Design, Specification and Construction of Specialized Measurement System in the Experimental Building

Małgorzata Fedorczak-Cisak¹, Paweł Kwasnowski², Marcin Furtak¹, Grzegorz Hayduk²

¹ Cracow University of Technology, ul. Warszawska 24, 31-155 Krakow, Poland
² AGH University of Science and Technology, Al. Mickiewicza 30, 30-059 Krakow, Poland
mfedorczak-cisak@pk.edu.pl

Abstract. Experimental buildings for "in situ" research are a very important tool for collecting data on energy efficiency of the energy-saving technologies. One of the most advanced building of this type in Poland is the Malopolskie Laboratory of Energy-saving Buildings at Cracow University of Technology. The building itself is used by scientists as a research object and research tool to test energy-saving technologies. It is equipped with a specialized measuring system consisting of approx. 3 000 different sensors distributed in technical installations and structural elements of the building (walls, ceilings, cornices) and the ground. The authors of the paper will present the innovative design and technology of this specialized instrumentation. They will discuss issues arising during the implementation and use of the building.

1. Introduction
In the light of the EPBD directive (Energy Performance of Buildings Directive) [1], [2] of the European Parliament the problem of the energy consumption of buildings gained new practical meaning in two first decades the 21st century. Cracow University of Technology is trying to meet challenges. The result is construction and operation of the Malopolskie Laboratory of the Energy-saving Buildings (MLBE) - laboratory, in which it is possible to conduct research of the building energy-efficient technologies, materials, structural solutions, technological installations and comfort of using low-energy buildings. Simultaneously, by equipping the building with many diverse sources and receivers of the energy and very wide measurement systems of both heating and cooling elements of technological systems, and structural members of the building, the MLBE building is a research tool and the subject of the research. The MLBE building after circa 2 years of the design and the construction works was put into use in October 2014. In the building two distributed electronic systems were installed: Supervisory Control and Data Acquisition System for supporting technological installations of the building (sources, distribution and receivers of the heat and coolness, the ventilation, the air-conditioning and the illumination) and Specialized Measurement System of outside barriers (walls) and ground measurements. The first of these systems works as an extended BMS system (Building Management System) which is not only fulfilling the role of "classical" system of the automation of comfort and managing the technical infrastructure of the building, but enables also to conduct research of functioning of this infrastructure in different technological structures, possible to be configured in the building. The second system – Specialized Measurement System is a subject of
the present article. This system is a unique measurement system of structural components of the building, enabling examining the real distribution of temperatures and the heat flow in such structural components as outer walls, ceilings, cornices, poles, foundation and ground beneath the building.

Amongst examinations possible to be carried out with this Measurement System there are: verification of the methodology of energy performance characteristics preparation of buildings through comparing the methods based on calculations with method based on measurements, as well as the verification of simulation methods of the heat flow and distribution of temperatures in outside walls with real measuring data coming from matrices of temperature sensors located in the structural components of the building.

In the article the authors concentrated on a detailed presentation of solutions for temperature measurements in structural components of the buildings and on the structure of the entire measurement system, methodology of the design and properties of the system of data acquisition, registration, visualisation and the data processing of the measured data.

2. Design assumptions of Specialized Measurement System

Assumptions and requirements for Specialized Measurement System (SMA) of the envelopes/external walls/barriers and ground measurements of the MLBE building were formulated by a team of Cracow University of Technology [3]. Specialized Measurement System includes the following measurements:

- temperature measurements in the envelopes/external walls/barriers,
- temperature measurements in the ground under the building and in its surrounding,
- measurement of ground heat exchangers.

2.1. Temperature measurements in the envelopes

Due to planned comparative studies of temperature field distribution in the envelopes/external walls/barriers depending on comparing computer simulation results with the actual temperature distribution in the envelopes/external walls/barriers and installation of sensors while pouring structural concrete elements of the building strict requirements were set as far as precision and stability of temperature measurements in the envelopes/external walls/barriers are concerned. It was assumed that electronic digital temperature sensors of very high accuracy and long term stability are necessary to be installed, that would not demand periodical calibration during exploitation.

For sensors installed in the envelopes the following requirements were set:

- Measurements from the external side of the envelopes (so called “cold” sensors):
  - measurement range from -25°C to +55°C,
  - measurement accuracy ±0,3°C.
- Measurements from the internal side of the envelopes (so called “warm” sensors):
  - measurement range from 0°C to +40°C,
  - measurement accuracy ±0,1°C.

The places in which temperature sensors were to be installed in the envelopes were precisely determined in document [3] on the basis of PN EN 14863 standard, in which typical places of thermal bridges are determined. As reference points measurements from the middle area of the walls were taken into consideration, far from the thermal bridges.

Planned location of measurement areas is shown in Figure 1.
In some measurement areas, a horizontal single layer of sensors was assumed, in other areas – particularly for ceilings, cornices, corners and roof – spatial distribution of sensors in the matrix containing many layers, rows and columns of sensors was considered.

To systematize distribution of sensors and their unequivocal identification denotations of so called “Details” of sensor distribution were established and layers of the sensors were defined in the scale of the whole building. Taking into consideration the number of the installed sensors, their unequivocal identification is a problem of key importance when interpreting measurement results.

An example of defining “Details” of measurement areas on the plan of a chosen storey is shown in Figure 2.

In Figure 3 distribution of particular sensors within a defined “Detail” is shown. The colours of the sensors refer to cold (blue) and warm (red) sensors.
Figure 3. Documentation of distribution of temperature sensors within the “Detail”

The next figure illustrated an exemplary spatial distribution of sensor matrix in the ceiling and cornice of chosen “Details”.

Figure 4. Spatial matrix of sensors in the ceiling and cornice

Denotations of the “Levels” of sensors in the scale of the whole building are illustrated in Figure 5. The figure shows single “Levels” of sensors distributed in the middle of the walls’ height, e.g. levels a, b, and g and many “Levels” of sensors in the ceilings, e.g. “Levels” d, dd, ddd, ee, e and es in the ceiling of the third floor and “Levels” i, j, jj, kk, k, ks and l in a slab roof.
An additional element facilitating identification of particular measurement areas of the building construction and navigation between these areas is the idea of a “Column of Details”. A “Column of Details” is formed by “Details” located in the same place on the horizontal plan of the building on different storeys. Altogether fourteen “Columns of Details” were designated marked from KS1 to KS14 (an example is given in Figure 5).

2.2. Temperature measurements in the ground under the building and in its surroundings

To measure temperature in the ground it was assumed that electronic digital temperature sensors of high accuracy and stability would be used, which do not require calibration. Ground measurements are taken by means of vertical probes with temperature sensors installed at proper distances. It was assumed that the sensors would be of identical characteristics to the sensors in external walls. Ground probes were planned in some axes placed on the plan of the building. Figure 6 shows location of the ground measurement axes.

An example of sensor distribution for one of the axes of ground measurements is illustrated in figure 7.

3. Structure and elements of Specialized Measurement System

Specialized measurement system consists of the following elements:

a. Sensors:
   - Temperature sensors built in in the structure of the building and in the ground under the building during building works.
   - Temperature and humidity sensors in the soil channels, horizontal heat exchangers.
   - Temperature sensors on the ground and vertical heat exchangers.
- Measurement sensors of accumulating walls.
  b. Signal hubs from the sensors.
  c. Infrastructure of data collection network and data conversion, among them automation servers.
  d. Computer system (hardware and software) to collect, register, visualize and process measured data.

**Figure 6.** Ground measurement axes

**Figure 7.** Distribution of ground sensors in one of the ground measurement axes
3.1. Temperature sensors in a building construction

Having analysed the market of electronic temperature sensors when realising the project TSic™ family of sensors of a Swiss producer, Innovative Sensor Technology was identified, which met the requirements of the system sensors. In TSic™ sensors a precise reference source based on bandgap reference is used, using compensation of temperature influence by the method of generating current proportional to absolute temperature – PTAP [16]. Such a solution ensures high precision and long-term stability of the sensor with no need for calibration during usage. Additionally, individual calibration of the sensors and internal processing by means of DSP processor and digital value transmission measure according to ZacWire standard make the measurement result independent from the length of the wires connecting the sensor with data hub. On the basis of elements TSic™ 306 [4], which were calibrated at the factory for the required range of temperatures (from -25°C to +55°C with ± 0.3°C accuracy), there were developed and made sensors installed on the external side of the outside barriers, so called “cold” sensors – CCT-1. On the basis of elements TSic™ 506F [5], which were also calibrated at the factory for the required range of temperatures (from 0°C to +40°C with ± 0.1°C accuracy), there were developed and made sensors installed in the interior and from the internal side of the barriers, so called “warm” sensors – CCT-2. Temperature sensors CCT-1 and CCT-2 were made in the form of one-sidedly closed stainless steel tubes of 6 mm in diameter and 30 mm in length. Electronic measurement elements TSic™M were placed on a drop of a thermally conductive paste at the bottom of a tube, and then the interior of the tube was flooded with an elastic sealing resin recommended by the producer of TSic™ elements. Additionally, the wire outlet from the sensor was sealed with a heat shrink sleeve covering the tube and the connection wire.

CCT-1 and CCT-2 sensors are connected with the KCT data hubs, which serve readings from the sensors and transmit measurement data to the data collecting system.

Figure 8. Example of a temperature sensor CCT

Sensors were installed in probes installed in walls and ceilings during construction process of the building. In Figure 8 the single probe for installation in ceiling “Details” is presented. In next two Figures 9 and 10 application of probes in simple and complex sets of measurement areas is shown.

Figure 9. Single probe (row of sensors) for ceiling temperature measurement
**Figure 10.** The single row of probes shown just before flooding with concrete.

**Figure 11.** Matrix of sensors in one of complex “Detail” of ceiling before flooding with concrete

**Figure 12.** Detail presentation in SMS computer system
4. Structure and elements of Specialized Measurement System

Specialized Measurement System involves some layers of data acquisition (Figure 14). At the bottom layer there are hubs being a direct interface to read digital CCT-1 and CCT-2 sensors as well as Dallas DS18B20.

**Figure 13.** Sensors in wall isolation

**Figure 14.** Structure of Specialized Measurement System and data acquisition layers

- Stacja nadrzędna systemu SOS – SOS Master Station
- Wizualizacja – Visualisation
- Archiwum – Archives
- Procesowa b. danych – Process data base
- Klient – Client
- Brama – Gateway
4.1. Data hubs from object sensors

Using 157 KCT hubs, measurements are read from 2274 sensors in the building construction, and further 36 KCT hubs are used to read 359 sensors in the ground probes. Six KCD hubs serve to read 156 sensors in WGWC vertical ground heat exchangers. Then seven LINX servers (Modbus/RTU protocol, as Master nodes) are used to read connected with them Modbus main lines of KCT hubs. Readings take place through asking every 30 or 60 seconds all registers from subsequent hubs (Read Input Register function). Incomplete use of KCT ports and the number of measurements in LINX servers is the result of measurement of different areas of the building and the necessity to locate KCT and LINX appliances in direct closeness of the installed sensors. Another reason of such an organization are reliability considerations, that is KCT or LINX breakdown will cause measurement loss in the area served by these appliances only.

In below Figures the components of the data acquisition and processing levels are presented.

**Figure 15.** Two KCT temperature sensor hubs

**Figure 16.** LINX data servers

**Figure 17.** Matrix of temperature sensor hubs of one-storey sensors in external cornices, outer part of ceiling and outer walls
4.2. Repository of object layer specification

Apart from the equipment structure of data collecting, no less important element is organization of the object layer specification that is sensors in the building construction, probes, exchangers or accumulating wall. Assumptions and Requirements of the Investor [3] and Executive and Post-executive Projects contain only cross-sections in the form of drawings with marked sensors (their symbols and location). Drawings show Details in the building construction and location of the sensors. However, they are not a repository to which it would be possible to send an electronic filter query, grouping or sorting according to chosen location criteria, type or the way to re.

The location of a Detail in the building, the sensor in the Detail and on the Level as well as data collection track (KCT and LINX). It also comprises the remaining signals not connected with the measurement of the building construction.

5. Methodology of designing Specialized Measurement System

Specialized Measurement System was designed on the base of industrial system of class SCADA-HMI, in which there were implemented a number of functions expanding SCADA system in order to meet the requirements and needs of the realised system. A set of tables modelling the measurement system was designed. The table Sensors defines all sensors together with identifying hub KCT and server LINX. In LINX server configuration were defined analogue data points (of floating-point arithmetic type) connected with Modbus registers of KCT hubs of int16 type). After having formed digital specification of the object part of the system, included into the tables of database, and on their basis the changeable of OPC client and SCADA system, visualization and historical registration were elaborated as well as sets allowing analysis of chosen fragments of the building ("Details", "Columns", "Levels").

Sensor screens in a construction (Figure 19) include:
- a fragment of vertical cross section of the building with marked level shown on the screen,
- a fragment of a storey outside walls cross section
- with a marked Detail (a Column of Piles) on the screen,
- legend of colours referring to temperatures (it is dynamically designated, by calculating the middle value of the legend as an average from all presented on the screen temperature measurements),
- symbols of sensors and their up to date readings marked on a groundwork/ bitmap being an architectonic fragment of a building.

In terms of measurements alone in a building construction, the system comprises 128 screens. To effectively and at the same time correctly design visualization screens, it was decided to create adequate sub-programmes in SCADA environment, supporting their formation based on specification of sensors in the database. These sub-programmes serve for:

- introducing and setting up fragments of horizontal and vertical cross sections,
- introducing bitmaps,
- introducing sensors in a proper position (x, y) according to the bitmap.

As it can be noticed on an exemplary screen, apart from the sensors themselves, also their symbols have to be properly placed (which was also implemented in sub-programmes of SCADA environment).

Figure 20 shows an example of measurement visualization of ground sensors. Here the rule is the same as in the legend – the middle value corresponds to the average temperature on the displayed screen, allowing to have an immediate view on lower and higher temperatures than the average one.

In terms of historical registration, a sub-programme which configures all measurement variables in the service of SCADA archiving was prepared. The SOS system records all signals from the sensors.

In the next stage. An adequate user’s interface was prepared making use of specifications from the database allowing to choose sensors from appropriately filtered list, presenting them on elastically customizable graph and entry in csv format for analysis through external software (e.g. Matlab, LabView, etc.).

Filtration may take place parallel for all criteria (“Level”, “Column of Piles” or “Detail”, “Pile”) – in the final effect the user gets a list of sensors meeting one or some of the chosen criteria.
Together with the location choice, the user gets information about the number of accessible sensors after having applied chosen criteria (Figure 21). In this way, it is possible to avoid the choice of criteria leading to the area where there are no sensors. For example, choosing column KS6, the user can see that it includes levels from a 0 to 1 (detailing the number of sensors on a given level). Adding to the filtration condition level 6 with 66 sensors, the system specifies how many sensors are in the remaining columns on level d (still having both conditions active – column and level).

The graphs may be formed as time course or X-Y (relationship of one measurement in reference to another one). Time courses may also present measurements of the same sensor in different periods of time, facilitating their comparison (e.g. imposed courses from days d-1 and d-2).
6. **“In-situ” research perspectives**

The presented Specialized Measurement System of the MLBE building together with IT tools for collecting and processing measurement data allow conducting in-situ research of a number of phenomena taking place in the building in real conditions. The research may include the following subject areas:

- a. Methodology of conducting studies in the field of heat diagnostics of the building.
- b. Energy balance of a building.
- c. Thermal properties of a building and of its particular construction elements.
- d. Verification of models of heat flow through building barriers.
- e. Verification of methodology of preparing energy performance characteristic of a building.
- f. Energy performance of technological installations and various heat and cool sources.
- g. Influence of control and automation systems and management of technological installations on energy effectiveness of a building in reference to EN_PN 15232 standard.

7. **Conclusions**

The article presents a unique Specialized Measurement System for external barriers/walls (construction elements of a building) and ground measurements of the MLBE building. It was successfully designed and implemented based on document [3] formulating its assumptions and requirements for the system. The main concentration point was a detailed presentation of the measurement structure comprising 2633 temperature sensors in the building construction and in ground sounders, as well as presenting methodology of designing parent system. The system, apart from the mentioned areas, includes also measurement of exchangers and accumulating walls, however they were not the subject of the detailed presentation in the article.

System designing methodology is based on the specification of sensors of the object part in the database and sub-programmes of SCADA environment. These sub-programmes not only allowed to effectively and correctly realise the system of collecting and visualizing measurements, but also to indicate specification errors at the stage of system implementation (duplicated or lacking sensors). In the case of modification or development of the system within the same structure, created mechanisms will be used in their present form. Developed database of sensor specifications may also be used by external software for analysis. To use standard database and to gain measurements in the form of a file in csv format is made possible by effective use of the data from the system.

The final part of the article presents in-situ research perspectives for MLBE building on the basis of developed and installed Specialized Measurement System described in the article.

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