Building and Environment 122 (2017) 343–353

Contents lists available at ScienceDirect

Building and Environment

journal homepage: www.elsevier.com/locate/buildenv

Experimental analysis of indoor air quality improvement achieved by using a Clean-Air Heat Pump (CAHP) air-cleaner in a ventilation system

Ying Sheng [a], Lei Fang [b, *], Jinzhe Nie [c]

[a] Tianjin Key Laboratory of Indoor Air Environmental Quality Control, School of Environmental Science and Engineering, Tianjin University, Tianjin, China
[b] International Centre for Indoor Environment and Energy, Department of Civil Engineering, Technical University of Denmark, Lyngby 2800, Denmark
[c] School of Environment and Energy Engineering, Beijing University of Civil Engineering and Architecture, Beijing 100044, China

ARTICLE INFO

Article history:
Received 10 December 2016
Received in revised form
22 May 2017
Accepted 16 June 2017
Available online 19 June 2017

Keywords:
Perceived Air Quality (PAQ)
Air purification
Silica gel rotor
Ventilation

ABSTRACT

This study investigated the air purification effect of a Clean-Air Heat Pump (CAHP) air-cleaner which combined a silica gel rotor with a heat pump to achieve air cleaning, heating and ventilation in buildings. The experiments were conducted in a field laboratory and compared a low outdoor air supply rate with CAHP air purification of recirculated air with three different outdoor air supply rates without recirculation or air cleaning. Sensory assessments of perceived air quality and chemical measurements of TVOC concentration were used to evaluate the air-cleaning performance of the CAHP. The results of the experiment showed that the operation of the CAHP significantly improved the perceived air quality in a room polluted by both human bio-effluents and building materials. At the outdoor airflow rate of 2 L/s per person, the indoor air quality with CAHP was equivalent to what was achieved in the same room with 10 L/s per person of outdoor air ventilation without air cleaning. The percentage dissatisfied was as low as 5.2% with the CAHP in operation, based on adapted perception assessment. The outdoor air supply rate can be reduced by 76% by using CAHP, as the Clean Air Delivery Rate (CADR) was over three times the outdoor air supply rate when the CAHP was in operation. The chemical measurements indicated a single-pass efficiency of over 92% for the removal of indoor air pollutants when the regeneration temperature was 60 °C. No VOC accumulation on the desiccant wheel was observed.

1. Introduction

In recent decades, great changes have taken place in building materials, consumer goods and occupants' lifestyles, and this has had an effect on the air pollutants originating from walls, floors, furniture, fittings, cosmetics, detergents, plastics and from indoor activities such as printing, cooking and smoking etc. [1–3]. Occupants exposed to these air pollutants run an increasing risk of experiencing symptoms of headache, eye irritation, throat irritation, mental confusion, allergy etc. collectively known as SBS symptoms [4], all of which can have a negative effect on their productivity [5].

In order to improve indoor air quality, three main methods may be adopted, i.e. pollution source control, ventilation and air purification. Pollution source control is clearly the best way to avoid indoor pollution. Although great efforts have been made to reduce gas-phase emissions [6–10], materials that emit gas-phase pollutants are still widely used in many buildings. In most indoor volumes nowadays, e.g. classrooms, the occupants themselves are the major source of indoor air pollution and clearly cannot be removed, so ventilation is still the most common method of indoor air quality control in practice. The outdoor air supply rate prescribed by existing ventilation standards and guidelines [11,12] is in the range of 2.5–10 L/s per person. It has been reported that around 40% of building energy is used for ventilation and associated air conditioning. Recent research has found that a higher ventilation rate (over 25 L/s per person [13]) would be required to minimize the prevalence of SBS symptoms. This is hardly acceptable from an energy point of view. Several air-cleaning technologies are therefore recommended to remove indoor air pollutants. A limited number of scientific studies of air-cleaning technologies have been

* Corresponding author. International Centre for Indoor Environment and Energy, Technical University of Denmark, Building 402, DK-2800 Lyngby, Denmark.
E-mail address: fl@byg.dtu.dk (L. Fang).

http://dx.doi.org/10.1016/j.buildenv.2017.06.032
0360-1323/

Nomenclature

ACC	ACCeptability of air quality
AD	Air Dryness
AF	Air Freshness
CADR	Clean Air Delivery Rate
CAHP	Clean Air Heat Pump
OI	Odour Intensity
PD	Percentage Dissatisfied
PAQ	Perceived Air Quality
VOCs	Volatile Organic Compounds
TVOC	Total Volatile Organic Compounds (as toluene equivalents)
SD	Standard Deviation
c	TVOC concentration
Q	Airflow rate
RH	Relative Humidity
V	Volume of test room

Greek symbols

η	Air cleaning efficiency
ε	Mass balance of CAHP

Subscripts

r	Return air
s	Supply air
o	Outdoor air
p	Purging air
2,5,10,20	Outdoor air supply rate in L/s per person

conducted in buildings. A study by Sidheswaran et al. [14] indicated that a combination of activated carbon fibre air cleaning with a 50% reduction in ventilation would still remove 60–80% of indoor VOCs, although only 12–40% of formaldehyde would be removed, and the energy used for ventilation would be reduced by 35–50% according to a simulation study. Bivolarova et al. [15] studied a ventilated mattress for the improvement of air quality in a hospital room. It was found that bio-effluents were reduced by 70% and body-emitted ammonia was reduced by 96% when an activated carbon fibre (ACF) blanket was used with a ventilated mattress whose ventilation rate was only 1.5 L/s. Han et al. [16] built a detailed model based on a low-energy office building with nearby traffic as the pollution source. The results showed that a combination of ventilation and air-cleaning technology was a promising way to achieve the indoor air quality constraints for major indoor compounds and that the annual energy use was reduced by 11% in a mild climate. Cho et al. [17] found that the annual energy use was reduced by 19.5% when an air-cleaning unit was operated with demand control ventilation in an energy simulation using TRNSYS software. Ventilation combined with air-cleaning may therefore be the most effective method to obtain a healthy and comfortable indoor environment while reducing energy consumption.

One of the most critical factors affecting perceived air quality is what type of air-cleaning technology should be adopted. It has been reported [18] that sorption was the most effective method for removing gaseous pollutants when comparing various air purification techniques such as catalytic oxidation, filtration, ozone oxidation, plasma, sorption and UVGI (use of ultraviolet wavelengths of light), following a review of the 133 most scientific valuable publications selected from 26,000 papers on air purification. Sorption techniques usually use porous materials such as active carbon, silica gel or zeolite to adsorb airborne chemicals. The sizes of the internal cavities in zeolite are relatively consistent so that it can only adsorb chemicals in a narrow range of molecular size [19]. Activated carbon is one of the most commonly used sorption techniques in practice. Some common problems of activated carbon as an absorbent are that the temperature must usually be higher than 150 °C to achieve adequate regeneration, that this requires abundant energy, and that the air-cleaning effectiveness for formaldehyde is relatively low [17,20].

Silica gel has a mass of pores of different sizes that can adsorb water and a variety of gaseous organic and inorganic chemicals [21–25]. Fang et al. [26] studied the use of the co-sorption effect of a silica-gel desiccant wheel for improving the indoor air quality. It was found that more than 80% of the sensory pollution load was removed and the percentage dissatisfied with the air quality decreased from 70% to 20% in an experiment in a climatic chamber. This suggested that the air-cleaning capacity of a regenerative silica-gel desiccant wheel could with advantage be integrated into a ventilation system. Nie et al. [27,28] then designed a Clean Air Heat Pump (CAHP) system and analysed the air cleaning performance of the CAHP in theory. In their study, the operation of CAHP was controlled with fixed supply air temperature and humidity. When the humidity ratio of inlet process air to the rotor was high, the moisture removal was large and a higher regeneration air temperature was required to achieve the fixed supply air humidity. Hence an increase in the regeneration air temperature of the rotor could lead to a higher dehumidification and high VOCs removal levels. The results also showed that the CAHP could remove VOCs from indoor air with an efficiency of at least 65% under the assumed conditions. However, the real air-cleaning performance of the CAHP (especially the impact of air cleaning on human comfort perception after adaptation) was not tested so reference could only be made to the earlier studies of Fang et al. [26] and Zhang et al. [25] on the co-sorption effect of a silica-gel desiccant wheel.

In evaluating the air-cleaning effect of competing technologies, comparative research has been a common method. Sun et al. [29] evaluated the air cleaning effect of air-purifiers that used photocatalytic oxidation (PCO) technology in an aircraft cabin. Chemical and physiological measurements and human assessments were conducted when the PCO was either turned on or off. Kolarik et al. [30] examined the effect of a photocatalytic air purifier on Perceived Air Quality (PAQ) at three different outdoor air supply rates, and subjective assessment of PAQ was used both when the purifier was in operation and when it was not. Hesaraki et al. [31] compared the influence of four different ventilation levels from low to high on indoor air quality in a single-family house. In the original study of the air-cleaning effect of a desiccant wheel [26], the comparative method was also used. PAQ was assessed in a test room polluted by four different pollution sources when the desiccant wheel was either turned on or off. Comparative research can provide a convincing demonstration of the ability of an air purifier to improve air quality. The same approach was therefore adopted in the present paper. The evaluation of the CAHP was conducted in a field laboratory at four different ventilation rates, with CAHP air-cleaning in operation only at the lowest ventilation rate.

Chemical measurement was also used in the evaluation of the performance of the CAHP system. Proton-Transfer-Reaction Mass-Spectrometry (PTR-MS) was originally used to measure the effects of a desiccant wheel on VOC concentrations in indoor air [26,29]. It is a chemical ionisation mass spectrometry technique that uses proton transfer reactions with H_3O+ ions for real-time measurements of VOCs in air. In the present study, another instrument, the INNOVA 1312, was used for measuring VOCs. INNOVA is based on the photoacoustic infrared detection method and measurements are available in real time. It is capable of measuring almost any gas that absorbs infrared energy down to the ppm level.

The present study examined the performance of the CAHP system on indoor air quality in a field laboratory polluted by human bio-effluents and emissions from building materials, furniture and other indoor fittings. Both sensory measurements with human subjects and chemical measurements were used to quantify the effect on air quality.

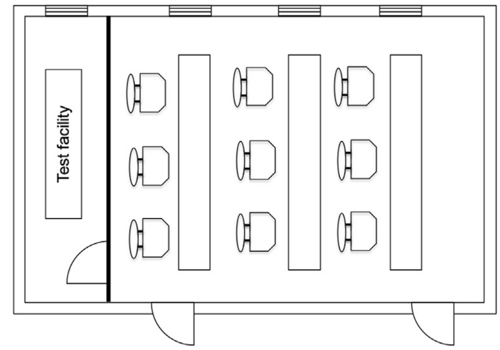
2. Method

2.1. Approach

In order to examine the air-cleaning effect of the CAHP purifier on air quality in the presence of the complex pollutant mixtures occurring indoors, the test room was ventilated with four different outdoor air supply rates. The CAHP was used only at the lowest level of ventilation. This design made it possible to compare the impact of clean air delivered by the CAHP to the equivalent impact of increasing the outdoor air supply rate. Under these conditions, the perceived air quality in the test room was assessed by human subjects. When the CAHP was in operation, chemical measurements of indoor gas-phase VOC contaminants were conducted to evaluate the effectiveness of the air cleaning.

2.2. Test room

The present investigation was carried out in a “field laboratory” (a realistic test room) located in an office building in the Technical University of Denmark. The dimensions were12 × 6 × 3 m. The field laboratory was divided into two parts by a wall made of low-emitting construction material as shown in Fig. 1. The space in front of the wall was used as a test room and the space behind the wall was used to accommodate the experimental ventilation system.



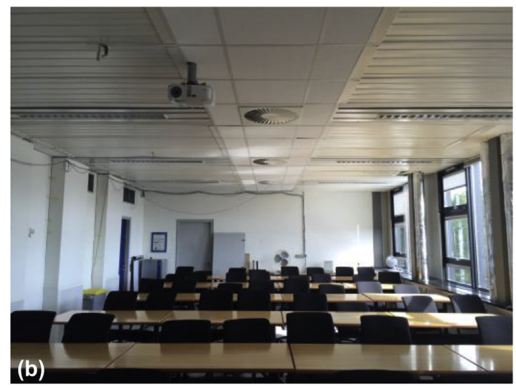


Fig. 1. Plan and view of the test room.

2.3. Experimental facility

The field laboratory ventilation system included a CAHP air-cleaner and an outdoor air-handling unit as shown schematically in Fig. 2. The outdoor air handling unit was able to process the outdoor air intake to simulate the hydro-thermal conditions of outdoor air in different seasons. The CAHP included a commercially-available silica gel rotor (whose properties are given in Table 1) and a heat pump.

When the CAHP was in operation, Dampers 1–6 were open. Damper 1 was fully open but Dampers 2–6 were partly open. The openings of Dampers 2–6 were adjusted to control the airflow rates to the intended values. One stream of outdoor air was mixed with a large amount of return air to be successively processed by the silica gel rotor and the evaporator of the heat pump for dehumidification, purification and cooling, and delivered into the test room to maintain the required indoor environment. Another stream of outdoor air was divided into two airflows. One stream of outdoor air was heated by Condenser 1 and used to regenerate the silica gel rotor. The other stream passed through Condenser 2 and was used to reject the extra heat generated by the heat pump. This dual-condenser configuration was required to avoid overheating the silica gel rotor (see Ref. [27] for details).

When the CAHP was not in operation, the heat pump was off and the desiccant wheel did not rotate. Dampers 1–3 &6 were closed and Damper 4 was fully open. The opening of Damper 5 was adjusted to control the airflow rate delivered to the test room. Outdoor air was treated only by the initial outdoor air handling unit before being delivered into the test room.

2.4. Experimental conditions

The experiment comprised exposure to the four air quality conditions shown in Table 2, i.e. four levels of outdoor air supply rate: 5, 10, 20 and 2 L/s per person, encountered by the subjects in that order. The CAHP was operated only at the lowest level of ventilation (2 L/s per person) and when the test room was ventilated at 5, 10 and 20 L/s per person of outdoor airflow, the CAHP was not operated. It should be noted that subjects encountered a progressively improving level of air quality in the first three conditions, followed by the condition in which the CAHP was used to compensate for a drastic reduction in outdoor air supply rate. Any contrast effects will therefore be to the detriment of this last condition, so that the performance of the CAHP was evaluated conservatively.

These experimental conditions were designed to determine which outdoor air supply rate was equivalent to the effective clean air delivery rate from the CAHP. The four levels of outdoor air ventilation rate covered the full range of ventilation rate prescribed by the major international standards on indoor environment e.g. ISO, EU and ASHRAE standards [11,12and32]. The outdoor air supply rate of 5, 10, 20 L/s without air cleaning were selected based on the EU ventilation standard for non-residential buildings - EN 13,779 [11]. In EN 13,779, an outdoor air supply rate is recommended at four levels 5, 8, 12.5 and 20 L/s per person which cover four levels of indoor air quality, i.e. low, moderate, medium and high. The still lower outdoor air supply rate of 2 L/s per person with air cleaning was selected in order to demonstrate the effect of air cleaning by

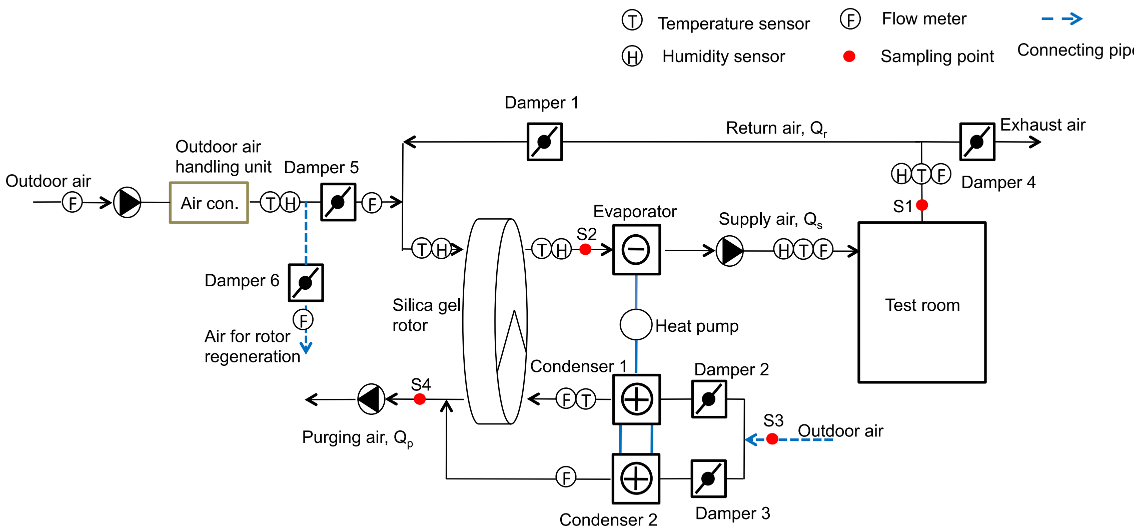


Fig. 2. Schematic diagram of the test facility for maintaining the desired environment.

Table 1
Physical properties of the silica gel rotor.

Parameters	Value
Diameter	450 mm
Thickness	200 mm
Proportion process/regeneration sections	2:1
Specific heat of silica gel	920 J/(kg*K)
Specific heat of substrate	900 J/(kg*K)
Rotation speed	11.6 r/h

comparing indoor air quality in the test room under this condition with the indoor air quality achieved when the test room was ventilated by outdoor air at levels corresponding to those recommended in the EU Standard, in order to be able to estimate directly the clean air delivery rate of the CAHP.

To guarantee a clean outdoor air supply, the humidity of the outdoor air supply was not controlled by using the steam humidifier in the outdoor air handling unit, since the steam humidifier produced odour in the humidified air stream due to emissions from the materials used in the humidifier at high temperature. However, due to the modest outdoor humidity during the experimental period, indoor humidity was always within the very comfortable range of 40–50% RH. The air temperatures in the test room were controlled using the outdoor air handling unit (Condition 1–3) which was equipped with a cooling coil and a heating coil. Whenever the measured return air temperature was lower than the expect temperature, the opening of the valve controlling the flow of hot water was increased.

With the operation of the CAHP in Condition 4, the control strategy of CAHP was to ensure the indoor air temperature and humidity. The air temperature was controlled by a frequency invertor to regulate the speed of the compressor. Whenever the measured return air temperature was higher than the set point, the compressor would speed up and vice versa. The air humidity was controlled by regulating the opening of the two valves connected to the condensers. When the measured return air humidity ratio was higher than the set point, more refrigerant was distributed to Condenser 1 so as to raise the temperature of the regeneration air, and when the measured humidity ratio was lower that the set point, more refrigerant would be distributed to Condenser 2 so that it would reject more condensing heat from the heat pump and reduce the temperature of the regeneration airflow. The rotation speed of the wheel was kept constant.

2.5. Physical and chemical measurement

Air temperature, humidity ratio and airflow rates were measured continuously throughout each experiment in the locations indicated in Fig. 2. The airflow rates were measured using IRIS dampers with differential-pressure transmitters. The air temperature and the humidity ratio of the return air were measured by CAREL transducers to describe the thermal-hygrometric parameters in the test room. The regeneration temperature for the silica gel rotor was measured and automatically controlled. The sensor types and their accuracies are listed in Table 3.

The air was sampled in the inlet and outlet air ducts of the CAHP (S1~S4 as shown in Fig. 2) when the CAHP system was in operation. The concentration of VOCs at S1 was identical to that inside the test room while the concentration of VOCs at S2 was that of the supply air after purification by the CAHP. The concentration of VOCs at S3 may be regarded as that in outdoor air while the concentration at S4 is that of the VOCs that were rejected from the CAHP by regeneration of the desiccant rotor.

The concentrations of VOCs were measured under Condition 4 only, using a Photoacoustic Gas Monitor-INNOVA 1312 with

Table 2
IAQ conditions listed in the order encountered by the subjects.

Conditions	Planned room Temp. (°C)	Planned room RH (%)	Planned outdoor air rate (L/s per person)	CAHP On/off
Condition 1 (C1)	22	50%	5	Off
Condition 2 (C2)	22	50%	10	Off
Condition 3 (C3)	22	50%	20	Off
Condition 4 (C4)	22	50%	2	On

Table 3
Models and accuracies of the measuring devices in the ventilation system.

Measured parameter	Device	Measuring range	Accuracy
Temperature and relative humidity	CarelDPD010000 Duct Probe thermal meter	−20 °C–70°C/ 10%–90% RH	±0.5 °C at 25 °C, ±0.9 °C at −20 °C to 70 °C; ±3% at 25°C/50%RH, ±6% at −20°Cto 70 °C.
Airflow rate	IRIS damper and Huba Control AG 669 pressure transmitter	0 m^3/ h −1260 m^3/h	±5% of the measuring range

photoacoustic infrared detection and real time measurement. It was capable of measuring almost any gas that absorbs infrared energy down to the ppm level, expressed as its toluene equivalent. The accuracy of these measurements was ensured by the INNOVA's ability to compensate for temperature and pressure fluctuations, water vapour interference and interference from other gases known to be present. Sampling air was continuously drawn from the centre of each ventilation duct.

In order to evaluate the air cleaning effect of the CAHP, its single-pass air cleaning efficiency and the mass balance between the adsorption and desorption sides were calculated. The average TVOC concentrations in the return air, supply air, outdoor air and purging air were used for the calculations after steady state conditions had been reached, which was usually 1 h after the test room was occupied. The air cleaning efficiency η and the mass balance of the CAHP ε were calculated using the following formulas:

$$\eta = \frac{Q_r(c_r - c_0) - Q_s(c_s - c_o)}{Q_r(c_r - c_o)} \quad (1)$$

$$\varepsilon = \frac{Q_p(c_p - c_o)}{Q_r(c_r - c_o) - Q_s(c_s - c_o)} \quad (2)$$

where c_r and c_s are the average TVOC concentrations in sample S1 and S2 of return air and supply air, respectively, mg/m^3; c_o is the average TVOC concentration in sample S3, mg/m^3. It represents the background TVOC concentration level that is equal to the TVOC concentration in outdoor air. c_p is the average TVOC concentration in sample S4 of the exhaust air rejected by the CAHP, mg/m^3. Q_r is the average airflow of return air processed by the CAHP, Q_s is the average supply airflow, and Q_p is the average rejected airflow from the CAHP, all expressed in m^3/h.

The measured TVOC concentrations eventually reached a steady state, at which the slope of the linear regressions of the TVOC concentration of return air, supply air and purging air against time was 0. Once steady state was established, the average TVOC concentrations of S1~S4 were calculated and the single-pass efficiency and mass balance were obtained. Further detail is given in the Results section.

2.6. Subjective sensory assessment

Thirty-six subjects participated in the experiment. Each of them experienced all 4 conditions in the stated order. They were students at the Technical University of Denmark and were aged from 18 to 30 years old. Before the first exposure, the subjects were instructed on how to perform the sensory assessments. The exposure to each condition lasted 3 h. In this period, the major indoor air contaminants included human bio-effluents, emissions from building materials and furniture and contaminants originating from other sources such as the ventilation system and the outdoor environment. In the final 10 min of each exposure, the subjects reported the indoor air quality using a questionnaire (Fig. 3) [30] that included the acceptability of the air quality (ACC), the odour intensity (OI), air freshness (AF) and air humidity (AD). Subjects assessed the air quality to which they were exposed on each occasion by marking the continuous scales shown in Fig. 3. A rating of zero acceptability of the air quality meant just acceptable/unacceptable while 1 = clearly acceptable and −1 = clearly unacceptable. The value from 0 to 5 represented the six levels of odour intensity from “not perceptible” to overpowering. Air humidity was assessed as 0 = air too humid and 1 = air too dry. Similarly air freshness was rated 0 = air stuffy and 1 = air fresh.

In this study, the adapted perception of air quality by occupants was used, as this directly reflects the impact of air cleaning on the sensory assessment of occupants, as opposed to visitors. The disadvantage of this method was that occupants adapt to the environment and their sense organs become much less sensitive to the air quality. The immediate perceptions of visitors are used in some Standards [11,12], but in the present experiment the major pollution source in the test room was the occupants themselves. If another group of subjects had been recruited to evaluate the indoor air as visitors, entering a test room full of people would have a strong psychological impact on their subjective assessment. For this reason, the perceived air quality was evaluated in the experiment by the occupants themselves.

Using the mean vote on the acceptability of air quality (ACC), the Percentage Dissatisfied (PD) with air quality was calculated. Perceived Air Quality (PAQ) in decipol was used to calculate the Clean Air Delivery Rate (CADR), which was used to express the air cleaning effect of the CAHP system as being equivalent to an additional airflow of fresh air to the test room. PD, PAQ and CADR were calculated using the following equations [33,38]:

$$ACC = \frac{\sum_{i=1}^{N}(ACC_i)}{N} \quad (3)$$

$$PD = \frac{\exp(-0.18 - 5.28*ACC)}{1 + \exp(-0.18 - 5.28*ACC)} \quad (4)$$

$$PAQ = 112*[\ln(PD) - 5.98]^{-4} \quad (5)$$

$$CADR = 3.6Q_0\left(\frac{PAQ}{PAQ_{CAHP}} - 1\right)\Big/V \quad (6)$$

where CADR [38] is clean air delivery rate of the CAHP in air change per hour (h^{-1}); Q_o is the outdoor air supply rate in L/s, PAQ (decipol) is perceived air quality with the CAHP turned off and PAQ_{CAHP} (decipol) is perceived air quality with the CAHP in operation. V is the volume of the test room in m^3.

The software STATISTICA was used for statistical comparisons between conditions. In this experiment, there were only 36 subjects and we did not wish to assume that the ratings were Normally distributed. Nonparametric statistics do not assume any particular distribution of the variable of interest. The Wilcoxon Matched-Pairs Signed-Ranks Test was therefore used to test the Null Hypothesis of no difference in reported perception between conditions and medians and the 25% and 75% percentiles were calculated. The significance level of the null hypothesis test was set to $p < 0.05$.

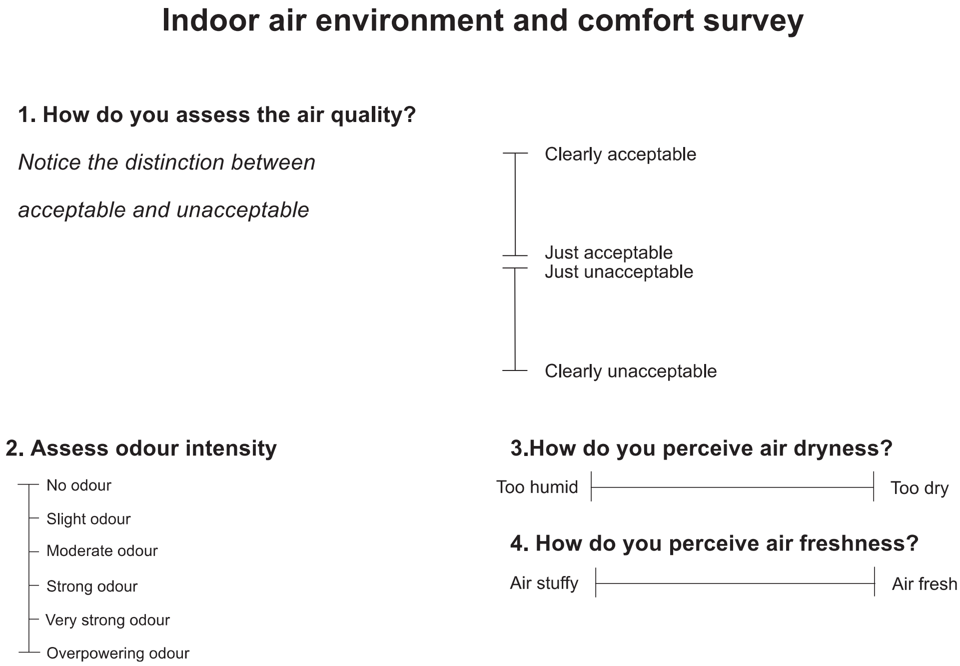


Fig. 3. Scales used by subjects in the present experiment to assess the air quality.

2.7. Experimental procedure

In each experimental condition, the systems started from 11:00 and they took approximately 2 h to achieve the desired temperature and relative humidity conditions in the field laboratory. The subjects then entered at 13:00 to study for 3 h and completed the questionnaires in the last 10 min. During the exposure, no smoking or alcohol was allowed. When the CAHP system was turned on, the regeneration air temperature of the silica gel rotor was gradually increased until it reached approx. 60 °C to obtain the planned thermal condition in the test room.

3. Results

3.1. Results of physical measurement

When the subjects entered the test room, the indoor air temperature was higher than the desired temperature. By reducing the amount of hot water flowing to the outdoor air handling unit, the indoor air temperature was gradually decreased to the intended temperature and then kept constant under Conditions 1 to 3. Table 4 shows the measured mean values of air temperature and humidity ratio at the sensor positions under the three conditions examined (5, 10, 20 L/s per person) when steady state had been established, with the standard deviations (SD) in parentheses. The return air temperature and humidity represent the indoor air condition. They show that the measured values of air temperature and humidity were close to the planned values even though the air humidity was not actively controlled. Under Condition 4, with the CAHP in operation, the indoor air temperature and humidity were continuously controlled until they were close to the intended indoor thermal conditions. Table 5 shows the air temperature and humidity on average under Condition 4 when steady state had been reached. Comparing the data in Tables 4 and 5, it is worth noting that the air humidity in the test room at Condition 4 was not significantly lower compared to the air humidity of the other three conditions. This was because the moisture emission of the occupants at the lowest level of outdoor air supply rate (2 L/s per person) counteracted the dehumidification effect of the CAHP. The airflow rates measured in the air ducts are given in Table 6. They show that the outdoor air supply rate was successfully controlled to 5, 10, 20 or 2 L/s per person, respectively, under the four conditions, except in Condition 4 with the CAHP in operation. The outdoor airflow rate was 63.8 L/s on average, equal to 1.8 L/s per person, with an accuracy of approximately 10%.

Table 4
Average values of air temperature and humidity at the measuring locations for the three conditions without CAHP.

Conditions	Condition 1	Condition 2	Condition 3
CAHP on/off	off	off	off
Return air temp.(°C)	21.7 (0.1)	22.2 (0.2)	22.1 (0.2)
Return air humidity ratio (g/kg)	7.9 (0.2)	8.1 (0.2)	7.9 (0.2)
Supply air temp.(°C)	11.5 (0.2)	17.0 (0.2)	19.2 (0.2)
Supply air humidity ratio (g/kg)	6.5 (0.2)	7.1 (0.3)	7.4 (0.2)

Note: the value represents as mean (SD).

3.2. Results of chemical measurement

Fig. 4 shows the time course of the TVOC concentration measured at the four sampling locations under Condition 4, representing the TVOC concentrations in return air, supply air, purging air and outdoor air. It may be seen that TVOC concentrations in the return air, supply air and purging air all simultaneously decreased after the subjects entered the test room until they reached steady state conditions, implying that the TVOC concentration in the test room was decreased due to the air cleaning effect of the CAHP. The TVOC concentration in the outdoor air was not controlled and remained constant between 13:00 and 15:00. After 15:00, the outdoor TVOC concentration increased unexpectedly. This was probably due to external activities or increased road traffic. The increased outdoor air concentration of TVOC caused slight increments in the other three TVOC concentrations measured after 15:00. However, linear regressions of the concentrations of return

Table 5
Average values of air temperature and humidity at the measuring locations for the condition with CAHP.

	Return air	Outdoor air	Process air before rotor	Process air after rotor	Supply air	Regeneration air before rotor	Regeneration air after rotor	Purging air
Temp. (°C)	22.3 (0.1)	23.0 (0.3)	22.5 (0.3)	30.1 (0.2)	14.7 (0.4)	59.8 (0.4)	37.9 (0.4)	52.6 (0.3)
Humidity ratio (g/kg)	7.6 (0.2)	6.3 (0.3)	7.3 (0.3)	6.2 (0.2)	6.2 (0.2)	6.3 (0.3)	8.8 (0.3)	7.6 (0.3)

Note: the value represents as mean (SD).

air, supply air and purging air against time between 14:00 and 15:00 show that the slope of the regression lines is 0, which means that the concentrations of TVOC measured in return air, supply air and purging air all reached steady state between 14:00 and 15:00. The mean concentrations in return air, supply air and purging air between 14:00 and 15:00 were then used for calculating the air cleaning efficiency and mass balance of the CAHP. Fig. 4 (a) shows that the TVOC concentration in the supply air was much lower than in the return air, which means that the CAHP removed TVOC from the recirculation airflow. From the results in Fig. 4 (b), the concentration of TVOC in the purging air rejected from the CAHP was significantly higher than it was in the outdoor air. This indicates that the pollutants adsorbed by the desiccant rotor were removed continuously from the rotor instead of being accumulated on the rotor surfaces.

In order to assess the air-cleaning efficiency of the CAHP system, the mean concentrations of TVOC in the four air streams were calculated using the data from 14:00 to 15:00. Fig. 5 shows the average concentrations of TVOC in the return air, supply air, outdoor air and purging air at steady state. From the results in Fig. 5, the TVOC concentration in the supply air after being processed by the CAHP was nearly as low as the level in outdoor air, which means that the return air after being processed by the CAHP was equivalent to outdoor air in terms of the level of TVOC concentration. In Fig. 5, the average TVOC concentration measured at S4 in the purging air stream was less than that in the return air (S1) because by then it had been diluted by mixing with the outdoor air that was used to reject the surplus condensing heat, as shown in Fig. 2. Based on the results in Fig. 5, the air cleaning efficiency η was calculated using Eq. (1) as 92% and the mass balance in the CAHP system ε was calculated using Eq. (2) as 100% at the regeneration temperature of 60 °C.

3.3. Results of the sensory assessments

The sensory assessments of the air under the four conditions are summarised in Table 7. The significance levels obtained when comparing the conditions with and without the CAHP system in operation are given in Table 8.

The acceptability of air quality (ACC) assessed by the occupants after 3 h of exposure increased with the increasing outdoor airflow rate from 5 to 20 L/s per person in Conditions 1–3, as expected, as increased dilution improves perceived air quality. In Condition 4, with the CAHP in operation but an outdoor air supply rate of only 2 L/s per person, the ACC and Odour Intensity (OI) were equivalent to what had been achieved with the high outdoor air rate of 10 or 20 L/s per person without CAHP. The air was perceived as being fresher with CAHP than in any of the other three conditions without CAHP. These results indicate a significant air-cleaning effect of CAHP. However, the perception of air dryness (AD) did not differ significantly between conditions. This shows that the very small decrease in indoor humidity caused by operating the CAHP desiccant rotor at a regeneration temperature of only 60 °C was not perceived by the subjects.

In general, ACC, OI and AF were significantly improved when the CAHP was in operation at the outdoor air supply rate of 2 L/s per person compared with that at the ventilation rate of 5 L/s per person without CAHP, i.e. the perceived air quality in the test room was significantly improved in the CAHP condition. The values of ACC, OI, AD and AF in Condition 4 with CAHP in Table 7 are close to those obtained at the intermediate outdoor air supply rate of 10 L/s per person without CAHP (Condition 2). In addition, the Perceived Air Quality (PAQ) in Condition 4 was calculated to be 0.32, which is also close to the value obtained at the airflow rate of 10 L/s per person in Condition 2.

Fig. 6 shows the mean air quality assessments expressed as the Percentage Dissatisfied (PD) under the four conditions. The results show that with the CAHP in operation the PD was 5.2% in the test room receiving only 2 L/s per person of outdoor air. This is almost as low as the PD calculated for outdoor air supply rates of 10 L/s per person or higher with no CAHP in operation. The potential for reducing the ventilation requirement in this way may be seen to be considerable.

Using Equations (3)–(6), the CADR may be calculated for Condition 4. The CADR is 3.5 h^{-1}, which is 207 L/s. This means that the cleaned and recirculated air in the 273 L/s of supply airflow constituted 76% of the supply air, reducing the outdoor air requirement by this amount.

4. Discussion

The present results show that operation of the CAHP can improve the perceived air quality in a test room polluted by human bio-effluents and emissions from building materials, furniture etc. It is worth noting that the perceived air quality assessment showed a relatively low Percentage Dissatisfied (PD) at all the three levels of ventilation rate ($PD_5 = 11.8\%$, $PD_{10} = 4.4\%$, $PD_{20} = 3.8\%$) and when operating the CAHP ($PD_2 = 5.2\%$). This is not due to the low air pollution in the test room but because the air quality assessments obtained in this study are an adapted perception of the air quality,

Table 6
Airflow rates measured during the experiment.

	Return air (L/s)	Outdoor air to test room (L/s)	Supply air (L/s)	Regeneration air (L/s)	Airflow through Condenser 2 (L/s)
Condition 1	–	179.8 (2.0)	180.0 (2.2)	–	–
Condition 2	–	357.6 (1.9)	357.9 (2.4)	–	–
Condition 3	–	717.7 (2.2)	718.0 (2.3)	–	–
Condition 4	209.2 (1.6)	63.8 (2.4)	272.9 (2.6)	117.6 (1.9)	119.0 (2.7)

Note: the value represents as mean (SD).

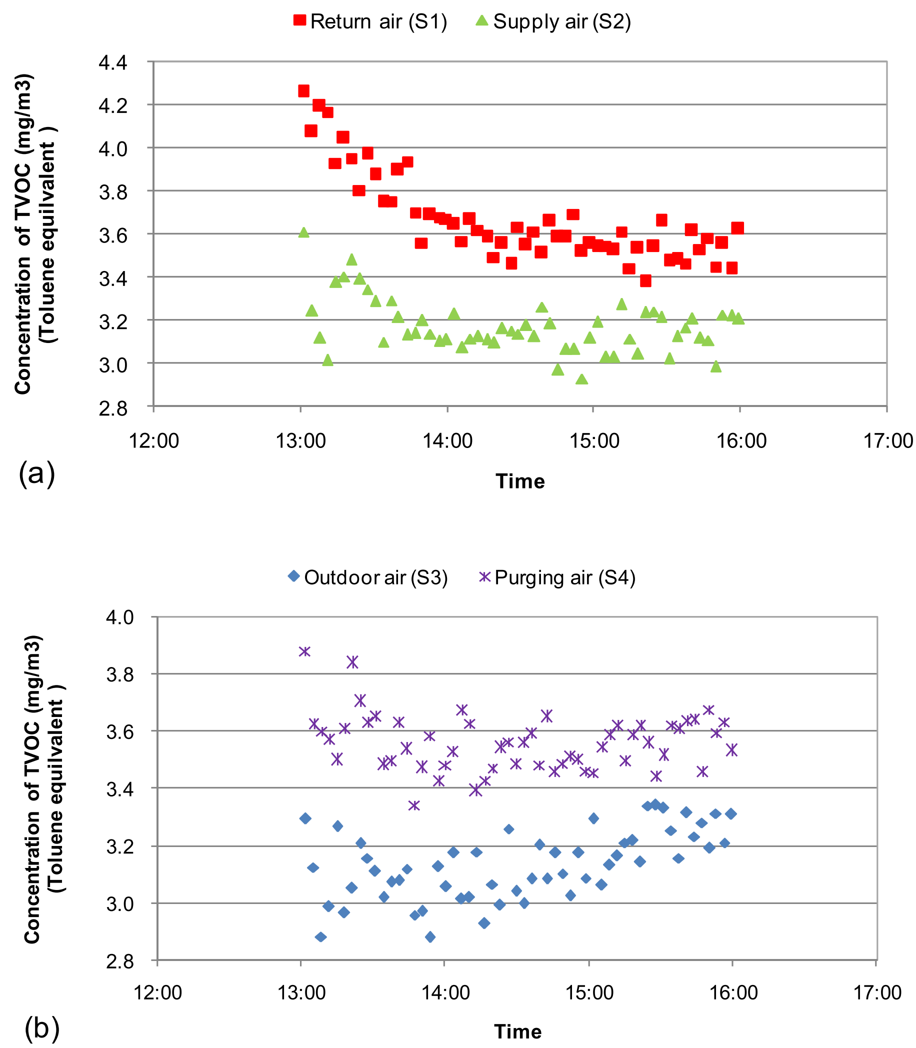


Fig. 4. Toluene equivalent concentrations of TVOC measured by INNOVA from 13:00 to 16:00 under Condition 4. (a) TVOC concentrations of return air VS. supply air; (b) TVOC concentrations of purging air expelled from CAHP VS. outdoor air.

made by occupants, not visitors. In most of the ventilation standards, immediate perception is recommended for evaluating perceived air quality. In the study by Fang et al. [26], immediate perception by visitors was also used to evaluate the perceived air quality before and after improvement by a desiccant wheel and the PD was less than 20%. However, in this experiment, the major source of the pollutants in the indoor air was the occupants. In order to obtain an immediate perception by visitors, another group of subjects would have been required to form a sensory panel. The visual environment might have had a strong psychological effect on subjective evaluations performed by a visiting sensory panel. Instead, using the occupants of the test room as a sensory panel more directly reflects the impact of air cleaning on the perceptions of the occupants. The method of adapted perception of the air quality is stipulated in ASHRAE Standard 62.1–2013 “Ventilation for acceptable indoor air quality” [12] to determine the required ventilation rate. The present study demonstrated that the CAHP significantly improved the perceived indoor air quality even after adaptation had occurred in a long exposure.

In this experiment, the chemical concentrations in the airflows were measured by using an INNOVA multi-gas analyser, which functions on a photoacoustic infrared detection principle [34]. Since most of the VOCs in the air absorbed infrared energy at the same wavelength, the INNOVA multi-gas analyser could not identify each individual chemical in the air. The VOC concentrations were expressed as toluene equivalent total VOC (TVOC) concentrations. However, the INNOVA could perform online monitoring of the TVOC in several parallel channels. This made it possible to observe the air cleaning process of the CAHP. For example, the TVOC measurement by INNOVA clearly shows that the silica gel rotor in the CAHP removed VOCs from the return air and the concentration of TVOC in the supply air was equal to what was measured in the fresh outdoor air supply; the VOCs removed from the processed return air were rejected from the purging air to outdoors instead of accumulated in the silica gel rotor. In earlier research on the air cleaning effect of a desiccant wheel [26], individual VOCs in the process air before and after a desiccant wheel were monitored online by Proton-Transfer-Reaction Mass-Spectrometry (PTR-MS). This study was able to show how well each individual VOC was removed by the desiccant wheel. However, due to the limitation on the monitoring channels of the PTR-MS, the experiment could not simultaneously monitor the concentration of VOCs in the purging air before and after the desiccant wheel. The VOCs in the purging air were measured by air sampling and

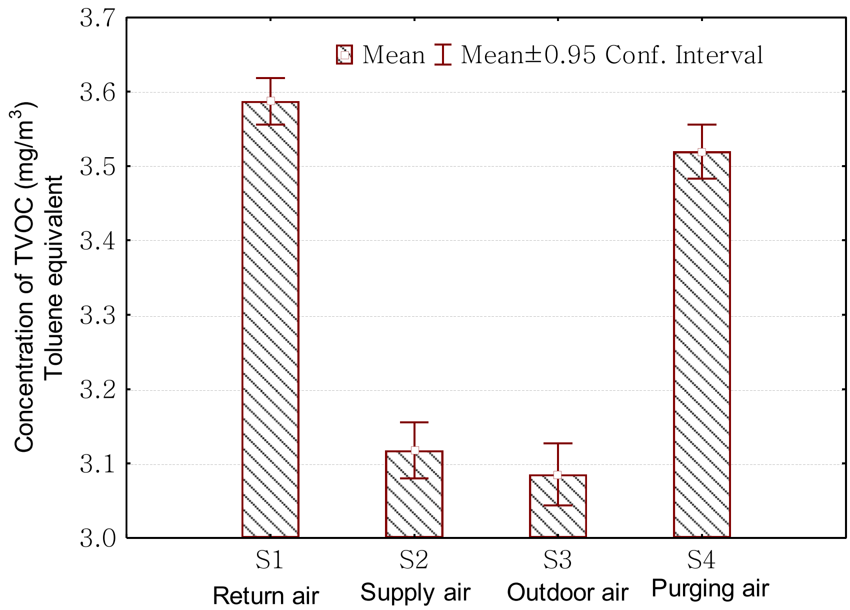


Fig. 5. The average concentration of TVOC in the return air, supply air, outdoor air and purging air expelled from the CAHP at steady state under Condition 4.

Table 7
Summary of the results of statistical analysis of subjective assessments in the four conditions.

Conditions	Condition 1	Condition 2	Condition 3	Condition 4
DW on/off	off	off	off	on
Planned Qo (L/s per person)	5	10	20	2
Acceptability of air quality (ACC)[a]	0.42 (0.15,0.60)	0.55 (0.40,0.80)	0.60 (0.41,0.65)	0.60 (0.28,0.70)
Odour intensity (OI)[a]	1.00 (0.40,1.50)	0.50 (0.20,1.00)	0.55 (0.10,1.00)	0.55 (0.10,1.00)
Air humidity/dryness (AD)[a]	0.50 (0.45,0.59)	0.50 (0.45,0.55)	0.55 (0.5,0.63)	0.50 (0.48,0.52)
Air freshness (AF)[a]	0.49 (0.25,0.66)	0.70 (0.38,0.90)	0.66 (0.52,0.84)	0.75 (0.58,0.90)
Perceived air quality (PAQ) (decipol)	0.74	0.27	0.24	0.32
Clean air delivery rate (CADR) (h^{-1})	-[b]	-[b]	-[b]	3.45

Note: ACC coded 1 = clearly acceptable, 0 = just acceptable/just not acceptable, −1 = clearly not acceptable; OI coded 0 = no odour, 1 = slight odour, 2 = moderate odour, 3 = strong odour, 4 = very strong odour, 5 = overpowering odour; AD coded 0 = air too humid; 1 = air too dry; AF coded 0 = air stuffy, 1 = air fresh.
[a] Value represents: median (25% and 75% percentile).
[b] Data not available.

Table 8
Wilcoxon matched-pairs signed-ranks test between the conditions of rotor on or off.

VA-scale	C1 vs C4	C2 vs C4	C3 vs C4
Acceptability of air quality (ACC)	**0.026**	0.475	0.549
Odour intensity (OI)	**0.045**	0.627	0.475
Air humidity/dryness (AD)	0.256	0.091	0.969
Air freshness (AF)	**0.001**	0.167	0.207

Note: Significant differences as indicated by Wilcoxon matched-pairs signed-ranks test ($p < 0.05$) on a 2-tail test are shown in bold.

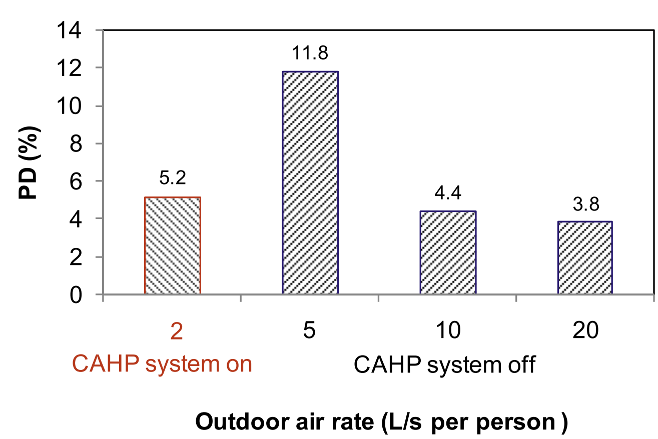


Fig. 6. Percentage Dissatisfied (PD) with the air quality in the field laboratory under the four conditions.

subsequent gas chromatography (GC) analysis. The mass balance between process and regeneration air was calculated based on measurements made by two different methods. The error from the measurement of the two methods meant that the mass balance did not match completely. In the present study, the concentrations of all VOCs at the inlet and outlet airflows of CAHP were measured by the same instrument, avoiding any systematic measuring errors.

Moisture in the air can take up the major capacity of a desiccant rotor for chemical removal. In principle, an increased moisture load on the desiccant wheel can decrease the effectiveness of VOCs removal. However, the VOC concentrations in indoor air are normally three to five orders of magnitude lower than the moisture concentration in the air. Removal of VOCs will thus use only a very small fraction of the wheel's capacity. Moreover, the wheel is regenerated in real time. It will always have a sufficient surface for adsorbing VOCs. Indoor humidity should therefore have little influence on the effectiveness of VOC removal by a rotor. In this study, the TVOC concentration was decreased successively, uninfluenced by the variation of moisture load on the rotor. Similar results were also obtained in our previous study [26].

The silica gel rotor can be completed regenerated at an air temperature of 120 °C according to the data supplied by the manufacturer. It will not be sufficiently regenerated when the regeneration air temperature is only 60 °C since some adsorbed VOCs will remain in the pores of the silica gel. From the results observed in this study, the VOCs adsorbed were expelled by regeneration and the index of mass balance was 100%. When the regeneration air temperature was kept constant at 60 °C, the TVOC concentrations at S1, S2 and S4 were relatively stable. The VOC concentration in the air was too low to saturate the desiccant rotor. It will therefore maintain a high VOC removal efficiency for a considerable time, probably for several years.

It is well known that a higher regeneration air temperature increases the effectiveness of dehumidification. The process of VOC removal takes place in parallel with moisture removal. An increase in the regeneration air temperature may therefore have a positive impact on VOC removal. In the present experiment the regeneration air temperature of the rotor was gradually increased up to about 60 °C in order to remove the moisture load from the occupants. During this period, the TVOC concentration in the return air quickly decreased, and then reached a dynamic balance when the regeneration temperature was kept constant at 60 °C. The positive effect of regeneration air temperature on air purification was confirmed. If less moisture must be removed, for example in a part load condition, the regeneration air temperature required to maintain constant indoor thermal conditions would be lower. In this condition, the air cleaning capacity of the CAHP and the perceived indoor air quality indoor requires further study.

Silica gel rotors are widely used for dehumidification. In some studies the exhaust air from the room was regenerated, since the dry indoor air could enhance the vapour pressure difference, aiding the desorption process. To achieve the same dehumidification, the regeneration temperature could then be reduced, reducing the amount of energy used to regenerate the desiccant wheel [35–37]. From an energy point of view, using exhaust indoor air for regenerating the desiccant wheel has some advantages. However, the exhaust indoor air contains a high concentration of indoor air pollutants, which may decrease the air-cleaning performance of the desiccant wheel. The advantages and disadvantages of using exhaust air for regenerating the desiccant wheel will be the subject of a future experiment. Both energy and the air-cleaning efficiency of a CAHP using exhaust air for regenerating the desiccant wheel will be studied, in comparison with the use of clean regeneration air.

Since the desiccant wheel used in this study was primarily designed for dehumidification, the air cleaning performance may not have been optimum. Silica gel is well known as a desiccant. A CAHP containing a silica gel rotor can appropriately be applied to sites where an excessive moisture load must be removed while its application in a dry indoor environment may lead to an adverse impact on the perceptions of occupants due to the resulting extreme dryness. Although moisture removal can be controlled by the operation of a CAHP, the presence of moisture is valuable in some buildings and should not be removed. In this case, optimising the adsorbent for the wheel would be one of the most effective ways of achieving air purification without moisture removal. Among the most common adsorbents, activated carbon is undesirable due to its less effective removal of formaldehyde [17] and the preferential adsorption of zeolite makes it useful for gas separation [19], making neither suitable alternatives to silica gel. It might be possible to develop hydrophobic silica gel that can intercept VOCs but allow water molecules to pass. The application of the CAHP would then be extended to conditions with low air humidity.

5. Conclusion

In this study, the effect of a CAHP system on the improvement of indoor air quality was examined experimentally. The air quality as assessed by human subjects was compared between a low outdoor air supply rate (2 L/s per person) with CAHP and three different outdoor air supply rates (5, 10, 20 L/s per person) without CAHP.

The results show that at an outdoor air supply rate of 2 L/s per person, the air quality with air-cleaning of recirculated air using the CAHP system was equivalent to the air quality at an outdoor air supply rate of 10 L/s per person without air-cleaning. The percentage of adapted subjects dissatisfied was 5.2% in the CAHP condition. 76% of the outdoor airflow can be saved by using the CAHP approach. The clean air delivery rate (CADR) was more than three times the actual outdoor air supply rate when the CAHP was used to clean recirculated air. VOCs were effectively removed by the CAHP. The air cleaning effectiveness of the CAHP was 92% at a regeneration temperature of 60 °C and no VOC accumulation on the silica gel rotor was observed.

It can be concluded that the operation of a CAHP air-cleaner can improve the perceived air quality in rooms polluted by human bioeffluents and emissions from building materials, fittings, furniture, office equipment, etc. The CAHP system can therefore be widely applied to auditoriums, classrooms and offices.

The results are limited to the specific conditions analysed in the present study. The air-cleaning performance of the CAHP when polluted exhaust indoor air is used to regenerate the desiccant wheel, a common practice when one is used for dehumidification only, must still be examined experimentally. The impact of the regeneration air temperature on the air cleaning performance of the CAHP requires further study. Development of a hydrophobic material for the rotor would extend the application of CAHP to buildings in which no moisture removal is required.

Acknowledgements

This study was financially supported by the EU Climate KIC pathfinder project – CAHP, the BjarneSaxhof foundation and the State Scholarship Fund in China. The authors thank their DTU colleague David P. Wyon for his comments on an earlier version of the manuscript and for the linguistic revision of this final version.

References

[1] P. Wargoki, Z. Bako-Biro, S. Baginska, T. Nakagwa, P.O. Fanger, C.J. Weschler, S. Tanabe, Sensory emission rates from personal computers and television sets, in: Proceedings of Healthy Building 2003 Conference, vol. 3, 2003, pp. 169–176. Singapore.
[2] P. Wargoki, P.O. Fanger, P. Krupicz, A. Sczecinski, Sensory pollution loads in six office buildings and a department store, Energy Build. 36 (2004) 995–1001.
[3] E. Kabir, K.H. Kim, An investigation on hazardous and odorous pollutant emission during cooking activities, J. Hazard. Mater. 188 (2011) 443–454.
[4] L. Fang, D.P. Wyon, G. Clausen, P.O. Fanger, Sick building syndrome symptoms and performance in a field study at different levels of temperature and humidity, in: Proceeding of Indoor Air 2002, 2002. California, USA.
[5] P. Wargoki, D.P. Wyon, Y.K. Baik, G. Clausen, P.O. Fanger, Perceived air quality, Sick building syndrome (SBS) symptoms and productivity in an office with two different pollution loads, Indoor air 9 (1999) 165–179.
[6] S. Park, J. Seo, Optimum installation of sorptive building materials using contribution ratio of pollution source for improvement of indoor air quality, Int. J. Environ. Res. public health 13 (4) (2016) 396.
[7] Y. Xu, Y.P. Zhang, An improved mass transfer based model for analyzing VOC emissions from building materials, Atmos. Environ. 37 (18) (2003) 2497–2505.
[8] Y.P. Zhang, X.X. Luo, X.K. Wang, K. Qian, R.Y. Zhao, Influence of temperature on formaldehyde emission parameters of dry building materials, Atmos. Environ. 41 (15) (2007) 3202–3216.
[9] J.Y. Xiong, Y. Yao, Y.P. Zhang, C-history method: rapid measurement of the

initial emittable concentration, diffusion and partition coefficients for formaldehyde and VOCs in building materials, Environ. Sci. Technol. 45 (8) (2011) 3584–3590.
[10] M. Derudi, S. Gelosa, A. Sliepcevich, A. Cattaneo, D. Cavallo, R. Rota, G. Nano, Emission of air pollutants from burning candles with different composition in indoor environments, Environ. Sci. Pollut. Res. 21 (2014) 4320–4330.
[11] CEN, Ventilation for Non-residential Buildings - Performance Requirements for Ventilation and Room-conditioning Systems, 2007. EN 13779, European Committee for Standardization.
[12] ASHRAE, ANSI/ASHRAE Standard 62.1-2013 Ventilation for Acceptable Indoor Air Quality, American Society of Heating, Refrigerating and Air- Conditioning Engineers, Inc., Atlanta, GA, 2013.
[13] J. Sundell, T. Lindvall, B. Stenberg, Associations between type of ventilation and air flow rates in office buildings and the risk of SBS-symptoms among occupants, Indoor air (supplement No. 2/94) (1994) 239–251.
[14] M.A. Sidheswaran, H. Destaillats, D.P. Sullivan, S. Cohn, W.J. Fisk, Energy efficient indoor VOC air cleaning with activated carbon fiber (ACF) filters, Build. Environ. 47 (2012) 357–367.
[15] M.P. Bivolarova, A.K. Melikov, C. Mizutani, K. Kajiwara, Z.D. Bolashikov, Bed-integrated local exhaust ventilation system combined with local air cleaning for improved IAQ in hospital patient rooms, Build. Environ. 100 (2016) 10–18.
[16] K.H. Han, J.S. Zhang, B. Guo, A novel approach of integrating ventilation and air cleaning for sustainable and healthy office environments, Energy Build. 76 (2014) 32–42.
[17] W. Cho, D. Song, S. Hwang, S. Yun, Energy-efficient ventilation with air-cleaning mode and demand control in a multi-residential building, Energy Build. 90 (2015) 6–14.
[18] Y.P. Zhang, J.H. Mo, Y.G. Li, J. Sundell, P. Wargocki, J. Zhang, J.C. Little, R. Corsi, Q.H. Deng, M.H.K. Leung, L. Fang, W.H. Chen, J.G. Li, Y.X. Sun, Can commonly-used fan-driven air cleaning technologies improve indoor air quality? A literature review, Atmos. Environ. 45 (2011) 4329–4343.
[19] A.L. Hines, T.K. Ghosh, S.K. Loyalka, Indoor Air: Quality and Control, PTR Prentice Hall, New Jersey, 1993.
[20] W. Chen, J.S. Zhang, Z. Zhang, Performance of air cleaners for removing multiple volatile organic compounds in indoor air, ASHRAE Trans. 111 (2005) 1101–1114.
[21] A.L. Hines, T.K. Ghosh, Investigation of Co-sorption of Gases and Vapors as a Means to Enhance Indoor Air Quality – Phase 2: Water Vapor Uptake and Removal of Chemical Pollutants by Solid Adsorbents, Chicago, Report of Gas Research Institute: GRI-92/0157.2, 1993.
[22] A.L. Hines, T.K. Ghosh, S.K. Loyalka, R.C. Warder, Investigation of Co-sorption of Gases and Vapors as a Means to Enhance Indoor Air Quality – Phase 2: a Summary of Pollutant Removal Capabilities of Solid and Liquid Desiccants from Indoor Air, Chicago, Report of Gas Research Institute: GRI-92/0157, 1993.
[23] M. Popescu, T.K. Ghosh, Dehumidification and simultaneous removal of selected pollutants from indoor air by a desiccant wheel using a 1M type desiccant, J. Sol. Energy Eng. 121 (1999) 1–13.
[24] S.L. Kuo, A.L. Hines, Adsorption of chlorinated hydrocarbon pollutants on silica gel, Sep. Sci. Technol. 23 (1988) 293–303.
[25] G. Zhang, Y.F. Zhang, F. Fang, Theoretical study of simultaneous water and VOCs adsorption and desorption in a silica gel rotor, Indoor Air 18 (1) (2008) 37–43.
[26] L. Fang, G. Zhang, A. Wisthaler, Desiccant wheels as gas-phase absorption (GPA) air cleaners: evaluation by PTR-MS and sensory assessment, Indoor Air 18 (5) (2008) 375–385.
[27] J.Z. Nie, L. Fang, B.W. Olesen, Experimental evaluation on energy performance of innovative clean air heat pump for indoor environment control in summer and winter seasons, Energy Build. 84 (2014) 641–650.
[28] J.Z. Nie, L. Fang, G. Zhang, Y. Sheng, X.R. Kong, Y.F. Zhang, B.W. Olesen, Theoretical study on volatile organic compound removal and energy performance of a novel heat pump assisted solid desiccant cooling system, Build. Environ. 85 (2015) 233–242.
[29] Y.X. Sun, L. Fang, D.P. Wyon, A. Wisthaler, L. Lagercrantz, P.S. Tejsen, Experimental research on photocatalytic oxidation air purification technology applied to aircraft cabins, Build. Environ. 43 (2008) 258–268.
[30] J. Kolarik, P. Wargocki, Can a photocatalytic air purifier be used to improve the perceived air quality indoors? Indoor air 20 (2010) 255–262.
[31] A. Hesaraki, J.A. Myhren, S. Holmberg, Influence of different ventilation levels on indoor air quality and energy savings: a case study of a single-family house, Sustain. cities Soc. 19 (2015) 165–172.
[32] ISO standard, ISO/DIS 17772–1, “Energy performance of buildings – Indoor environmental quality – Part 1: Indoor environmental input parameters for the design and assessment of energy performance of buildings” 2015 (draft).
[33] P.O. Fanger, Introduction of the olf and the decipol units to quantify air pollution perceived by humans indoors and outdoor, Energy Build. 12 (1988) 1–6.
[34] INNOVA Multi Gas Monitoring Instruments. Luma Sense Technologies.
[35] X.J. Zhang, Y.J. Dai, R.Z. Wang, A simulation study of heat and mass transfer in a honeycombed rotary desiccant dehumidifier, Appl. Therm. Eng. 23 (2003) 989–1003.
[36] C.X. Jia, Y.J. Dai, J.Y. Wu, R.Z. Wang, Use of compound desiccant to develop high performance desiccant cooling system, Int. J. Refrig. 30 (2007) 345–353.
[37] C.X. Jia, Y.J. Dai, J.Y. Wu, R.Z. Wang, Analysis on a hybrid desiccant air conditioning systems, Appl. Therm. Eng. 26 (2006) 2393–2400.
[38] CEN, TC156, Guideline for Using Indoor Environmental Input Parameters for the Design and Assessment of Energy Performance of Buildings, 2016. EN 16798–2 TR, European Committee for Standardization.