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A COMPARATIVE STUDY ON CONCRETE CORE ACTIVATION AND CHILLED CEILINGS IN GEOTHERMAL, NEARLY ZERO-ENERGY OFFICE BUILDINGS

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Abstract

Two of the leading technical concepts in sustainable office buildings are Concrete Core Activation (CCA) and Chilled Ceilings (CC). Both water-based systems rely on a radiant cooling or heating capacity, but where CC is directly controlled by the indoor temperature (θ_i), CCA relies on a large thermal inertia of structural elements, making it hard for a good control strategy to be determined. The purpose of this paper is to analyse and compare CCA and CC in a geothermal office building, adding a relevance to their overall performance. This comparative study shall research and discuss the advantages and disadvantages of both emission systems, their accompanying supply mechanisms and their influence on cost, and aims to assist architects and future builders in their choice for a technical concept by providing the necessary information with regard to making a more thorough decision. The research is performed with the help of elaborate computer simulations in TRNSYS and an economic analysis on the basis of a Return On Investment (ROI). The results show that both systems have the ability to provide a good comfort and thus a proper hydraulic concept, but where CC will excel in a higher overall comfort, CCA will achieve a lower energy use and shorter ROI (without the productivity assessment). This conclusion alters with and remains highly depending on the applied approach of productivity.

near zero; simulation; GEOTABS; economic sustainability

1. Introduction

The concept of Nearly Zero-Energy Buildings (NZEB) aims that the energy in a new building is supplied sustainably so that they would meet the new requirements imposed by the Energy Performance of Buildings Directive (EPBD). The energy use in the tertiary sector, according to the Federation of the Belgian electricity and gas companies (FEBEG), equals approximately 21.95% of the total energy use in Belgium. A large part of that energy is used for the heating of domestic hot water and the climate

control in buildings. This study distincts itself from other comparative studies as it pursues a holistic perspective by means of comfort, energy use as well as economic decision variables. Never before have the two main HVAC systems for office buildings been put together and evaluated with one another.

When using CCA, the full thermal mass of a building will be actively, or passively, heated or cooled. This means that by using CCA the thermal capacity can be utilised in order to reduce the peak power and the need for passive cooling or active heating can be shifted in time. Due to the large thermal surface it is possible to decrease the temperatures of the water in the tubes which results in heating with low and cooling with rather high temperatures [1]. The temperature difference between the indoor environment and the surface temperature of the concrete slabs is relatively small, causing for an important self-regulating effect in case the ratio between concrete and space temperature would change considerably. The thermal inertia of the concrete mass does not allow for fast reactions, making it hard to achieve an optimised control strategy, which is why a fast reacting secondary system is preferably implemented to enable sudden operation mode changes. The implementation of CCA is usually based on zones instead of rooms due to the incorporation in the building structure [2].

The other concept operates by installing radiant panels to the supporting ceiling and is known for its ability to counteract an increase in θ_i by means of a more direct approach. In this research a closed ceiling will be considered where one can use a high cooling temperature, usually between 16°C and 19°C to cool.

Both water-based emission systems have the advantage that the required water temperature, for both heating and cooling, may be close to the desired θ_i . These techniques, by means of a ground-coupled heat pump (GCHP), can be linked with geothermal energy (GEO), which in case when CCA is applied, is called GEOTABS. These systems require only a limited amount of electricity, which results in a great energy efficiency and sustainability.

2. Methods

The research is performed using an existing office building as reference case, this building and its properties are used for the different simulations. With the dynamic simulation tool TRNSYS [5] different hydraulic configurations and control strategies will be implemented in the sample building. The first two configurations are equipped with CCA, which can be implemented in TRNSYS by means of an active layer. Since CCA requires a secondary fast reacting emission system we will select convectors in the first case and VAV in the second case. The two last configurations are those with CC. In the first case a building equipped with a GCHP is assumed. In

the second case the building is equipped with a more standard composition for CC, consisting of a condensing boiler for the convectors and a monobloc for the CC.

2.1 Sample building

The building on which this research is based is the CGW building in Bruges, Belgium. The building has a rectangular shape with a floor surface of 700m²; an abstraction of this building is made where only the four floors with office spaces are simulated. The building is well insulated, In case of CCA the characteristics depend on these of the concrete, the tubes and water. The tubes are embedded in the 0,28m thick concrete slab at a depth of 0,08m from the ceiling surface. In case of CC, a ceiling with a cavity is assumed, with steel tubes on top of a steel plate, where the distance between two conduits is 0,2 m. The building is accommodated with solar fins as a first line of defense, next to that we have the variable shading. The air-handling unit (AHU) in all configurations is designed to achieve the IDA2 class. The hygienic ventilation in case of VAV is assumed as before, while the maximum available ventilation flow is set up to a IDA1 class. This in order to supply an extra airflow in case heating or cooling is required. Furthermore, the air ducts are accommodated with an extra heating coil per room in case the regular preheated air does not suffice. In case of CC the AHU is also equipped with a dehumidifier controlled by an iterative feedback controller, where the control signal is the water supply flow rate. The controlled variable is determined as the maximum RH of all the spaces on the basis of psychometric calculations. The set point of the RH is set to 60%. It is formulated to only dehumidify when the CC is on and thus when cooling is required.

The set temperature for hot water is 30°C for the TABS and 50°C for the convectors, the supply water temperature for cooling is provided passively directly from the Borehole Energy Storage or BES-field, this temperature varies between 10 and 12°C. The GCHP is coupled to a BES-field composed out of 60 boreholes with a depth of 100m in a grid of 6 by 10 with a spacing of 5m. In case a condensing boiler is used, the set point temperature of this boiler is 50°C.

The control consists of two layers, at first the building has different modes in which it can operate, a heating mode, dead band and cooling mode. In case of CCA the according mode is defined by the mean outdoor temperature (θ_o) of the three previous days, measured between 8am and 17pm. In the cases with CC the actual mean θ_i defines the building mode. The second layer of control is the control of the supply water temperature, in cases with CC a constant temperature of 18°C is maintained while in

CCA the supply temperature is based on the same mean θ_e according to the study of Sourbron et al. [6]. The need for extra heating by the convectors in case of CCA is done according to the proportional difference with the optimal θ_i . The CCA will only be activated at night between 22pm and 6am, while the large heat load at the end of the day is compensated using night ventilation.

Control Setting GEOTABS	
Dead Band	$8^{\circ}\text{C} < \theta_{\text{mo}} < 13^{\circ}\text{C}$
Supply period	22h - 6h
Flow temperature	$-0, 16. \theta_{\text{mo}} + 20,8 / -0, 22. \theta_{\text{mo}} + 23,6$
Control Setting CC	
Heating or cooling	$0, 11\theta_{\text{e,ref}} + 21,55 / 0, 11\theta_{\text{e,ref}} + 22,45$
Flow temperature	18 °C

Table 1: Control settings for the Geotabs building

2.2 Simulation model

Each configuration is simulated using TRNSYS dynamic simulation software. Figure 1 shows a schematic layout of the models. In TRNBuild we have defined a total of 56 spaces. Of which the majority are office spaces and meeting rooms. These 56 spaces are grouped in three zones per floor. These zones match with the circuits of the CCA. For CC an abstraction was made, to minimize the calculation time the CC is also controlled using the same three zones. The occupancy rate of the building differs from room type and the hour of the day. All other possible heat gains are taken into account

2.3 Evaluation factors

For the evaluation of the different configurations an appeal is made on several evaluation factors, the first being the energy use. Since we are talking about nZEB-buildings, it is important that the energy use is limited. It will play an important role in the ROI of the different configurations. Depending on the configuration, we define various groups of energy users, which usually can be divided into usage for heat pumps (HP) or monoblocs for both the primary emission system and the secondary, and the energy use of pumps for both the hot water circuit and the cold-water circuit, but also the ventilation circuit and the BES-field. Furthermore, the energy use of the dehumidifier in case of CC is defined. The energy efficiency of the HP or monobloc depends on the COP or EER These are modeled using the characteristics from a technical manual of an HP or monobloc by which a

function could be composed, resembling the characteristics of an actual HP/monobloc. The boiler is simulated using type 751 of the TESS library with a maximum efficiency of 101%.

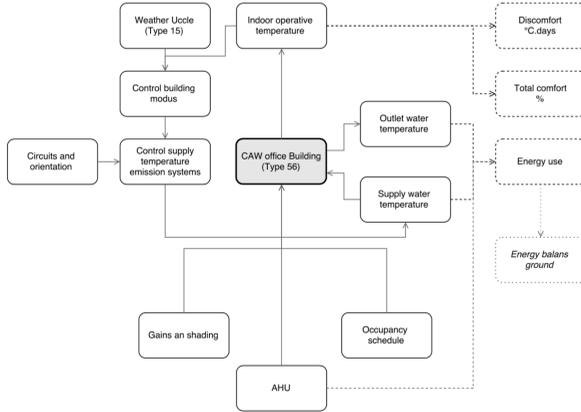


Figure 1: Overview of the model components

$$COP = -0,096 \cdot \theta_h - 0,0034 \cdot \theta_h \cdot \theta_{bhe} + 0,2404 \cdot \theta_{bhe} + 7,89$$

$$EER = -0,0905 \cdot \theta_e + 0,0000612 \cdot \theta_e \cdot \theta_c + 0,0840 \cdot \theta_c + 5,954$$

For the energy consumption of the pumps we will select two types of pumps. One for the circulation in the different circuits and a larger one for the circulation to the BES-field. This gives us a pump with a head of about 4m, giving a power of; 78,4 J/h per kg boosted liquid. For the second type a head of 7m will be sufficient, the power needed is then 137,2 J/h per kg boosted liquid.

Second evaluation factor in case of configurations with a GCHP is this of the energy balance in the soil. The energy balance is calculated as the energy, which is sent to the soil, depending on the flow rate Q , the specific heat capacity of the transport medium, usually a glycol mixture, and the temperature difference.

Another important factor is the thermal comfort in the building, considering three different evaluation methods. A first method is this of a weighted exceeding temperature. As upper and lower limits we consider class B, namely [8]:

$$\begin{cases} \text{Upper limit} = 23,45^\circ\text{C} + 0,11 \cdot \theta_{e,ref} \\ \text{Lower limit} = 19,55^\circ\text{C} + 0,11 \cdot \theta_{e,ref} \end{cases}$$

The weighing factors obtained by the difference of the operative temperature and the limit temperature are then integrated over time and added together. As a result we obtain the number of degree days too warm, when the upper limit is exceeded and the number of degree days too cold, when the lower limit is exceeded.

As second method one can evaluate the comfort in a more thorough way using the PMV model for the thermal comfort and evaluating the indoor air quality (IAQ), the Relative Humidity (RH), the thermal asymmetry and the acoustic comfort. Combining these factors one can obtain the total comfort and later on the performance improvement.

2.4 Economical study

In the economic study several assumptions must be made according to the current economic climate. An electricity price per kWh of €0,1751 during the day and €0,1245 during the night is assumed and a gas price of €0,0778 per kWh according to [9] and [10]. The energy price varies during the lifetime of a building so three scenarios are defined: an optimistic scenario with no price increase, a standard scenario using the price increase according to the European commission [11] and a pessimistic model with an 4,3% increase. The economic climate is defined by an inflation of 2% a market interest rate of 2,57% resulting is a real interest rate of 0,58%. For the calculations, both the current real interest rate and a safer real interest rate of 5% are considered, which are imposed by the EC [12] with reference to the cost-benefit analysis, this analysis is made using the total actual cost method (TAC).

3. Results and discussion

3.1 Analysis of the acoustic performance

In the field of acoustics, the comparison between two products is generally based on the reverberation time (RT) produced, calculated in a reverberation room. By comparing the nominal sound absorptive coefficients of both concrete and an acoustic insulated climate ceiling, one could conclude that, with a α_s of 0,03 and 0,8 ~ 0,9 respectively, the climate ceiling would be the better choice. However, basing our conclusion solely on the achieved absorptivity of one material would be a sign of negligence. CC is generally considered as a good option for acoustic comfort because they give the possibility to add an acoustic insulating membrane. In CCA covering the concrete ceiling prevents the emission system to be effective. However, this means a limitation of the area with a more acoustically viable

material. In the standard layout of office spaces with CCA, the walls and floor consist of the same materials as before, but the concrete ceiling is partially implemented with acoustic baffles, which is seen as an enhancement that can and should be made in order to fulfil the imposed requirements. By adding vertical acoustic baffles one can influence the sound quality by a large amount while only decreasing the effectiveness of CCA a little. This leads to the conclusion that the majority of the offices are equal with regard to acoustic comfort. But where for CCA it asks for a small investment to be optimised, it is self-evident for CC, with the possibility to be improved if there is a desire to do so.

3.2 Analysis evaluation parameters

For The discomfort one can observe a large difference in both degree-days too warm and too cold (fig. 2c). In case of CCA a high number of too warm is perceived, while a small amount of degree-days too cold appears. In contrast, the discomfort in buildings with CC is more balanced. A lower amount of too warm is achieved while a higher degree of too cold occurs. Due to many internal heat gains, the typical development in an office building is ascendant throughout the day and nearly nothing can be done to counter it when no fast reacting emission elements are implemented. Due to the absence of these fast reacting elements in GEOTABS, overheating can occur in warmer periods. Only by actively cooling the fresh supply air a certain fast reacting cooling capacity can be created. Wrongly estimating the mean θ_e could mean the heating modus is activated, while cooling or a dead band should be applied. The smaller discomfort too warm in configurations with CC is due to the fast response ability of CC and an average of 1,5 °C.days per room is achieved, based on the primary occupied spaces. The higher discomfort too cold in CC, compared to CCA, is due to a certain period where the convectors will not emit enough heating capacity or periods where cooling is activated due to a too high mean θ_i , but where the room specific temperatures of smaller spaces will be lower. This is because of the simplified control model and not considering a start-up period for the convectors before occupants arrive. Overall the discomfort of both systems is good, with an average total discomfort of 4 °C.days for GEOTABS buildings and 3,2 °C.days in case of buildings with CC.

The energy use (fig. 2b) in buildings with CCA is remarkably lower than that of CC. Yet, it is not so much the chilled ceilings nor the dehumidifier that are the main cause for this higher demand. Even though the pumps responsible for the cold-water flow possess a shorter working period, they

have a higher energy use since more heat needs to be extracted from the rooms and a higher flow rate is applied. A small difference is that in case of GEOTABS the hot pumps supply both the CCA and the secondary heating elements, in CC they only supply the convectors. A major difference between on one side the geothermal systems with CCA and on another side those with CC is the energy input required to keep the buffer tank supplying the convectors at the desired temperature. Due to the higher activity of the convectors, the HP is asking for more energy. The monobloc in the last configuration is there to replace the otherwise passive geothermal cooling capacity. The boiler on the other hand is the equivalent of the HP and shows a larger energy use due to the lower efficiency. Both of these factors are only applicable for this configuration, making it rather difficult to compare them with the other energy users.

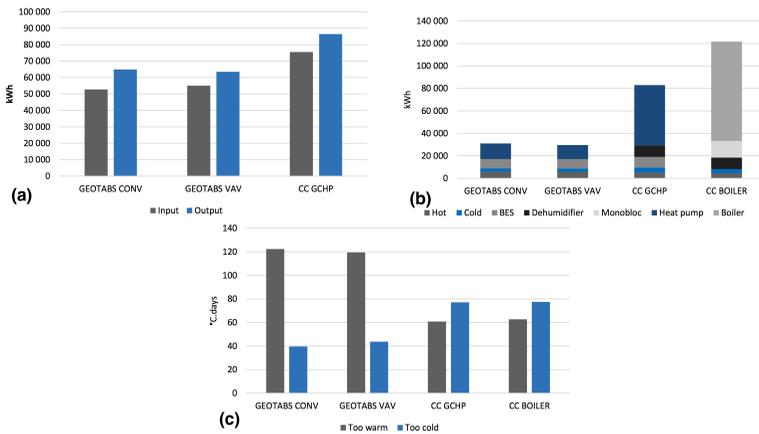


Figure 2: energy balance (a), Energy use (b) and discomfort (c)

The energy balance is briefly discussed. Since it is not so much a desire as it is a must to obtain a decent balance in the soil. Having no balance would only weaken the installation, nullifying the use of sustainable energy and a lot of extra energy will have to be added to obtain the same results concerning comfort. That being said, the configurations achieve an acceptable degree of balance, where the difference between input and output is mostly negative. Still, in case of CCA, night ventilation had to be applied in order to obtain these results, while in case of CC solar pump shading could be removed.

In terms of thermal comfort both perform well, but there where CC is simplified to create a compatible model, CCA is optimised and can only be optimised a little further in terms of control in case a night load shifting

strategy is applied. However, optimising the building envelope would result in plenty of new opportunities for CCA to be optimised, while the actual effect of CC does not really get influenced that much by an optimised envelope. In this factor we evaluate that the acoustic comfort has the largest differentiating influence on the total comfort.

3.3 Sensitivity study

Three sensitivity cases are investigated, one where the mean θ_e is generally hotter, one where the mean θ_e is colder than an average year and one where the occupancy was doubled. All three are based on natural occurrences since it is indeed possible that one year is colder or warmer than our reference year and that a company decides to provide less floor space per employee simply because of the increase in office rent cost or due to too little workable space.

The results of the sensitivity research prove that all office buildings relying on geothermal energy are very dependent on the mean θ_e . Only when the outdoor conditions cause for a balanced control of both heating, dead band and cooling an energy balance in the soil is possible. A frequent occurrence of warmer or colder years can cause for a great unbalance in the soil, which could mean that, in order to prevent these situations, a secondary element should be implemented. In case of too much input dry coolers or a cooling tower are used to transfer excessive heat to the outdoor air. In case of too much output a hybrid system can be considered with a condensing boiler.

3.4 Economic analysis

On the basis of partially calculated values, based on a quantity survey and actual energy prices, the final total actual cost can be calculated. By adding the total actual cost of the investment, the maintenance and the energy use over a period of twenty years, reference values can be obtained (fig. 3). It is noticeable that the TAC for the investment is still far above the other values after twenty years, due to the possible reinvestments in worn out parts, which is incorporated under the form of a warranty contract. Another remarkable topic is the TAC of CC with GCHP after a longer period. This is where the higher investment cost is to blame, on top of the higher maintenance cost and the energy cost which is both higher than for configurations with CCA. A building with CC, monobloc and condensing boiler is more effective since the energy price can be suppressed by relying on gas, which is very cost-beneficial. One of the most important aspects within this economic study is the return on investment (ROI). A base case was designed to be able to calculate the ROI time, based on a reference

investment for an office building. This calculation was made for the three energy scenarios, but also with a higher real interest rate of 5%. In the evolution of a pessimistic price increase to an optimistic one we can conclude that the ROI becomes worse when no price increase would occur. Durable systems consume very little energy, and the energy cost relative to the reference increases more slowly. On the long term, in case a serious energy price increase would present itself, the sustainable systems would gain more terrain, compared to systems with a condensing boiler. The low energy use in sustainable buildings will be a more determining factor on the TAC. The configuration with CC and a GCHP has no realistic ROI due to the large investment costs, while the CC configuration with monobloc and boiler has an acceptable ROI (30 years) due to a smaller investment cost and the low price of gas, while both GEOTABS buildings are paid back in 11 years. If we were to examine the influence of an increase in the real interest rate to about 5%. We may conclude that in case a real interest rate of 5% is used, the progress lines of each of the configurations intersect faster with the reference case.

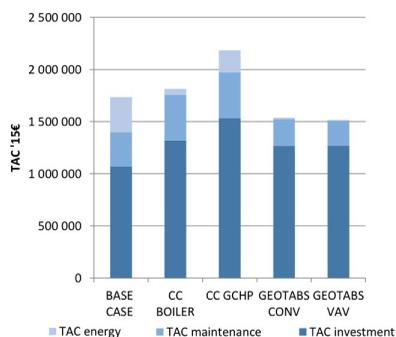


Figure 3: Total actual cost over a period of 20 years.

The comfort is translated in a productivity gain or loss in order to include the productivity as a parameter in the ROI of a building. A productivity gain for each value of total comfort was determined by Coolen et al. [11] and Haynes et al. [14]. By relying on Coolen et al. [13] a higher comfort will result in a productivity gain rather quickly. A base comfort of 52,63% is assumed in case we base ourselves on data from Coolen et al., and 78,01% by working with the values of Haynes et al. Where the base case represents a standard office with a 100% normal productivity both for comparison and the calculation of the ROI. Therefor we assume 80 employees, each with a monthly wage of 3258 euro [15].

On a period of twenty years and with a comfort of 80,28%, 4 million euros can be saved using Haynes et al. The values based on the linear progression stated by Haynes et al. appear to have an acceptable impact. In addition, this method considers the objective measurable comfort parameters. In Coolen et al. the total comfort consists of both objective and subjective parameters that can influence the comfort. Based on Haynes et al. and the total actual cost the new TAC of a building can be calculated in order to determine the ROI afterwards. After this period CC configurations become more profitable and therefore are paid back on a faster rate. Since 97% of the total cost after twenty years is determined by the wages one could say that the influence of comfort on productivity, and so TAC, is quite important. It is therefore that the configurations with a better comfort perform better. Table 2 provides the actual intersections with the base case in years in order to summarize the ROI of every configuration based

	ROI [years]					
	Without Performance			With Performance		
	Positive	Normal	Negative	Positive	Normal	Negative
CC BOILER	35	30	24	14	13	11
CC GCHP	∞	∞	∞	98	76	53
GEOTABS CONV	11	11	9	9	8	7
GEOTABS VAV	11	10	9	9	8	7

Table 2: ROI for all simulations with real interest rate of 0,58%

4. Conclusion

While there are many smaller differences, such as the visual appearance of either concepts, or the architectural liberty by integrating the heating and cooling devices in the building structure, or the fact that, in case a short term power failure would occur, the CCA will not get affected by a large amount, these are not the major conclusions of this comparative study. Through extensive research, simulations and an economic analysis we can conclude that both hydraulic concepts have their advantages and disadvantages. The main conclusions that can be drawn are:

- Generally CC has a higher acoustic performance, compared to CCA.
- The achievable level of comfort is higher in case of configurations equipped with CC. This due to a fast reaction of both the heating and cooling elements, causing for a very low discomfort. This is also based on the fact that the optimisation of CCA is a lot harder than CC.
- CCA will succeed further in suppressing the energy use, the energy cost and the total actual cost, resulting in a shorter ROI period.

- When the assumption is made that an increase in comfort causes for a certain productivity gain, the buildings with a higher comfort are more profitable. This subjective matter should always be used with the right amount of common sense.
- Both systems, with their respective adjustments, can have an energy balance in the soil, but should always be accompanied by a hybrid installation in order to maintain an energy balance in the BES-field.
- In the end it is up to each and every person to decide for themselves which of these elements (people, planet, profit) holds priority and to which extent over the others.

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