Proceedings of the REHVA Annual Meeting Conference
Low Carbon Technologies in HVAC
23 April 2018, Brussels, Belgium

https://www.rehvam2018atic.eu/

ENERGY EFFICIENT HVAC SYSTEMS IN SHOPPING CENTERS

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ABSTRACT

With a typical primary energy consumption of 374 kWh/(m²a) and an installed area of 15 million m² sales area in Europe while steadily growing, shopping centers contribute a considerable amount of the total energy consumption. About 116 kWh/(m²a) of the total figure (31 %) are used by HVAC systems due to the high cooling loads coming from internal heat sources like lighting, people and machinery. Thus, HVAC concepts compared to the standard all-air systems are studied in a multidisciplinary approach.

First of all, air quality studies of retail goods are performed in order to propose the minimum hygienic air flow rate suitable for shopping centers. We found that according to the measured dilution curves of odor-intensive retail goods, the air change rates can be reduced by 50 % compared to the standard values down to 1.75 h^{-1} without impacting odor perception significantly. Even higher reductions seem possible. By that, air-water systems can be applied, as they typically operate with low fresh air rates.

In a second step, we investigated the applicability of air-water systems, namely active chilled beams, for particularly high secondary air volume flow rates in order to reduce primary energy consumption by shifting the cooling load from the air to the water side. We show CFD simulations of the resulting room air flows and the setup of a field test with installed active chilled beams. Active chilled beams typically operate on higher cold water system temperatures compared to all-air systems, leading to a potential of alternative supply systems like free geothermal cooling.

In dynamic annual simulations of the building energy systems, containing the HVAC systems as well as the thermal building behavior with a low order approach and also occupancy profiles, different HVAC supply systems are compared. Special attention is paid to low exergy supply systems, meaning elevating the cold water system temperature of the air-water system, decreasing the air change rates and integrating renewable energy sources like geothermal systems. The simulations are verified against monitoring data and show an annual primary energy saving potential of up to 35.1 %.

KEY WORDS: Shopping Center, energy efficiency, low exergy supply systems

1. INTRODUCTION

The global amount of shopping centers in Europe, as well as in the Americas and Asia is growing. At the end of 2014, the total gross leasable area in Europe amounted to 152.3 million m^2 with an annual increase of 3.3 % [1]. The growth of the total gross leasable area in these three major regions combined amounted to 63.9 million

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m², totalling in 924.5 million m². The need for energy efficient HVAC systems is obvious, as those systems contribute a considerable amount of 31 % of the total primary energy demand of 374 kWh/(m²a) [2]. Typically, all-air systems are used to remove the cooling loads, which can amount up to 150 W/m² due to intense lighting, other inner loads like customers, machinery and external loads like solar radiation [3]. Using only air, high air change rates are required. Therefore, additional circulating air cooling units are often used (fan coils). In prior studies, Mathis et al. [4], [5] showed that the introduction of air-water systems operating with higher cold water supply temperatures and lower air change rates is possible without compromising to air quality, thermal comfort or draught risk.

To apply as low air change rates as possible is interesting from the energy efficiency point of view, because fewer air has to be conditioned and transported to the occupant zone. A limiting factor might be the air quality in terms of odor emissions. Thus, the minimum amount of fresh air has to be determined in a first step.

Then, the implementation of air-water systems in terms of active chilled beams in shops is investigated and performed in a CFD (Computational Fluid Dynamics) simulation environment alongside with fundamental research for the optimization of active chilled beams like described in [5]. Also, a field test has been set-up in an electronics shop, where an air-water system with active chilled beams is installed alongside an all-air system with supplementary circulating air cooling units, allowing the user to switch between both systems and compare them via an energy monitoring system.

Finally, the results from the air quality and the air-water systems research are combined in dynamic annual building energy system simulations. Applying different building energy systems suggest great potential for increasing the energy efficiency of shopping centers. The aim of these considerations is, on the one hand, to compare different primary energy supply concepts with each other. For this purpose, the primary energy requirements of different system variants are simulated. On the other hand, the impact of reducing air change rates and applying air-water systems is examined with regard to its energy saving potential in the overall system.

2. AIR QUALITY ASSESSMENT

To deduce a minimum fresh air rate, dilution curves for typical retail goods are recorded to investigate the correlation between perceived odor intensity and fresh air volume flow.

2.1 Methods: All measurements of emissions from retail products are examined by a trained human panel consisting of eight persons using an intensity reference scale [6]. The reference scale provides a set of acetone-air mixtures of six concentrations in the range of 0 to 15 pi (perceived intensity). A value of 6 pi marking the transition from low to medium and a value of 12 pi from medium to high odor intensities [5].

For three representative retail goods in shopping centers (shoes, clothes and books), a typical shop situation concerning air change rate (3.5 $h^{-1,}$ based on VDI 2082) and the amount of emitting surfaces is emulated in three different emission chambers. For the three different retail goods, exposure-response functions are recorded, indicating the perceived intensity over emission loads. The emission load is calculated from the fresh air volume flow and the emitting surface, leading to higher emission loads with lower air change rates with the emitting surface being constant.

2.2 Results The exposure-response functions for the sales goods are evaluated after a period of four days while being constantly exposed to an air change rate of 3.5 h^{-1} in the emission chamber and thus an estimated steady state with regard to odor intensity is reached [7]. The time-depended decay is indicated in Figure 1 (right) showing a slight decline in odor intensity for shoes an almost constant intensity for clothes and books.

In the left part of Figure 1, the exposure-response function for clothes is shown. The red circles show the arithmetic mean value of the perceived intensity at different air volume rates, each one recorded by a trained human panel and fitted by log-function (red line). Based on the emitting surface and an air change rate of 3.5 h^{-1}, a perceived intensity of approximately 4.2 pi (blue dashed line) is found. Reducing the air flow rate by 50 % corresponding to an air change rate of 1.75 h^{-1} leads to a higher perceived intensity. However, only increasing by less than 1 pi to a value of 5.1 pi (orange solid line), staying in the low intensity region. So, even by reducing the air volume flow by far more than 50 % the increase in the perceived intensity would hardly be detected by a room occupant. The results for shoes and books are very similar with regard to the air change rate [7].

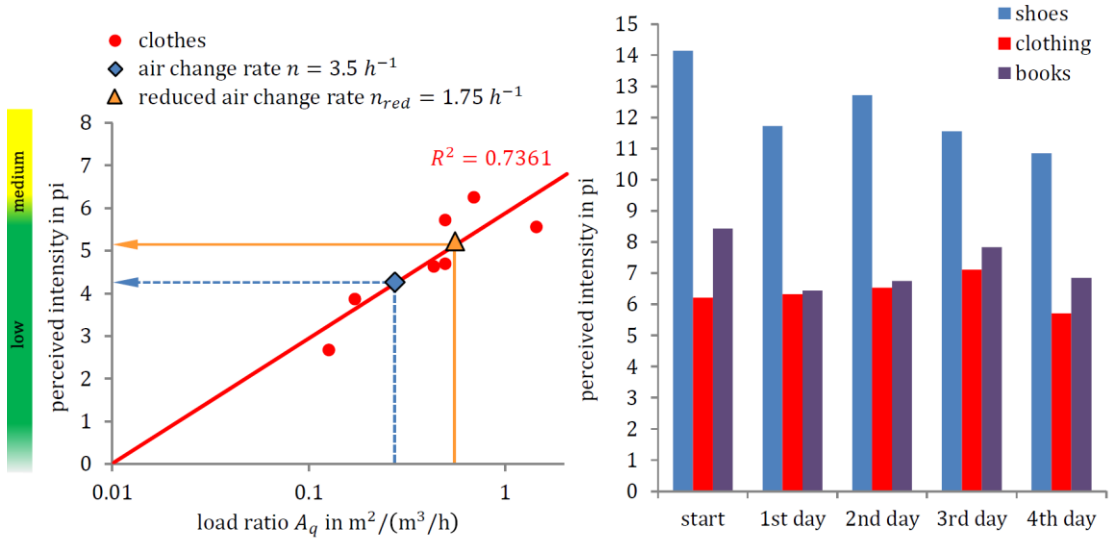

Fig. 1 Logarithmic exposure-response function for clothes (left) and perceived intensities of the temporal odor decay (right)

3. APPLICATION OF AIR-WATER SYSTEMS

The air quality assessment reveals a high potential of reducing the fresh air amount and thus the air change rate in shops significantly without increasing the odor perception to a high level. Air-water systems like active chilled beams use a small amount of fresh air to induce a high amount of room air allowing for a high amount of circulating air flow passing through and being cooled by an air-water heat exchanger. Thus, a large amount of the cooling load would be removed via the water circuit and not by the fresh air as in an all-air system. The applicability of active chilled beams is demonstrated in CFD (computational fluid dynamics) simulations as well as in a field test.

3.1 Methods First, CFD simulations of a generic shop including the active chilled beam are performed to ensure thermal comfort is not violated when active chilled beam systems with elevated cold water supply temperature are applied. The simulation methodology is shown in detail in [5] and is not repeated here. The active chilled beam system is modelled as a black box, delivering the cooling performance according to data sheets and the air flow at the appropriate temperature and velocity to the room. Then, the CFD methods are extended to a real shop geometry of an electronics retail store in Germany. A total area of 600 m² is equipped with both, a conventional all-air system with supplementary air circulating unites (fan coils) and an active chilled beam system, so that both systems can be run sequentially in the same supply area and thus be compared directly (Figure 2). Both systems are monitored with regard to room air conditions and energy demand. The area of the field test is simulated with CFD methods, leading to a mesh of about 5.7 million cells. The standard system as well as the active chilled beam system are simulated.

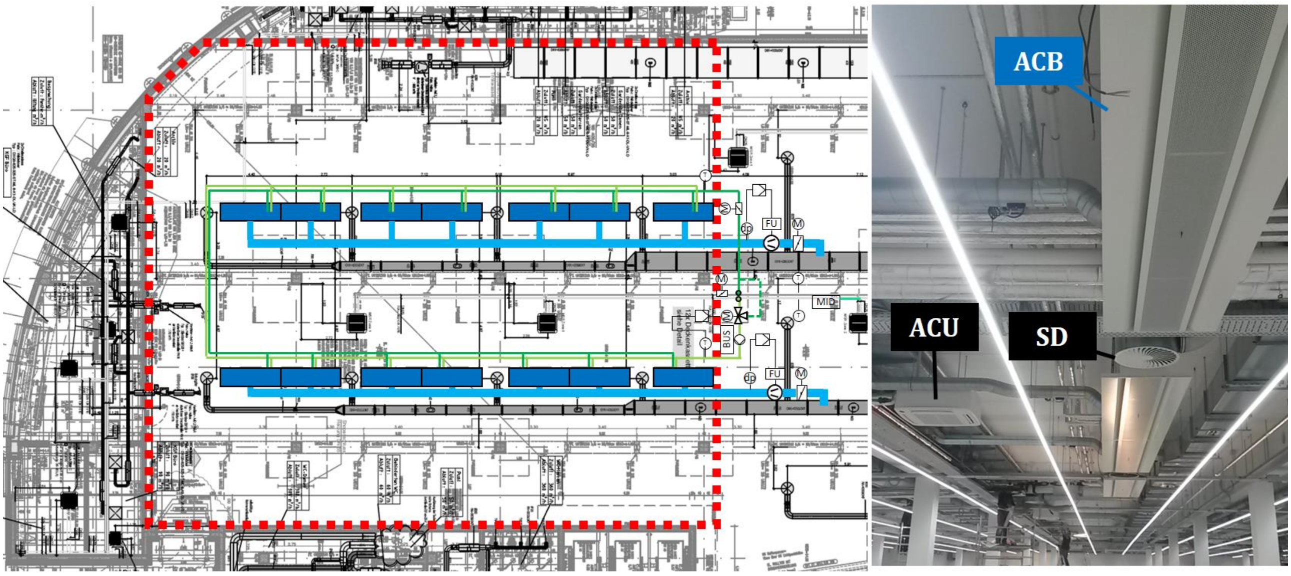

Fig. 2 Concept of the field test. Left: schematic drawing of the installation. Right: installed standard and air-water systems (ACB: active chilled beam; ACU: air cooling unit; SD: standard diffuser)

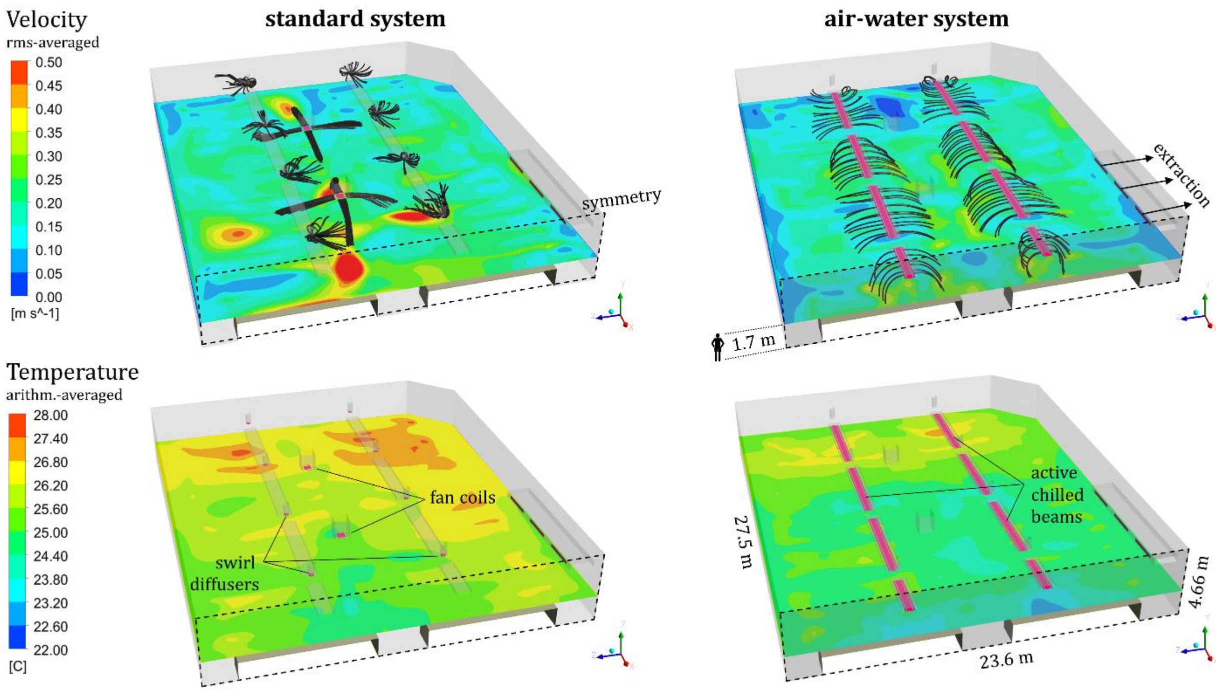

Fig. 3 Simulated velocity and temperature fields of the field test area at head level (1.7 m). Left: standard system with swirl diffusers and air cooling units (fan coils). Right: air-water system with active chilled beams.

3.2 Results The simulations in a generic shop show that the active chilled beam system is able to remove the required cooling loads and at the same time maintain the thermal comfort level from the standard system. The detailed results are described in [4] and [5].

The CFD simulations of the field test area (Figure 3) show, that both systems are able to meet the desired temperature. In the back region of the sales area, slightly higher temperatures are observed. This is due to the position of the extraction, which is situated in the front right upper corner, so that the heated air from the back needs to pass a longer distance to the extraction. The air in the vicinity of the extraction gets exchanged faster and thus does not heat as much. Also, the velocities in the new system do not exceed the velocity level of the standard system, rather the velocity level is even lower (Table 1). Thus, no deterioration of thermal comfort is expected: the average values for draught rating (DR) is about 9 % for both systems, with a lower peak value for the new system (17.9 % compared to 29.7 %), resulting from the jets coming from the fan coils.

All this is achieved with a fresh air flow of only 3500 m³/h at 16 °C in the air-water system compared to 5200 m³/h at 15 °C in the standard system, i.e. a reduction of 33 % fresh air volume flow and an even higher fresh air supply temperature. Moreover, the cold water system temperatures are elevated to 16/22.4 °C from a standard system operating at 6/12 °C, thus avoiding latent losses due to condensation. These effects are expected to lead to higher overall efficiency of the building energy system.

Table 1 CFD results

	standard system	**air-water system**	
vol. ave. Temperature	26.1	25.3	°C
ave. Temperture at 1.7 m	26.1	25.1	°C
ave./max. DR at 1.7 m	9.1/29.7	9.3/17.9	%
rms. Velocity at 1.7 m	0.19	0.17	m/s

First monitoring data of the field test is available (Figures 4 and 5). Two room temperatures and one CO_2-value are plotted for a period of three weeks in September 2017, with the standard system operating. The air handling unit operates in demand-controlled manner, i.e. only during the opening times. It also has a circulating air option in case the CO_2-level is low enough. The room temperature is maintained within a range of 20.5 to 23.5 °C, with only little fluctuation around a value of 22 °C, the fluctuations for one sensor being larger than for the other. During Sundays, the temperature curves are almost undisturbed. The CO_2-values decline all over the Sunday reaching outdoor conditions of about 400 ppm shortly before opening on Monday (Figure 5), then starting to rise rapidly, apparently with people entering the shop. Also, the small peaks in the CO_2-curves, where the downward slopes after the peak correspond to the local temperature decrease indicate a pulsating operation of the air handling unit.

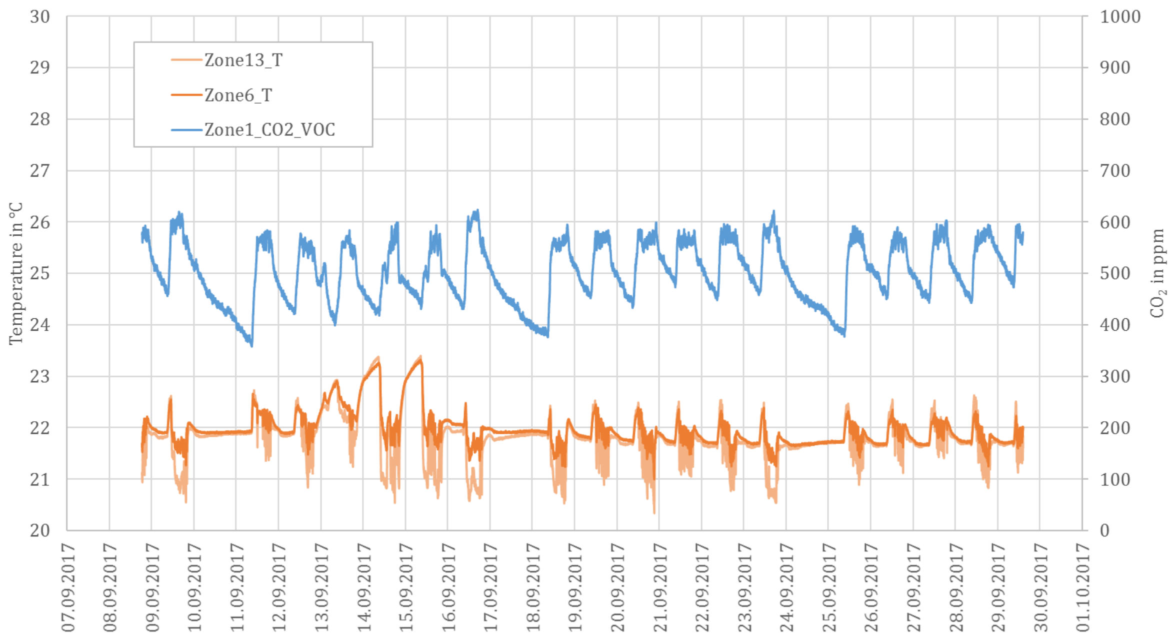

Fig. 4 Field test data for three weeks in September 2017 (standard system)

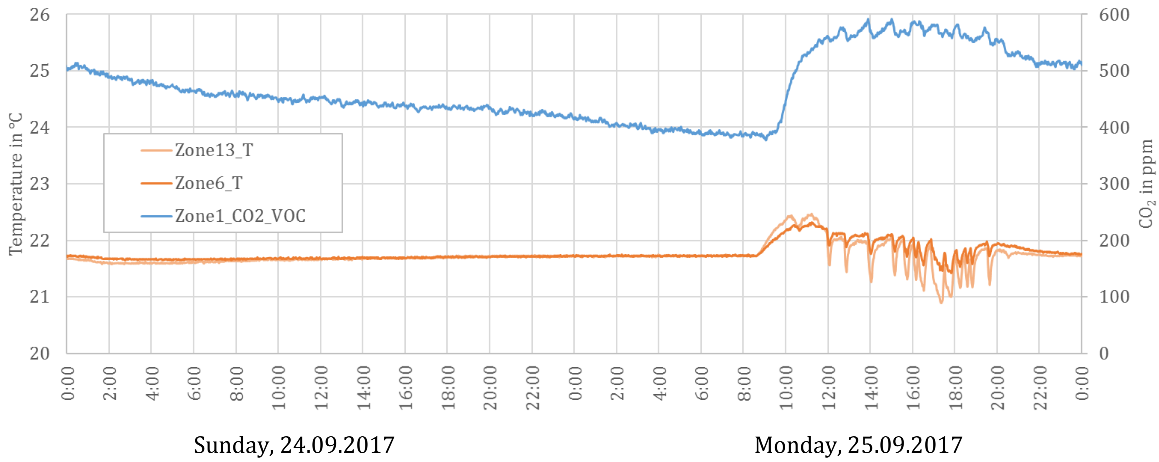

Fig. 5 Field test data for two days in September 2017 (standard system)

4. ANNUAL SIMULATIONS OF SHOPPING CENTER BUILDING ENERGY SYSTEMS

The saving potential of the new air-water system ventilation concept for shopping centers is presented by a case study based on a real shopping center building and verified with measured monthly energy consumptions [8]. Four different supply system variants are modeled:

"Chiller" in Figure 7: A conventional cooling supply system with air handling units for ventilation and air circulating units (fan coils) as supplementary systems operating with low water system temperatures (supply set temperature: 9 °C), whereby all cold requirements are met with an electrically driven chiller. The standard air change rates is 6.25 h^{-1} in the shops and 5 h^{-1} in the groceries.

"Chiller + geoth." in Figure 7: The conventional cooling supply system is then extended by the integration of a geothermal field, which is applied for pre-cooling the cold water circuit to 13 °C. The required cold water temperature of 9 °C is achieved by additional cooling power of the chiller.

"Chiller + ACB + geoth." in Figure 7: Additionally, the air circulating units are replaced by active chilled beams, allowing the cold water system temperature increase to 13 °C in this case and reducing the air change rate in two steps down to 2.4 h^{-1} and 1.6 h^{-1}, respectively. An additional pressure loss of 150 Pa in the air ducting is accounted for.

For system comparison, the primary energy demand for air conditioning is determined by annual simulations.

4.1 Methods For this purpose, the building is modelled as a simplified multi-zone model in the modeling language Modelica and extended by an air-water system. The building itself is modeled with a low order approach according to [9] and [10] and parametrized according to [11]. The shopping center is divided into 8 zones of similar use conditions, each with an individual air change rate and profile of inner loads with "shops" and "grocery" being the crucial ones for this paper. More details can be found in [8].

4.2 Results The results for cooling and heating demands of the standard system are depicted in Figure 6 and compared to monitoring data, which is only available on a monthly basis. In general, all relevant trends are captured with the model, leaving the simulation results with a maximum deviation of 19 % for the cumulated cooling demand. Despite the many unknowns and severe simplifications, the results are in a considerable range, allowing for fast system comparisons, as calculation times are within the range of minutes for a whole year for a time step of one hour.

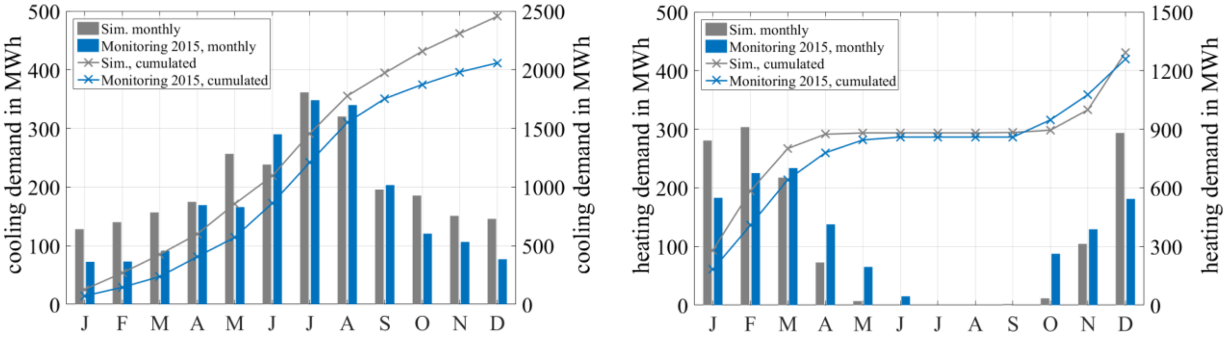

Fig. 6 Comparison of measured data of 2015 and simulated cooling and heating demands

The cooling and heating demand of the building is met with the introduced different HVAC supply systems and compared to each other in terms of their primary energy demand. The main consumers of the conventional system are the ventilation (fan power) with 62 % and the electrically driven chiller with 28 %. By introducing geothermal cooling, the overall primary energy demand is cut down by 5.6 %, mainly due to the reduced need for cooling, whereas the additional need for the geothermal pumps increases the share of water pumping. The share of heating and ventilation remains constant. When introducing active chilled beams, the cooling demand of the electrical chiller is further decreased, as the cooling load is shifted to the (geothermal) water side even more, leading to an increase of the water pumping share. But due to lower air change rates, the ventilation demand is cut significantly, even with higher pressure drops in the ducting system, resulting in an overall reduction of 30.4 % in primary energy demand compared to the conventional system. By reducing the air change rates even to 1.6 h^{-1}, this trend is continued, coming up with an overall reduction of 35.1 %. In this system, the water pumps have the main share (53 %) of the primary energy demand, compared to a 41 % share for ventilation.

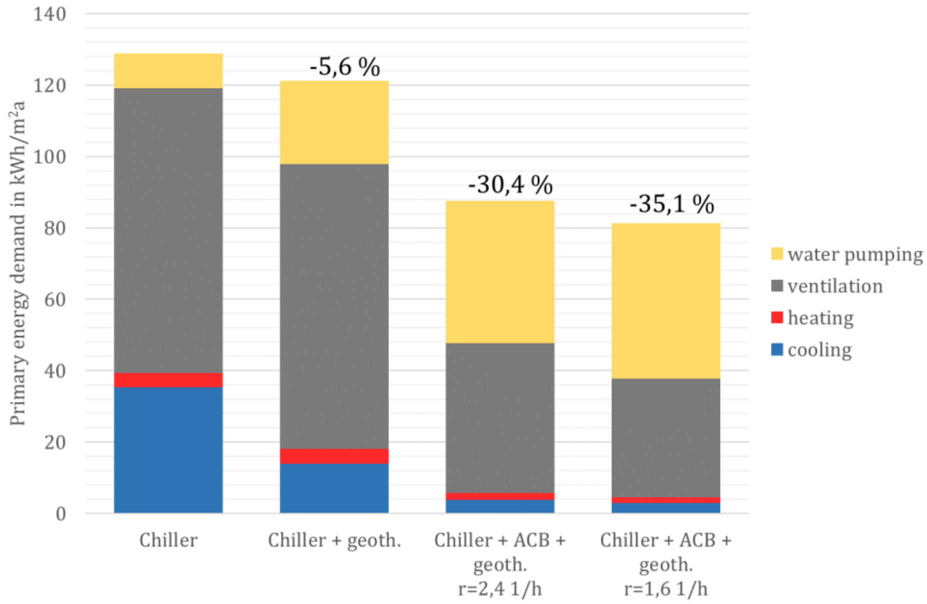

Fig. 7 System comparison – simulated annual primary energy demand for air conditioning

6. CONCLUSIONS

In this study, a multidisciplinary approach for comparison of novel HVAC concepts to the standard all-air systems in shopping centers is followed. We began with air quality studies for the determination of actually required fresh air volume flows for shops with representative sales goods. The applicability of the air-water systems, namely active chilled beams, for the resulting air flow rates and, in addition, for the elevated flow temperatures of the cooling circuit were subsequently investigated by means of CFD methods. In order to confirm the promising simulation results of the CFD studies and to gain further insights, a field test was set up in an electronics retail store. Finally, we investigated the energy-saving potential of the active chilled beam in the entire building energy system of a shopping center by using dynamic annual simulations. For this purpose, we considered different supply concepts, which also include the integration of renewable energy sources.

The exposure-response functions for representative sales goods show that the air change rates of corresponding shops can be reduced down to 1.75 h^{-1} without any noticeable deterioration in air quality for the room occupant. Furthermore, the results of the air quality studies show that a further reduction of the air change rate is possible without affecting the air quality, especially in shops for sales goods like clothes and books. Thus, the fresh air volume flows for shops with representative sales goods can be reduced by more than 50 % compared to current standards, which results in a high potential for significant energy savings in air handling and ventilation.

The simulation results of the CFD study show that the investigated active chilled beam systems are able to ensure the thermal comfort, even in an electronics retail store with comparably high thermal loads. In the case of the electronics store, the fresh air volume flow has been reduced by 33 % compared to a standard system. In addition, the flow temperature of the cooling circuit has been increased from 6° C to 16° C to avoid latent losses due to condensation. These measures are expected to lead to a higher overall efficiency of the building energy system. The presented field test with the real implementation of the investigated active chilled beam system is currently recording monitoring data. This data will be used to prove the applicability and energy savings.

The results of the annual simulations of shopping center building energy systems confirm the high energy saving potential of the presented active chilled beam systems. In combination with a geothermal field as a renewable cooling source, savings of up to 35 % in primary energy for air conditioning were determined. The results show also that by reducing the air exchange rates, the heat removal is increasingly shifted to the cooling circuit. With a share of up to 53 % of the primary energy demand, the water pumps can become one of the main consumers of the supply system.

ACKNOWLEDGMENT

Grateful acknowledgement for financial support by BMWi (German Federal Ministry of Economics and Technology), promotional reference 03ET1092B and the Heinz-Trox Foundation. “”

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