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Regenerative Cooling of Buildings Using an Open Sorption Cycle

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Abstract
The design of sustainable and energy efficient buildings needs alternatives for compressor based cooling and dehumidification of supply air below the dew point. The cooling demand of buildings is constantly increasing due to higher internal loads and architectural design aspects while current cooling technologies have high primary energy consumption as well as a high Global Warming Potential when hydrofluorocarbon refrigerants are applied.
One alternative method to cooling with dehumidification consists of a strict separation of both processes. In a first step outdoor air will be dehumidified by a sorption process running in an open cycle while the warmed, but dry air is then cooled down by means of indirect evaporative cooling. Both processes only need a small portion of the necessary energy to cool down air below the dew point and heating up again to supply air temperature level as done today.
This paper introduces a new concept and the technical challenges addressed in the fundamental research project "OptiMat" funded by the German Federal Ministry of Education and Research and explains the methodology of Thermal Driven Cooling.

Keywords - Thermal driven cooling, Adsorption materials, Innovative cooling concept

1. Introduction

Non-residential buildings like office buildings, museums or sport arenas have individual heating and cooling demands depending on the application as well as climate zones and building design. During the last years a clear trend is visible that new buildings become lighter in design by means of steel structure and a high share of glass fronts while on the other hand cooling demands are increasing due to internal loads from people, lighting and machinery like personal computers and copiers.

The traditional way of cooling and air conditioning including dehumidification of outdoor air has not changed at all since Willis H. Carrier invented the air conditioning system in the beginning of the 20th century [1]. Although compressor technology has improved dramatically and new types of refrigerants were invented during the last decades, the energy consumption of cooling and dehumidification takes a high portion of building energy consumption. Following building certifications like LEED or BREEAM, this part has got a share of approx. 30 % [2].

This paper describes briefly the way of cooling and dehumidifying outdoor air for a typical office building with compression cooling and illustrates the legal requirements in terms of energy efficiency and usage of refrigerants with Global Warming Potential (GWP) according to the European F-Gas regulation.

Next, the alternative concept of sorption based dehumidification in combination with indirect evaporative cooling is introduced. The main aspects are described and discussed.

In a further section the status of current research work is introduced showing the direction of further developments towards a green building technology.

Finally, the potential of sorption based cooling is evaluated.

2. Air Conditioning of an Office Building

For a typical office building operated on a hot summer day, the outdoor air has to be filtered, cooled and dehumidified to match the comfort parameters of human beings. The cooling load depends on the location and building design. The typical range of the thermal comfort zone (temperature and humidity) based on the work of Fanger [3] is shown in the following Mollier h-x- diagram, Fig. 1.

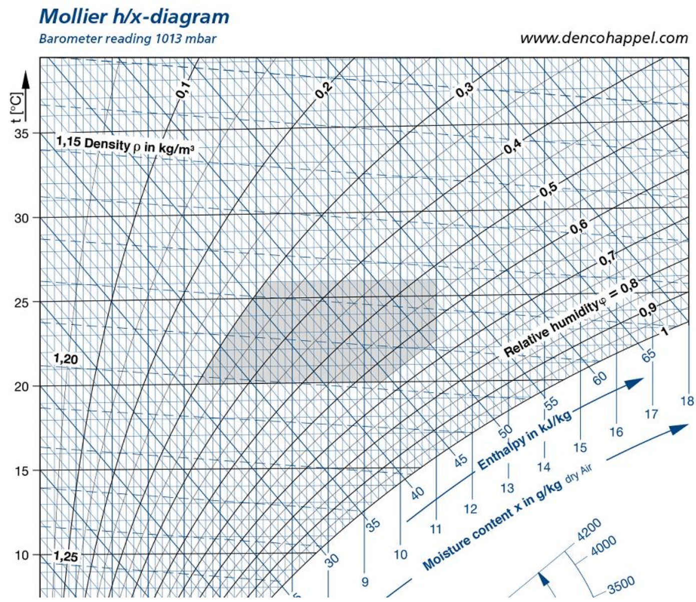

Fig. 1 Mollier h-x-diagram with comfort zone (grey)

The simplest air handling unit for air conditioning consists of a filter, a cooling coil with droplet separator, a heater and a fan, Fig. 2. To generate cold water for the cooling coil a compression cooling cycle (refrigeration cycle) is used. As a simplification, energy recovery or horse shoe circuits for the heater in combination with the refrigeration cycle are neglected.

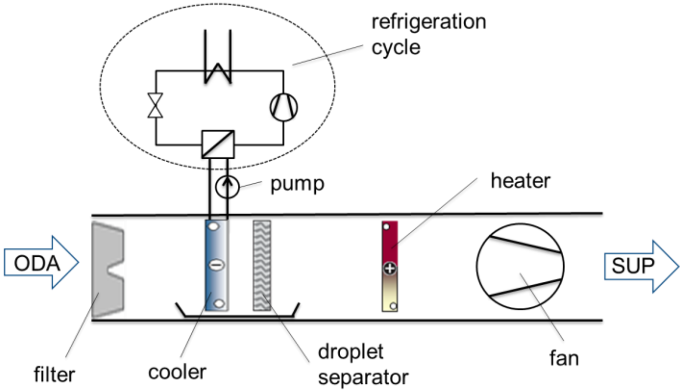

Fig. 2 Air handling unit for air conditioning and refrigeration cycle

The process is shown in Fig. 3 for a given set of boundary conditions. The hot and humid outdoor air (1) is filtered and cooled down in the cooler to dew point temperature (2) of the desired supply air humidity resulting in dry, but too cold air (3a). The heater is needed to reheat the air to supply air temperature matching the comfort parameters (3b). The extract air (5) is not considered here.

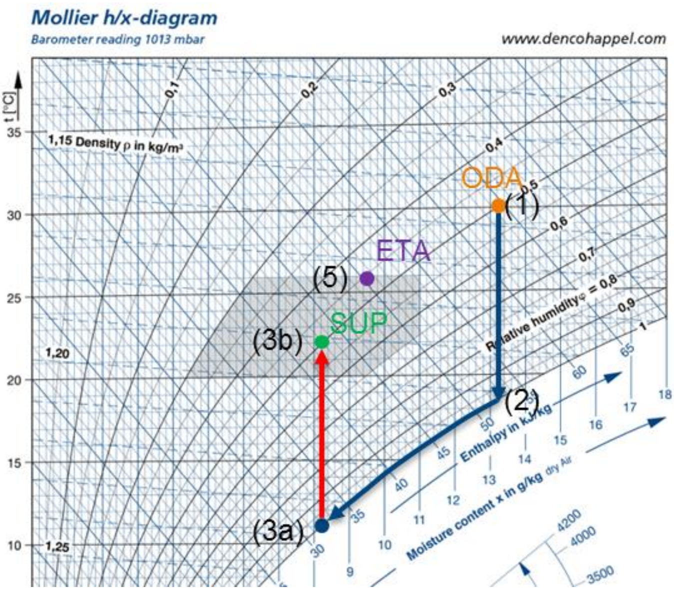

Figure 3 Cooling and dehumidification process (compression cooling)

Refrigeration cycles are typically operated with R410A as refrigerant. R410A has got a GWP of approx. 2000. According to the F-Gas directive from the European Union [4], these types of refrigerants will be banned from the market in the following years and will be replaced by either new refrigerants with lower GWP or even by new technologies. Changing the refrigerant always includes redesign of components and controls for compressors and expansion valves and has a major impact on the interaction of the system components.

Another European directive to consider is the Energy Performance of Building Directive (EPBD) [5] which specifies the maximum allowable energy consumption of a building. The implementation deviates from country to country. In Germany for example, the primary energy consumption of a reference building is calculated. From this value 50 % of the cooling demand has to be generated by renewable energy sources. As a conclusion, sustainability is the driver to introduce new technologies for building operations.

3. Thermal Driven Cooling

One concept to reduce the primary energy demand for cooling is called Thermal Driven Cooling or sorption based cooling. Hot and humid air is dried by passing a heat exchanger coated with a sorption material. The water vapor is stored as liquid water within the sorption material which would heat up the air due to the latent heat of vaporisation. Therefore, the heat exchanger is cooled to keep the air temperature at the same level. Using indirect evaporative cooling by means of a plate heat exchanger and a water spray on the extract air side the air is cooled down to achieve the desired supply air temperature. The following figure shows the process and the main components.

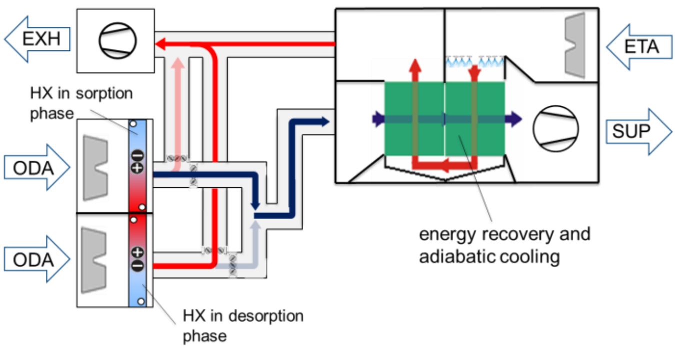

Figure 4 Concept of Thermal Driven Cooling

Outdoor air passes the filter and is dehumidified within the heat exchanger coated with sorption material and cooled by water. The air (blue path in Figure 4) then flows through the plate heat exchanger and is cooled down by the energy recovery system with adiabatic extract air cooling. In parallel outdoor air is used to drive out the humidity from the other sorption heat exchanger (red path in Figure 4). This one is heated up by hot water to generate the needed partial pressure potential for water vapor to diffuse into the outdoor air.

The water storage capacity of the sorption material is limited and needs regeneration. Therefore, a switch over process with a second, similar heat exchanger with sorption material is needed. While one heat exchanger is in dehumidification mode, the other is regenerated by means of hot water or hot air to drive out the water from the sorptive coating.

Figure 5 shows the process within a Mollier h-x-diagram. The hot and humid outdoor air (1) is filtered and then dried by the adsorption process. Due to the phase change from vapor to liquid water most of the heat is rejected by the heat exchanger while a smaller portion heats up the air (2). By means of an adiabatic spray and a plate heat exchanger as energy recovery system, the air is cooled down to supply air temperature. The extract air is humidified and cooled to dew point temperature (6) and heated up in the plate heat exchanger to exhaust air temperature (7) and serves as a heat sink for the supply air side.

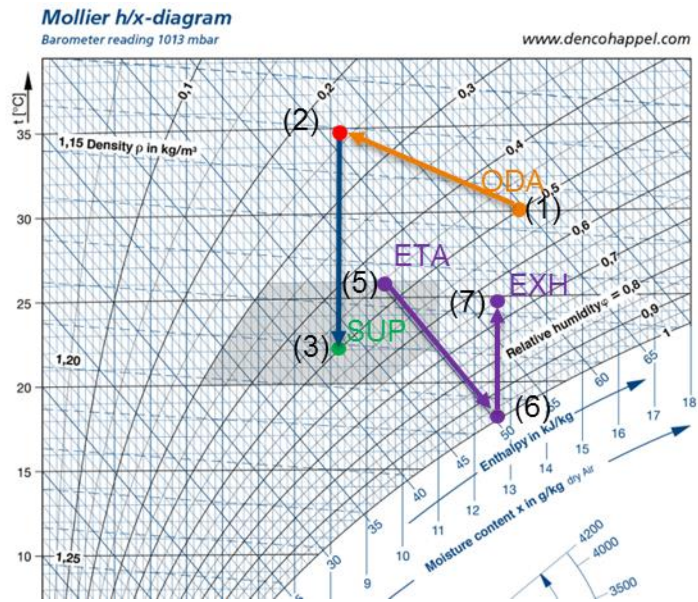

Figure 5 Cooling and dehumidification process (Thermal Driven Cooling)

The following table gives an overview of already existing systems and their properties compared to the open sorption cycle described here. The performance rating is given by a thermal COP (coefficient of performance) defined in the equation below:

$$\mathrm{COP} = \frac{\dot{Q}_{cooling}}{\dot{Q}_{heating}}$$

The values result from internal calculations assuming state of the art technology. Heating energy is needed to drive the desorption cycle of the different systems given in Table 1.

Table 1. Comparison of alternative dehumidification systems

System	Desiccant Cooling with sorption wheel (DEC)	LiCl Scrubber	Adsorption Heat Exchanger
Process	Rotating adsorption wheel	Spray of hygroscopic salt solution	Heat exchanger, coated with adsorbent
Adsorbent	Silica gel	LiCl	Zeolite or Metal Organic Framework
Thermal System-COP	< 0.7	~1.0	1.5 – 2.0
Desorption Temperature	70 – 90 °C	50 – 80 °C	60 – 80 °C (goal: 65 °C)
Advantages	Heat recovery in winter operation	Concentrated salt solution storable	High efficiency, simple design
Disadvantages	Possible odor transport to supply air	High price, LiCl highly corrosive, complex system	New product, parallel operation of adsorption and desorption

To guarantee a safe, reliable and performing operation of the building and its components some general aspects needs further consideration. First of all, air conditioning systems should improve the air quality and health of the building users. Thus, a hygienic unit design and operation is essential. In detail, access and cleanability of the main components such as cooling coils and energy recovery are the prerequisite of a hygienic operation. Here, regular inspection and cleaning is mandatory. A decent design catalogue and maintenance guideline is given by e.g. VDI 6022 [6].

Life cycle costs of a building show that the operation is the major cost driver due to the long life time of building and equipment. This is the reason why efficient energy usage is crucial for a sustainable building.

Today´s cooling systems have to fulfill the hygiene and efficiency requirements according to current legislation and state of the art technology. The new concept of Thermal Driven Cooling will fulfill the current demands as well and further anticipate upcoming trends in energy efficiency and hygienic inspections. Important trends to consider are reduced air velocity within the units and easy replacement of components for cleaning purpose.

4. Current Research Work

The dehumidification and cooling process in general is understood and tested at laboratory scale. To derive a safe, reliable and performing system, several development steps need to be done. In this section we will present the most important research areas to set the basis for a commercial product development.

a) Sorption Material Characteristics

Based on available research data, the material class of Metal Organic Frameworks (MOF) is identified as sorption material. The dynamic characteristics of this material class shows a higher potential compared to other materials as silica gel or zeolite in terms of water storage and drive out temperatures. Figure 6 shows the storage capacity of a MOF material depending on the partial pressure of water vapor in air. To maximise the efficiency of such a material a steep gradient ("step function") has to be achieved. Further, the material needs a long term stability to allow operation of such systems for more than 15 years without substantial loss of capacity.

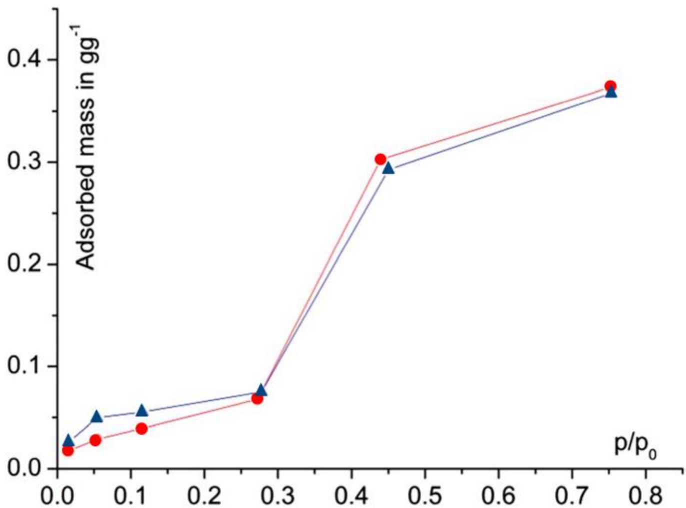

Figure 6 Equilibrium water desorption isobars of a representative mp-AF@Al coating after 1500 (●) and 4500 cycles (▲) [7].

As the sorption material is in contact with warm and humid air, the hygiene is of high importance. Therefore, first tests have been performed by a certified body to check the potential of metabolism. First results show inert characteristics against bacterial growth while fungal attack is visible with a microscope. Here, further improvements to remove this effect have started. Figure 7 shows a test sample of blue coloured MOFs after 4 weeks testing according to DIN EN ISO 846:1997, Method A [8].

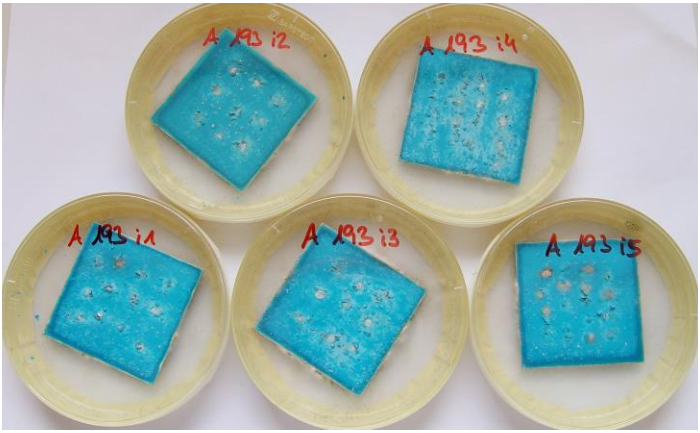

Figure 7 Material samples after 4 weeks of breeding at 24 °C and 95 % rel. humidity

b) Process Simulation

The intention of this project is to create tailor made sorption materials with the best possible characteristics for the specific application. To find the optimum between energy efficiency and life cycle costs, simulations will be carried out to investigate the influence of sorption and desertion dynamics, material usage and cycle durations. In a first step a model is developed to represent the thermo-physical properties of the process and its components. The model will be developed in close cooperation with the laboratory group within the project.

c) Experimental Proof of Concept

Two types of experiments are needed to collect and verify the necessary data for a complete process.

First, the sorption kinetics of the materials and the coating have to be described by experiments. Based on these results the above mentioned simulation model is designed. In a next step, a functional model will be built to validate the optimised parameters coming from the simulations. Further, the components are tested for long term stability and energy efficient design.

Pre-studies to define the set and range of parameters using an already available sorption material confirm the principle concept.

Figure 8 shows the schematic test set up for dehumidification of an air flow from 300 m³/h up to 900 m³/h corresponding to an air velocity between 1 m/s and 3 m/s. Here, the switch over duration and its impact on the temperature changes are investigated.

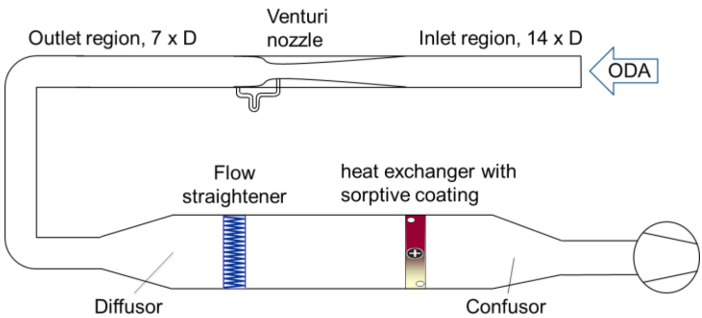

Figure 8 Schematic test set up for capacity tests of sorption material

The test rig is not designed for continuous operation. An example of the resulting dehumidification is given in Figure 9.

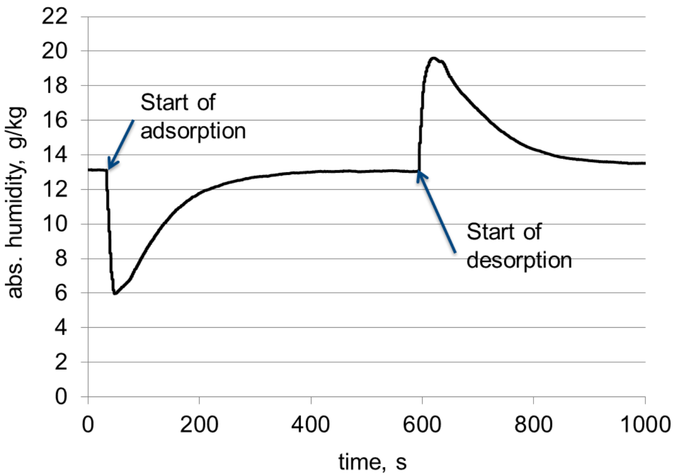

Figure 9 Absolute humidity for one test cycles (adsortion & desorption) with an air velocity of v = 1.4 m/s

The absolute dehumidification from 13 g/kg to 6 g/kg gives a potential Δx = 7 g/kg, which is in the desired range. Unfortunately, the dehumidification process is rather short (about 100 s). For a continuous operation the switch over period would be in that range (1-2 minutes). One objective of the project is to increase the dehumidification time to approx. 15 minutes at a constant dehumidification rate of Δx = 5 g/kg.

Continuous operation with switch over of two coated heat exchangers would result in the following humidity levels, Figure 10.

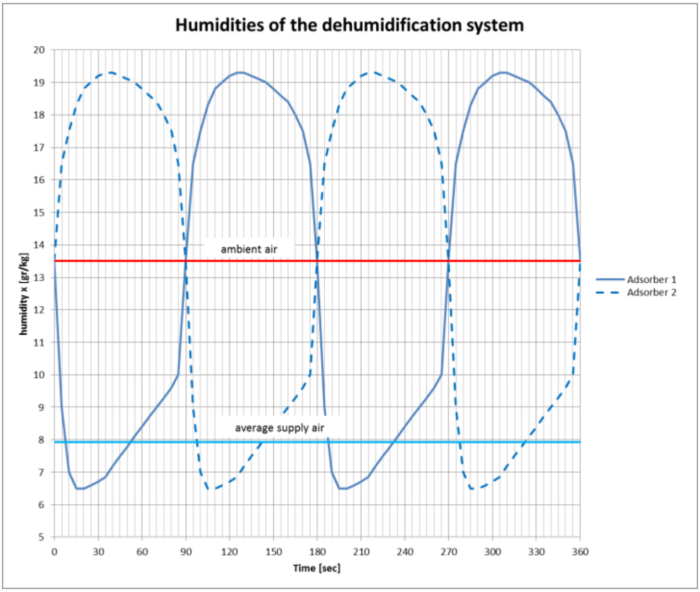

Figure 10 Switch over process for continous operation

5. Conclusions and Outlook

Dehumidification with an open sorption cycle needs auxiliary systems to circulate the water flow for cooling and heating up the sorption material. Further the coated heat exchanger and necessary dampers to separate the air flows result in additional pressure losses. Nevertheless, we believe that the additional energy needed to allow continuous operation is finally far less than for comparable systems. Thermal Driven Cooling is especially designed for an operation with a cogeneration power plant where the waste heat temperature is on an appropriate exergy level and of no further use for heating during summer time.

All in all, first results look promising and the route to a commercial product is visible. Nevertheless, a lot of basic research is needed to generate a safe, reliable and performing process.

Acknowledgment

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