Multi-Source Cooling System Control in the MLBE Building – a Pilot Experimental Study

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Abstract. Computer simulations of buildings in the context of improving their energy efficiency, performed by the Design Builder – type computer programs, are a very useful tool. However, in the case of simulation studies on the impact of automatic control systems on the energy efficiency of buildings, the results are often overly optimistic. Energy savings are overestimated in comparison to the results achieved in the real environments. Therefore the results obtained by the simulations should be validated in a real environment. The Małopolska Laboratory of Energy Efficient Building (MLBE) of Cracow University of Technology provides an opportunity to perform an experimental real scale research of the building automation systems to improve the buildings energy efficiency and occupants’ comfort. This paper presents a part of the multi-source cooling system with selected cooling sources and room’s cooling methods, implemented in the MLBE building. The purpose of the summer study was to verify the work of selected technical equipment and installations that realize the cooling process in actual conditions. A gas heat pump and a passive cooling system using the cooling capacity of the soil were used. Furthermore, the fan coil units and the plane systems were used at the room level. Together with the possibilities of the building automation and control system implemented in MLBE, the results shown in this paper will become – in the future planned research – a base for creating optimized algorithms for controlling the studied system in the context of the search for energy-efficient installation and programming solutions. The obtained results will form the basis to develop more effective control strategies for the tested cooling system, both in the economic context as well as in the context of the required users’ comfort.

1. Introduction
It is estimated that buildings have a 30-40% [1, 2] share in global primary energy and consumes about 60% [1] of the world’s electricity production. In developed countries, buildings consume 20-40% of final energy. In the European Union, the share of buildings in the total energy use is 40%. For comparison, transport absorbs 32% and industry 25% [3].
Computer simulations of buildings in the context of improving their energy efficiency, performed by Design Builder – type computer programs, are a very useful tool. However, in the case of simulation studies on the impact of automatic control systems on the energy efficiency of buildings, the results are often overly optimistic. Energy savings are overestimated in comparison to results achieved in real environments. Therefore the results obtained by simulations should be validated in a real environment [4]. The Małopolska Laboratory of Energy Efficient Building (MLBE) of Cracow University of Technology provides an opportunity to perform experimental real scale research of building automation systems to improve buildings energy efficiency and occupants’ comfort [5, 6]. Different cooling technologies are used in buildings. The integration of the heating and cooling system with building automation and control system (BACS) enables directing of energy flow according to the demand for the rooms where it is needed [3].

2. Cooling of buildings
Different methods of cooling are used in buildings. In the literature, preliminary cooling of the ventilation air was considered using horizontal air – ground heat exchangers, both in summer [7, 8] or transitional seasons [9]. In turn, in [10] the control of heating and cooling of a building was considered, depending on the presence of users. Another study [11] presents the meaning of the room’s blinds control for the regulation of solar heat gains, as well as thermal transmittance of the building's external partitions. On the other hand, [12] shows integrated sunblind, cooling, and lighting control to minimize the energy consumption of a building. Furthermore, in [13], the work of a heat pump was considered for simultaneous generation of heat and cold, which can be used in various processes (e.g. cooling of a building’s space and domestic water heating).

3. Experimental study of MLBE’s cooling system
The experiment was carried out in Małopolska Laboratory of Energy Efficient Building (MLBE). The MLBE provides an opportunity to perform experimental, real scale study of building automation systems to improve buildings’ energy efficiency and occupants’ comfort. The construction and equipment of the MLBE were financed by the Project MRPO.05.01.00-12-089/12-00 – funded by the Małopolska Regional Operational Program for the years 2007-2013. The creators of the project were DSc arch. Marcin Furtak and PhD Małgorzata Fedorczak-Cisak.

Experimental study on a selected part of MLBE’s cooling system was planned for and carried out in summer (August 2015). Building-lab has been launched in the autumn of a previous year, and the 2015 summer season was the first in which various equipment and systems were examined in the context of different types of cooling scenarios for the object. The study involved two levels of operation of the cooling system in the MLBE building: global (entire building) and local (2 selected experimental rooms of the building). The first concerned globally the work of cooling sources with their supporting equipment and installations, and the latter was connected to the cooling modes used locally in selected areas of the building. The aim of the study at the global level, using the power of BMS, was to compare the energy consumption of individual cooling sources, supported continuously by the ventilation system CW1-EAHX, under certain pre-set and constant operating conditions inside the laboratory-building. The local (rooms) level study was conducted to verify which of the cooling modes used locally in selected areas – underfloor cooling, fan coil or their combined effect – will help to reach the pre-set temperature conditions, taking into account the work of the cold source (on the global level). When planning a control strategy for this type of actuators, on the Integrated control system level, one should keep in mind the inertia characteristic for the cooling process.

3.1. Global (entire building) level
This study used two primary cooling sources: a natural gas heat pump (HP2) with AWS exchanger, a ground heat pump (HP1) with vertical heat exchangers (GWC) – both devices with their supporting elements are shown in figure 1 – and, supportively, an air unit (CW1) cooperating with two horizontal
ground air heat exchangers (EAHX). The basic parameters and modes of operation of these devices are given below:

- Natural gas heat pump (HP2), Aisin Toyota P560 + Yoshi AWS 20HP-E1 heat exchanger – the cooling capacity of the system is 52 kW. The natural gas heat pump has a motor with variable speed, which directly translates into a smooth change of cooling capacity (17-52 kW).
- Ground heat pump (HP1), Viessmann Vitocal 300 G BW 301.A21 – a brine-to-water type with electric drive and a cooling capacity of approx. 17 kW. Three vertical geothermal probes are the lower source of cold (a depth of 125.0 m b.g.l. each). The pipes are filled with a 30% solution of propylene glycol. Two cooling modes are possible – active or passive. In the course of this experiment, only passive cooling mode was used (called hereafter the passive cooling system), in which, a heat pump’s compressor is turned off and only circulating pumps operate to ensure the flow of refrigerant to use the soil’s coldness.
- Ventilation unit (CW1) with the system of horizontal ground air heat exchangers (EAHX) – supports the building’s spaces on the ground, the first, and the second floor, except for communication spaces and toilets. Ventilation unit is equipped with a rotary recuperator and a water cooler with a power of 5.94 kW. The intake air can be acquired from the outside through the wall air intake and/or through EAHX intakes. EAHX system consists of two independent air heat exchangers buried in the ground under the MLBE building and in its immediate vicinity (pre-conditioned air). Rehau Awadukt Thermo system solution was used – round DN 200 pipes with forced-in joints [7, 8, 9].

![Figure 1. Cooling sources control panel with natural gas heat pump, ground heat pump and energy storage (cold water tank) marked red](image)

3.2. Local (rooms) level
An important issue that requires further detailed study is the impact of operating modes of cooling equipment and installation applied locally in selected areas on the resulting temperature conditions for the pre-set operating conditions of the tested cooling sources. For the experiment at the local scale, experimental rooms 1.06 and 2.04 were selected which are located respectively on the first and second
floor (see figure 2). Both rooms have the same dimensions, glazing and the type of wall and ceiling partitions. They are both equipped with similar cooling equipment and metering systems, allowing planned measurements accordingly to a given control strategy. The experimental rooms are placed on two consecutive floors, one below the other, on the south side of the building. They have full triple glazing to the south and 1/3 length of the east wall glazing (floor to ceiling windows). The experimental rooms are located inside the building and are surrounded by other rooms with ensured similar climatic conditions for the time of the experiment. Unlike the first floor, the entire second floor is equipped with horizontal blinds, with automatically controlled lamella angle. A significant equipment difference between the compared rooms, therefore, lies in the shadowing of windows in the room 2.04 and the lack of such functionality for the room 1.06 (see figure 3). In the surveyed areas, for the purpose of the experiment, two local cooling systems were used:

- underfloor cooling system (UFC), Rehau – the installation was designed with the cooling tubes running from the manifold to the floor cooler in the floor of the room. Its closet distributor is equipped with a pump-mixing system with a Wilo Yonos circulation pump with a thermostatic valve on supply end and a regulating valve on return end. Instead of flowmeters on the distributor beam, precise control valves were used. Design of the switching system is based on the two-way valves that function as switchers – breakers with an electro-thermal actuator.
- four-piped, underceiling fan coils with EC motor (FC), Galetti – the airflow through the fan coil unit is forced by a fan with fixed virtual steps 33%, 66%, and 100% efficiency.

PI controllers have been implemented for rooms’ cooling systems. Both systems use accumulated cold water from the central cooling tank. In addition, their work is supported by preconditioned air supplied via ventilation ducts from CW1 - EAHX ventilation system.

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Figure 2. Experimental rooms 1.06 (left) and 2.04 (right) marked red, located respectively on the first and second floor
3.3. Building automation and control system
The above-mentioned devices are managed by the building automation and control system (BACS). Their key parameters are archived on the Server in a SQL database. This allows for relatively easy processing of the results. One can also use data collected by other systems connected via the BMS into a unified whole, such as an outer weather panel measurements or intruder alarm, indicating, among others, whether any windows are open inside the study area or in areas adjacent to it. In the final assessment, it can be indicated which of the cold sources are more efficient from an economic point of view (taking into account data on energy consumption) and if the selected sources provide inside the building the heating comfort or the technological conditions as required by the user under certain weather conditions.

3.4. The scenario of the experiment and equipment settings
Each time, on the chosen day of the study, it consisted of turning all equipment and installations included in the experiment’s schedule to ‘day’ operation mode, during working hours (from 7.30am to 2.30pm) and to ‘night’ operating mode throughout the remaining hours of the day. A single measuring cycle lasted two days and covered both ‘day’ and ‘night’ settings. Four two-day experimental cycles were planned and carried out on MLBE’s working days, which took into account both efficiency study of selected cooling sources and pre-set working modes of the local level equipment.

- First cycle – HP2 was set as a cooling source in the ‘day’ mode. In the ‘night’ mode, only CW1-EAHX system was on. At the local level, underfloor cooling (UFC) was launched in the ‘day’ and ‘night’ modes.
- Second cycle – HP2 was set as a cooling source in the ‘day’ mode. In the ‘night’ mode the passive cooling system was launched. At the local level, the fan coil unit (FC) was launched in both working modes.
- Third cycle – HP2 was set as a cooling source in the ‘day’ mode. For the ‘night’ mode passive cooling system was launched again. At the local level, a tandem of both underfloor cooling and fan coil unit was running in both working modes (UFC + FC).
- Fourth cycle – this cycle was carried out with the passive cooling system set as the cooling source in both ‘day’ and ‘night’ modes. At the local level, a tandem of both underfloor cooling and fan coil unit was running in both working modes (UFC + FC).

For all tested cycles, the ventilation system CW1-EAHX worked continuously at the set supply air temperature of 20°C, and the set air supply and exhaust flow of 1000 m³/h. An equal amount of air with the same parameters was supplied to both experimental rooms. Fresh air was drawn partly from the outside through a wall air intake and partly through EAHX system. The cooling temperature of the medium assigned for the experiment duration was 15°C. This temperature was measured at the HP2 natural gas heat pump, localized on the roof of the building (‘day’ operating mode). For the subsequent measurement, the refrigerant temperature at refrigeration equipment in the surveyed areas.
was higher by about 1-1.5°C than the set temperature at the HP2 pump. In the ‘night’ mode and in the fourth, last test cycle, the same logic was upheld in relation to the pump HP1.

At the local level, in the experimental rooms the constant room temperature was set at 22°C. In order to generate the possibly similar temperature conditions in the neighboring areas adjacent to the test rooms vertically and horizontally, the corresponding cooling systems based on coil fans were turned on, with set temperature of 22°C. Temperature change in these areas was also being monitored. This precaution was taken to exclude ambient’s temperature effect on the temperature in rooms 1.06 and 2.04 (due to heat transfer through the walls). During the study, the opportunity to verify the impact of windows shading on the temperature conditions in the studied areas was also taken: room 2.04 had the angle of external blinds set at 45° during the whole experiment, while for the room 1.06 blinds were not applied. During the study cycle, in order to maintain similar experimental conditions, all others MLBE building’s equipment, installations and systems were working in a fixed mode.

Conducting the study in the ‘day’ and ‘night’ modes and using BACS, change trends of many technical parameters of devices and installations were monitored and archived. Only some of them were connected undertaken in this study topic. The two examined cold sources, supported by the work of ventilation system CW1-EAHX, differ in terms of the consumption of their medium. In case of HP2 with its complementary AWS, in order to determine the value of consumed energy, work of the gas meter and the electricity consumption of the cooperating elements of pump system had to be monitored. Due to the different load on the pump HP2 system, depending on the load and temperature conditions outside, the gas consumption measurements were taken hourly. Moreover, the energy consumption of the ventilation system CW1-EAHX and the refrigerant circulation pumps in the building has been monitored. The circulation pumps are used both to circulate the refrigerant from building’s cooling sources to the cold water tank and distribute the coolant from the buffer to the local systems of individual rooms on all floors of the building. The former works when a given cold source is turned on, and the latter when any of the local systems in a given room is switched on (each room has its own circulation pump). Actuators are connected with systems of pumps and hydraulic circuits. The energy supplied to them – due to their control system – is negligibly small and hence was not monitored when testing the parameters. Furthermore, a local weather station was used. Weather data analysis allows to determinate the impact of weather conditions on the operation of the tested system – both at the global level for the whole building, and at the local level for the experimental rooms.

4. Results and discussion
During the experiment, while the natural gas pump HP2 was in operation, it was necessary to establish a relatively high coolant temperature in the installation. Such a circumstance arose because of the risk of condensation of water contained in the air in contact with the cold surface of the floor (figure 4). For a too low coolant temperature, with the conditions in the rooms during the experiment (temperature and relative humidity), would lead to the formation of condensate due to the value of dew point. The need to raise the temperature of the coolant throughout the building stemmed from a failure to control the temperature of refrigerant directly inside the rooms, in plane cooling devices, due to the lack of adequate local control of the rising temperature of the medium above the dew point. Such a solution significantly limited the cooling possibilities of fan coils (fitted with drain piping), but it was the only way to use plane cooling systems in the planned comparisons, without the risk of condensation on them of water from the air.
Figure 4. Underfloor cooling system during operation visible on the FLIR P660 thermal imaging camera; set temperature range on the color scale of the thermographic image from 17 to 32.1°C

For the study of data obtained during the four experimental cycles, a simple numerical analysis was used. On the global level, average hourly electricity power consumption by the ventilation unit, circulation pumps, and HP2 natural gas heat pump was presented for each of the cycles and broken down by ‘day’ and ‘night’ modes (figure 5 and 6). Since the results from ‘night’ mode in Cycle 2 were incomplete, their interpretation was abandoned in the above mentioned list. In addition, for the three cycles in which the HP2 was working, gas consumption was listed for the ‘day’ mode (figure 7). In Cycle 1 and 3, the circulation pumps system has consumed much more energy during the day than at night. In turn, the energy consumption of the CW1 ventilation unit was relatively constant in all cycles both during the ‘day’ and ‘night’ modes (it resulted mainly from fan drives). The highest daily and peak gas consumption is visible for Cycle 1. During Cycle 1 and Cycle 3, in the first phase of the day, HP2 uses the most gas. Successively, at lunchtime, another gas consumption increase is observed (lower than the consumption peak in the morning), which results from the dynamics of the building's cooling system. The increase in the cooling demand of the building during the day resulted from solar heat gains and an increase in the outside temperature. The effect was intensified by the work of only the passive cooling system in the 'night' mode, which was characterized by low efficiency. In addition, the ventilation unit was operating at a constant ventilation temperature (no night cooling mode was used), which led to the lack of overnight cold accumulation in the building. Because Cycle 1 was the first measurement, the building had to cool down to the set parameters. It is not without significance that, in the early days of the experiment, the highest external temperature for the entire study period was registered (figure 8). It may be also noted that the lack of passive cooling at night meant that the next day gas pump had to make up losses. In Cycle 2 (figure 5), for the HP2 heat pump working during the day and assisted by the ventilation system, most of the electric energy was consumed by the HP2 and circulation pumps system. The overall balance should include gas used by HP2 (figure 7). For studies conducted in Cycle 4, for the work of the passive cooling system in ‘day’ mode, the lowest power consumption of comparable cycles was obtained, and in the ‘night’ mode indications were similar to those in other cycles (figure 5 and 6). It should be emphasized that at this time HP2 gas pump was not in operation, and therefore no gas consumption was recorded. The lower energy
Consumption for cooling in the 'day' mode in subsequent cycles (1, 3, 4) led to higher consumption of electricity for the operation of circulation pumps in the 'night' mode, which resulted from the more intense work of room’s cooling systems in 'night' mode.

Figure 5. Comparison of electricity consumption during 'day' mode

Figure 6. Comparison of electricity consumption during 'night' mode

Figure 7. Comparison of gas consumption in 'day' mode
At the local level, temperature changes in the experimental rooms during the 'day' mode were analyzed. The preset temperature was not achieved in any of the measuring cycles and modes of operation of local temperature change actuators in rooms 1.06 and 2.04 (figure 9 and 10). Comparing the temperature in the studied areas, it can be concluded that the assumed strategy of cooling does not provide a predetermined level of temperature. There is a noticeable change towards lowering the room temperature in room 2.04 under the influence of the cooling system, except in the case of the passive cooling system (Cycle 4). During the Cycle 4, due to relatively low cooling power of the passive cooling system, the highest temperature rise in the experimental rooms was noted despite the work of both room’s systems (UFC + FC). The temperature in room 1.06 tends to increase for each analyzed cooling strategy. For the same working conditions of cold sources and actuators, whatever their mode of operation, one can see the significant impact of the use of shading in room 2.04 in relation to the lack of shading in room 1.06 on reducing the solar heat gains. Room 1.06 is located on the lower floor, so the sunlight interference on temperature conditions therein should be lower (due to shading by surrounding objects). However, the lack of outer windows shading causes a significant temperature rise in the room with respect to the room is 2.04.

This experiment was a pilot study of initial control algorithms of refrigeration systems, aimed at verifying the laboratory's measurement capabilities in the field of experimental evaluation of the energy efficiency of a cooling installation - both different cooling sources and local cooling systems at the room level. In the next planned tests, plane cooling systems in rooms will be equipped with dew point sensors, preventing moisture condensation, which will enable lowering the temperature of the refrigerant in the building for more efficient cooling with the use of fan coils. In subsequent tests, the energy consumption of circulation pumps of individual experimental rooms will be considered independently. We will also continue to work on creating a comprehensive model of the MLBE building in the Design Builder program, including detailed HVAC installation solutions, in order to validate the results obtained during the simulation in the real object.
Figure 9. Comparison of temperature change in experimental room 1.06 during ‘day’ mode

Figure 10. Comparison of temperature change in experimental room 2.04 during ‘day’ mode

5. Conclusions
Experimental study of a fragment of the cooling system used in the Małopolska Laboratory of Energy Efficient Building presented in this paper provides a basis for assessing the energy efficiency of selected cooling sources and cooling modes of cooling actuators applied locally. The results obtained during the measurements using the building automation and control system will serve for further comparisons and analysis. Based on the energy consumption assessment for utilized cooling sources, it can be said that many factors affect the reduction of the energy consumption in the modern energy-efficient building. Among them there are: the type of a cooling source, devices and systems which it cooperates with, proper selection of the type of cooling used locally, but also windows shading and reduction of the impact of solar radiation on the temperature conditions indoors. The use of the building automation, both monitoring and controlling, operating these components according to a predetermined algorithm improves the system as a whole.

At present, integrated process control systems are used in buildings more often. Both in the case of new and modernized buildings, building automation components are being introduced. The rapid development of information technology and changes in the legislation obliging investors to use the
energy-saving materials and technologies shows that the building automation is an important element of the energy-efficient construction. In addition, ensuring adequate comfort of use of buildings and keeping the energy consumption at a certain predetermined level, may be easier when advanced building automation solutions are applied. There is a need for scientific research of innovative technical solutions in an independent and objective study by specialized units. This is also the role of the newly created Małopolska Laboratory of Energy Efficient Building.

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