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DEVELOPMENT OF A FIELD MEASUREMENT METHODOLOGY FOR STUDYING THE THERMAL INDOOR ENVIRONMENT IN HYBRID GEOTABS BUILDINGS

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ABSTRACT

GEOTABS buildings combine an energy efficient heating and cooling system (Thermally Active Building Systems, TABS) with a renewable energy resource (ground, GEO) to heat and cool buildings in an energy efficient and sustainable way.

Within the scope of a new EU project (HORIZON 2020-10 project EE-04-2016), hybrid GEOTABS buildings are studied in details in terms of optimal system design and dimensioning methodology, control, and in other terms. Model Predictive Control (MPC) algorithms will be developed by project partners and the developed algorithms will be implemented in demonstration buildings. The three demonstration buildings were an office building in Luxembourg, an elderly care home in Belgium, and an elementary school in Czech Republic. All of these buildings are equipped with hybrid GEOTABS systems; however, they vary in size and function, which requires a unique measurement methodology for studying them.

These buildings already have advanced Building Management Systems (BMS); however, a more detailed measurement plan was needed for the purposes of the project to document the current performance of these systems regarding thermal indoor environment and energy performance, and to be able to document the improvements after the implementation of the MPC.

This study provides the details of the developed field measurement methodology for each of these buildings to study the indoor environmental quality (IEQ) in details. The developed measurement methodology can be applied to other buildings of these types and to buildings with similar heating and cooling systems.

KEY WORDS: hybrid GEOTABS, Horizon 2020 - Grant No 723649 - MPC-.GT, Indoor Environmental Quality (IEQ), Thermally Active Building Systems (TABS)

1. INTRODUCTION

Water-based radiant surface heating and cooling systems are defined as systems, where at least half of the heat transfer from the heated or cooled surface is by radiation [1]. An example of water-based radiant surface heating and cooling systems is Thermally Active Building Systems (TABS).

TABS have several advantages, such as benefiting from the low temperature heating and high temperature cooling principle [2], [3], coupling with renewable heat sources and sinks [3], transferring peak loads to off-peak hours and peak load reductions [1], [4].

One particular building type that couples TABS with renewable energy resources is GEOTABS buildings. GEOTABS buildings combine an energy efficient heating and cooling system (TABS) with a renewable

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energy resource (ground, GEO) to heat and cool buildings in an energy efficient and sustainable way. The performance of GEOTABS buildings has been studied thoroughly in an earlier EU project, GEOTABS - Towards Optimal Design and Control of Geothermal Heat Pumps Combined with Thermally Activated Building Systems in Offices [5].

A new EU project (HORIZON 2020-10 project EE-04-2016, Model Predictive Control and Innovative System Integration of GEOTABS in Hybrid Low Grade Thermal Energy Systems - hybrid GEOTABS [6]) is taking the analyses that were carried out within the GEOTABS project further. A previous study has already identified the system concept, individual modules, and the interfaces between system components for these buildings and for generic hybrid GEOTABS buildings [7].

Within the scope of this new project, hybrid GEOTABS buildings are studied in details in terms of optimal system design and dimensioning methodology, control, Indoor Environmental Quality (IEQ) and in other terms. The developed Model Predictive Control (MPC) algorithms will be implemented in demonstration buildings. Three demonstration buildings were selected; an office building in Luxembourg, an elderly care home in Belgium, and an elementary school in Czech Republic. All of these buildings are equipped with hybrid GEOTABS systems; however, they vary in size and function, which requires a unique measurement methodology for studying them.

These buildings already have advanced Building Management Systems (BMS); however, a more detailed measurement strategy was needed for the purposes of the project to document the current performance of these systems regarding thermal indoor environment and energy, and to be able to quantify the improvements after the implementation of the MPC.

This study provides the details of the developed field measurement methodology for each of these buildings to study the thermal indoor environment in details. The developed measurement methodology can be applied to other buildings of these types and to buildings with similar heating and cooling systems.

2. BUILDING DESCRIPTIONS

The following demonstration (demo) buildings were selected (Fig. 1):

1) SolarWind, Windhof, LU, office building, large size;
2) Ter Potterie, Bruges, BE, elderly home, medium size;
3) Libeznice elementary school, Libeznice, CZ, school, small size.

a) b) c)

Fig. 1. Three types of hybrid GEOTABS buildings, a) SolarWind office building (Luxembourg), b) Ter Potterie elderly care home (Belgium), c) Líbeznice elementary school (Czech Republic).

2.1. Office building (Solarwind) in Windhof, LU

The office building SolarWind is located in Luxembourg. The building was completed in 2012 and it has several certifications including BREEAM (very good), HQE (exceptional), and DGNB (gold). The net floor area of the building is 20,000 m^2, half of which is conditioned. It uses several renewable energy resources, such as geothermal (boreholes), solar, wind, and biomass. The envelope of the building was carefully designed to minimize heat losses and gains.

The building is heated and cooled with TABS, which is geothermally fed (i) directly during cooling and (ii) indirectly via intermediary heat pumps during heating (the heat pumps are bypassed during cooling). Four Ground Source Heat Pumps (GSHP) arranged in cascade (total capacity of 120 kW) provide warm water for TABS, for the heating coils in the variable air volume (VAV) system, and for floor heating. Seventy-six borehole-type ground heat exchangers having total capacity of 240 kW can operate as a cooling source in passive cooling mode and as heat sink in active heating mode. An adiabatic cooling machine using rainwater meets additional cooling demands of the datacenter directly and of the rest of the building via the air-handling units (AHU) and VAVs.

High temperature heating is provided by evacuated tube solar collectors on the roof and by biomass boilers. Radiators (only two in the building), domestic hot water, and the heating coils in the main AHUs are the emission systems that require high temperature water.

2.2. Elderly home (Ter Potterie) in Bruges, BE

Ter Potterie is an elderly home located in Bruges, Belgium, completed in 2016. There are three conditioned floors having 121 occupied rooms, an attic and an underground garage. The net floor area is 16,103 m^2, 62.4% of which is conditioned (10,048 m^2). The building has a high domestic hot water demand since it is occupied throughout the whole year, and each room has a sink and a shower. Additionally, a high indoor temperature requirement results in a high energy demand.

TABS is the main heat emission (heating) and removal (cooling) system. The ground floor is conditioned using radiators and floor heating/cooling. Radiators are installed in all rooms and AHUs (central mechanical ventilation system with supply, exhaust, and heat recovery) meet the residual load. The ventilation system removes part of the load in the cooling season. No other mechanical cooling systems are installed.

Two heat pumps (connected in parallel) coupled with borehole-type ground heat exchangers (GHEX) are used as the main medium temperature heat source. The total capacity of GSHPs is 186 kW and these provide warm water for TABS and floor heating circuits in the ground floor. Passive cooling is utilized in the cooling season (cooling provided to TABS, floor circuit and the cooling coils in AHUs). The borehole field consists of ninety 75 m deep borehole-type heat exchangers and has a total capacity of 260 kW.

Two natural gas fired condensing boilers having a total capacity of 580 kW are the high temperature heat source. They provide hot water to the domestic hot water tank, radiators and to the air-handling units. When necessary, boilers can act as a backup for the GSHPs providing hot water to the TABS circuits.

2.3. Elementary school in Libeznice, CZ

The elementary school in Líbeznice, Czech Republic was built in 2015. The building has an annular shape with an atrium in the middle and eight classrooms are located in the periphery. The building has one floor with a net floor area of 1,000 m^2 that is fully conditioned (heated/cooled).

The building is equipped with TABS in the ceiling as a single circuit. TABS is the main heating and cooling system and is supplemented by the ventilation system. TABS has a capacity of 17.4 kW in heating mode and 23.5 kW in cooling mode. The main heating/cooling source is a GSHP that can operate in active heating mode (55 kW), in active cooling mode (65 kW) and in passive cooling mode. The GSHP is fed by ethylene glycol circulating through six borehole-type GHEX. The total capacity of the GHEX is 65 kW. In passive cooling mode, ethylene glycol can bypass the GSHP.

The GSHP provides heat for TABS, AHUs, and the domestic hot water tank equipped with electric heater in active heating mode, while the heat is exhausted via a cooling tower. An electric boiler (24 kW) is used as a supplementary heating source and as a backup if GSHP capacity is not enough or it fails. The cooling is provided to the TABS circuit and to the air-handling units (AHU).

The heating and cooling system of the building is already controlled by a model predictive control algorithm, which takes into account weather forecast, a thermodynamics model of the heat pump, the TABS, and the spot market electricity prices [7].

3. METHODOLOGY

The measurement approach of the project consists of three parts; system operation parameters (supply and exhaust air temperatures from zones, ventilation rates, etc.), energy performance of the building (energy use for different building functions, and energy production, if applicable), and indoor environment (operative temperature, relative humidity, radiant temperature asymmetry, CO_2 concentration, etc.). These data will be used for validating the simulation models, performance assessment of the buildings and for creating a link between the indoor environment with system performance and control improvement (Rule Based Control vs. Model Predictive Control).

The rest of this paper focuses on the details of the indoor environment measurements. The measurements described correspond to long-term measurements and aim at characterizing the thermal indoor environment in and within the demo buildings, before and after the implementation of the MPC.

3.1 Measurement equipment

Air and globe temperatures were measured with TMCx-HD temperature sensors. Air and globe temperature sensors had an accuracy of ±0.2°C within the temperature ranges expected in indoor environments (i.e. 10-30°C). The output from the air and globe temperature sensors were logged with portable data loggers. These portable data loggers were HOBO U12-013 (two external channels, and integrated temperature and relative humidity sensors) and HOBO UX120-006M (four external channels, no integrated measurement devices).

Air temperature sensors were shielded from the radiation effects by a metal cylinder placed around them. Globe temperatures were measured with a matt grey globe sensor, 40 mm in diameter. This sensor has the same relative influence of air- and mean radiant temperature as on a person and, thus, at 0.6 and 1.1 m heights will represent the operative temperature of a sedentary or a standing person, respectively [8].

CO_2 concentration was measured with a Vaisala GMW22 sensor and its output was logged with a HOBO U12-012 (one external channel, and integrated temperature, relative humidity, and light intensity sensors). The CO_2 sensor had an accuracy of ±100 ppm + 2% of reading, within the range of 0-5000 ppm.

Window opening and closing behavior was monitored with a HOBO UX90-001 state logger and a magnet placed on the windows.

Surface temperatures were measured with iButtons (DS1922L), which had an accuracy of ±0.5°C within the range of -10°C to 65°C.

Relative humidity was measured either with a HOBO U12-013 or with a HOBO U12-012. Relative humidity measurements had an accuracy of ±2.5%, within the range of 10-90% RH.

All sensors were calibrated prior to installation in the buildings. Data logging interval was 10 minutes for all measurements.

3.2 Measurements in the office building (Solarwind) in Windhof, LU

The office space of the building owner was selected for the measurements. The measurement locations were selected to capture the different room types and orientations. The selected measurement locations were a small open plan office (reception area), a two-person office next to the reception area, a corner office (two-persons), and a large open plan office.

A measurement stand was placed in each of these four areas (measurement locations). Air and globe temperatures were measured at 0.1 m (ankle level), 0.6 m (center of the body for a seated person), 1.1 m (head level for a seated person and center of the body for a standing person) and 1.7 m (head level for a standing person) heights on this stand [9]. Another sensor on this stand (at 1.3 m height) was measuring the CO_2 concentration. The CO_2 concentration is intended to be used as an indicator for the air quality and to evaluate the performance of the ventilation system. Relative humidity was also measured on this stand.

At the same location as the stand, ceiling and floor surface temperatures were measured, since in buildings with TABS, indoor spaces are heated and cooled through these surfaces. These surface temperatures could also be used to calculate the mean radiant temperature.

Fig. 2 shows the measurement stand used in a measurement location in the office building.

Fig. 2. The measurement stand used in a measurement location in the office building.

3.3. Measurements in the elderly home (Ter Potterie) in Bruges, BE

In the elderly home, there are single rooms, which consist of a living area with a bed, and a bathroom. These rooms are identical. There is also possibility for couples to live in two rooms (“double room”), which then one room becomes the living room and the other room becomes the bedroom (both of these rooms have bathrooms). There are also common living areas, where the occupants can spend time during the day and interact with other occupants.

For the measurements in the elderly home, sensors were installed in two single rooms, in a double room (in the living room and in the bedroom) and in a common living area.

The measurements carried out in the common living area was similar to the measurement strategy described for the office room (a measurement stand with air and globe temperature sensors and a CO_2 concentration sensor, and ceiling and floor surface temperatures).

The measurement strategy followed in the other rooms (two single rooms and a double room) were identical to each other. In these rooms, it was not possible to use the same measurement stand due to safety concerns. Therefore, a smaller stand was built. This stand consisted of the structural part, a portable data logger, and the air and the globe temperature sensors. In each room, there were two of these small stands placed in the positions where the occupants were expected to be (e.g. close to their bed, next to their chair, etc.).

In each room, there were two operable windows (one large and one small). The opening and closing state of these windows were logged.

In each room, CO_2 concentration and relative humidity were also logged. In addition to the logged floor and ceiling surface temperatures in the rooms, radiator surface temperature in the middle of the radiator was also logged. This measurement could help in setting up the energy balance of the rooms for manual calculations or for dynamic building simulations, and to identify the occupant preferences and behavior.

Fig. 3 shows the measurement stand used in the common living area and the small stand built for the measurements in the elderly home.

a)  b) 

Fig. 3. a) The measurement stand used in the common living area, b) The small stand built for the measurements in the elderly home.

3.4. Measurements in the elementary school in Libeznice, CZ

In the elementary school, two identical classrooms were selected for the measurements. The measurement strategy followed in the two classrooms were identical.

There were two stands (measuring air and globe temperatures at 0.1, 0.6 and 1.1 m heights) positioned close to a wall (0.3 m away from the wall). This was not the optimal positioning; however, it was not possible to place the stands in a more central position in the classrooms due to safety concerns.

In addition to this, on the opposite side of the classroom, air and globe temperature sensors were placed on the wall (slightly sticking out from the wall and at 1.25 m height corresponding to approximately the same height as the BMS sensor). This was done in order to compare the temperature measurements in the opposite sides of the classroom and to compare the temperature measurements with the measurements from the BMS sensor.

Relative humidity was also measured in the classrooms. CO_2 concentration was measured in the classrooms but not on the stands due to wiring limitations.

Since this building had TABS only in the ceiling slab, the surface temperatures were measured only on the ceiling. The surface temperatures were measured at two points. One surface temperature was measured on a point that was facing the room directly and the second surface temperature was measured on a point that was covered by one of the hanging acoustic sound absorbers. This was done to be able to study the effects of acoustic sound absorbers on the heat transfer between the activated ceiling surface and the classroom [10].

Fig. 4 shows the measurement stand used in the classrooms and the surface temperature measurements on the ceiling.

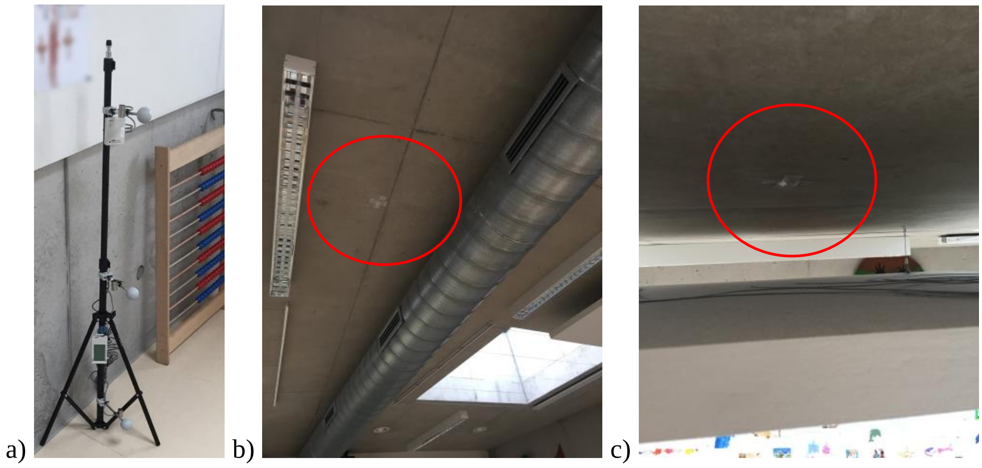

Fig. 4. a) The measurement stand used in the classrooms, b) Surface temperature measurement on the ceiling surface facing the room, c) Surface temperature measurement on the ceiling surface covered by the acoustic sound absorber.

3.5. Spot measurements and questionnaires

The measurements described earlier correspond to long-term measurements. These long-term measurements will be supported with spot (short-term) measurements and periodic questionnaires that will be distributed to the building occupants.

Spot measurements will consist of measurements of air velocity, turbulence intensity and air temperature (which will then allow determination of the draught rate), radiant temperature asymmetry, noise and lighting level. Spot measurements will also allow focusing on the most problematic areas (where occupants have complaints). The results of both long- and short-term measurements will be analyzed according to EN 15251:2007 [11] (this standard is currently under revision [12], [13]) and ISO 7730:2005 [14], which will enable evaluating both the overall thermal indoor environment and the local thermal discomfort factors.

In addition to these physical measurements, questionnaires will be distributed to the building occupants to evaluate the occupant satisfaction with the indoor environment. These questionnaires will allow obtaining subjective responses from the occupants about their satisfaction with the indoor environment.

Even though this procedure is well established for office buildings, further considerations are required for elderly homes and schools since layout of questionnaires and their formulation may differ from office buildings due to the specifics of the minority group (age, evaluation of the thermal comfort, ability to understand questions, etc.).

The responses to the questionnaires (satisfaction with the indoor environment) will be compared to the physical measurements to identify the correlation and the discrepancies between them.

4. DISCUSSION AND CONCLUSION

This study explained the long-term physical measurement strategy (measurement parameters and locations, sensor types, etc.) to study the indoor environmental quality in the demo buildings of the hybrid GEOTABS project. Due to their different sizes and functions (office building, elderly home, and elementary school), all buildings required adjustments to the initially proposed measurement strategy.

It was a challenge to place sensors in the buildings, which would allow capturing the real conditions that the occupants experience and at the same time do not interfere with the daily use of the buildings and activities of the building occupants. Even though some of the sensor locations might not be optimal, they were placed within the occupied zone and will provide reliable and useful data.

The measurement data will be compared to the measurements from the BMS to identify the discrepancies. The measurements before and after the implementation of the MPC will allow quantification of the effects of MPC on the indoor environmental quality parameters. The measurements will also be used in the future to calibrate the simulation models of these buildings.

The physical measurements (long-term and spot measurements) and the questionnaires will complement each other for obtaining a complete understanding of the indoor environment and user satisfaction in hybrid GEOTABS buildings. This will make it possible to provide improvement suggestions, which could improve health, productivity and comfort of the occupants in these buildings.

The results of the measurements and the questionnaires will be reported in further publications.

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