UNIVERSITY OF ZIELONA GÓRA

CEER CIVIL AND ENVIRONMENTAL ENGINEERING REPORTS

CIVIL AND ENVIRONMENTAL ENGINEERING REPORTS

E-ISSN 2450-8594

CEER 2024; 34 (4): 0001-0021
DOI: 10.59440/ceer/192146
Original Research Article

INFLUENCE OF TEMPERATURE SENSOR (PT100) ACCURACY ON THE INTERPRETATION OF EXPERIMENTAL RESULTS OF MEASURING TEMPERATURE ON THE SURFACE

Maria Teresa MAŁEK[1], Halina KOCZYK
Poznan University of Technology, Faculty of Environmental Engineering and Energy, Institute of Environmental Engineering and Building Installations, Poland

A b s t r a c t

This article presents the impact of accuracy of sensors, or more specifically Pt100 temperature sensors, on result analysis of experimental studies. For this purpose, an experiment was carried out consisting in measuring the temperature on the surface of a partition - a concrete wall, beneath its insulation layer. The tested surface was separated from external environment and could only be influenced by the wall structure. Therefore, the expected result of the experiment, i.e. the difference in temperature sensor readings in identical locations on both sides of the partition, should reach a value close to 0. This article also presents the values of absolute error for sensors which were determined before their installation on the surface, and on which their location depended. The obtained deviations were included in the results of the experiment, which led to a decrease in temperature differences on both sides of the partition, in some cases even reaching the expected value of 0. This analysis showed how important it is to know the measurement error and then eliminate it in result interpretation.

Keywords: temperature measurement; absolute error; Pt100 temperature sensors; pipe-embedded wall; experimental measurements; box and whisker plot

1. INTRODUCTION

Sensors are used to measure specific physical quantities, and thus determine the properties of materials or components of entire systems. The study of a building structure solution based on a thermal barrier, i.e. thermoplastic pipes contained inside it and filled with a low-temperature medium, was carried out by researchers, among others Krzaczek and Kowalczuk [1,2]. In their publications, a concept of a system was described which consisted of a thermal barrier located inside a partition, solar collectors as well as a multi-zone ground heat storage system, whose operation was subjected to computational analysis in the ABAQUS program. Thus, it was demonstrated that a partition with pipes placed in the construction

[1] Corresponding author: Poznan University of Technology, Faculty of Environmental Engineering and Energy, Institute of Environmental Engineering and Building Installations, Berdychowo 4, 60-965 Poznań, Poland, maria.malek@put.poznan.pl, +48 61 665 2534

layer should contain at least three layers and should be insulated from the outside, while the inner layer should be a material of low heat conductivity. Then Krzaczek, together with a team of researchers, extended the work to field research [3], which showed that thermal barrier supply temperatures in real conditions in the southern wall were for the summer (15.1°C - 20.5°C), and for winter (7.9°C - 25.3°C). A study, which was carried out on an object specially constructed for this purpose, was also described in Dharmasastha et al. [4]. The measurements focused on cooperation of a specific building material - thermally activated glass fibre reinforced gypsum - with a thermally activated system installed in the roof structure of a free-standing room. The thermally activated system consisted of copper pipes embedded in concrete and connected to the cooling system. On the basis of the study results, the authors demonstrated a positive effect of the applied solution on maintaining thermal comfort in the room by reducing temperature fluctuations on the roof surface. Another approach, this time consisting of carrying out calculations on the basis of a numerical model, followed by verification of the obtained results against the results of the experiment was presented by Zhou and Li [5]. Their study showed the influence of the location of the pipes forming the thermally active part of the structure and the temperature of the medium supplying such a system on reducing energy consumption. A certain modification of the idea was proposed by Barkanyi in publication Kisilewicz et al. [6], who introduced pipes between insulation layers inside the reinforced concrete layer, and patented this idea as active insulation. On the basis of preliminary study in a real building, he also noticed a reduction of heat loss through the partition.

The studies above present operational analysis of the entire system, focusing on its control, or on assessment of individual components, e.g. improvements in available building materials or on influence of parameters such as: location and temperature of supply pipes inside the partition. This is significant due to the considerable share of buildings in energy consumption, as indicated by authors: Bíró-Szigeti [7] and Dragicevic et al. [8] and the need to use renewable energy sources described in publications for example: Azzopardi et al. [9] and Piwowar et al. [10], furthermore it is essential to consider thermal comfort: Antczak-Jarząbska and Krzaczek [11]. But it still does not change the fact that, mentioned publications about thermal barrier focus on presentation and evaluation of the concept, and not on examination of measuring instruments used.

A different approach is to use the system itself, or, more precisely, an experimental stand for purposes assessment of test method and accuracy, for other purposes that it was made, i.e. to test the functionality of the entire solution. Then, conducting an experiment, the final result of which is predictable, enables verification of measurement accuracy, in accordance with the idea presented by Witkovský and Frollo [12] that “measurement science is the science of sciences”. Additionally, the repeatability of the studies allows verification of the adopted method: Cieślikiewicz et al. [13].

2. SUBJECT AND METHODS

The idea of this paper is to show a significant influence of the knowledge of measurement error on interpretation of experimental results. For this purpose, measurements were carried out on an experimental stand made as part of a doctoral dissertation [14] and publication [15]. The experiment consisted in recording the temperature on both sides of the partition, i.e. the concrete wall, on the surfaces under its insulation layers (internal and external). The sides of the partition: internal and external were named after the air space they were adjacent to. One of the air space was supplied with outside (fresh) air - external air space, while the second space was filled with internal air - internal air space. However, during the research described in this article, in both air space, the air remained internal (still air).

The experimental stand consists, as already mentioned, of a concrete wall 15 cm thick and 202 cm high, insulated on both sides with 13 cm thick polystyrene. Inside the partition, in its axis of symmetry, a loop of 20x2mm thermoplastic pipes is embedded, arranged in the shape of a meander form with a spacing of 10 cm and connected to an cooling bath thermostat with the possibility of controlling water supply temperature and water flow. The wall structure is covered with oriented strand board (OSB), creating a 30.5 cm wide air space between it and the concrete wall. The experimental stand was also separated from the environment in such a way that it was raised 10 cm above the floor of the laboratory hall, and this space was filled with XPS extruded polystyrene and the entire OSB casing was insulated with 10 cm thick polystyrene. The parameters of building materials: concrete and polystyrene are presented in Table 1. Figure 1 shows a diagram of the test stand, while in the photo, see Fig. 2, its view is shown.

Table 1. The parameters of building materials applied in pipe-embedded wall with insulation [14]

Parameter / **Building material**	Thickness [m]	Density [kg/m^3]	Thermal conductivity [W/(m·K)]	Specific heat [J/(kg·K)]
Concrete	0.15	2120	2.24	903
Polystyrene	0.13	30	0.031	1460

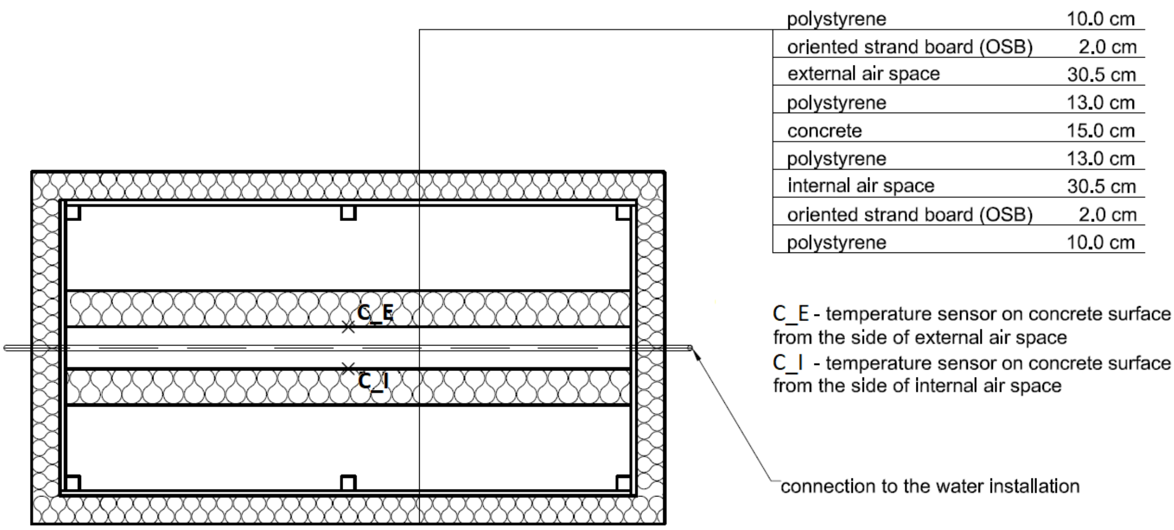

Fig. 1. Diagram of the experimental stand

Fig. 2. View of the experimental stand

A total of 40 Pt100 resistance temperature sensors with accuracy class according to manufacturer's data equal to 1/3 B for the range of positive temperatures were placed on the concrete surface under the polystyrene layer (20 sensors on each side of the partition). The location of individual measurement points on the partition surface is shown in Fig. 1 and Fig. 3. Symbol C denotes the location on concrete surface, markings: I and E refers to the location on surface adjacent to a specific air space i.e. I - the internal, E - the external (Fig. 1). The numbers denote a specific location on the wall surface (Fig. 3), the dimensions are given in centimeters.

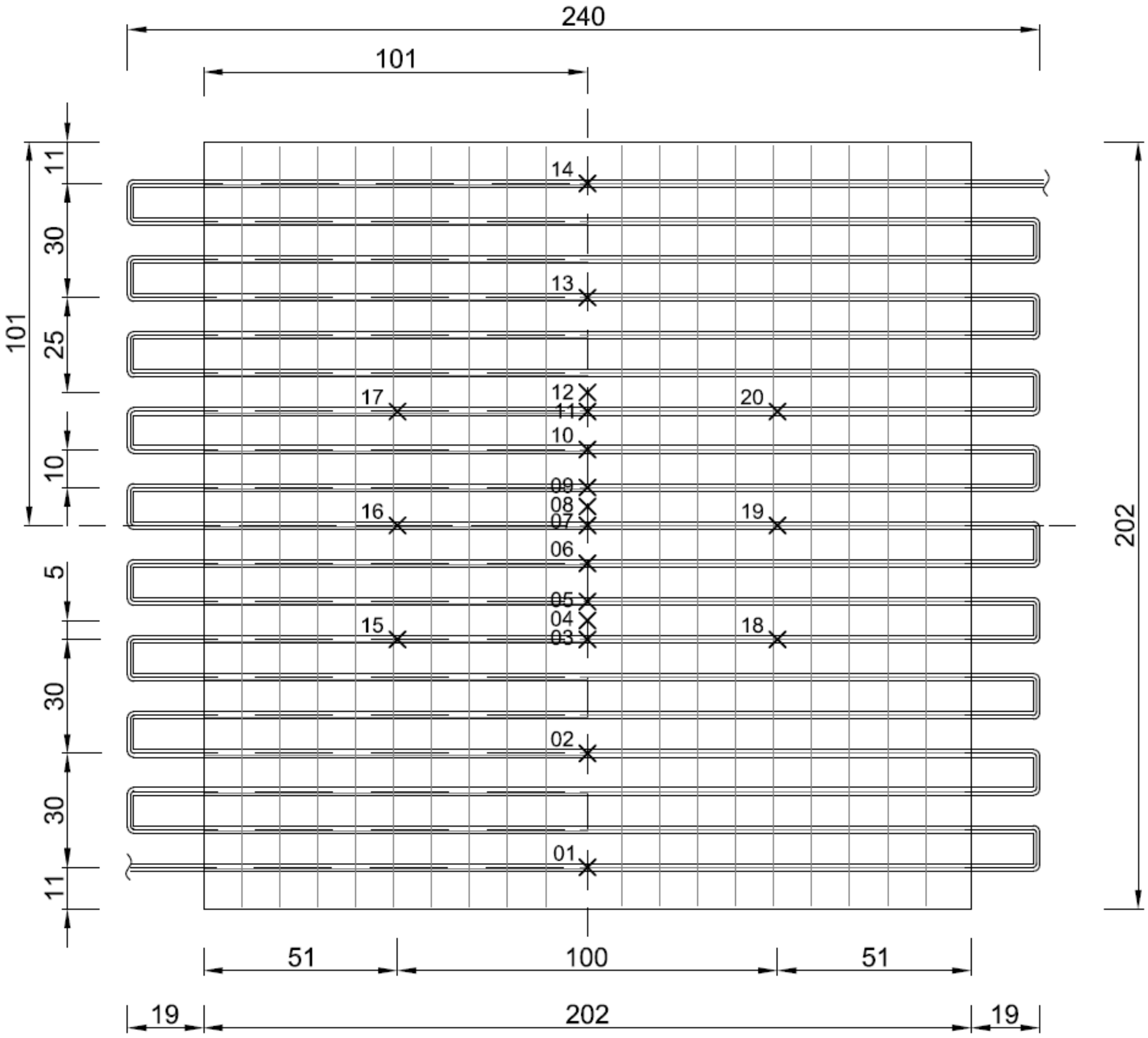

Fig. 3. Location of measurement points on the surface of the partition

For temperature sensors, the deviation measurement was made with CS175 calibrator by EUROLEC INSTRUMENTATION Ltd. of accuracy of +/- 0.05°C and a resolution of 0.01°C, the ALMEMO data logger by AHLBORN with a resolution of 0.01°C and an electronic thermometer P795 by company DOSTMANN electronic with a Pt100 sensor with accuracy of +/- 0.015°C and a resolution of 0.001°C with a calibration certificate (Fig. 4). According to the data provided by the sensors' manufacturer on the absolute error at 100°C, the maximum value of 0.15°C occurs for sensor C_E_16, whereas minimum value for 4 sensors: C_I_07, C_I_13, C_E_11 and C_E_19 is in the order of 0.02°C. According to the IEC 60751: 2022 [16] standard, the permissible deviation for platinum resistors at 100°C should be +/- 0.27°C, therefore the values from the technical data are within the expected range and are more accurate. Unfortunately, due to the temperature range up to + 85°C of the calibrator, no measurements were made for 100°C. The tests carried out on it were in the settings of: 5°C, 10°C, 15°C, 20°C and 25°C, i.e. the conditions in which the partition can operate.

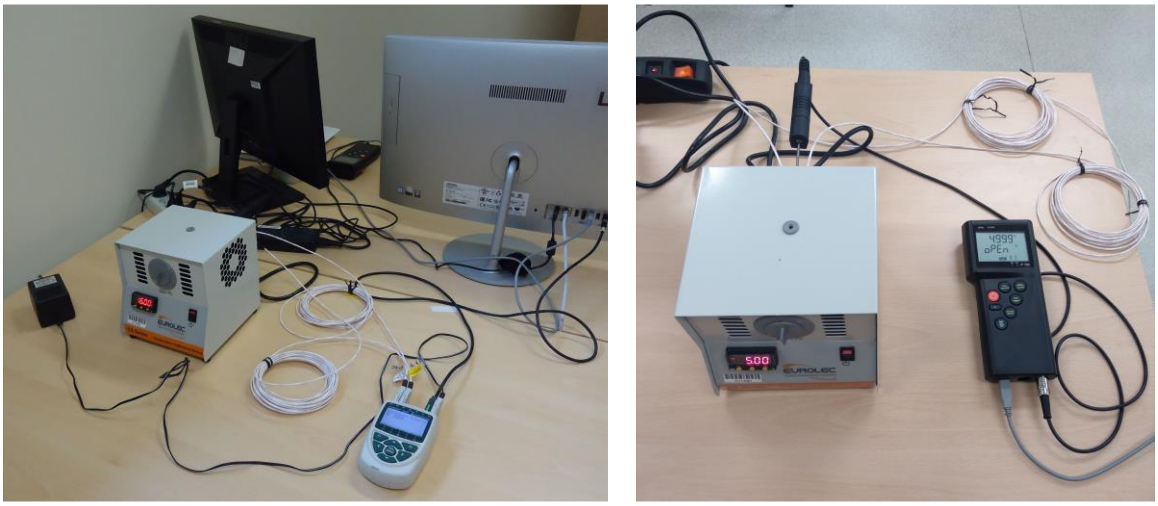

Fig. 4. The deviation measurement for temperature sensors

The procedure involved placing 2 surface sensors in the calibration chamber, at least 1 hour after the operating temperature of the calibrator was set. According the calibrator's operating instructions, the manufacturer allows waiting only 30 minutes, before taking any readings. The readings were extended twice, in order to be sure of the results obtained and due to the impossibility of repeating the deviations values tests after the experiment, i.e. after sensors were placed on the concrete wall, the beneath its insulation layer. For the same reason, the readings from the data logger for temperature sensors were taken after approximately 40 minutes. In the next step the results obtained for surface sensors were compared with the values indicated by the electronic thermometer, which was placed also in the calibration chamber. And the electronic thermometer is a standard instrument. Discrepancy results obtained for temperature readings are presented in chapter 3. In the same chapter was included the results of the main part of the experiment consisting in the assessment of influence of previously determined deviation on the interpretation of experimental results, i.e. temperature measurement on the concrete surface.

3. RESULTS AND DISCUSSION

The graphs below (Fig. 5 - Fig. 8) show deviation curves of Pt100 sensors for the given temperature settings set in the calibrator. An upward trend is noticeable, not exceeding +/- 0.1°C for the temperature of 25°C; however, only for one C_I_02 sensor (Fig. 6), the measurement at this temperature is exposed to absolute error of -0.12°C. For several sensors, a deviation of 0.01°C is achieved, which value is also the resolution of the measuring instrument. Referring to the conclusions of other researchers, certain similarities can be noticed. In the publication Jovanović and Denić indicate advantages and disadvantages of platinum resistance temperature sensors [17]. These sensors are characterized by: high accuracy and wide temperature range, but they have lower sensitivity and longer response time. The authors: Piechowski et al. [18] indicate that the group of the most accurate temperature sensors includes Pt100 sensors and mention their use also in industry around high voltage equipment. Another application is described by Echarri et al. [19]. In this publication Pt100 sensors were used to monitor the actual behaviour of building enclosure.

Returning to deviation measurement, the obtained results were crucial in deciding about assigning a given sensor to a place on the wall. The sensors with the lowest range of deviation values in temperature range of supply medium of partition (most often temperature range 16°C - 22°C) were located in central location on surface concrete layer. So for sensors on the locations points from 3 to 12 deviation values were within range: -0.14°C - 0.01°C for temperatures 15°C - 20°C (Fig. 5 and Fig. 7). Only 1 sensor reached value below -0.10°C for 20°C and it was C_E_09 with deviation value equal to -0.12°C (Fig. 7). For the sensors located on the rest part of surface of concrete layer (points from 1 to 2 and from 13 to 20) deviation values were within range: -0.19°C - 0.00°C for temperatures 15°C - 20°C (Fig. 6 and Fig. 8). And 8 sensors reached value below -0.10°C for 20°C: C_I_01 (-0.14°C), C_I_02 (-0.14°C), C_I_14 (-0.13°C), C_I_15 (-0.12°C), C_I_17 (-0.12°C) C_I_20 (-0.12°C) in Fig. 6 and C_E_14 (-0.13°C), C_E_17 (-0.11°C) in Fig. 8.

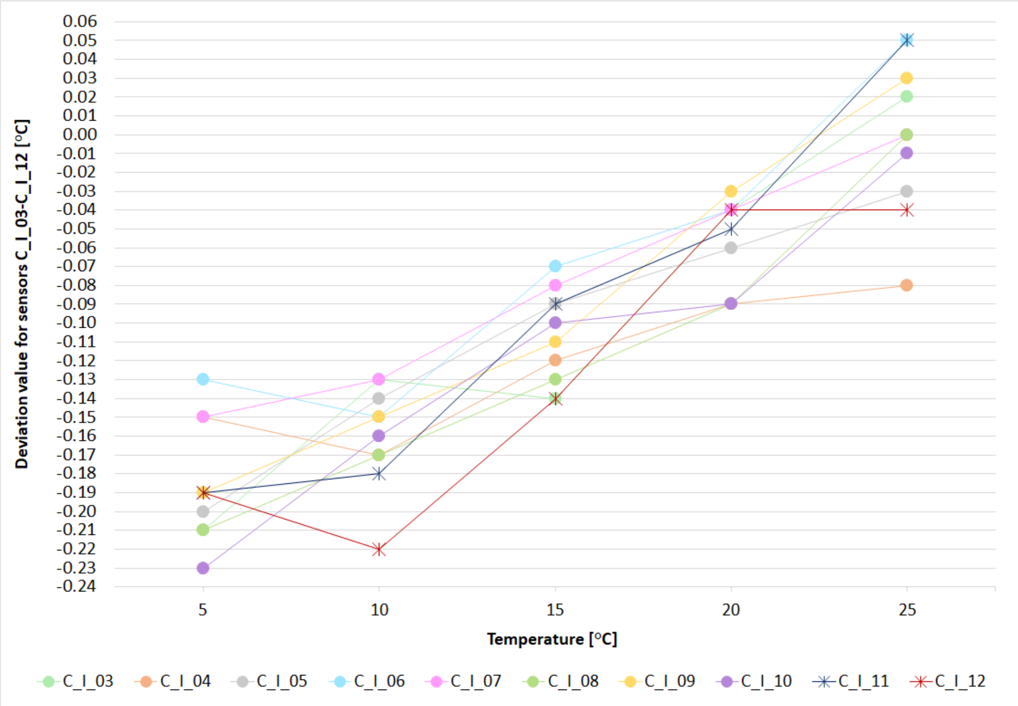

Fig. 5. Deviation values for sensors been mounted on the concrete internal surface under the polystyrene layer for C_I_03 - C_I_12

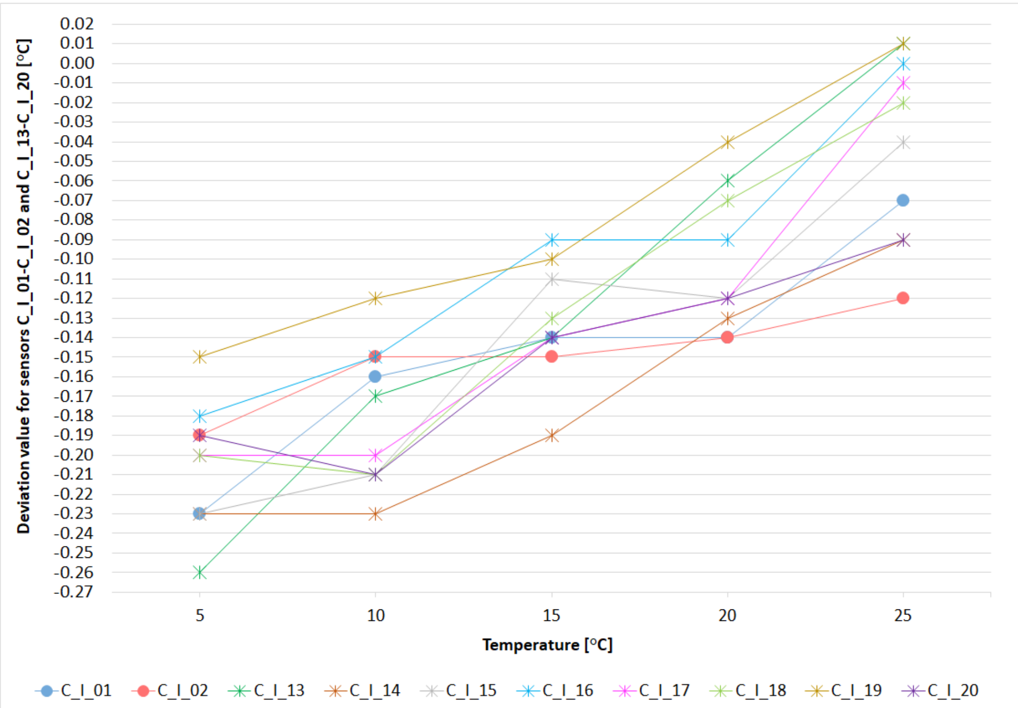

Fig. 6. Deviation values for sensors been mounted on the concrete internal surface under the polystyrene layer for C_I_01 - C_I_02 and C_I_13 - C_I_20

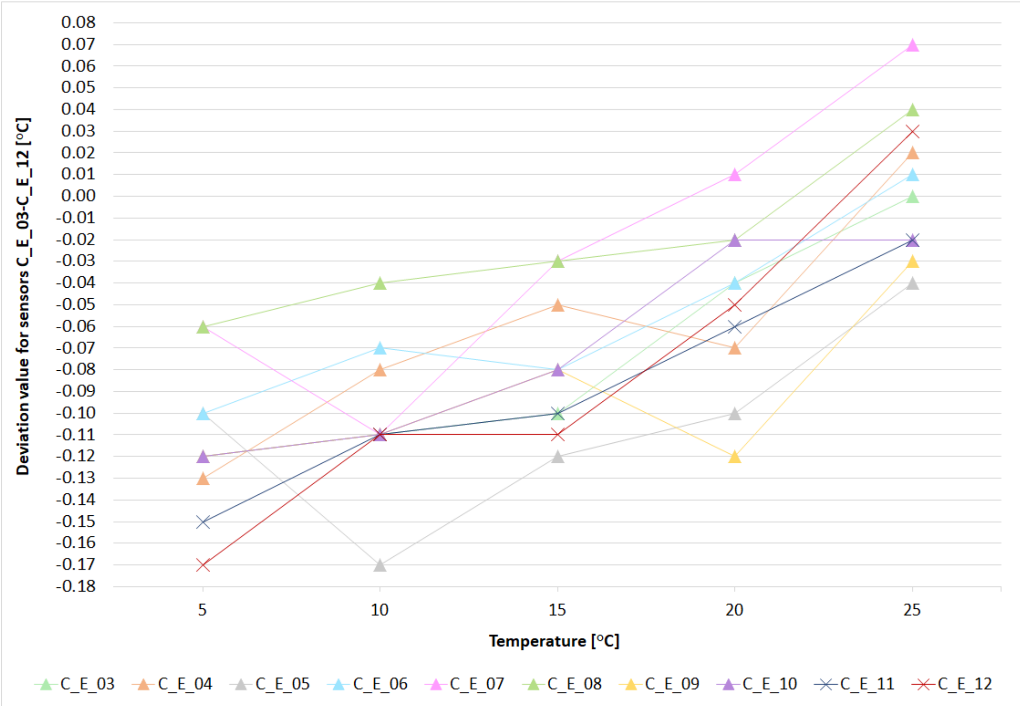

Fig. 7. Deviation values for sensors been mounted on the concrete external surface under the polystyrene layer for C_E_03 - C_E_12

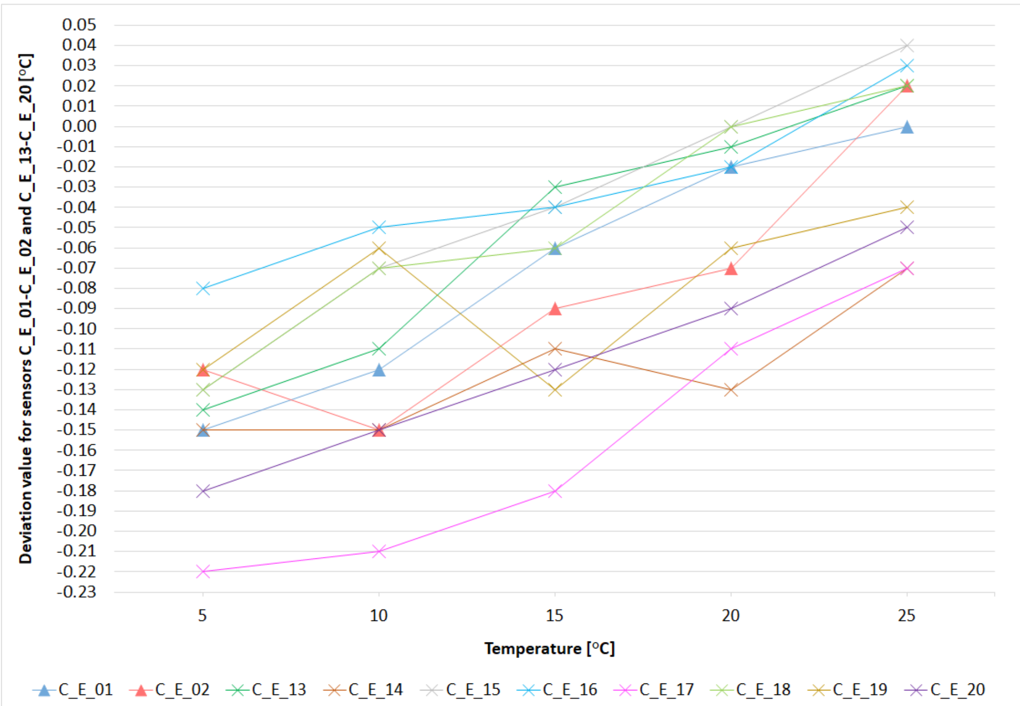

Fig. 8. Deviation values for sensors been mounted on the concrete external surface under the polystyrene layer for C_E_01 - C_E_02 and C_E_13 - C_E_20

The main part of the experiment consisted in determining temperature difference on both sides of the partition on its surface under the insulation layer. Due to the fact that the measurement took place under a polystyrene of the same thickness, which limits heat conduction, and in addition, the concrete wall is enclosed in an insulated casing, in which the temperature is the same on each side of the partition, temperature sensors located under the polystyrene on the concrete surface in identical places, only on different sides of the partition, should indicate similar values. Therefore, the temperature difference determined on the basis of measurements with such sensors should amount to approximately 0.

The tests were carried out for 4 supply temperatures of the loop in the wall: 16°C, 18°C, 20°C and 22°C. These values of temperature were different from the calibration's temperatures settings (5°C, 10°C, 15°C, 20°C and 25°C), because it was wanted to obtain universal deviation values for all temperature sensors mounted in the experimental stand. The total of 50 surface sensors were mounted: 40 on the concrete surface under insulation layer, and 5 on the insulation (polystyrene) surface on each side adjacent to air space. For sensors located on the polystyrene layer, the temperature readings were in wider ranges, because it was depending on the stage of research. However, this article presents results for 40 sensors on the concrete surface under insulation layer and without air flow into the air space, because in order to have no doubts as to the final results obtained i.e. the difference in temperature sensor readings in identical locations on both sides of the partition, should reach a value close to 0. A type of this partition i.e. pipe-embedded wall with insulation, should be supplied by low-temperature medium, earlier mentioned, most often, e.g. 16°C, 18°C, 20°C and 22°C. Measurements were recorded every 5 seconds, and the graphs were prepared (Fig. 9 - Fig. 24), the period for the temperature stabilization inside the partition was used. The number of measurements used to make box plots (box and whisker plots) was 1,805 measurements for respective temperature settings in the cooling bath thermostat at 16°C, 18°C, 20°C and 22°C. The asterisk (*) denotes differences in the readings of the sensors for whose deviation was taken into account. The red dash-dot line marks temperature difference of 0.00.

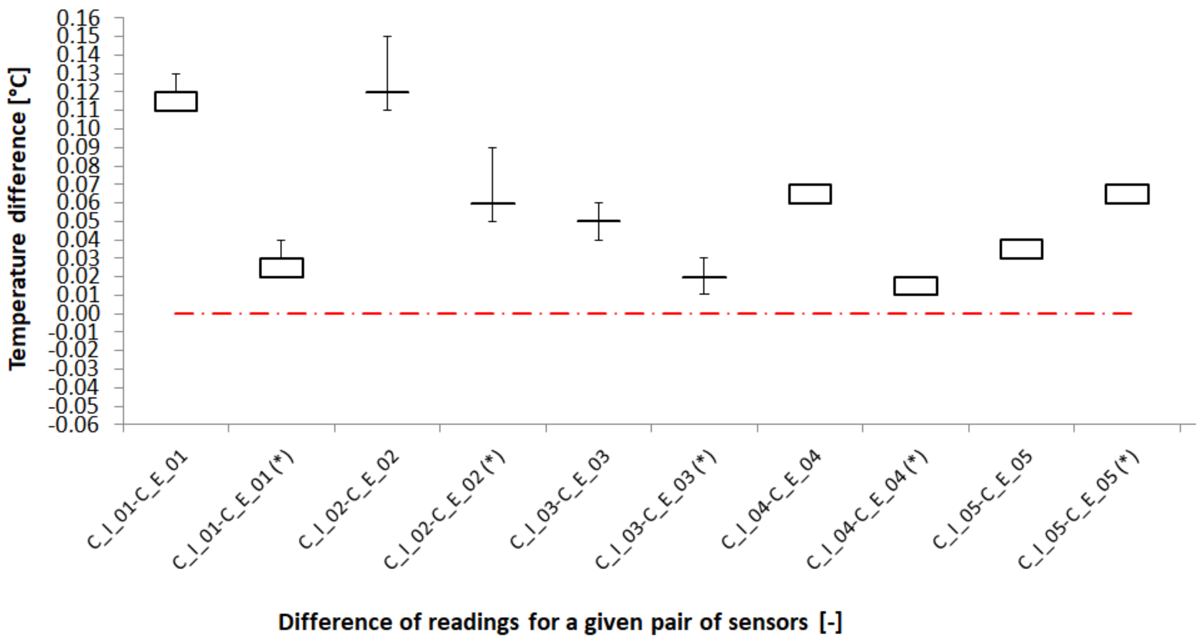

Fig. 9. Box and whisker plot for a setting of 16°C for sensors pairs 1 to 5

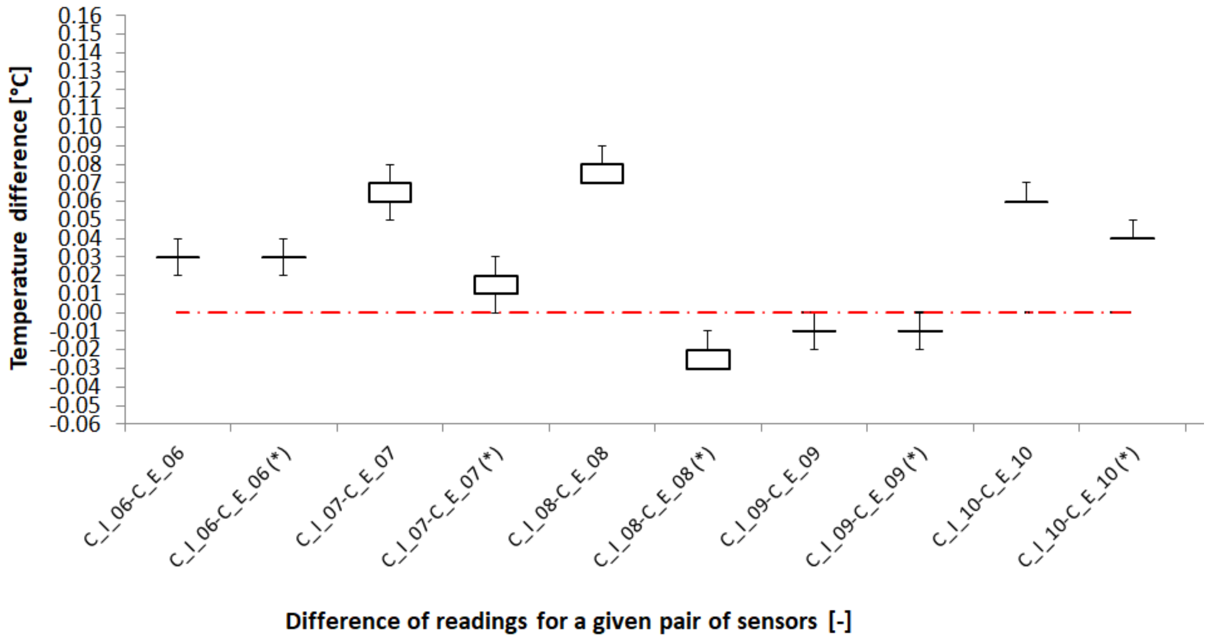

Fig. 10. Box and whisker plot for a setting of 16°C for sensors pairs 6 to 10

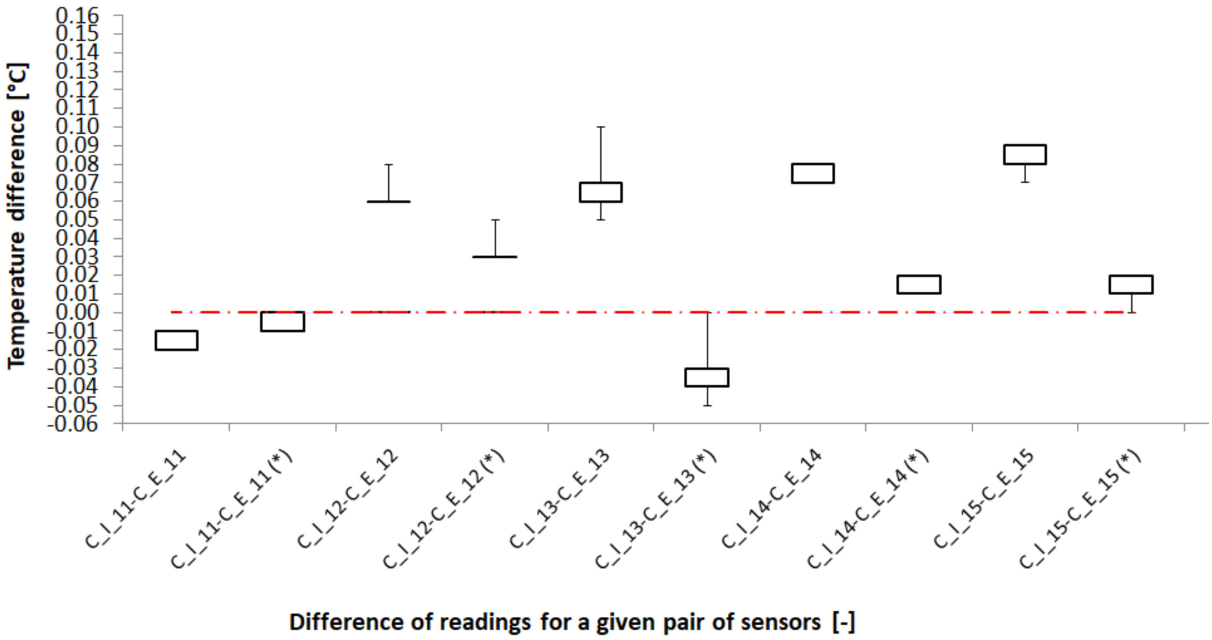

Fig. 11. Box and whisker plot for a setting of 16°C for sensors pairs 11 to 15

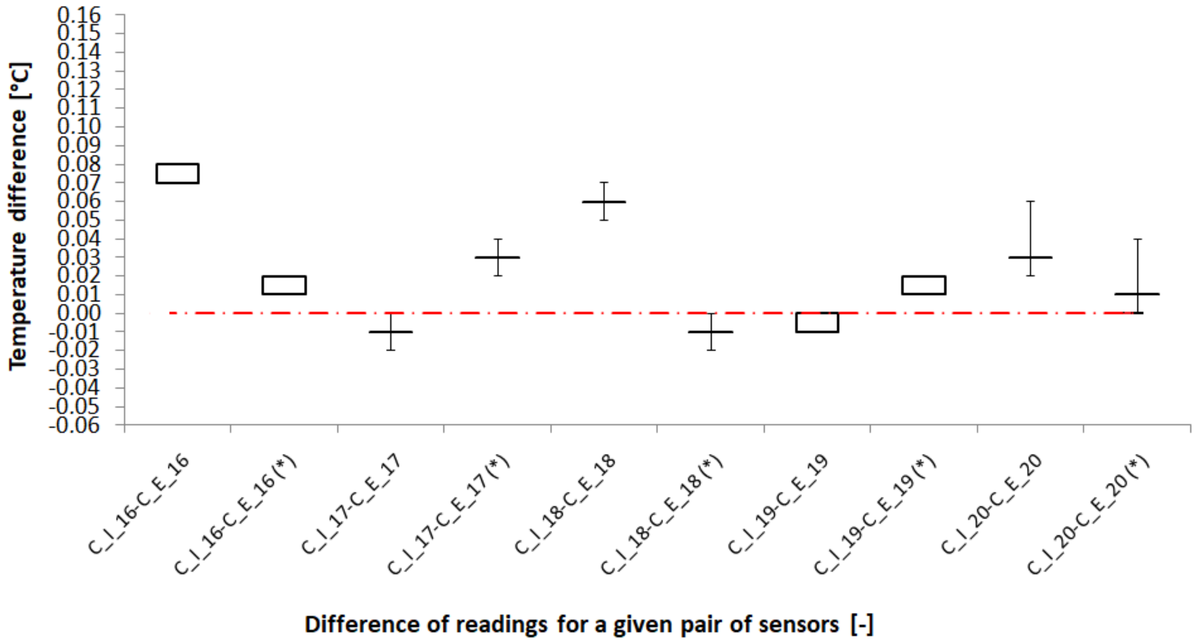

Fig. 12. Box and whisker plot for a setting of 16°C for sensors pairs 16 to 20

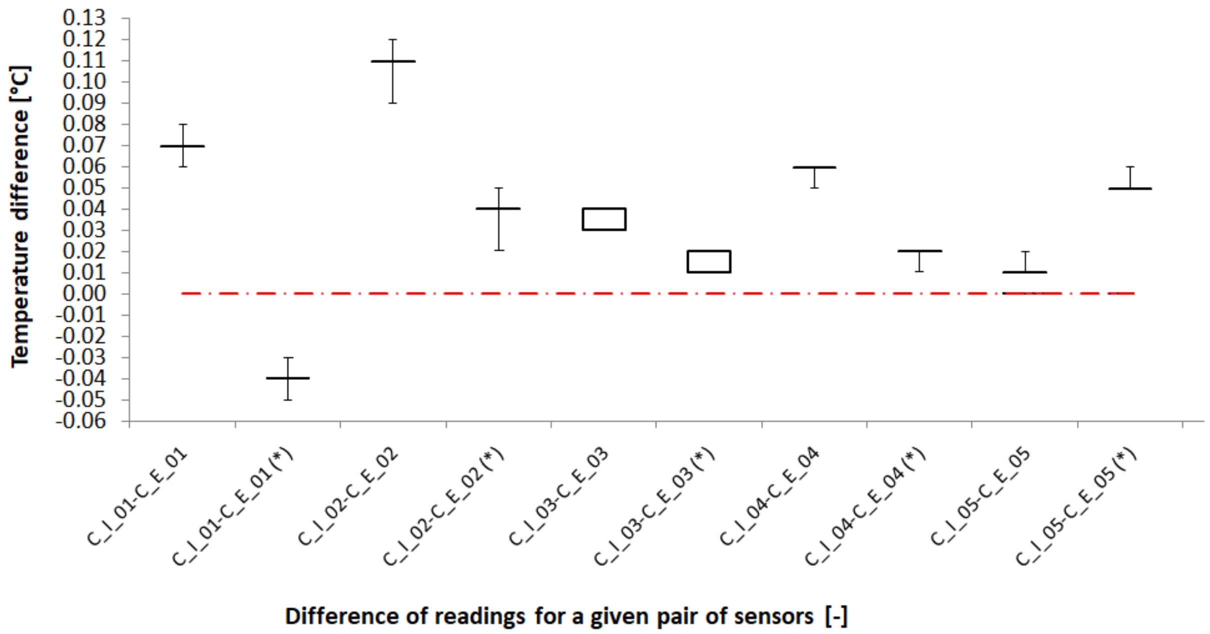

Fig. 13. Box and whisker plot for a setting of 18°C for sensors pairs 1 to 5

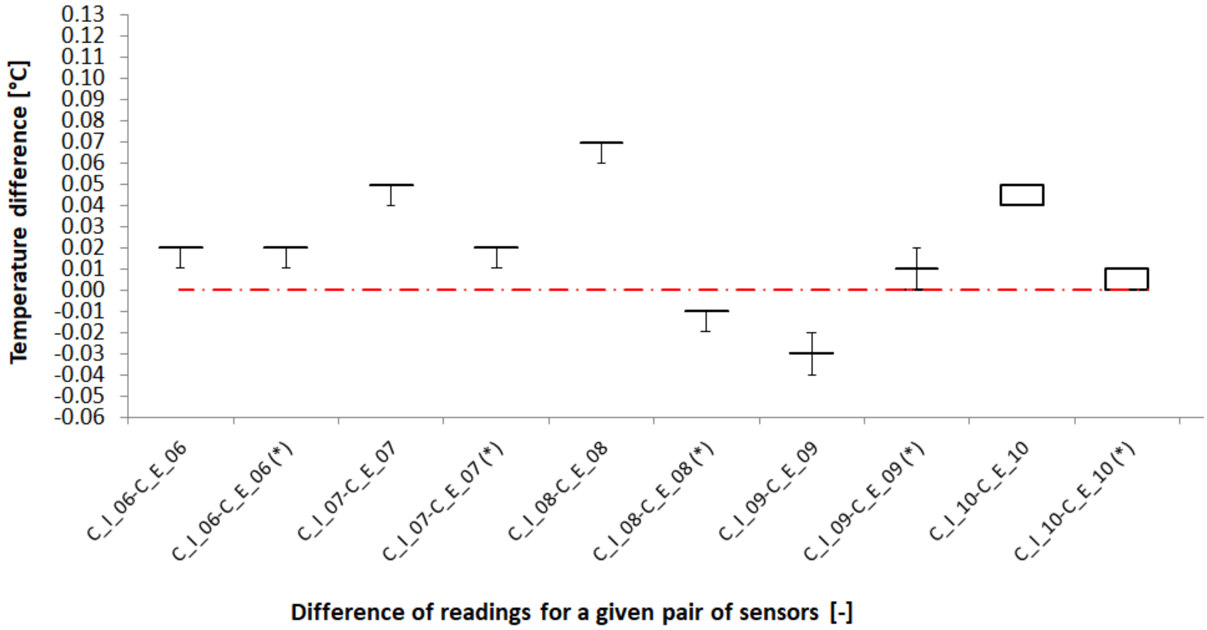

Fig. 14. Box and whisker plot for a setting of 18°C for sensors pairs 6 to 10

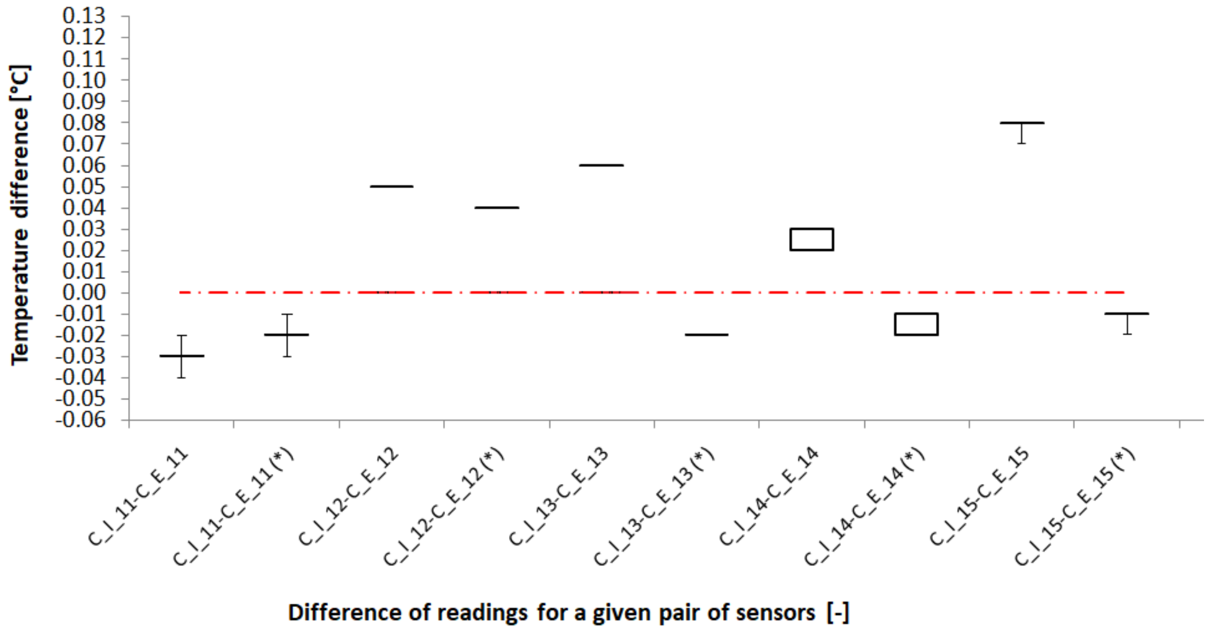

Fig. 15. Box and whisker plot for a setting of 18°C for sensors pairs 11 to 15

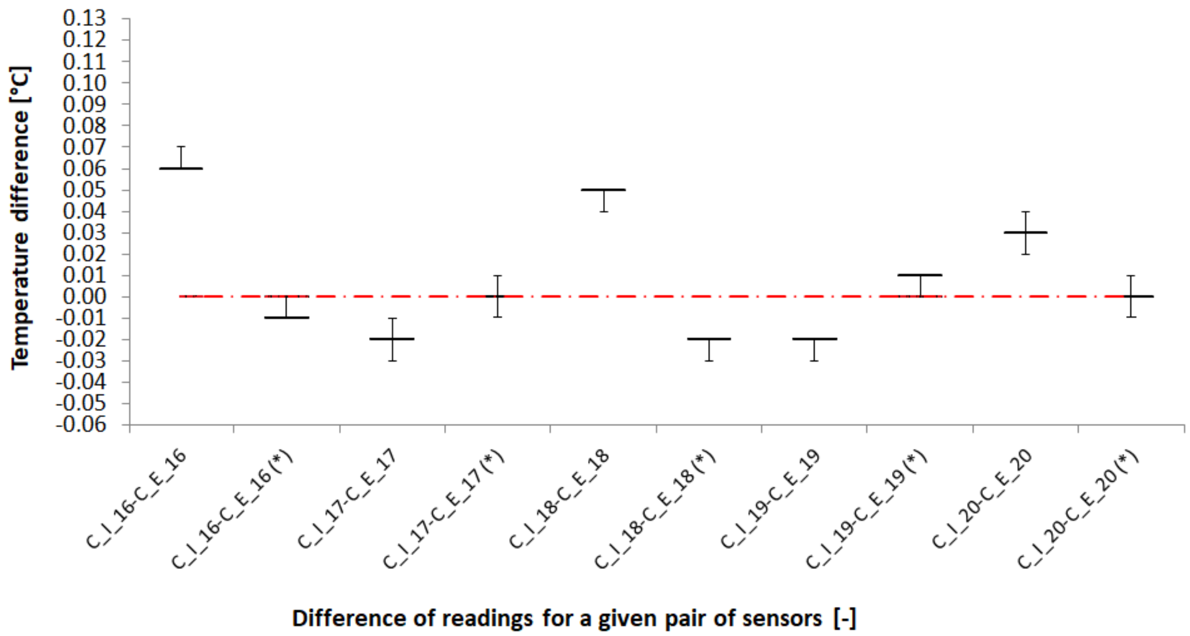

Fig. 16. Box and whisker plot for a setting of 18°C for sensors pairs 16 to 20

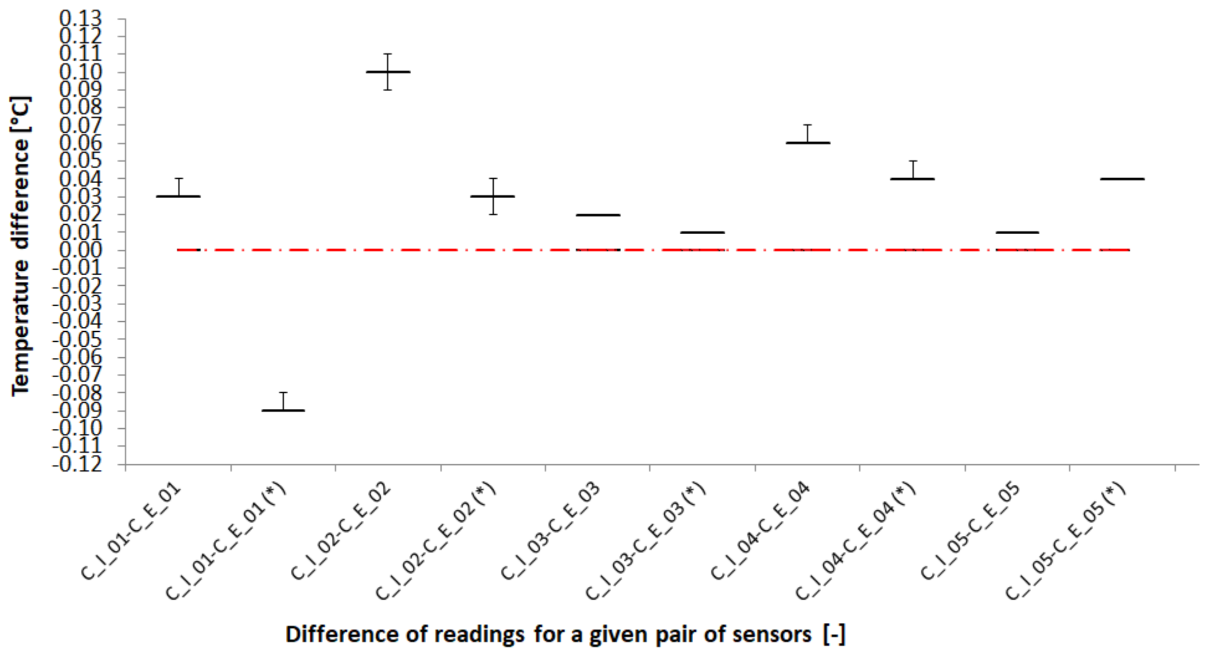

Fig. 17. Box and whisker plot for a setting of 20°C for sensors pairs 1 to 5

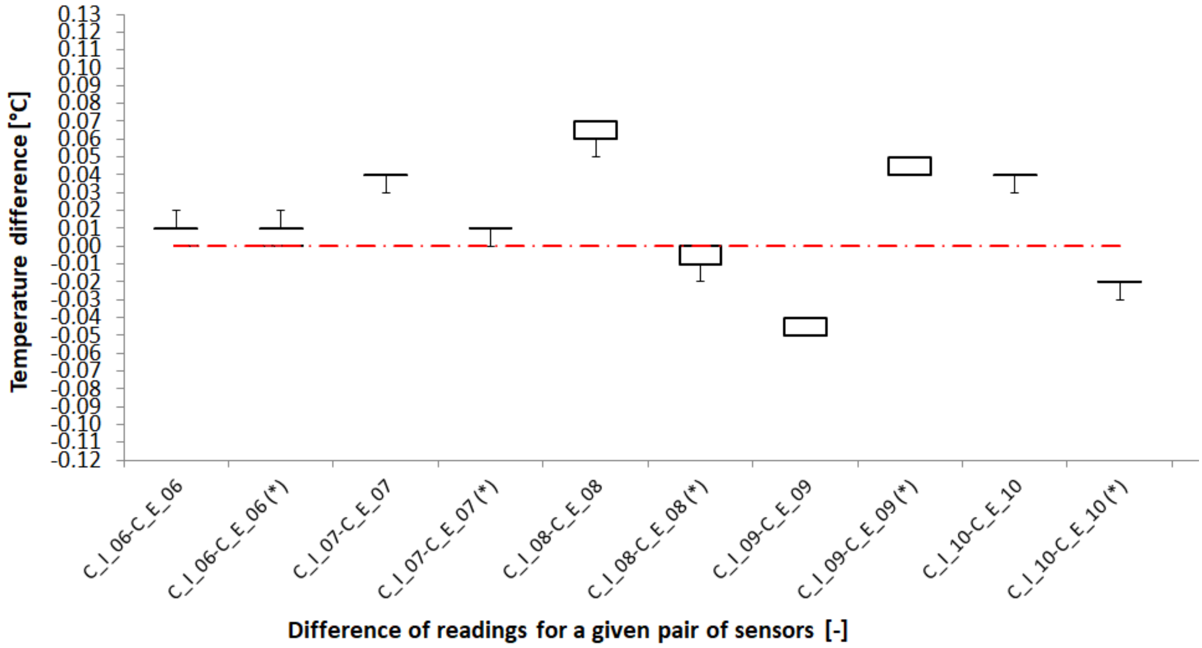

Fig. 18. Box and whisker plot for a setting of 20°C for sensors pairs 6 to 10

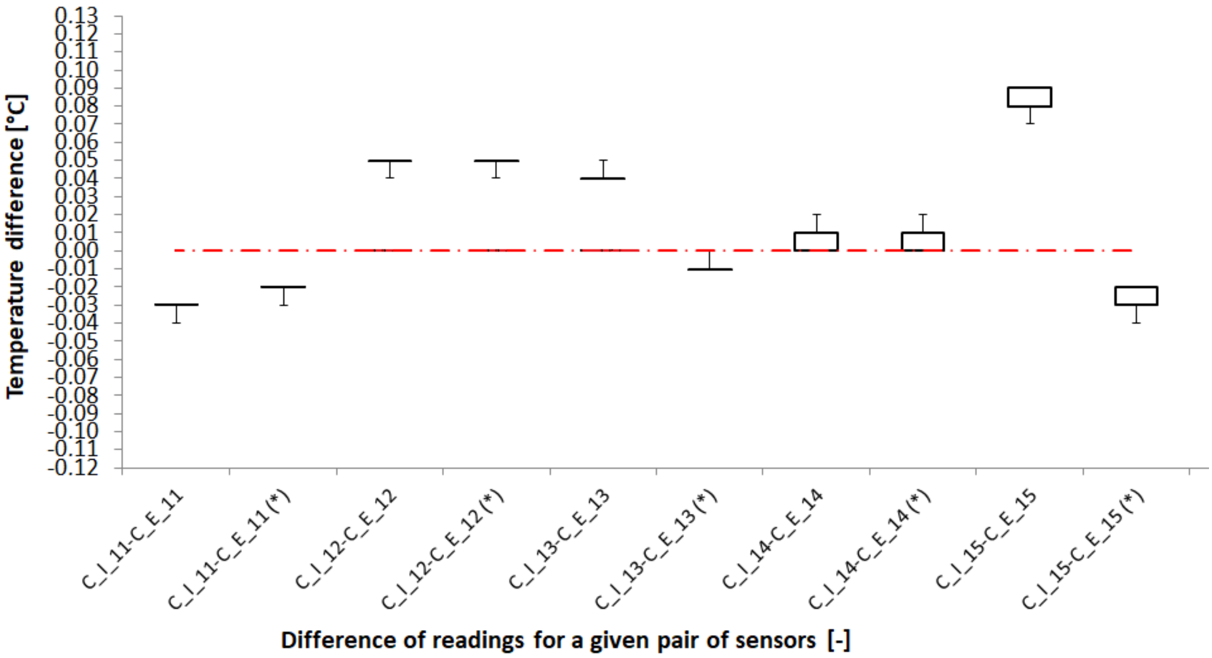

Fig. 19. Box and whisker plot for a setting of 20°C for sensors pairs 11 to 15

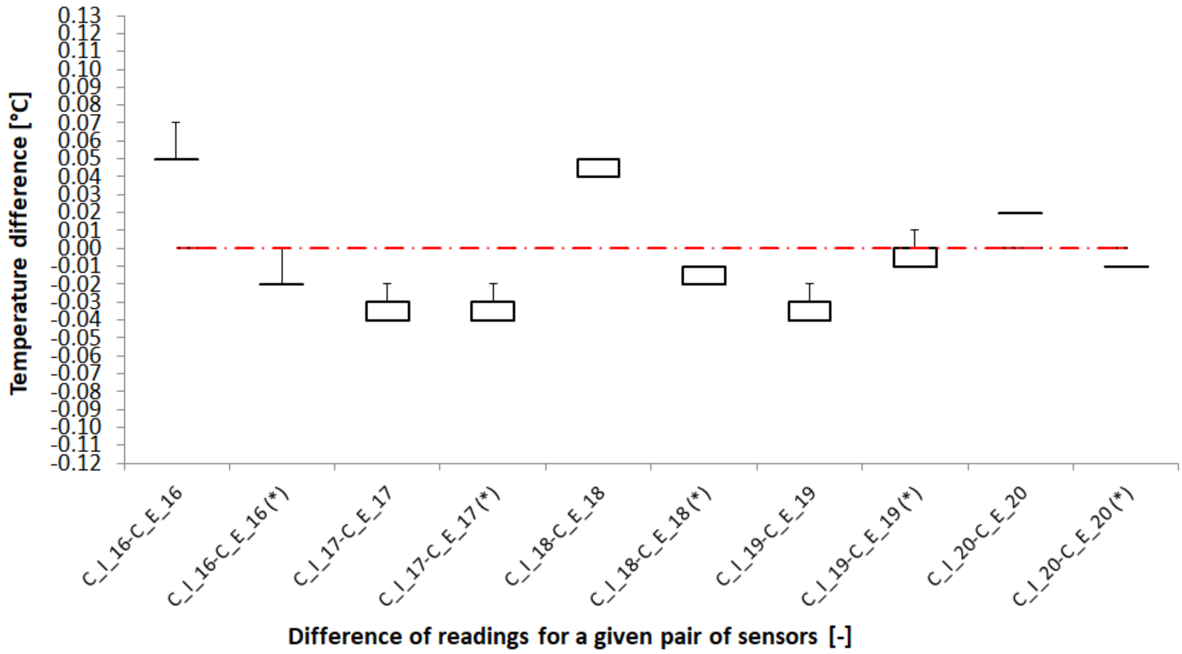

Fig. 20. Box and whisker plot for a setting of 20°C for sensors pairs 16 to 20

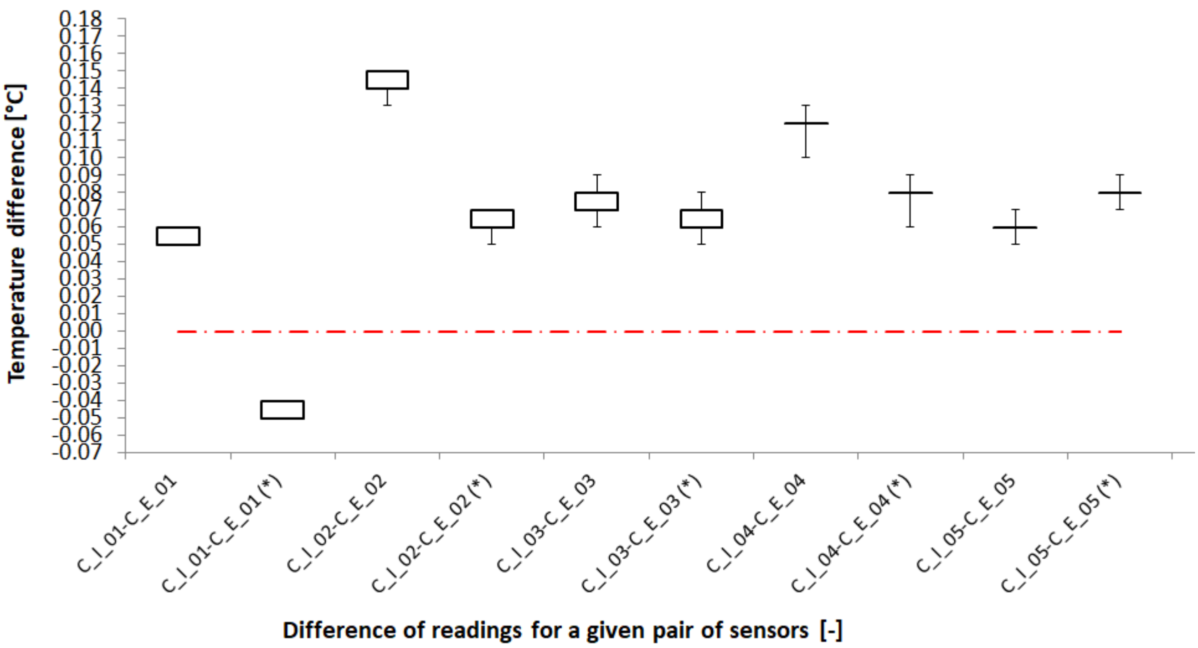

Fig. 21. Box and whisker plot for a setting of 22°C for sensors pairs 1 to 5

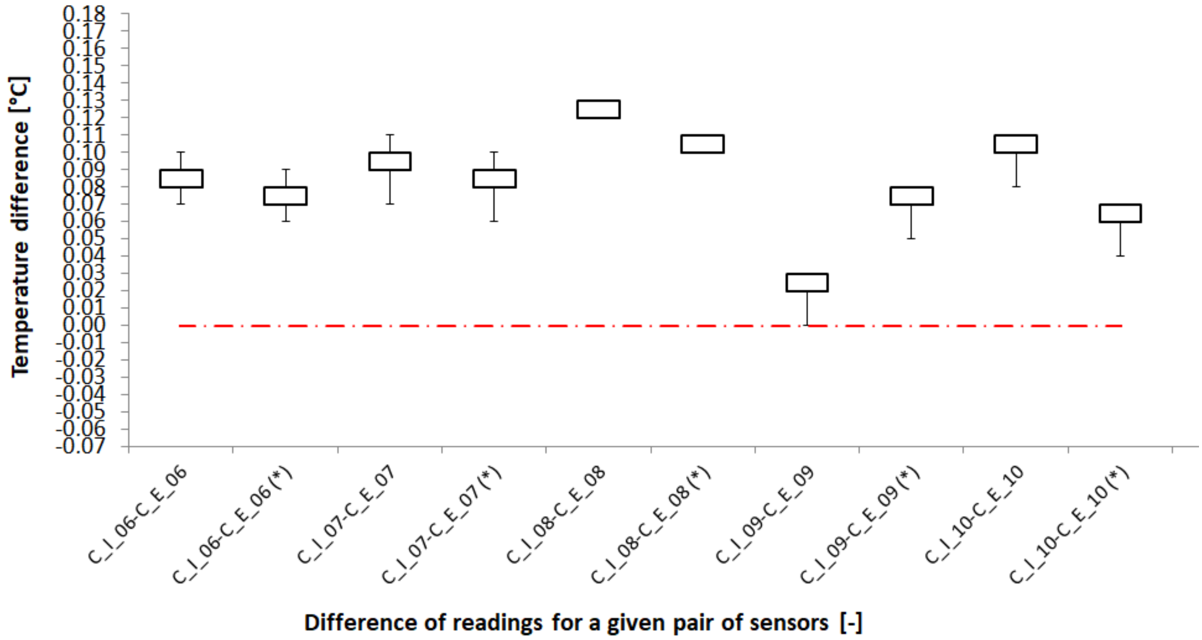

Fig. 22. Box and whisker plot for a setting of 22°C for sensors pairs 6 to 10

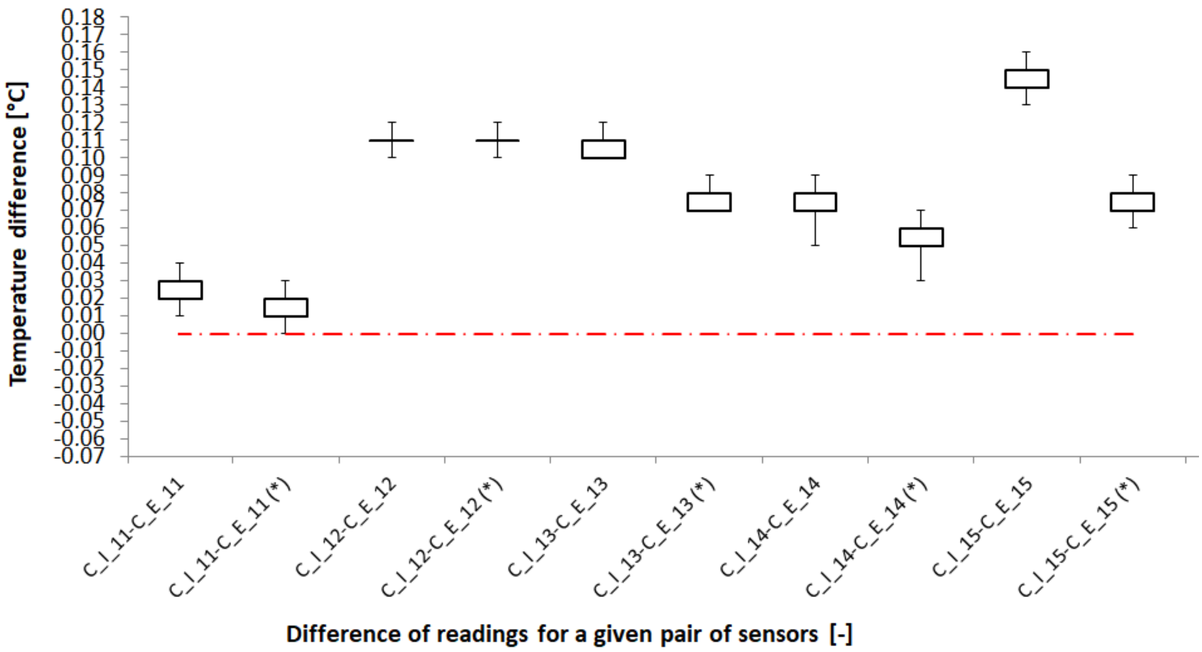

Fig. 23. Box and whisker plot for a setting of 22°C for sensors pairs 11 to 15

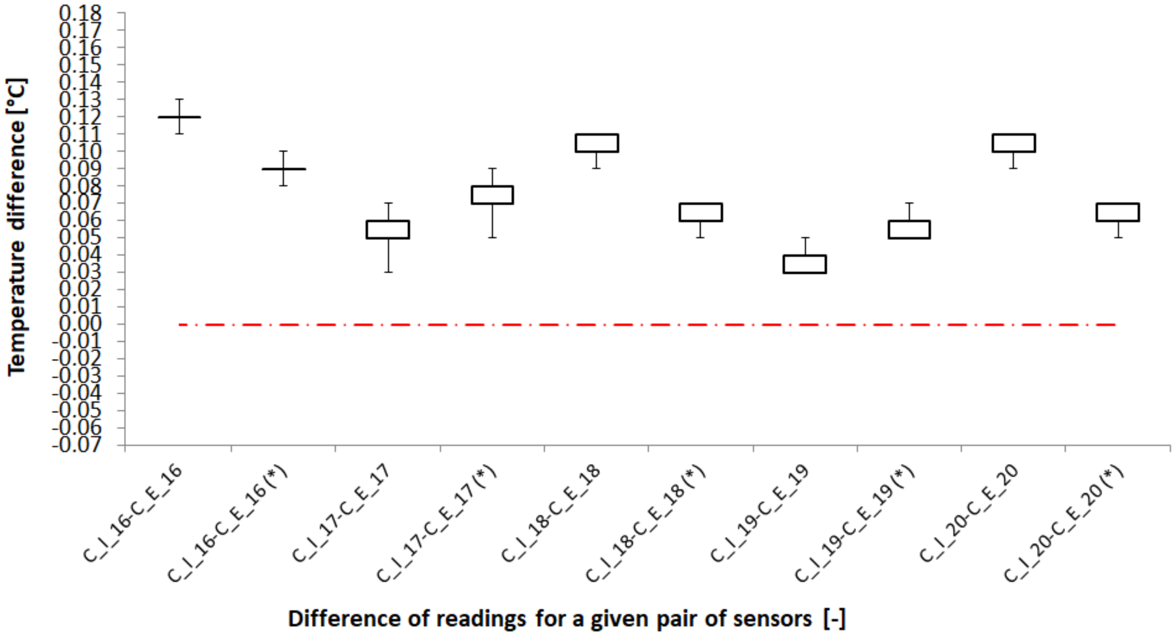

Fig. 24. Box and whisker plot for a setting of 22°C for sensors pairs 16 to 20

For differences in temperature readings between both sides of the partition, the third quartile was determined, which is interpreted in such a way that 75% of the observations are located below it. The greatest number of such cases, 32 out of 40 possible, occurred for the loop supply temperature in the concrete wall of 22°C (Fig. 21 - Fig. 24). Additionally, for some sensors maximum and minimum values were recorded for the differences, e.g. for sensors C_I_07 and C_E_07 for both supply temperatures of 16°C (Fig. 10) and 22°C (Fig. 22), in the other two settings, the distribution of differences was the same, i.e. throughout the analyzed period the sensors showed the same values whose differences were identical (Fig. 14 and Fig. 18). A similar situation was observed for sensors C_I_13 and C_E_13, but for the 22°C setting only the maximum value was registered (Fig. 23). For the pair of sensors C_I_14 and C_E_14, the distribution was always within the temperature range between which the difference was 0.01°C, regardless of the temperature setting (Fig. 11, Fig. 15 and Fig. 19); however, for the 22°C setting, maximum and minimum values were also observed (Fig. 23). The loop supply temperature in the partition for which the most situations with an even distribution of differences occurred was 18°C, then 34 such cases out of 40 were recorded (Fig. 13 - Fig. 16). For sensors C_I_12 and C_E_12, the distribution of differences was the same regardless of the temperature setting in the cooling bath thermostat; nevertheless, there were individual situations when it was possible to record extreme values (minimum - for 20°C in Fig. 19, maximum - for 16°C in Fig. 11 or both - for 22°C in Fig. 23).

Taking absolute error of the sensors into account in the measurements made the differences in the temperature indications closer to the expected level, i.e. the value of 0. For some sensors it was possible to achieve this: C_I_07 and C_E_07 (for the settings: 16°C in Fig. 10, 20°C in Fig. 18), C_I_08 and C_E_08 (for the setting: 20°C in Fig. 18), C_I_09 and C_E_09 (for the settings: 16°C in Fig. 10, 18°C in Fig. 14), C_I_10 and C_E_10 (for the setting: 18°C in Fig. 14), C_I_11 and C_E_11 (for the settings: 16°C in Fig. 11, 22°C in Fig. 23), C_I_13 and C_E_13 (for the settings: 16°C in Fig. 11, 20°C in Fig. 19), C_I_14 and C_E_14 (for the setting: 20°C in Fig. 19), C_I_15 and C_E_15 (for the setting: 16°C in Fig. 11), C_I_16 and C_E_16 (for the settings: 18°C in Fig. 16, 20°C in Fig. 20), C_I_17 and C_E_17 (for the setting: 18°C in Fig. 16), C_I_18 and C_E_18 (for the setting: 16°C in Fig. 12), C_I_19 and C_E_19 (for the settings: 18°C in Fig.16, 20°C in Fig. 20) and C_I_20 and C_E_20 (for the settings: 16°C in Fig. 12, 18°C in Fig. 16).

In 5 cases for sensors: C_I_01 and C_E_01 (for the setting: 20°C - Fig. 17), C_I_05 and C_E_05 (for the all settings: 16°C - Fig. 9, 18°C - Fig. 13, 20°C - Fig. 17 and 22°C - Fig. 21), C_I_09 and C_E_09 (for the setting: 22°C - Fig. 22), C_I_17 and C_E_17 (for the settings: 16°C - Fig. 12, 22°C - Fig. 24.), C_I_19 and C_E_19 (for the settings: 16°C - Fig. 12, 22°C - Fig. 24) the effect was opposite, but the differences still remained small, i.e. not exceeding 0.09°C.

For certain sensors, introducing the deviation did not change anything in the value of the temperature difference on both sides of the partition. This happened for the following sensors: C_I_06 and C_E_06 (for the settings: 16°C - Fig. 10, 18°C - Fig. 14, 20°C - Fig. 18), C_I_09 and C_E_09 (for the setting: 16°C - Fig. 10), C_I_12 and C_E_12 (for the settings: 20°C - Fig. 19, 22°C - Fig. 23), C_I_14 and C_E_14 (for the setting: 20°C - Fig. 19) and C_I_17 and C_E_17 (for the setting: 20°C - Fig. 20). In this chapter 3 should also mentioned about potential limitations of the experimental setup. During the deviation measurement the sensors were placed in calibration chamber, but during the experiment the sensors were located on the surface of concrete layer. The uniformity of the concrete layer may also important. To make readings it is necessary connected sensors to data logger by connectors. Potential limitation can resulted of measurement's equipment, for example accuracy, resolution and operating range.

4. CONCLUSIONS

Each measurement is by its nature flawed, which affects measurements taken and, consequently, conclusions drawn. Measurement errors should therefore be identified and eliminated. For systematic errors, deviations determined in the article above for temperature sensors are applied. In some cases, they were equal to the resolution of the data logger, and thus may be omitted in further analyses. Regardless of the value of such errors, including them in the correction of sensor readings makes measurements more accurate, therefore final results are closer to those expected. It was confirmed by the experiment described in this article, in which the temperature difference indicated by sensors placed in an identical place on both sides of the partition should be approximately 0. In some cases, this was achieved: 3 times (for 16°C), 0 (for 18°C), 1 time (for 20°C) and 1 time (for 22°C), but only after taking into account temperature deviations the number of cases increased to: 6 (for 16°C), 6 (for 18°C), 6 (for 20°C) and 1 (for 22°C). In 5 cases this was achieved, but only after taking into account temperature deviations the number of cases increased to 19, i.e. an almost 4-fold increase. The surface Pt100 resistance temperature sensors achieved high accuracy. The deviation values obtained values from -0.26°C to 0.07°C for the temperature range 5°C - 25°C; however the values reached the 0.00°C level for the temperature range 20°C - 25°C. Thanks to the deviation measurement, the results became more accurate, so it was worth used it in specialized measurement. In the case of not formal tests, when the high accuracy is not so important, the deviation measurement may be neglected.

ADDITIONAL INFORMATION

This work was supported by a grant number 0713/SBAD/0990 MK, awarded by Poznan University of Technology.

REFERENCES

1. Krzaczek, M and Kowalczuk, Z 2012. Gain Scheduling Control applied to Thermal Barrier in systems of indirect passive heating and cooling of buildings. *Control Engineering Practice* **20(12)**, 1325-1336. https://doi.org/10.1016/j.conengprac.2012.07.007
2. Krzaczek, M and Kowalczuk, Z 2011. Thermal Barrier as a technique of indirect heating and cooling for residential buildings. *Energy and Buildings* **43(4)**, 823-837. https://doi.org/10.1016/j.enbuild.2010.12.002
3. Krzaczek, M et al. 2019. Improved energy management technique in pipe-embedded wall heating/cooling system in residential buildings. *Applied Energy* **254**, 113711. https://doi.org/10.1016/j.apenergy.2019.113711
4. Dharmasastha, K et al. 2020. Experimental investigation of thermally activated glass fibre reinforced gypsum roof. *Energy and Buildings* **228**, 110424. https://doi.org/10.1016/j.enbuild.2020.110424
5. Zhou, L and Li, C 2020. Study on thermal and energy-saving performances of pipe-embedded wall utilizing low-grade energy. *Applied Thermal Engineering* **176**, 115477. https://doi.org/10.1016/j.applthermaleng.2020.115477
6. Kisilewicz, T et al. 2019. Active thermal insulation as an element limiting heat loss through external walls. *Energy and Buildings* **205**, 109541. https://doi.org/10.1016/j.enbuild.2019.109541
7. Bíró-Szigeti, S 2014. Strategy Support of Residential Energy Saving Investments in Hungary with the Method of Technology Roadmapping. *Acta Polytechnica Hungarica* **11(2)**, 167-186. https://doi.org/10.2478/msr-2020-0001
8. Dragicevic, S et al. 2013. Measurement and Simulation of Energy Use in a School Building. *Acta Polytechnica Hungarica* **10(2)**, 109-120. https://doi.org/10.2478/msr-2020-0001
9. Azzopardi, B et al. 2023. Energy Transition in Power, Heating and Transport Sectors, based on the Majority of RES and Energy Storage. *Acta Polytechnica Hungarica* **20(10)**, 217-231. https://doi.org/10.12700/APH.20.10.2023.10.13
10. Piwowar, A et al. 2023. The Potential of Wind Energy Development in Poland in the Context of Legal and Economic Changes. *Acta Polytechnica Hungarica* **20(10)**, 145-156. https://doi.org/10.12700/APH.20.10.2023.10.9
11. Antczak-Jarząbska, R and Krzaczek M 2016. Assessment of natural ventilation system for a typical residential house in Poland. *Civil and Environmental Engineering Reports* **22(3)**, 25-44. https://doi.org/10.1515/ceer-2016-0032
12. Witkovský, V and Frollo, I 2020. Measurement Science is the Science of Sciences – There is no Science without Measurement. *Measurement Science Review* **20(1)**, 1-5. https://doi.org/10.2478/msr-2020-0001
13. Cieślikiewicz, Ł et al. 2019. Development of the experimental stand with centrally located specimen for the investigation of heat and moisture phenomena in porous building materials. *Civil and Environmental Engineering Reports* **29(1)**, 53-65. https://doi.org/10.2478/ceer-2019-0005
14. Małek, MT 2022. *Wpływ parametrów przegrody aktywowanej termicznie na komfort cieplny i zużycie energii [The influence of parameters of a thermally activated of building structure on thermal comfort and energy consumption]*. [Doctoral dissertation, Poznan University of Technology]. https://bip.put.poznan.pl/artykul/mgr-inz-maria-malek
15. Małek, MT and Koczyk H 2023. Influence of environmental conditions on the temperature distribution in a pipe-embedded wall (with a thermally activated element) – analysis of the measurement results. *Instal* **10**, 9-14. DOI 10.36119/15.2023.10.2
16. IEC 60751:2022. International Standard. Industrial platinum resistance thermometers and platinum temperature sensors.

17. Jovanović, J and Denić, D 2021. Mixed-mode Method Used for Pt100 Static Transfer Function Linearization. *Measurement Science Review* **21(5)**, 142-149. https://doi.org/10.2478/msr-2021-0020
18. Piechowski, L et al. 2021. The Precise Temperature Measurement System with Compensation of Measuring Cable Influence. *Energies* **14(24)**, 8214. https://doi.org/10.3390/en14248214
19. Echarri, V et al. 2017. Thermal Transmission through Existing Building Enclosures: Destructive Monitoring in Intermediate Layers versus Non-Destructive Monitoring with Sensors on Surfaces. *Sensors* **17(12)**, 2848. https://doi.org/10.3390/s17122848