Experimental Study on Air Cleaning Effect of Clean Air Heat Pump and Its Impact on Ventilation Requirement

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1. Concept

In EU counties, nearly 40% of total energy consumption was consumed in buildings and two-thirds of this energy consumption is used for heating, ventilation and air-conditioning (HVAC). Clean air heat pump (CAHP)[1] is a newly developed concept by DTU that combines HVAC with air cleaning and energy recovery for buildings. It provides healthy and comfortable indoor environments and is expected to reduce up to 60% of energy consumption for HVAC in buildings.

This project is a lab evaluation on air cleaning performance of a developed prototype CAHP which is the key to determine the innovation opportunities of the CAHP technology. Existing HVAC system only controls hygrothermal conditions of air. Indoor air quality is usually controlled by the quantity of ventilation air which consumes the major portion of energy used in HVAC system. Replacing ventilation by air cleaning is the major approach of energy saving in the CAHP concept. This project will study the air cleaning effect of CAHP technology by experiment and validate the feasibility of replacing ventilation by air cleaning using CAHP. The experimental study was conducted in a laboratory at DTU using both subjective (human response) and objective (chemical measurements) experimental approaches. A prototype unit of CAHP was installed in the lab for evaluating its performance on air cleaning and ventilation equivalency. The study also provided data for revising the existing ventilation standards and improving the design of HVAC systems in the future.

2. Main objectives of the project

The main objectives of this project are to study the air cleaning effect of CAHP technology by experiment and validate the feasibility of replacing ventilation by air cleaning using CAHP.

3. Summary of achievements

3.1 Main achievements

- The air cleaning effect of CAHP[2] on volatile organic compounds (VOCs) removal from indoor air was validated.
- The TVOC measurements shown that the CAHP can remove up to 95% of the total volatile organic compound (TVOC) in the room air which may be used to recirculate partly the room air to replace outdoor air ventilation.
- Sensory assessment of the occupants proofed that the perceived air quality of indoor air at 3L/s per person of ventilation with air cleaning by CAHP was equivalent to 10L/s per person of ventilation without air cleaning meaning that it is possible to reduce 70% of ventilation requirement by using CAHP.
- The impact of air humidity and regeneration temperature of the desiccant rotor on the air cleaning performance of CAHP was investigated and well understood.
- The performance of CAHP on chemical removal of both polar and non-polar compounds of VOCs was studied and well understood.

3.2 Main lessons learned

- The experiments found that VOC removal performance of the existing silica gel rotor decreased with decreasing regeneration temperature and increase of air humidity which direct us to develop a new generation of low regeneration temperature rotor to further improve the air cleaning and energy performance of CAHP. The development of low regeneration temperature rotor is being conducted at Munters AS.

4. Detailed description of experiment

According to the objective of the project, a laboratory test of the CAHP was conducted at BYG, DTU. Both chemical measurements (including photoacoustic gas analysing and GC-MS VOCs analysing) and sensory assessment of indoor air using human subjects were performed. Detailed description of the laboratory study is described below.

4.1 Method

4.1.1 Test room and the test unit of CAHP

A prototype CAHP was installed in a field lab at the International Centre for Indoor Environment and Energy at DTU. The field lab is a 72 m^2 classroom (Figure 1) which equipped with a ventilation system that can simulate outdoor air supply from winter to summer conditions (Figure 2). A prototype CAHP was installed in the test room as its ventilation system. The clean air heat pump technology is based on adsorption air purification principle. The adsorption media is a regenerative silica gel rotor which is regenerated continuously during operation. Heat is required to regenerate the rotor. In clean air heat pump, the regeneration heat is obtained from the condenser of the heat pump. The novel design of the clean air heat pump is that together with regenerating the silica gel rotor, the condensing heat of the heat pump is used either for heating (in winter for warming up the ventilation air) or for cooling (in summer for dehumidifying the ventilation air). On the other side of the heat pump, the evaporator is used for energy recovery (in winter recover heat from exhaust air) or for reducing the temperature of the ventilation air (in summer cooling recirculated room air). Such a design makes the clean air heat pump extremely energy efficient and, due to the air purification effect of the silica gel rotor, outdoor air ventilation rate can be greatly reduced. Since air cleaning is a side effect of the silica gel rotor, it doesn’t require any extra energy in the rotor than the regeneration energy used for moisture control. Thus, the air cleaning process of the clean air heat pump can be regarded as energy free. Figure 3 shows the principle of the clean air heat pump. The total air supply of the CAHP to the classroom was 250 L/s. Among this air flow, 75% is recirculated air which was cleaned by the CAHP and 25% is the clean outdoor air.

Figure 1. The test room used for evaluating the CAHP.

Figure 2. The ventilation system for the test room that can supply air simulating different outdoor climate conditions.

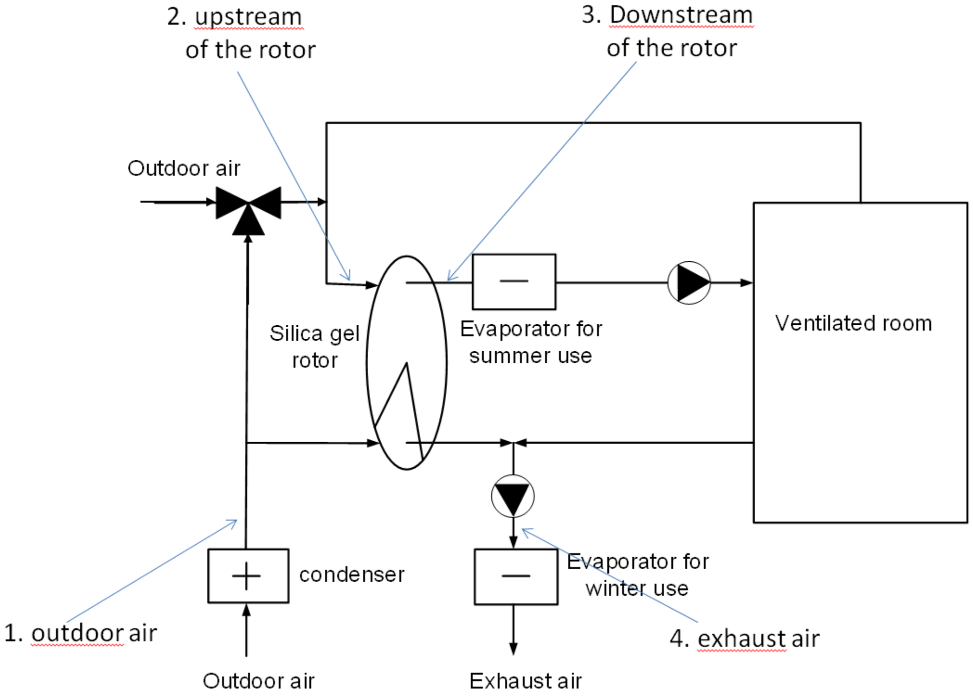

Figure 3. Ventilation system of the test room with CAHP, the air samples were taken from the four locations indicated by the numbers 1,2,3 and 4.

(a) (b)

Figure 4. The clean air heat pump (a) and the desiccant rotor (b) developed for the test of air cleaning.

4.1.2 Chemical and sensory measurements

The chemical measurements were conducted using photoacoustic online gas analysing and gas chromatography (GC) offline analysing. Each chemical analysis method has its advantages and disadvantages. The two methods complement to each other. The photoacoustic gas analyser can perform online real time measurement and capture any changes occurred during the experiment but the instrument can only be used to observe TVOC or VOC compounds occurring in the air individually. The GC analysis can analyse the concentration of each individual VOC compound in a mixture of an air sample. However, the analysis can only be made offline and only an average value of the measured chemicals can be obtained. The uncertainty of the GC analysis is usually high.

The air was sampled in four location for the chemical analysis as shown in Figure 3, i.e. outdoor air, upstream of the desiccant rotor (represent indoor air), downstream of the desiccant rotor (represent the air after cleaned by the rotor) and the exhaust air.

Sensory assessment of the air quality is essential for the evaluation of the air cleaning effect of CAHP since the air cleaning technology is for human comfort and human sense is more sensitive than chemical instruments in many cases. The sensory assessments were conducted using a panel of 30-40 naive subjects to evaluate the air quality in a test room. The sensory assessments included perceived air quality, odour intensity and air way irritation assessment.

4.1.3 Evaluation of air cleaning effect

The air cleaning effect was evaluated using clean air delivery rate (CADR) which shows an equivalent amount of clean air that ventilated the room equipped with an air cleaner. The clean air delivery rate was calculated using the perceived air quality (PAQ) assessed in the test room with and without the air cleaner. CADR can be calculated by the following three equations (eq. 1,2,3).

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

$$PAQ = 112 * \left[\ln(PD) - 5.98\right]^{-4} \qquad (2)$$

$$CADR = 3.6 Q_0 \left(\frac{PAQ}{PAQ_{CAHP}} - 1\right) / V \qquad (3)$$

Where Q_0 is outdoor air supply rate, L/s, PAQ (decipol) is perceived air quality with CAHP turned off and PAQ_{CAHP} (decipol) is perceived air quality with CAHP in operation. V is the volume of test room, m^3. PAQ is converted from the percentage of dissatisfied (PD) which is derived from the mean acceptability (ACC) of a group of naive sensory panel.

4.1.4 Experimental procedure

The experiment was carried out in the test room with and without human occupancy. Some used carpet and linoleum were placed in the test room as pollution sources. When the test room was not occupied, four chemicals (toluene, ethanol, acetone and 1,2-dicloroethane) were dosed into the air of the test room. When the room was occupied, no chemicals were dosed in the room.

Test room with occupancy

The tests were combined with several 2-hour lectures in a classroom which was occupied by students. The lectures took placed on each Thursday. The number of students attend the lecture on each Thursday were not equal but varied from 26 to 39. The students were used as both source of indoor air pollution and sensory panel. The experiments were repeated in four lecture days with and without running CAHP. With running the CAHP, the outdoor air ventilation rate was controlled at 3 L/s per person; without running the CAHP, the outdoor air ventilation rate was controlled at 5, 10 , 20 L/s per person each on one of the three lecture days. During the occupancy, the online photoacoustic TVOC monitoring were conducted continuously and the sampling for GC analysis was conducted after 1-hour occupancy in the test room.

The sensory assessment conducted at the end of each 2-hour lecture. The students attend their lecture as they usually did and were blind to the change of ventilation rate and/or air cleaning by the CAHP. The only additional job they need to do was to fill in a questionnaire at the end of each day’s lecture before they left the classroom.

The test room without occupancy

Four VOCs were dosed using four wash bottles. The concentrations of the four chemicals in the test room were controlled in the range from 0.05 to 1 ppm without running the CAHP. The TVOC removal rates were measured at five levels of regeneration temperature of the CAHP i.e. 30, 40, 50, 60 and 70 °C. Online photoacoustic TVOC monitoring were conducted continuously during the experiments and the sampling for GC analysis was conducted after the concentration of four VOCs in the test room reached the steady state.

The GC analysis was conducted by the Fraunhofer Institute for Building Physics. The GC analysis identified and quantified VVOCs, VOCs and SVOCs (up to C22) by TD-GC/MS (ISO 16000-6).

4.2 Results

The concentration of TVOC downstream of the desiccant rotor measured by photoacoustic gas analyser were summarised in Figure 5. This result showed that more than 95% of TVOCs in the air were removed by the rotor when the rotor was regenerated at 70°C. At very low regeneration temperature, e.g. 28 °C, the rotor can still remove around 30% TVOCs from the air.

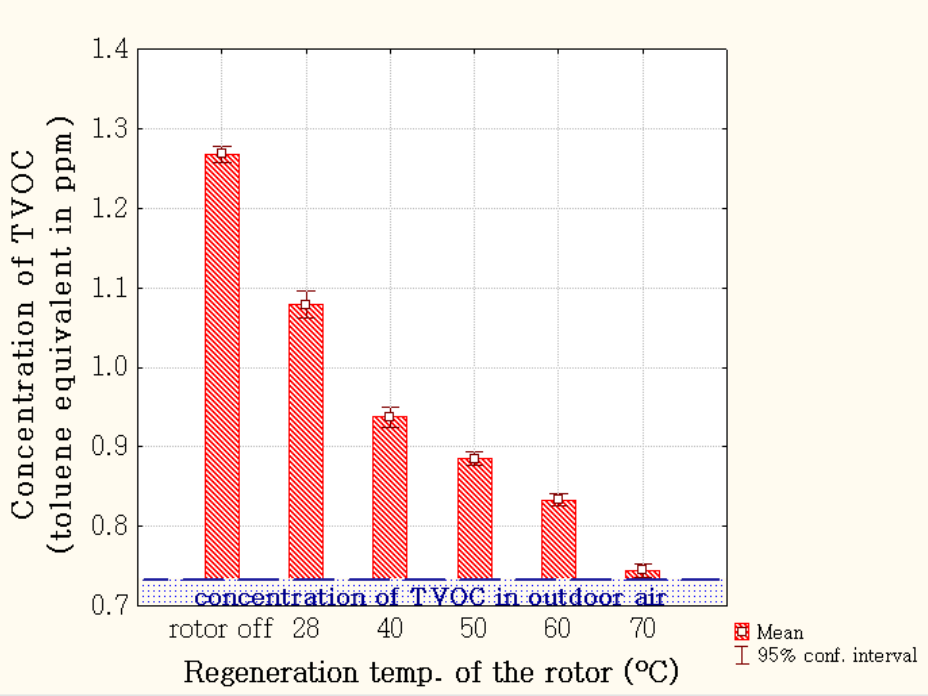

Figure 5. TVOC measurement using photoacoustic gas analyser at downstream of the desiccant rotor.

The removal rate for each of the four dosed chemicals analysed by GC were summarized in Figure 6. This result was obtained at the regenerating temperature of 60°C. The results from GC analysis showed that the desiccant rotor is more effective on removing water soluble VOCs than non-water soluble VOCs.

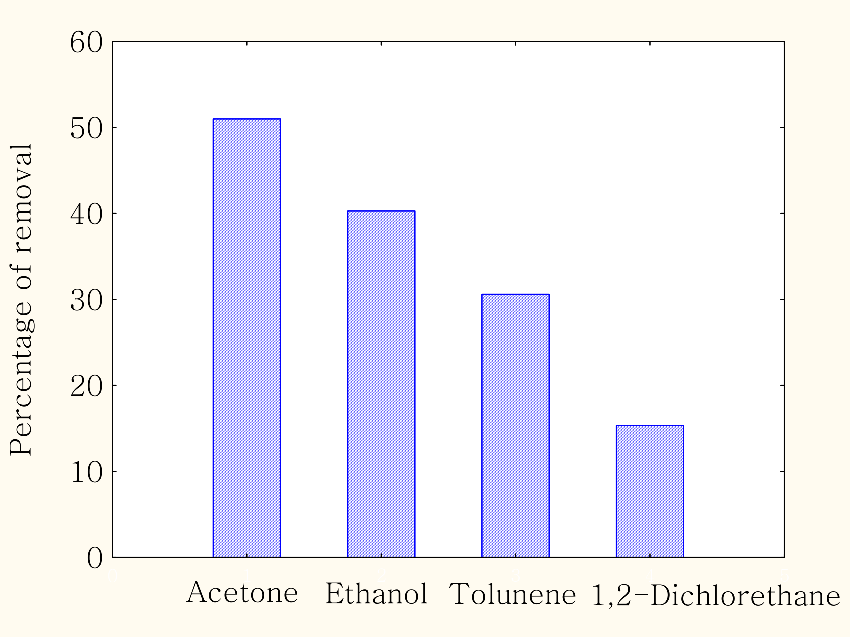

Figure 6. Percentage of removal by the desiccant rotor for the four dosed chemicals analysed by GC-MS.

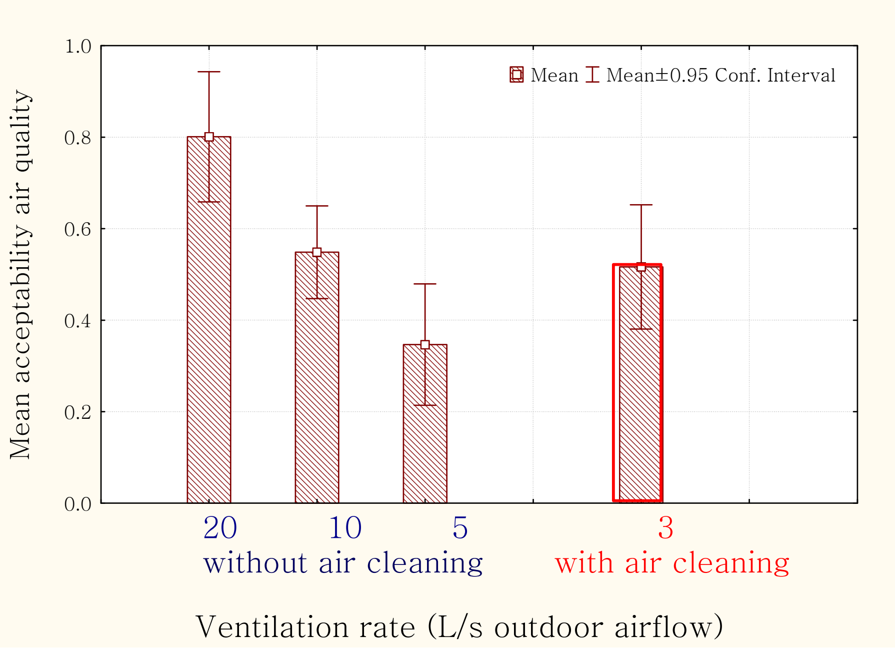

Figure 7. Mean acceptability of the air in the test room at three levels of ventilation rate without CAHP compared with the mean acceptability of the air in the test room at low ventilation rate with CAHP.

The sensory assessments of the air without air cleaning of the CAHP at three levels of ventilation rate (5, 10 and 20 L/s per person) and with the CAHP at low ventilation rate of 3L/s per person were summarized in Figure 7. The results showed that the outdoor air ventilation rate at 3 L/s per person using CAHP was equivalent to the outdoor air ventilation rate of 10 L/s per person without using CAHP in terms of perceived air quality. The equivalent clean airflow delivered to the test room using CAHP is 3.3 times as much as the outdoor air delivered by a ventilation system without using the CAHP. The corresponding clean air delivery rate (CADR) calculated using equations 1-3 is 3.5 h^{-1} which gave the same result of 3.3 times of clean air delivery. Based on these results, 70% of the outdoor air ventilation can be saved using CAHP.

5. Conclusions

The CAHP is very effective on removing gas phase indoor air contaminants. 70% reduction of the ventilation requirement for comfort can be achieved by using CAHP. Combined with the previous study[1] on energy performance of the CAHP, the CAHP technology is recommended for ventilation in Denmark and other part of the world except for the area where the climate is hot and dry.

6. Communication and dissemination

A manuscript of an article presenting the results of this project is being prepared and planned to be submitted to the international journal of Building and Environment and will be presented later in the international conference of “Healthy Buildings” or “Indoor Air”.

Several companies manufacturing ventilation and energy recovery equipment, desiccant dehumidification devices and air-conditioning system have been contacted. Commercialization of the CAHP technology is under discussion.

7. References

[1]. Nie, Jinzhe; Fang, Lei and Olesen, Bjarne W; 2014, “Experimental evaluation on energy performance of innovative clean air heat pump for indoor environment control in summer and winter seasons”, ***Energy and Buildings***, Vol. 84, p. 641-650.

[2]. G. Zhang, Y.F. Zhang and L. Fang, 2008, “Theoretical Study of Simultaneous Water and VOCs Adsorption and Desorption in a Silica Gel Rotor”, ***Indoor Air***, Vol. 18, no.1, p.37-43.