Carbon capture from indoor air as an alternative ventilation technique

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Abstract. A polluted indoor space is a serious problem for the occupants especially for office workers who require high attentiveness levels. Indoor pollutants, especially carbon dioxide (CO_2), reduce the workers performance by increasing sickness risk and impairing cognitive abilities needed to make informed decisions. Typically, indoor air quality is improved by diluting indoor contaminants with fresh outdoor air. However, the outdoor air should be dehumidified and cooled before it is entrained into the office, especially in hot and humid climates. Nonetheless, this solution is energy intensive since conventional systems use vapor compression-based air-conditioning. This increases the building electricity consumption as well as its carbon footprint. To mitigate the danger of global warming emerging from the increased carbon emissions, sustainable ventilation techniques must be conceived. The use of the recirculated indoor air, characterized by lower temperature and humidity levels than the outdoor air, could reduce the ventilation load. However, the indoor air suffers from increased CO_2 levels generated by the occupant. To overcome this problem, adsorption-based CO_2 removal from the room air can be a good solution. Recently, this system has become more promising due to the emerging of new generation of solid adsorbents, the metal-organic frameworks (MOF). They can be produced to exhibit high capacity and affinity towards carbon dioxide and can be regenerated at low temperature energy such as solar and waste energy. CO_2 capture by adsorption reduces the ventilation load by reducing the outdoor air requirement to modest levels needed to maintain healthy levels of VOCs and O_2. A sustainable cooling system is developed using MOF-packed adsorption beds for CO_2 capture to treat the indoor air and resupply it to the space. A numerical model simulating the heat and mass transfer in the adsorbent bed is developed and used to size the adsorption system for a case study of a typical office in the hot and humid climate of Beirut, Lebanon. The proposed ventilation system reduced the outdoor air requirements and ventilation load by 72.6 % and 36 %, respectively during the peak load month of August.

Keywords. Carbon capture, sustainable ventilation system, metal organic frameworks, indoor air quality.
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1. Introduction

Concerns about acceptable indoor air quality (IAQ) in the workplace environment are rapidly increasing [1]. This is due to the IAQ's direct effect on the workers' well-being and their decision-making abilities [2, 3]. A healthy environment is thus provided by diluting air contaminants level below a certain threshold [4, 5]. Although not a direct contaminant, high CO_2 concentration leads to dizziness and fatigue sensation. Similarly, high indoor relative humidity (RH) levels cause mould growth [6] and affect the thermal comfort perceived by the occupants [7]. Moreover, indoor spaces are typically characterized by high concentrations of VOCs, such as formaldehydes that are generated from furniture and surface finishes among others [8, 9]. Outdoor air is used to dilute these contaminants; however, it requires excessive dehumidification and cooling, especially in hot and humid climates [10]. Conventionally, such air-conditioning has been achieved using vapor compression-based cooling systems, which run on high amount of electricity [11]. Subsequently, ventilation and air-conditioning systems consumes more than half of the building's electrical energy [12]. Since more than 80 % of electricity is produced from fossil fuels [13], there is pressing need to pursue more sustainable ventilation techniques. This is important to move towards a more productive workplace while also limiting the building's carbon footprint.

A prominent solution is the use of indoor recirculated air with adsorption-based CO_2 treatment techniques [10, 14]. Using adsorbent materials, excess CO_2 is removed from the room air before it is resupplied to the space [15]. The saturated adsorbent is then regenerated by increasing its temperature to the desorption temperature [16]. Conventional adsorbents such as zeolites suffers from low capacity for CO_2 at the dilute levels required in indoor spaces (<1,000 ppm), which is further degraded in presence of water vapor [17]. Amine-functionalized adsorbents are insensitive to water presence and have high capacities for dilute CO_2; however, they require high regeneration energy to desorb the chemically bonded CO_2 [18, 19]. The limitations of these conventional sorbents can be overcome by using the metal organic framework (MOF), a new generation of porous material [20, 21]. MOF are synthesized from metal ions clusters connected using organic linkers, called ligands [22]. With the appropriate choice of the metal ions and ligands, MOF can be produced to exhibit the required properties for efficient CO_2 treatment of the return air [18]. Such properties include high capacity and affinity for CO_2 at dilute levels, low H_2O selectivity over CO_2 and low regeneration temperature and energy to enable the use of low-grade thermal energy [23, 24]. Nonetheless, the use of such advanced materials is currently hindered by its high investment cost. It is important thus for the selected MOFs to be commercially available at economic prices. MOF-74- Mg is therefore a suitable candidate due to its low price and regeneration temperature and good capacity for dilute CO_2 in dry conditions. It can be used in conjunction with a low-price, and low regeneration temperature desiccant, such as silica gel, to remove the competition with H_2O present in the return air [25].

A ventilation system is proposed that incorporates desiccant and MOF adsorbents for the treatment of the return air through a sequential removal of excess water vapor and CO_2. This system can reduce the outdoor air requirements to minimal levels needed to maintain acceptable indoor VOCs levels as well as replenish the consumed O_2 by the occupants. Therefore, it is important to evaluate the performance of this proposed system in the reduction of the vapor compression cooling system' s outdoor air intake and the subsequent energy consumption. For this reason, a mathematical model is developed for the heat and mass transfers in the water and CO_2 adsorbents as well as in the indoor space. The models are then integrated and used for a case study of a typical occupied office space located in the hot and humid climate of Beirut, Lebanon. The system's energy consumption is evaluated over the peak load month of Beirut's cooling season and compared to that of the conventional air-conditioning system.

2. System description

In this work, a typical air-tight office space is considered located in Beirut. A mixing ventilation system is adopted to supply cool, dry, and CO_2-lean air. Thermal comfort is achieved by regulating the indoor air temperature and RH between 20 – 24 °C and 40 – 60 %, respectively. In addition, acceptable IAQ is provided by maintaining CO_2 levels below 1,000 ppm [26], while those of formaldehyde, representer of the VOCs family [14], should be kept below 8 ppb [8]. Additionally, O_2 levels above 19.5 % must be ensured for the office workers [10]. These indoor conditions are achieved using the proposed ventilation and air-conditioning system that integrates two adsorption beds in series that are packed silica gel and MOF-74-Mg followed by the evaporator coil of a vapor compression cooling system as shown in **Fig. 1(a)**.

The psychrometric process of the supply air using the proposed system is shown in **Fig. 1(b)**. The extracted room air at state (2) is divided into 3 streams: a part $\dot{m}_{oa}$ is exhausted to the outdoor environment, a part $\dot{m}_{ta}$ is treated in the adsorption beds and the remaining bypasses them. $\dot{m}_{ta}$ is first dehumidified to state (3) in the silica gel packed bed. The hot and dry air is then passes in the MIL-101-Cr packed bed to remove the excess CO_2. The resulting air stream at state (4) is mixed with the outdoor air at state (1) and flowrate $\dot{m}_{oa}$. The air mixture at state (5) is mixed with the bypassed air at state (2), forming the supply airstream $\dot{m}_{sa}$ at state (6) that is cooled to the supply temperature at state (7).

The system operation is regulated in terms of the supply, outdoor and treated air flowrates ($\dot{m}_{sa}$, $\dot{m}_{oa}$, $\dot{m}_{ta}$) to remove the space' s both latent and sensible load as well as meeting the needed IAQ constraints for the different species at minimal thermal regeneration energy consumption and minimal electric power consumption for both the bed's blowers and the compressor of the cooling system.

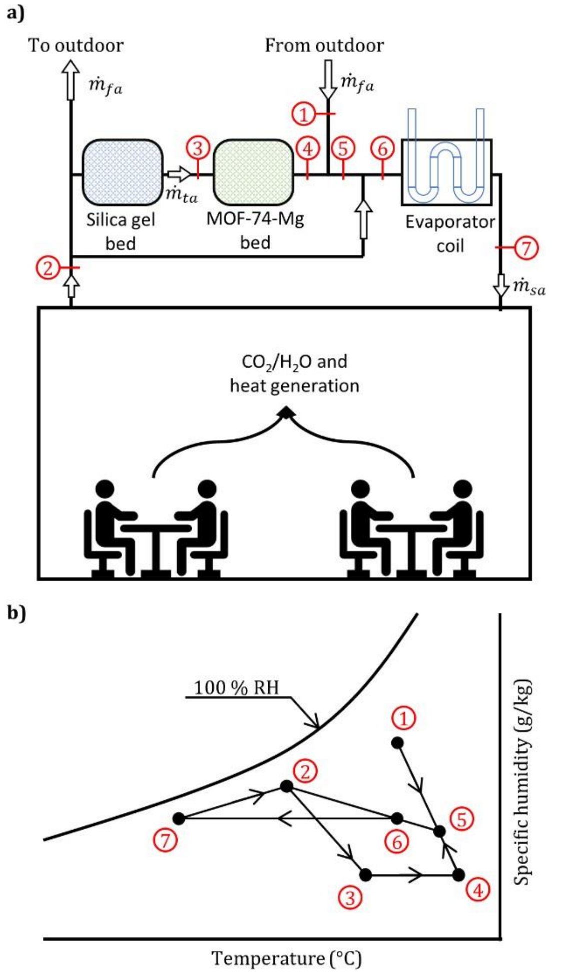

Fig. 1 – Schematic of a) the proposed ventilation system and b) the psychrometric process of the supply airflow.

3. Methodology

Mathematical models are developed for the heat and mass balances taking place in the adsorption bed as well as the office space. The models are integrated and used to size the different packed beds and evaluate the proposed system's energy consumption over the peak load month of Beirut's climate and compare it to that of conventional cooling system.

3.1 Adsorption model

Packed beds are used to selectively remove either H_2O or CO_2 from the room recirculated air. Such process is exothermic, requiring thus coupled heat and mass balances [27, 28]. A transient-one dimensional model is developed to predict the heat and species transfer between the airstream and the adsorbent. Due to the dilute nature of both H_2O and CO_2, the loss in species' mass does not affect the overall flowrate, enabling the assumption of a constant velocity along the flow path with plug flow pattern [29, 30]. Using these assumptions, the species mass balance considers the transient or storage effect, the convective and diffusive mass fluxes as well as the sink/source terms related to adsorption/desorption stages as given by [27, 28]:

$$\frac{\partial x_i}{\partial t} + u\frac{\partial x_i}{\partial z} - D_{zi}\frac{\partial^2 x_i}{\partial z^2} + \left(\frac{1-\varepsilon_b}{\varepsilon_b}\right)\rho_s\frac{\partial \bar{q}_i}{\partial t} = 0 \quad (1)$$

where x_i (kg/m^3) and $\frac{\partial \bar{q}_i}{\partial t}$ (kg/kg·s) are the concentration and the average adsorption rate of species "i" (H_2O or CO_2) in the gas phase, u (m/s) is the flow velocity, ρ_s (kg/m^3) is the adsorbent density, respectively. ε_b (-) is the bed void fraction. D_{zi}(m^2/s) is the axial diffusion coefficient. $\frac{\partial \bar{q}_i}{\partial t}$ is given by the linear driving force model [27, 28]:

$$\frac{\partial \bar{q}_i}{\partial t} = k_{LDFi}(q_i - \bar{q}_i) \quad (2)$$

where K_{LDFi} (s^{-1}) is the linear driving force model time constant, and $\bar{q}$ (kg/kg) is the equilibrium concentration evaluated at the adsorbent temperature and the species partial pressure in the airstream. The energy balances on the airstream and adsorbent takes into consideration the transient storage effect, diffusive heat flux and heat source/sink due to the exchange of heat of adsorption during adsorption/desorption stages. In addition, the airstream energy balance considers the convective heat flux. These equations are detailed by Myers et al. [27] and are not reported here for simplicity.

Based on the packed bed dimensions and inlet air conditions, the adsorption model yields the outlet air conditions in terms of temperature and species (H_2O or CO_2) concentration.

3.2 Office space indoor air model

The validated indoor air model developed by Yassine et al. [31] is adopted in this work. It considers the heat and species balances inside the office, where the air conditions are assumed homogeneous (well mixed assumption). The heat balance considers the heat generated internally by the occupants, lighting, and electrical equipment. In addition, the heat balance accounts for the heat gain from the office envelop and the heat removed by advection using the ventilation and air conditioning system. For the mass balance, the adopted model considers the net species transfer by advection from the ventilation and air-conditioning system as well as the internal generation of H_2O/CO_2 by the occupants, formaldehyde by the indoor furniture, and the rate of consumption of O_2.

Based on the office envelop characteristics, occupancy and equipment schedules, the indoor air temperature and species concentrations are determined.

3.3 Numerical methodology

The conservation equations are solved numerically using the finite volume method. For the disctrization, backward Euler scheme is used for temporal gradients, while first order upwind and second order central difference schemes are used for first and second order sapctial gradients. A time step independence test results in a 1×10^{-5} s time step for the integrated model. Convergence is reached when the relative error between two consecutive iterations falls below 1×10^{-6} for all calculated parameters. Note that the adsorption model is validated by the authors as presented in [25, 32].

4. Case Study

This work considers a case study of a typical office space (5 m × 5 m × 3 m) located Beirut, in the coastal region of Lebanon characterized by hot and humid climate. The weather conditions during the cooling season of Beirut are adopted from typical meteorological year database as presented by El Loubani et al. [33]. The office envelope properties and occupancy schedule are adopted Katramiz et al. [34]. Each occupant is responsible for the generation of 11.57 mg/s of H_2O [35], 10.8 mg/s of CO_2 [36] and the consumption of 9.92 mg/s O_2 [10]. The formaldehyde generation rate from the different office is set to 30 mg/h [8, 9].

The beds are sized to capture the maximum H_2O during the peak load month and the maximum CO_2 mass during peak occupancy. Based on Beirut weather and the office maximum occupancy of 4 occupants, it was found that design $\dot{m}_{ta}$ is 0.03 kg/s and that August is the peak load month. Accordingly, the required silica gel and MOF-74-Mg masses are 4.1 kg/bed and 4.0 kg/bed respectively. The packed bed diameter and length are 0.2 m and 0.1 m, respectively for silica gel, and 0.25 m and 0.15 m, respectively for MOF-74-Mg. Note that the sizing is based on a regeneration temperature of 75 °C and 50 °C with feed-to-purge airflow ratio of 0.6 and 0.45 for the silica gel and MOF-74-Mg, respectively.

5. Results and discussion

The proposed system operation is regulated in terms of the supplied outdoor air ($\dot{m}_{oa}$) and the treated air ($\dot{m}_{ta}$) in the adsorption beds, and the supply air ($\dot{m}_{sa}$) to the space. The resulting hourly variation of these parameters along with the corresponding thermal and electrical energy requirements are presented in **Fig. 2**.

During the occupied hours, the supplied flowrate varied between 0.35 kg/s and 0.45 kg/s (**Fig. 2(a)**) that ensured an indoor temperature within the comfort range. The minimum was needed at *8:00 hr* when the space load was low, while the maximum was needed during peak load hour (*15:00 h*). Due to the night-time infiltration of outdoor air, the initial CO_2 levels were near the ambient levels (400 ppm). This enabled the system to completely bypass the adsorption bed during the first occupied hour with a $\dot{m}_{oa}$ of 0. 04 kg/s to meet the IAQ constraints of CO_2, VOCs and O_2 (**Fig. 2(a)**). After *8:00 h*, $\dot{m}_{oa}$ was reduced to a minimum of 0.01 kg/s that was dictated by the formaldehyde generation rate (**Fig. 2(a)**). Consequently, the O_2 levels were also above the allowable threshold of 19.5 %. Simultaneously, $\dot{m}_{ta}$ was increased to 0.1 kg/s between *9:00 h* and *14:00 h* when the outdoor humidity was low. However, it was increased to 0.15 kg/s for the remaining occupied hours (**Fig. 2(a)**). This is necessary to dilute the water vapor levels in the supply stream, which are caused by the increase in the outdoor humidity during the afternoon.

The resulting thermal energy consumption (E_t) for the bed regeneration varied between 1.36 kWh and 2.1 kWh (**Fig. 2(b)**). The electrical energy consumed by the packed bed fans ($E_{e,fans}$) varied between 0.86 kWh and 1.64 kWh (**Fig. 2(b)**). Moreover, the electrical energy consumed by the compressor of the air-conditioning system ($E_{e,coil}$), which reflects the proposed system ventilation load, varied between 1.55 kWh and 1.84 kWh (**Fig. 2(b)**). The variation pattern of E_t and $E_{e,fans}$ followed that of $\dot{m}_{ta}$, whereas the variation of $E_{e,coil}$ depended largely on $\dot{m}_{sa}$.

For comparison purposes, a vapor compression air-conditioning system with a COP of 3.2 is adopted. In addition, the conventional system is operated with the same $\dot{m}_{sa}$ since the space load does not depend on the choice of the system. Furthermore, the conventional system is operated with $\dot{m}_{oa}$ of 0.05 kg/s throughout the occupied hours to enable the same level of IAQ created by the proposed system. Accordingly, it can be concluded that the proposed system was able to reduce the outdoor air flowrate requirements and the ventilation load on the cooling coil by 72.6 % and 36 %, respectively.

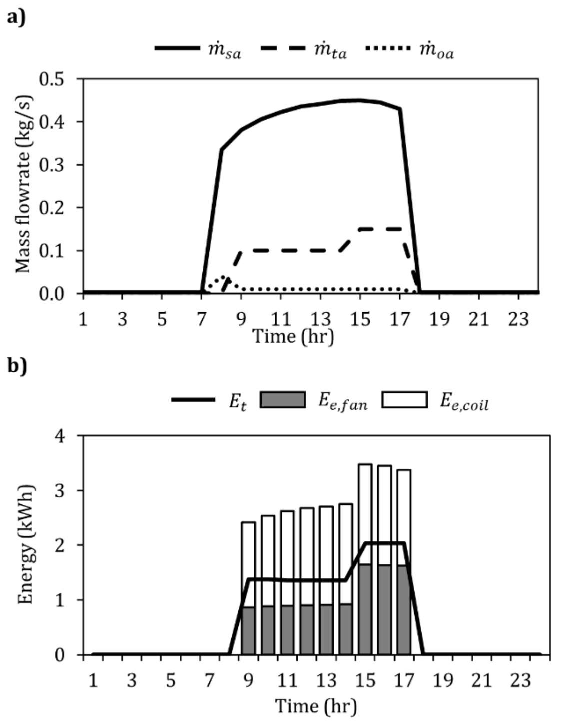

Fig. 2 – The hourly variation of a) the system's operating parametrs and b) the corresponding electrical and thermal energy cosumptions.

6. Conclusion

In this work, the performance of sustainable ventilation system is studied for a case study of a typical office in the hot and humid climate of Beirut, Lebanon. The proposed system integrates adsorption beds packed with either silica gel or MOF-74-Mg to sequenially treat the room recirculated air and reduce the outdoor air intake. Numerical models for the heat and mass transfers were developed to assess the performance of this system vis-a-vis the vapor compression-based ventilation and cooling systems. The model is used to determine the system operation in terms of required outdoor and treated air flowrates that meet the office indoor air constraints at minimal energy consumption. The hourly operation reduced the outdoor air intake and ventilation load by 72.6 % and 36 % as compared to that of a conventional system maintain the same indoor air conditions.

7. Acknowledgement

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9. Data availability

The datasets generated during and/or analysed during the current study are not publicly available because they are contained within the article but are/will be available upon request.