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

https://www.rehvam2018atic.eu/

GEOTABS CONCEPT AND DESIGN: STATE-OF-THE-ART, CHALLENGES AND SOLUTIONS

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ABSTRACT

GEOTABS refers to the combination of a geothermal heat pump with thermally activated building systems, and is applied in low temperature heating and high temperature cooling of buildings. TABS is a radiant heating and cooling system and is beneficial in terms of thermal comfort and energy efficiency. When combined with a geothermal heat pump, it allows to make efficient use of low grade renewable energy sources. In this paper the benefits and opportunities of GEOTABS are explained. From current practice challenges are identified that prevent the system to be operated at an optimal efficiency and to be widely implemented. Key challenges are (1) to maintain thermal comfort when sudden and significant changes in heating or cooling loads appear, (2) to maintain the thermal balance of the ground, (3) to design and control the system optimally, and (4) to decrease investment, design and commissioning costs. In the hybridGEOTABS H2020 project, three solutions are proposed and developed to tackle these challenges: (1) to integrate GEOTABS with secondary emission and heating/cooling generation systems, (2) to develop a robust and adaptive model predictive control and a toolchain that allows to derive the model architecture and parameters semi-automatically, and (3) to develop a holistic and easy-to-use design procedure that allows optimal integration, sizing and controlling of GEOTABS and secondary systems while avoiding case-by-case simulation work. This integrated solution will allow a near-optimal design and energy-efficient operation of hybridGEOTABS buildings within the boundaries of good thermal comfort and economic feasibility.

KEY WORDS: European Union (EU), Horizon 2020, hybridGEOTABS, GEOTABS, design, SWOT

1. INTRODUCTION

In 2010, the European Union introduced the Europe 2020 strategy, a wide-ranging ten-year growth strategy. One of the five headline themes is tackling climate change and promoting energy sustainability in order to introduce smart, sustainable and all-inclusive growth. This theme contains three specific targets for the EU that must be achieved before 2020 and are the implementation of the Kyoto Protocol: (1) the greenhouse gas emissions must be 20% lower than in 1990, (2) 20% of the energy use must come from renewable resources and (3) primary energy use must be reduced by 20% by improving energy efficiency [1]. Via the Horizon 2020 research and innovation programme the EU supports projects that contribute to the realisation of these targets. The hybridGEOTABS project "*Model Predictive Control and Innovative System Integration of GEOTABS in Hybrid Low Grade Thermal Energy Systems – Hybrid MPC GEOTABS*" (www.hybridgeotabs.eu) is one of them.

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According to EU statistics, buildings are responsible for 40% of the total energy consumption and emit 36 % of all greenhouse gases in the EU. The Energy Performance of Buildings Directive enforces all member states to ensure that by end 2020, all new buildings are nearly zero-energy buildings (nZEB) and by end 2018, all new public buildings are nZEBs [1]. Furthermore, the indoor environmental quality plays a vital role for the wellbeing, health and productivity of humans. Consequently, building projects face a double challenge: buildings should provide functional, comfortable and healthy indoor spaces and at the same time be sustainable and emit as few greenhouse gases as possible. One promising concept is GEOTABS: the combination of thermally activated building systems (TABS) with geothermal heat pumps that allows to increase the renewable share of thermal generation and achieve good thermal comfort conditions with estimated energy savings of 20 to 71% [2–4].

In section 2 of this paper, the GEOTABS concept is explained. Section 3 summarises the main benefits and opportunities of GEOTABS with regard to thermal comfort, sustainable energy use and costs. The concept also has a few limitations and it is found that when designing and implementing the concept today, a number of challenges arise that may prevent the solution from operating optimally and/or being widely implemented Therefore in section 4, GEOTABS limitations and challenges are explained, with regard to the TABS, the geothermal source, the control and the design strategy and integration. Finally, section 5 presents the solutions proposed to tackle these challenges in the hybridGEOTABS project .

2. GEOTABS CONCEPT

GEOTABS is an acronym for the combination of geothermal heat pumps with thermally activated building systems (TABS). TABS generally use a circuit of ducts or pipes with thermally treated fluids that are embedded in the structure of the building. An example is concrete core activation (CCA) where water pipes are embedded in the concrete structure of the building (e.g. in floor slabs). Due to the large emission surfaces, heating and cooling supply temperatures relatively close to the desired indoor temperatures can be used (as low as 24°C for heating and as high as 21°C for cooling). Since the difference between these supply temperatures and ground temperatures (8°C-12°C in Central Europe) are relatively small, geothermal heat pumps can operate with a high energy efficiency. Moreover, the ground can work alternately as heat source and heat sink in order to allow seasonal underground thermal energy storage (UTES).

As Fig. 1 shows, GEOTABS generally has three working modes: (1) In heating mode, the low temperature ground source is upgraded through heat pumps in order to obtain the required supply temperatures for the TABS. (2) For cooling, on the other hand, the ground temperature is often sufficiently low in order to obtain the required supply temperatures by direct use of the ground source. No heat pumps need to be implemented and singular passive cooling is possible in most cases. (3) To achieve a higher cooling power, however, reversible heat pumps (that can change their work mode between heating and cooling) can be implemented to achieve lower cooling supply temperatures [2].

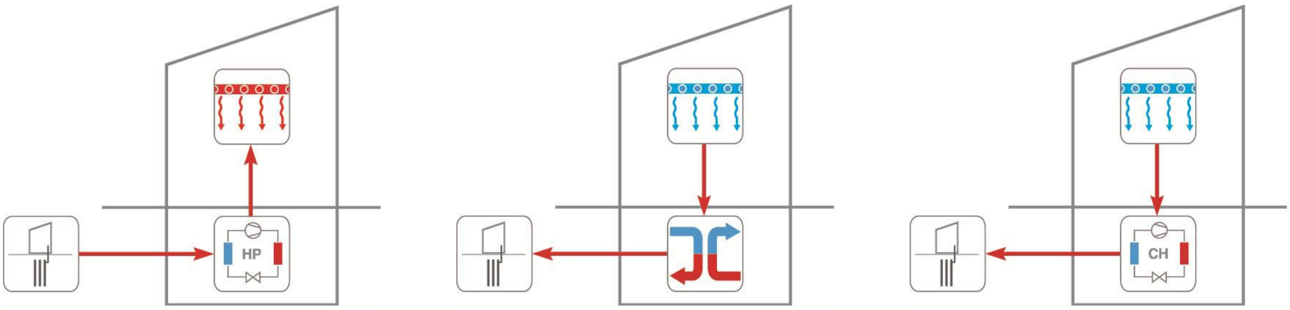

Fig. 1 (1) Heating mode, (2) passive cooling mode, and (3) active cooling mode **[2]**

3. GEOTABS BENEFITS AND OPPORTUNITIES

This subsection discusses firstly the opportunities of TABS regarding energy savings, sustainable energy use, costs and thermal comfort.

3.1 TABS and Thermal comfort

TABS is an example of a radiant heating and cooling system: heat is mainly exchanged with other room surfaces, objects and occupants by radiation in contrast to convective emission systems such as fan coil units that exchange heat exclusively with the indoor air by convection. Consequently, TABS responds more efficiently to the operative temperature, which is the weighted average of the indoor air temperature and the mean radiant temperature, which is a function of the room surface temperatures and the location of the occupant with respect to these surfaces. Thus, better thermal comfort conditions can be achieved [5].

Secondly, the large emission surface of a TABS (in most cases the entire ceiling or floor) allows heat to be distributed uniformly over the entire zone and temperatures to be equal. Due to the aforementioned small difference between the surface temperature of the TABS and the indoor temperature, the large emission surface reduces the possibility of local discomfort such as radiant asymmetry, vertical air temperature differences and too high or too low surface temperatures. Moreover, air moves at velocities that are negligible in comparison to systems such as FCUs, so that the draught risk is reduced to a minimum.

The small differences between the indoor temperature and the TABS surface temperature enable a self-regulating effect: a relatively slight change of the indoor temperature results in a significant change of the heat flux. In order to enable the self-regulating effect of TABS, an indoor temperature drift during the day must be allowed. This is in contrast to fast reacting systems such as all-air systems which maintain a constant set-point temperature. According to ISO 7730 the temperature should not rise or fall with a difference above approximately 2 K/h in order to maintain thermal comfort, and a comfortable temperature range of 20 to 24°C is prescribed in winter and 23 to 26°C in summer [6]. Toftum et al. even ensured that this value can be increased to 4 K/h [7]. However, according to Olesen indoor temperatures fluctuate in a range of approximately only 0.5 to 1 K/h in TABS buildings [8].

Finally, the TABS envisaged in this study are heavy-weight type of radiant systems, more specifically concrete core activation and thermally activated ceiling panels with phase change materials [9]. These systems are having a high thermal inertia. This allows TABS to buffer the room temperature fluctuation by storing or releasing heat, leading to gradual changes in indoor conditions and a flattening of the peaks in the heating and cooling loads [10]. An overview of different types of radiant systems is provided by Vercautere and Laverge and in the REHVA Guidebook No. 7 [9,11]. Romani et al. give an overview of TABS types and nomenclature [10].

3.2 Sustainable energy use

The operation of the TABS at temperatures close to the indoor temperature allows the use of low-grade renewable energy sources such as the ground, but also ambient or exhaust air, sewage or surface water. In case of ground coupled passive cooling (operation mode 2 in Fig. 1), the low-grade energy source is directly used. Moreover, in active heating and cooling modes, the upgrading of the low-grade energy source by use of a ground source heat pump also highly efficient, because the temperature difference between the heat source (e.g. the ground) and the heat sink (e.g. the TABS) of the system is relatively small. The remaining (and significantly reduced amount of) energy needed to feed the heat pump can be provided by renewable energy sources such as electricity from solar or wind energy, resulting in a mostly renewable energy use for heating/cooling and no greenhouse gas emissions on the building site. In literature, energy savings of 20 to 71% have been reported by comparing a well-designed GEOTABS buildings to buildings with conventional heating and cooling systems, as well as a reduction of operational and energy costs [2–4].
In heavy-weight TABS the thermal mass of the building structure is thermally activated and acts as a thermal storage: energy absorbed during buffering periods can be released in other periods. This high thermal inertia

thus allows peak load shaving, resulting in a downsizing of heating and cooling plants. Secondly, in an intelligent GEOTABS management the load shifting ability is used to shift the load to periods when thermal generation is most beneficial in terms of energy efficiency, cost efficiency or operation of the smart grid. In smart electricity grids load shifting can be used to stabilize the electric grid and match supply peaks with demands [2]. The peak load shifting ability also compensates the limited availability of some renewable energy sources (RES) such as ambient air for cooling (which is coldest at night) or solar radiation for heating (which is only available during the day), again increasing the share of RES. Additionally, production systems can be downsized, since the peak load is reduced and redistributed.

4. GEOTABS LIMITATIONS AND CHALLENGES

4.1 TABS

The high thermal inertia of heavy-weight TABSs and their limited average heat flux (40 to 50 W/m²), make that the system is unable to maintain thermal comfort in case of sudden and significant changes in the heating or cooling loads of a room, for example as a result of sudden high solar gains or internal gains. The TABS will react to these changes rather quickly, due to its self-regulating characteristics, but the indoor conditions will only change slowly which may cause temporary thermal discomfort. Therefore, current design recommendations, as found in the REHVA Guidebook No. 20, impose constraints to the building in order to apply TABS. The requirements include a building envelope design with a high insulation level, reduced window-to-wall ratio and an effective solar shading system. These lead to a reduction of the building heat losses and of the solar gains. Also the internal heat gains should be reduced, e.g. by limiting heat production from artificial lighting and appliances [2]. In summary, for the application of TABS a constant, uniform and highly predictable heat/cooling load is preferred. However, this also limits the application range of the technology, for example for buildings with higher internal loads or large glazing areas. Alternatively, the REHVA Guidebook no. 20 already mentions the possible necessity of applying additional emission systems to deal with the high thermal inertia of the TABS [2]. In these hybrid comfort systems, TABS is combined with a more flexible system such as heating and/or cooling coils, fan coil units or radiators. However, these additional systems may not overrule nor counteract the TABS, and for example simultaneous heating and cooling must be avoided. Therefore, the design and control must incorporate the dynamic effects of the system operation and consider the interaction of both systems. GEOTABS, usually the most sustainable and energy-efficient part of the entire system, must provide a maximum part of the heating and cooling load in order to maximize the renewable share of thermal generation.

Further considerations in the design of a thermally activated building system are documented in the REHVA Guidebook no. 20 [2,9]. One is the clustering of the rooms in a building into a minimum of zones with different thermal characteristics (e.g. due to orientation or use), knowing that within one zone the rooms cannot be controlled separately by the TABS. A second consideration is that the TABS surfaces should remain free as much as possible in order to ensure effective heating and cooling. The use of suspended ceilings, raised floors or finishing materials with a high thermal resistivity reduces the heat transfer between the concrete core and the indoor environment and should be avoided, or their selection should consider the role of the upper and lower surfaces of the slabs for the conditioning of each room: e.g. most office buildings with concrete core activation use raised floor systems (indispensable for the distribution of ventilation ducts, electricity, etc.) but the ceiling remains uncovered. This implements, however, additional measures in order to prevent acoustic discomfort, e.g. baffles. A third consideration is that TABS cannot deal with humidity and in relatively warm humid climates condensation can occur on the surfaces if their temperatures are below the dew point. An optimized air handling unit with dehumidification is indispensable.

4.2 Geothermal system

In a geothermal system, the ground can be used as a heat source and/or a heat sink. However in order to maintain the thermal balance in the ground on the long term, the amount of heat introduced in the ground should be approximately equal to the amount of heat extracted from the ground [2]. If the ground is used just as heat source or just as heat sink, the thermal balance can only be maintained in case of a good thermal conduction in the soil and/or a sufficient ground water flow. Otherwise, local excessive heating or cooling of the ground can result in a significant decrease of performance of the system and disturbances in its operation. If the ground is alternately used as heat source and heat sink, the performance of the system can be increased. The high thermal energy storage capacity of the ground enables seasonal underground thermal energy storage. A logical way to compensate for the heat extracted from the ground in winter, is to use the lower ground temperatures in summer for passive cooling. Alternatively, an additional heat generation system (e.g. a gas boiler or cooling tower) can also replace the geothermal system if the annual thermal balance of the ground is threatened. Also thermal energy from renewable energy systems such as solar collectors or exhaust process heat can also be injected into the ground in order to increase the regeneration of the soil. A more extensive introduction to the different types of geothermal systems and their properties is provided in [2,9].

Geothermal systems typically bring along a higher investment cost than traditional heat generation systems. The main questions is whether the groundside possibilities of the geothermal system allow to cover a sufficiently large part of the heating and cooling loads of the building, so the higher investment costs can be compensated by lower operational costs. Also, if the geothermal system is the only (singular) heat generation system in the building, it should be sized so it can cover the entire range of heating and cooling loads occurring, including peak loads that occur only a very limited portion of the time. Therefore, an alternative to avoid the installation of excessive and expensive heat pump power, is to combine the heat pump with additional heat generation systems. The resulting hybrid generation system can be controlled and operated in different ways, as introduced by Vercautere et al. [2,9]. The combination of hybrid emission and hybrid generation, results in a hybrid GEOTABS concept, where GEOTABS is combined with secondary emission and heat generation systems.

4.3 Model Predictive Control

Traditionally, rule based control (RBC) strategies are used to control GEOTABS and hybrid GEOTABS systems. These strategies are, however, unable to harvest the full potential of the system because they are determined by fixed rules based on static building models. The difficulty to generalize the rules on the level of the whole building and the complexity of most RBC strategies make it impossible to optimize these strategies on the building level. The increasing complexity of building automation systems in actual buildings (e.g. office buildings) even enhances this problem [12]. In RBC strategies, the time delay of the response of TABS is taken into account by heuristic rules, which result in trial-and-errors to tune the control parameters and thus in time-consuming and case-by-case study work. Moreover in good practice, this iterative design process is done by use of dynamic simulations, which raises the engineering costs during the design and commissioning phase, resulting in high design and commissioning costs.

Model predictive controls (MPC) are promising strategies for controlling GEOTABS buildings. These controls use predictions of variations in both the energy sources and the heating and cooling demands and satisfy this demand with a minimum primary energy use (other optimization criteria are possible, e.g. minimum energy cost) and exploit the thermal energy storage capacity whenever beneficial, resulting in significant energy savings. Due to their ability of implementing the buffering effect, sizing according to MPC approaches allows much smaller components than sizing according to rule based assumptions, resulting in a reduction of the investment costs and a more efficient system operation. MPC was already integrated in a GEOTABS office building and measurements showed energy savings of 17% compared to the original rule based control strategy as well as a better thermal comfort, reduced energy peaks, increased HVAC system efficiencies, an increased lifetime of the equipment and operational cost savings [13].

Current approaches to MPC are, however, black- or grey-box approaches: extensive measurements need to be done in the building in order to provide the data that are needed for the design of the MPC. Therefore, MPC strategies can only be implemented a time after the delivery of the building. Moreover, the grey-box approach requires additional modelling and identification work and the sizing of the system components is currently done based on assumptions of a typical RBC approach. Although the operational costs can be largely reduced by using MPC strategies, the engineering, monitoring and commissioning costs to set up a MPC strategy are too high to make it currently an economically feasible solution.

4.4 System design

For a successful application GEOTABS buildings should be developed according to an integral design process. The use of GEOTABS should be considered at the very beginning of the project in a feasibility study, which leads to a simple yes/no decision and a rough technological concept. The summarized SWOT analysis included in the REHVA Guidebook no. 20 is a useful instrument to evaluate the feasibility of a GEOTABS building. Currently, the feasibility study takes into account the numerous constraints of the concept, including technical and constructional aspects, system operational aspects, thermal comfort and limited individual control [2]. These constraints result into severe restrictions regarding the building and its environment, and thus also into restrictions on the applicability of the solution. When the GEOTABS concept has passed the feasibility study, at the installation phase it is found that the investment cost of a GEOTABS building is about 20% higher than for a traditional heating and cooling system. However, in practice the system is often oversized due to the lack of sufficient knowledge or experience of the designers, further increasing the investment costs and reducing system efficiency.

As mentioned before, the combination of TABS with more flexible heating and cooling emission systems, and the geothermal system with additional heat generation systems, increases the applicability and feasibility of the concept. However, the design and control of the system becomes more difficult. The REHVA Guidebook no. 20 mentions hybrid generation systems for TABS and several research projects clarify the problem [2,14,15]. However, no generally accepted guidelines have been developed for the particular design conditions for the sizing and integration of secondary systems. This not only leads to further increase of the investment costs, but also to excessive engineering and commissioning costs, since the sizing and control of the system requires case-by-case simulation work and extensive commissioning work.

5. HYBRID GEOTABS SOLUTIONS

As a result of the limitations and challenges mentioned in section 4, the potential of GEOTABS is often insufficiently exploited in current practice. The hybridGEOTABS consortium proposes an integrated solution that provides a purified design strategy and increases the efficiency regarding energy use, thermal comfort and in particular investment, engineering and commissioning costs.

5.1 Hybrid

The first part of the proposed solution aims at optimally integrating GEOTABS with secondary emission and generation systems in order to obtain a hybrid, partly flexible comfort system. Therefore, a reduced share of the heating and cooling loads that does not vary during short periods of time (several hours to days), also known as the base load, must be defined. The GEOTABS component takes care of the base load while more flexible emission systems such as heating and/or cooling coils in the air handling units, fan coil units or radiators take care of the remaining loads caused by sudden, unpredictable and/or disproportional fluctuations of heat gains and losses in order to maintain good thermal comfort conditions in the individual rooms. This not only results in an improvement of indoor environmental quality, but also yields an improvement in the efficiency and cost of the GEOTABS itself, because the heat pump can work more continuously at lower and efficient temperatures, and it does not need to be sized to cover all cooling and heating loads in the building. Secondary generation systems provide heat/cold to the secondary emission systems, allow to cover the more variable loads in the building, and may assist in keeping the thermal balance of the ground source.

5.2 Model Predictive Control

Traditionally used Rule Based Control strategies are not able to harvest the full and dynamic potential of the slow-reacting and buffering effect of the GEOTABS and its integration with secondary systems. Moreover the tuning of the control parameters requires a lot of trial-and-error, and optimisation of the control on the level of the whole building is practically impossible [12]. Therefore, Model Predictive Control strategies are proposed as an innovative and high performance alternative. As mentioned before, currently applied MPC's rely on extensive measurements of the building as training data and require substantial modelling and identification work – these are grey-box and black-box approaches. m

Therefore, the second part of the solution aims at developing a generic model predictive control (MPC) model for hybrid GEOTABS. An optimal control model minimizes total energy use and/or costs, maximizes the use of low-grade energy sources and optimizes thermal comfort conditions, by playing with the GEOTABS and secondary systems control parameters. Therefore, the controller implements the thermal inertia of the system and considers also weather forecasts and historical data in order to predict heating or cooling loads. An existing grey-box control approach will be extended and compared to a newly developed white-box control approach, where model inputs such as disturbances and thermal power, are precomputed from building design data. A toolchain is developed that allows to estimate the model parameters and architecture in a semi-automated way [16]. Furthermore, the controller will be robust and adjust itself automatically to the building and to changing conditions (e.g. changing user profiles) by indoor temperature feedback.

5.3 Holistic design procedure and integration of appropriate components

The design of a GEOTABS system requires assumptions on the spread of the load in relation to the buffering capacity and thermal inertia of the system, and the integration of secondary fast-reacting systems requires knowledge about how to size and integrate the different parts of the hybrid system. Therefore, the third part of the hybridGEOTABS solution is the development of an integrated design methodology that allows a near-optimal design and sizing of the hybrid GEOTABS system and the selection of appropriate components (e.g. ground source heat exchangers, heat pumps, TABS, control systems and secondary supply and emission systems). The design methodology relies on a splitting of the heating and cooling load of the building into a baseload that is covered by the GEOTABS and a residual load covered by the secondary systems. Secondly, the near-optimal sizing takes into account the model predictive control of the system. Thirdly, standardised and modular system component packages are developed, in which the individual components are sized and developed to work together optimally and for the specific operation points of the hybrid GEOTABS system.

Case-by-case dynamic building energy simulations require expert knowledge and increase the labour intensity of the design process significantly. Today this is often a reason to reject the hybrid GEOTABS concept already in the stage of the feasibility study. Therefore, the developed design methodology will allow the conceptualisation, sizing and energy performance assessment of the system in feasibility studies and predesign phase, based on generalised an easy-to-use design rules and using input data that is typically available in this phase (e.g. building function, building geometrical data, overall energy-efficiency of the building envelope, glazing area, orientation etc.). The goal is to make the degree of difficulty and duration of the design phase comparable to the design of more traditional technologies. The method is developed while focusing on 4 building types: offices, multi-family buildings, elderly homes and schools.

6. CONCLUSIONS

GEOTABS matches a low-temperature radiant heating and cooling system, beneficial in terms of thermal comfort and energy efficiency, with a geothermal heat pump, making efficient use of low grade renewable energy sources. From current practice challenges are identified that prevent the system to be operated at an optimal efficiency and to be widely implemented. Key challenges are (1) to maintain thermal comfort when sudden and significant changes in heating or cooling loads appear, (2) to maintain the thermal balance of the ground, (3) to design and control the system optimally, and (4) to decrease investment, design and commissioning costs. In the hybridGEOTABS H2020 project, three solutions are proposed to tackle these challenges: (1) to integrate GEOTABS with secondary emission and heating/cooling generation systems, (2) to develop a robust and adaptive model predictive control and a toolchain that allows to derive the model architecture and parameters semi-automatically, and (3) to develop a holistic and easy-to-use design procedure that allows optimal integration, sizing and controlling of GEOTABS and secondary systems while avoiding case-by-case simulation work.

ACKNOWLEDGMENT

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 723649. The project is being realised thanks to the following project participants: Ghent University (BE), Climate Futures ltd. (UK), Danish Technical University (DK), Energoklastr (CZ), GEOTER sl (ES), University of Leuven (BE), Lemon Consult ag (CH), REHVA (EU), Boydens engineering (BE), Maastricht University (NL), Uponor (FI), VIESSMANN (D,BE).

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