 2014. **92**(5): p. 961-988.
17. Rodrigues, A.E., M.D. LeVan, and D. Tondeur, *Adsorption: Science and technology*. Vol. 158. 2012: Springer Science & Business Media.
18. Jradi, M., N. Ghaddar, and K. Ghali, *Optimized operation of a solar-driven thermoelectric dehumidification system for fresh water production.* Journal of Energy and Power Engineering, 2012. **6**(6): p. 878.
19. Zangwill, W.I., *Non-linear programming via penalty functions.* Management science, 1967. **13**(5): p. 344-358.
20. Zhang, H., et al., *Thermal sensation and comfort models for non-uniform and transient environments: Part I: Local sensation of individual body parts.* Building and Environment, 2010. **45**(2): p. 380-388.
21. Karaki, W., et al., *Human thermal response with improved AVA modeling of the digits.* International journal of thermal sciences, 2013. **67**: p. 41-52.
22. Harrouz, J.P., K. Ghali, and N. Ghaddar, *Integrated solar–Windcatcher with dew-point indirect evaporative cooler for classrooms.* Applied Thermal Engineering, 2021. **188**: p. 116654.
23. Katramiz, E., N. Ghaddar, and K. Ghali, *Novel personalized chair-ventilation design integrated with displacement ventilation for cross-contamination mitigation in classrooms.* Building and Environment, 2022. **213**: p. 108885.
24. Prussin, A.J., E.B.G. II, and L.C. Marr, *Total virus and bacteria concentrations in indoor and outdoor air.* Environmental science & technology letters, 2015. **2**(4): p. 84.
25. Bhatt, P.M., et al., *A fine-tuned fluorinated MOF addresses the needs for trace CO2 removal and air capture using physisorption.* Journal of the American Chemical Society, 2016. **138**(29): p. 9301-9307.
26. Zendehdel, R., et al., *Doping Metal‐organic Framework Composites to Antibacterial Air Filter Development for Quality Control of Indoor Air.* Environmental Progress & Sustainable Energy: p. e13909.
27. Berlanga, F.A., et al., *Experimental assessment of different mixing air ventilation systems on ventilation performance and exposure to exhaled contaminants in hospital rooms.* Energy and Buildings, 2018. **177**: p. 207-219.