Experimental study on air cleaning effect of clean air heat pump and its impact on ventilation requirement

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SUMMARY
This study investigated air purification effect of a Clean-Air Heat Pump (CAHP) which combined a desiccant wheel with a heat pump for both air cleaning and HVAC of buildings. The experiment was conducted in a field lab at four different outdoor air supply rates with and without air cleaning by CAHP. Both sensory assessments of perceived air quality and chemical measurements of TVOC concentrations were conducted for evaluating the air cleaning performance of the CAHP. The results of experiment showed that running the CAHP improved significantly perceived air quality. At 2 L/s per person of outdoor air supply rate with operating the CAHP, the air quality was equivalent to the value at the higher outdoor air supply rate of 10 L/s per person without running CAHP. The TVOC measurements observed over 92% of efficiency on removal of indoor air VOCs and no VOCs accumulation on the desiccant wheel was observed.

KEYWORDS
Air purification, adsorption, silica gel wheel, VOCs

1 INTRODUCTION
In modern society, people spend more than 85% of their time indoors. Indoor air quality has significant impact on health, comfort and working performance. To improve the indoor air quality, two main methods are adopted traditionally, i.e. pollution sources control and ventilation. Although sources control is the most fundamental method to avoid indoor pollution and great efforts have been made on emission control of materials, materials that emit gas phase pollutants are still widely used in many buildings. In some spaces, e.g. classrooms, occupants are the major source of indoor air pollution that can’t be removed. Therefore, ventilation is still the most effective method of indoor air quality control in practice. However, the ventilation requirement prescribed by the existing ventilation standards (ASHRAE, 2013 and CEN, 2007) requires substantial amount of energy use. Many studies
documented that the ventilation requirement suggested by the existing standards should be doubled (e.g. 25 L/s per person) to minimize the prevalence of SBS symptoms (Wargocki et al., 2002). Such high ventilation rate is hardly acceptable from an energy point of view.

To save the energy use for ventilation, air cleaning in buildings is an alternative approach. Different air cleaning technologies are rapidly developed in recent years. Based on the reviews of 133 most scientific valuable literatures selected from 26,000 papers on air purification, Zhang et al. (2009) reported that the sorption was the most effective method for removal of gaseous pollutants among the various air purification techniques such as catalytic oxidation, ozone oxidation, plasma and UVGI etc. Fang et al. (2008) studied the co-sorption effect of a silica-gel desiccant wheel on improving indoor air quality. In a climate chamber experiment, they found that more than 80% of the sensory pollution load was removed and the percentage dissatisfied of air quality decreased from 70% to 20%. They also recommended that the regenerative silica-gel desiccant wheel could be combined with ventilation systems for air cleaning. Afterwards Nie et al. (2014) designed an innovative clean air heat pump (CAHP) based on the air cleaning effect of desiccant wheel. Compared to the conventional HVAC systems, the CAHP could provide better indoor thermal environment and save energy in the range from 5% to 59% depending on the outdoor climate.

The present study examined the performance of CAHP system on indoor air quality improvement in a field lab with real pollution source of human bio-effluents, building materials/furniture and other indoor facilities. Both sensory assessment with human subjects and chemical measurements were used to quantify its effect on air quality. The experiment further confirmed that air pollutants removed by the desiccant wheel was completely rejected by the warm regeneration air without accumulation on the desiccant wheel.

Figure 1. The ventilation system of the test room using CAHP. Air samplings were made at the locations of S1 to S4 for the TVOC measurement.

2 METHODS

Experimental facilities
The experiment was carried out in a field lab of 12x6x3 m³. This field lab was a classroom that can accommodate 50 people. The field lab equipped with a ventilation system that can
deliver air simulating different outdoor climate conditions (Fang et al., 2012). A CAHP (Nie et al. 2014) was installed in the ventilation system of the field lab to control the hygro-thermal and quality of the indoor air in the room (Figure 1).

**Experimental design**

In order to observe the air cleaning effect of CAHP on indoor air quality, the experiment was designed at four conditions, i.e. four levels of outdoor air ventilation rate of 2, 5, 10 and 20 L/s per person. The CAHP was used only at the lowest level of ventilation rate of 2 L/s per person. When the test room was ventilated at 5, 10 and 20 L/s per person of outdoor airflow, the CAHP was not operated. This design allowed for comparing the impact of clean air delivered by CAHP to the equivalent impact of outdoor air ventilation rate. Both sensory assessments of indoor air quality and chemical measurements of indoor gas phase VOC contaminants were conducted in the experiment to evaluate the air cleaning effect of CAHP.

**Subjective sensory assessments**

Thirty-six subjects participated in the experiment. They were students at the Technical University of Denmark. The age of sensory subjects was from 18 to 30 years old. Before each of experiments started, the subjects were instructed for conducting sensory assessments using questionnaires. To ensure the steady-state conditions, the climatic system or/and CAHP system were switched on at least 2 hours prior to the exposure of subjects. The exposure of subjects to each conditions lasted for 3 hours. In this period, the major indoor air contaminants included human bio-effluents, emission of building materials/furniture and the contaminants from other sources, e.g. ventilation system and outdoor environment. In the final 10 minutes of each exposure, the subjects evaluated perceived indoor air quality using four questionnaires (Kolarik and Wargocki, 2010) including acceptability of air quality (ACC), odour intensity (OI), air freshness (AF) and air humidity (AD).

**Chemical measurements**

The concentrations of TVOCs were measured by Photoacoustic Gas Monitor-INNOVA 1312. The air was sampled continuously at the inlet and outlet air ducts of the CAHP (S1~S4 as shown in Figure 1) when CAHP system was turned on. The concentration of TVOCs at S1 was identical to that inside the field lab while the concentration of TVOCs at S2 was the amount delivered into the field lab after the air cleaned by CAHP. The concentration of TVOCs at S3 could be regarded as that in outdoor air while the concentration at S4 showed how much TVOCs that were rejected from CAHP after regeneration of the desiccant wheel.

Based on the measured concentration of TVOCs and the airflow rate, the air cleaning effectiveness $\eta$ and the mass balance factor of the wheel $\varepsilon$ could be calculated as follows:

$$\eta = \frac{V_r (C_r - C_o) - V_i (C_i - C_o)}{V_r (C_r - C_o)}$$  \hspace{1cm} (1)

$$\varepsilon = \frac{V_r (C_{ex} - C_o)}{V_r (C_r - C_o) - V_i (C_s - C_o)}$$  \hspace{1cm} (2)

Where $C_r$ and $C_i$ were the average TVOC concentrations (mg/m$^3$) measured from the return air and supply air (sampling location S1 and S2 in Figure 1), respectively; $C_o$ was the average TVOC concentration (mg/m$^3$) in outdoor air (sample S3). $C_{ex}$ was the average TVOC concentration (mg/m$^3$) of the exhaust air rejected from CAHP (sample S4). $V_r$ was the average
airflow rate (L/s) of return air processed by CAHP, $V_s$ was the average airflow rate (L/s) supplied to the test room (this airflow was $V_r +$ small amount of fresh outdoor air added into the CAHP for ventilation), and $V_{ex}$ was the average airflow rate (L/s) that was rejected out of the CAHP (this was the total airflow went through the condenser of the heat pump and part of this airflow was used to regenerate the desiccant wheel).

**Experimental procedure**
In each of the experimental conditions, the systems started from 11:00 at noon and it took approximately 2h to achieve the desired temperature and relative humidity conditions in the field lab. The subjects then entered the field lab at 13:00 to study for 3 hours and completed the questionnaires at the last 10 mins of the 3-hour exposure. When CAHP system was turned on, the regeneration temperature of silica gel wheel in the CAHP system was controlled at 60°C. The airflow rates of $V_r$, $V_s$ and $V_{ex}$ as presented in equations (5)-(6) were controlled as 208, 272 and 240 L/s, respectively.

**3 RESULTS**
Figure 2 shows the time course TVOC concentration measured from the four sampling locations (as shown in Figure 1) representing the TVOC concentrations of return air (S1), supply air (S2), outdoor air (S3) and rejected air of the CAHP (S4).

![Figure 2](image)
Figure 2. Time course TVOC concentration measured during the experiment from return air, supply air, outdoor air and the air rejected after regeneration.

![Figure 3](image)
Figure 3. The mean concentrations of TVOC upstream and downstream of the process and regeneration sections of the desiccant

![Figure 4](image)
Figure 4. Mean acceptability of the air in the test room at three levels of ventilation rate without CAHP compared with the
wheel during the period when steady state
established between 13:30 and 15:00.

mean acceptability of the air in the test
room at low ventilation rate with CAHP.

Figure 3 shows the average concentration of TVOC upstream and downstream of the process and regeneration section after the system reached steady-state between 13:30 and 15:00. After 15:00, the concentration of TVOC in outdoor air elevated slightly. Therefore, the TVOC data obtained after 15:00 were excluded for calculating $\eta$ and $\varepsilon$ of the CAHP. Based on the data measured, the air cleaning effectiveness $\eta$ was calculated as 92% and the mass balance factor of VOCs on the wheel $\varepsilon$ was calculated as 100% at the regeneration temperature of 60°C. These results showed that CAHP was very effective on removing indoor air VOCs and contaminants were rejected by regeneration with no accumulation on the desiccant wheel.

The sensory assessments of the air without air cleaning of the CAHP at three levels of outdoor air supply rate (5, 10 and 20 L/s per person) and with the CAHP at low level of outdoor air supply rate (2 L/s per person) were summarized in Figure 4. The results showed that the perceived air quality at low level of outdoor air supply rate of 2 L/s per person using CAHP was equivalent to that at higher level of outdoor air supply rate of 10 L/s per person without using CAHP. Based on these results, around 80% of the outdoor air supply rate can be saved using CAHP. The clean air deliver rate (CADR) was calculated as 3.5 h$^{-1}$ when using the CAHP.

4 DISCUSSION

In this experiment, the chemical concentrations in the airflows were measured by INNOVA multi-gas analyser which can only measure the toluene equivalent total VOC (TVOC) concentrations. However, the INNOVA could perform online monitor of the TVOC in several channels. This allowed the observation of the air cleaning process of the CAHP. For example, the TVOC measured by INNOVA clearly showed that the silica gel rotor in the CAHP removed VOCs from the return air and the concentration of TVOC in the supply air was almost equal to that in the fresh outdoor air; the VOCs removed from the processed return air were rejected from the regeneration air to outdoors instead of accumulated in the silica gel wheel.

In Fang et al.’s early research (2008) on the air cleaning effect of desiccant wheel, individual VOCs in the process air before and after a desiccant wheel were monitored online by a proton-transfer-reaction mass spectrometry (PTR-MS). The study observed how each individual VOCs were removed by the desiccant wheel. However, due to the limitation on the monitoring channels of the PTR-MS, the experiment could not monitor simultaneously the concentration of VOCs in the regeneration air before and after the desiccant wheel. The VOCs in the regeneration air were measured by air sampling and gas chromatography (GC) analysis. The mass balance between process and regeneration air was calculated based on the measurement of two different methods. The error from the measurement of the two methods made the mass balance did not match completely. In this study, the concentrations of TVOCs at the inlet and outlet airflows of CAHP were measured simultaneously by the same instruments and avoided the systematic measuring errors due to using different methods of chemical measurement. Hence, the results of this study proved that no VOCs accumulation in a regenerative silica gel wheel of CAHP when it was used for dehumidification and air cleaning at a regeneration temperature of 60°C.

It is worth noting that the perceived air quality assessment showed relatively low PD in all the experimental conditions with and without using CAHP. This was not due to the low air
pollution in the test room but because that the air quality assessments performed in this study were adapted perceptions of the air quality. In most of the ventilation standards, immediate perception was recommended for evaluating perceived air quality. In Fang et al.’s study (2008), immediate perception was also used to evaluating the perceived air quality. However in this experiment, the major pollutants of indoor air came from the 36 occupants. Performing an immediate perception would require another group of sensory panel. The visual environment might have a strong psychological effect on the subjective evaluation of the sensory panel and affected the results of their sensory assessment. Instead, by using the occupants of the test room as the sensory subjects to evaluate the perceived air quality can truly reflect the impact of air cleaning on the feeling of the occupants. This study proofed that the CAHP improved significantly the perceived indoor air quality even after a long-term exposure (i.e. after adaptation).

5 CONCLUSION

- At 2 L/s per person of outdoor air supply rate, operation of CAHP system improved adapted perceived air quality to a high level of 5% dissatisfied which was equivalent to air quality at the outdoor air supply rate of 10 L/s per person without air cleaning. Based on these results, 80% of outdoor air supply rate could be saved.
- Online photoacoustic chemical analysis verified that the VOCs detected in the air were effectively removed by CAHP system. With regeneration temperature of 60°C, the air cleaning effectiveness of CAHP was 92% and the mass balance of the pollutants removal was 100% meaning no pollutants accumulation on the desiccant wheel in the CAHP.

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7 REFERENCES
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