Influence of environmental conditions on the temperature distribution in a pipe-embedded wall (with a thermally activated element) – analysis of the measurement results

Wpływ warunków zewnętrznych na rozkład temperatury w ścianie z wbudowanymi przewodami (z elementem aktywowanym termicznie) – analiza wyników pomiarów

MARIA TERESA MAŁEK, HALINA KOCZYK

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The article presents the influence of environmental conditions on the temperature distribution in a pipe-embedded wall. For this purpose, measurements were taken on a test stand, a concrete wall with thermoplastic pipes (with a thermally activated element) embedded inside it in its symmetry axis. The wall is insulated with polystyrene on both sides. Additionally, as a result of its closure in an insulated casing made of oriented strand board (OSB), 2 air zones were created on both sides of the wall. The concreted loop was connected to a cooling bath thermostat used to set the supply temperature in the pipes. In the case of air, its supply to the air zones was provided by ventilation ducts mounted to the housing. The tests consisted of two stages: stabilization of the temperature on the surface of the partition between the concrete and polystyrene layer and the reaction of the structure to a variable outside temperature when fresh outside air was supplied to one of the air zones. All measurements were performed for the following settings: 16°C, 18°C, 20°C and 22°C. It was noted that in order to achieve an even temperature on the wall surface, 24 hours were required from the moment the cooling bath thermostat was turned on. When outside air is supplied to one of the air zones, this partition is resistant to temperature fluctuations, and only after about 6 hours a temperature change of 0.1°C takes place for sensors located at the extreme measurement points and in the other air zone (without air inflow).
Keywords: pipe-embedded wall, thermally activated element, temperature distribution, temperature measurement, Pt100 temperature sensors

W artykule przedstawiono wpływ warunków otoczenia na rozkład temperatury w ścianie z wbudowanymi przewodami. W tym celu wykonano pomiary na stanowisku badawczym, betonowej ścianie z przewodami tworzywowymi (z elementem aktywowanym termicznie) wbudowanymi wewnątrz niej w jej osi symetrii. Ściana ta została z obu stron zaizolowana styropianem. Dodatkowo w wyniku zamknięcia jej w zaizolowanej obudowie wykonanej z płyt OSB powstały dwie strefy powietrzne z obu stron ściany. Zabetonowana pętla została podłączona do ultratermostatu, służącego do nastawienia temperatury zasilania w przewodach. W przypadku powietrza jego dostarczenie do stref powietrznych zapewniały zamontowane do obudowy przewody wentylacyjne. Badania składały się z dwóch etapów: stabilizacji temperatury na powierzchni przegrody między warstwą betonu a styropianu oraz reakcji konstrukcji na zmienną temperaturę zewnętrzną podczas dostarczania do jednej ze stref powietrznych świeżego powietrza zewnętrznego. Wszystkie pomiary odbywały się dla nastaw: 16°C, 18°C, 20°C i 22°C. Zauważono, że w celu osiągnięcia wyrównanej temperatury na powierzchni ściany potrzeba 24 godzin od momentu włączenia ultratermostatu. W przypadku dostarczania powietrza zewnętrznego do jednej ze stref powietrznych, przegroda ta jest odporna na wahania temperatury i dopiero po około 6 godzinach następuje zmiana temperatury o 0,1°C dla czujników zlokalizowanych w skrajnych punktach pomiarowych oraz w drugiej strefie powietrznej (bez napływu powietrza).
Słowa kluczowe: ściana z wbudowanymi przewodami, element aktywowany termicznie, rozkład temperatury, pomiar temperatury, czujniki temperatury Pt100

Maria Teresa Małek, Ph.D., ORCID: https://orcid.org/0000-0002-6731-1183, Halina Koczyk, Prof., Ph.D., D.Sc., ORCID: https://orcid.org/0000-0002-3818-658X – Institute of Environmental Engineering and Building Installations, Faculty of Environmental Engineering and Energy, Poznan University of Technology, Poznań, Poland. Adres do korespondencji/ Corresponding author: maria.malek@put.poznan.pl

Introduction

Energy-saving systems integrated with the building structure, such as pipe-embedded wall, allow to reduce energy consumption regardless of the season. This was confirmed by scientists Zhou and Li [1] in their research on a wall made of insulating boards: one made of polystyrene with pipes mounted on it, and the other serving as a cover and made of polyphenylene. In order to perform analyses for variable external conditions, two heating plates were installed on the measuring stand, which, thanks to the connection with a temperature regulator, were able to simulate the cooling and heating season. In their analyses, the researchers achieved a decrease of 13% and 33%, respectively, of heat gains during cooling and heat losses during heating.

Other benefits of using pipe-embedded wall, this time a reinforced concrete wall with pipes inside it and insulated from the outside with polystyrene, were indicated by scientists Krzaczek et al. [2]. They monitored real building measurements for the entire system: a thermal barrier cooperating with a solar collector and a ground heat storage system controlled by a fuzzy logic program. Researchers have demonstrated the possibility of maintaining changes in internal air temperature at a level not exceeding 0.8°C regardless of the season and reducing the temperature drop on the internal surface of the room partitions to 0.6°C in the winter season and 0.4°C in the summer season.

Similar conclusions regarding the temperature on the surface of the partition, in this case, the subject of the analysis was a roof with concreted copper pipes, were drawn by the researchers Dharmasastha et al. [3]. For the internal roof surface of a detached building consisting of one room, they achieved a decrease in daily temperature fluctuations by 5.1°C and 6.7°C, depending on the location on the roof surface.

Kisilewicz et al. presented other tests, also carried out in a real building, in which the pipes embedded in the partition structure were used [4]. In this work, the solution consisted in placing polyethylene pipes in the reinforced concrete layer insulated with polystyrene on both sides. Thanks to this approach, it was possible to reduce heat losses by an average of 63% compared to the use of insulation alone.

In addition to the tests carried out on experimental stands or in real facilities, theoretical analyses are performed on the basis of the available software or own numerical model.

Researchers Krzaczek et al. used the ABAQUS program to present the concept of a system based on a thermal barrier [5]. In this publication, they demonstrated the key importance of the number of layers and the type of wall construction materials. In such a case, the wall with a thermal barrier should consist of at least three layers, insulated on both sides by a massive structure with a heating loop. The entire system was controlled by the SVC system controlling the temperature of the supply of the thermal barrier from the ground exchanger and the mass flow of the medium.

Scientists Šimko et al. [6] presented a modification of the solution consisting in placing the pipes in the outer insulation layer in a two-layer partition (not counting the finishing layer – plaster). Thanks to the simulations carried out in the program of one of the co-authors of Šikula, they compared the wall structure with the other two variants, in which the heating loop is placed in the concrete layer or in the interior plaster. The partition has been tested for two operating modes: heating and thermal barrier. In the case of the heating function, comparing the heating efficiency with the other two solutions, it decreased by: 50% in relation to the pipes inside the concrete and 63% for the pipes inside the plaster. In a situation where the thermally activated element acts as a thermal barrier, scientists confirmed the reduction of heat loss and hence the reduction of insulation thickness. Therefore, this solution is advantageous as a way to modernize buildings.

Two of the co-authors, Krajčík and Šikula, developed the previous topic adding the issue of cooling [7]. When the pipes were placed in the layer of the internal plaster, they obtained a higher cooling capacity compared to the pipes inside the concrete. Additionally, when combining plaster with a material with low thermal conductivity, they obtained a short reaction time required to change the cooling capacity. The parameter that influences the cooling capacity in such a solution is the spacing between the pipes, while for the variant with the pipes placed in the concrete layer, it is the thickness of the insulation. Researchers also confirmed the ability to store energy and the possibility of its later use for the concrete layer with pipes embedded inside it.

A theoretical analysis on the thermal barrier efficiency was presented by Szaflik [8]. He considered 2 parameters of such a solution affecting its efficiency: the distance between the pipes and the thermal conductivity coefficient of the barrier material. The article also confirmed the conclusions contained in previous publications that despite the increase in the total energy given off by a partition with a thermal barrier compared to a classic wall (without a thermal barrier) [9] heating costs may decrease [10].

Test stand description

The pipe-embedded wall that was tested is a 15 cm thick concrete wall with dimensions of 202 cm x 202 cm (length x height) with a loop inside it, in its axis of symmetry, arranged in meander form made of 20x2mm thermoplastic pipes. The concrete partition was insulated on both sides with 13 cm thick polystyrene and then closed in a casing made of oriented strand board (OSB), thus creating two closed air zones 30.5 cm wide. In order to reduce the impact of the interior of the laboratory hall on the measuring stand, the casing was also insulated with 10 cm thick polystyrene, and the concrete wall was fixed 10 cm above the hall floor, thus enabling the resulting air gap to be insulated with XPS extruded polystyrene. The experimental stand was expanded with ventilation ducts along with fans ensuring air inlet and exhaust from the air zones and throttles used to cut off the air supply. In the case of the heating loop, it was connected to a cooling bath thermostat that allows the supply temperature and the pump rotational speed to be set. The diagram and photo of the test stand are shown in the figures below (Fig. 1 and in Fig.2).

The temperature on the surface of the concrete wall under the polystyrene layer

Fig. 1. Diagram of the test stand
Rys. 1. Schemat stanowiska badawczego

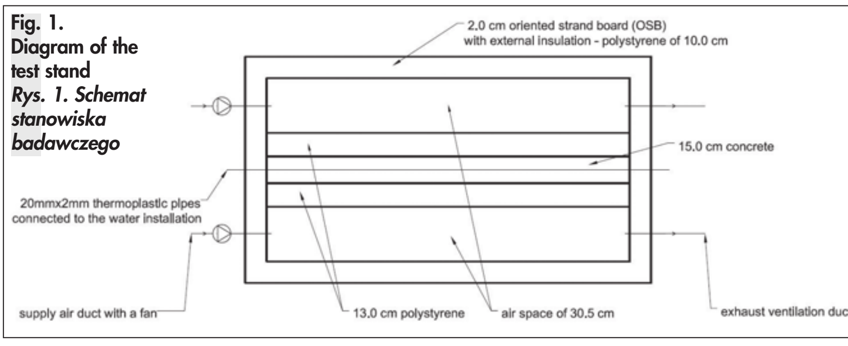

Fig. 2.
Photo of the test stand [11]
Rys. 2. Zdjęcie stanowiska badawczego [11]

was measured using Pt100 temperature sensors with the accuracy class provided by the manufacturer 1/3B. The arrangement of 20 sensors on both sides of the partition is shown in the drawings: Fig. 3 and Fig. 4. The designation B refers to the measurement on the concrete surface, while W or Z to the location on a specific side of the air zone (internal or external). The temperature in the air zones was also measured with sensors with the symbols POW_Z_1 and POW_W_1 (POW – air, and the meaning of the abbreviation Z and W as above). The dimensions in the figures are given in centimeters.

Method of measurement

Each measurement cycle carried out for the cooling bath thermostat temperature setting: 16°C, 18°C, 20°C and 22°C consisted of two test stages:

1. supplying the loop with a medium of constant temperature and flow, but without air circulation in the air zones, until the temperature stabilization on the partition surface is achieved,
2. after reaching the stabilized state, turning on the fan in the outdoor zone and blowing the outside air to the air zone.

The sensor readings were recorded every 5 seconds, while the water flow through the heating loop was measured by the weighting method at the maximum setting.

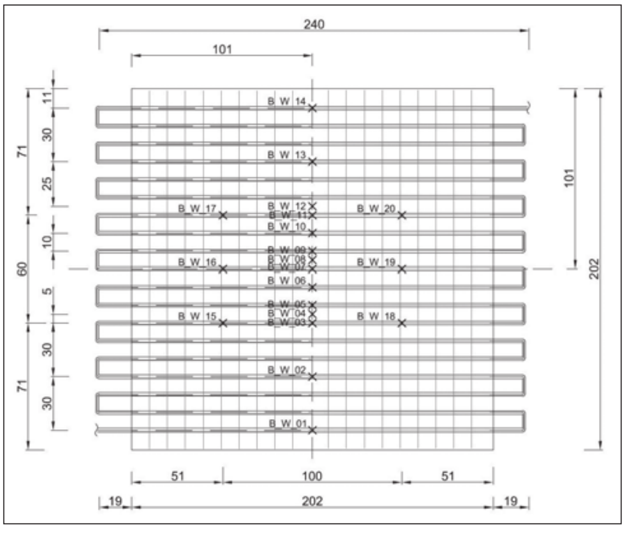

Fig. 3.
Arrangement of B_W sensors on the concrete surface under the polystyrene layer from the side of the internal air zone [11]
Rys. 3. Rozmieszczenie czujników B_W na powierzchni betonu pod warstwą styropianu od strony strefy powietrznej wewnętrznej [11]

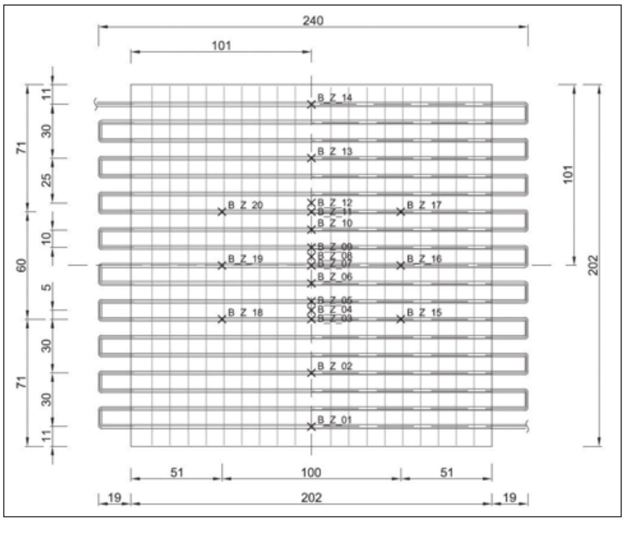

Fig. 4.
Arrangement of B_Z sensors on the concrete surface under the polystyrene layer from the side of the external air zone [11]
Rys. 4. Rozmieszczenie czujników B_Z na powierzchni betonu pod warstwą styropianu od strony strefy powietrznej zewnętrznej [11]

Results

The article presents the results of temperature measurements on the concrete surface under the polystyrene layer and in air zones during different temperature settings of the cooling bath thermostat. Due to the similar temperature at some measurement points on the concrete wall and the need to maintain clarity in presenting the results, the indications for sensors located in its axis of symmetry were selected:

- B_W_07 and B_Z_07 – located in the middle of the wall height (central),
- B_W_14 and B_Z_14 – extreme upper,
- B_W_01 and B_Z_01 – extreme lower,
- B_W_11 and B_Z_11 – located 30 cm above the central sensor,
- B_W_03 and B_Z_03 – located 30 cm below the central sensor.

In the case of flow measurements using the weighting method for measurement series, average values for the given temperature settings were obtained: 16°C equal to 4.53 l/min, 4.54 l/min in the case of 18°C, and 4.60 l/min for 20°C while at 22°C it was 4.59 l/min for the period of temperature stabilization on the partition surface. However, similar values obtained for the period of exposure to the outside air: 4.54 l/min (16°C), 4.53 l/min (18°C), 4.59 l/min (20°C) and 4.60 l/min (22°C).

The period of temperature stabilization on the partition surface

The graphs: Fig. 5 – Fig. 9 show the indications of temperature sensors at points on the concrete-polystyrene layer boundary when feeding the loop with a medium of different temperatures. The period presented in the graphs covers 25 hours from the moment of switching on the cooling bath thermostat until the temperature stabilization on the surface of the partition is achieved. The day (24 h) is sufficient to achieve the stabilization state. Sensors, which indicated similar value to each other with a difference of both sides of the wall only 0.01°C or 0.02°C regardless of the cooling bath thermostat temperature setting, they are, which were located centrally on the partition surface (B_W_07 and B_Z_07). Sensors located at the extreme lower place on the partition surface (B_W_01 and B_Z_01) recorded values that differ for each other by – 0.09°C for the setting of 20°C and 22°C and they were the greatest discrepancy between the inside and outside sides of the partition, these values are lower than 0.1°C.

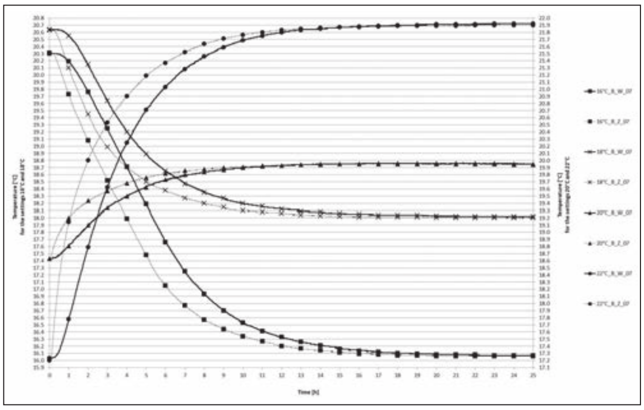

Fig. 5.
Temperature course for sensors B_W_07 and B_Z_07 for the settings: 16°C, 18°C, 20°C and 22°C until the temperature stabilization on the partition surface
Rys. 5. Przebieg temperatury dla czujników B_W_07 i B_Z_07 dla nastaw: 16°C, 18°C, 20°C i 22°C do momentu uzyskania stabilizacji temperatury na powierzchni przegrody

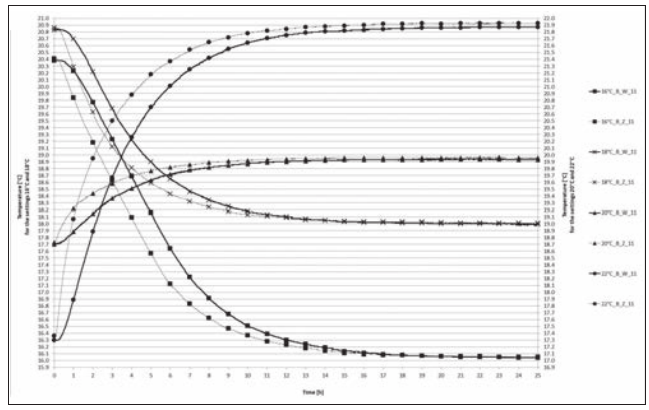

Fig. 8.
Temperature course for sensors B_W_11 and B_Z_11 for the settings: 16°C, 18°C, 20°C and 22°C until the temperature stabilization on the partition surface
Rys. 8. Przebieg temperatury dla czujników B_W_11 i B_Z_11 dla nastaw: 16°C, 18°C, 20°C i 22°C do momentu uzyskania stabilizacji temperatury na powierzchni przegrody

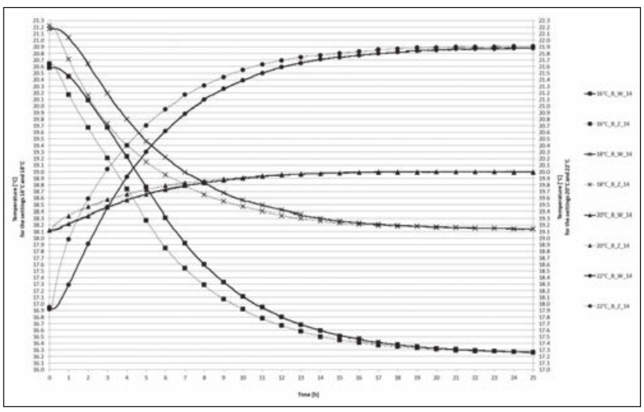

Fig. 6.
Temperature course for sensors B_W_14 and B_Z_14 for the settings: 16°C, 18°C, 20°C and 22°C until the temperature stabilization on the partition surface
Rys. 6. Przebieg temperatury dla czujników B_W_14 i B_Z_14 dla nastaw: 16°C, 18°C, 20°C i 22°C do momentu uzyskania stabilizacji temperatury na powierzchni przegrody

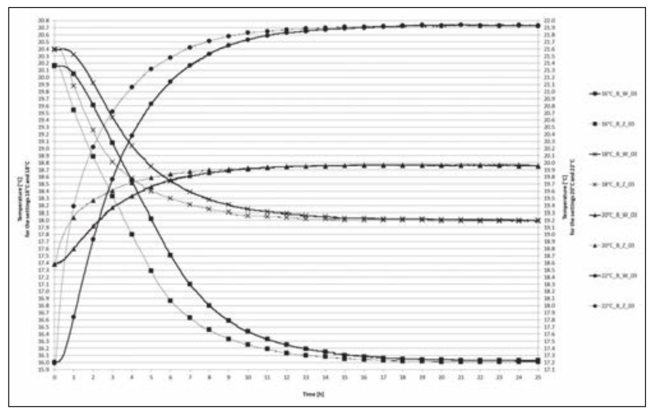

Fig. 9.
Temperature course for sensors B_W_03 and B_Z_03 for the settings: 16°C, 18°C, 20°C and 22°C until the temperature stabilization on the partition surface
Rys. 9. Przebieg temperatury dla czujników B_W_03 i B_Z_03 dla nastaw: 16°C, 18°C, 20°C i 22°C do momentu uzyskania stabilizacji temperatury na powierzchni przegrody

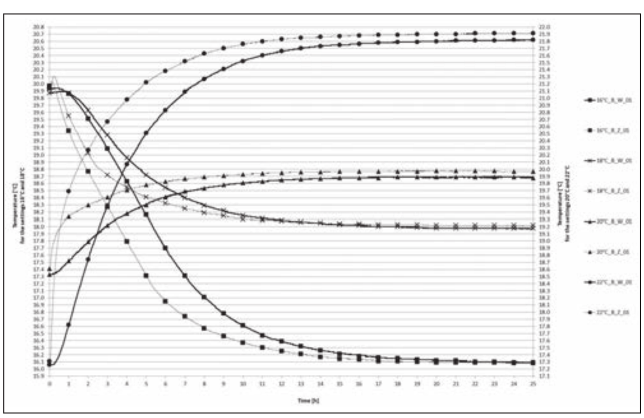

Fig. 7.
Temperature course for sensors B_W_01 and B_Z_01 for the settings: 16°C, 18°C, 20°C and 22°C until the temperature stabilization on the partition surface
Rys. 7. Przebieg temperatury dla czujników B_W_01 i B_Z_01 dla nastaw: 16°C, 18°C, 20°C i 22°C do momentu uzyskania stabilizacji temperatury na powierzchni przegrody

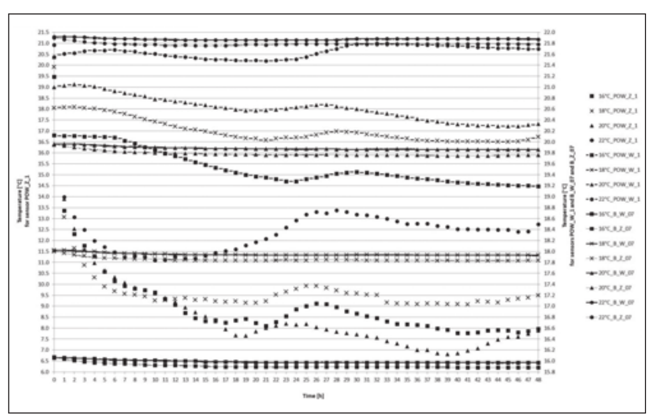

Fig. 10.
Temperature course for sensors POW_W_1 and B_W_07 and B_Z_07 for the settings: 16°C, 18°C, 20°C and 22°C for variable outside air temperature
Rys. 10. Przebieg temperatury dla czujników POW_W_1 oraz B_W_07 i B_Z_07 dla nastaw: 16°C, 18°C, 20°C i 22°C dla zmiennej temperatury powietrza zewnętrznego

The period of exposure to the outside air

The reaction of the partition structure to changing external temperature is shown in the graphs: Fig. 10 – Fig. 14. Apart from the temperature courses at the points of contact between the concrete partition and the polystyrene layer, the drawings show the variability of the external temperature in the air zone inside the experimental stand with a sensor with the symbol POW_Z_1 and the internal temperature in the second air zone (sensor POW_W_1).

Regardless of the location of the measuring sensor on the surface of the concrete wall and its supply temperature, a delay was noticed in the partition's response to changing outside air temperature. Table 1 summarizes the reading time measured

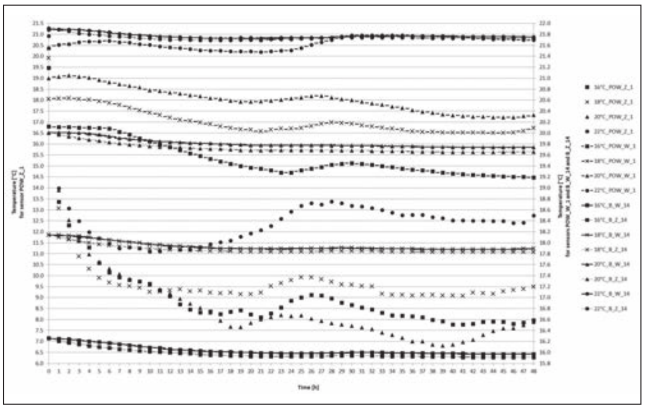

Fig. 11.
Temperature course for sensors POW_W_1 and B_W_14 and B_Z_14 for the settings: 16°C, 18°C, 20°C and 22°C for variable outside air temperature
Rys. 11. Przebieg temperatury dla czujników POW_W_1 oraz B_W_14 i B_Z_14 dla nastaw: 16°C, 18°C, 20°C i 22°C dla zmiennej temperatury powietrza zewnętrznego

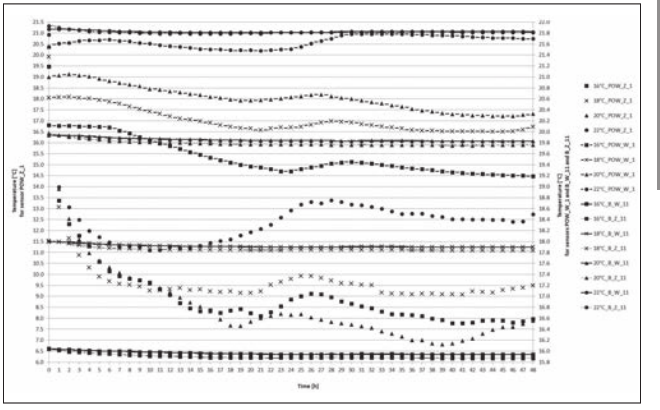

Fig. 13.
Temperature course for sensors POW_W_1 and B_W_11 and B_Z_11 for the settings: 16°C, 18°C, 20°C and 22°C for variable outside air temperature
Rys. 13. Przebieg temperatury dla czujników POW_W_1 oraz B_W_11 i B_Z_11 dla nastaw: 16°C, 18°C, 20°C i 22°C dla zmiennej temperatury powietrza zewnętrznego

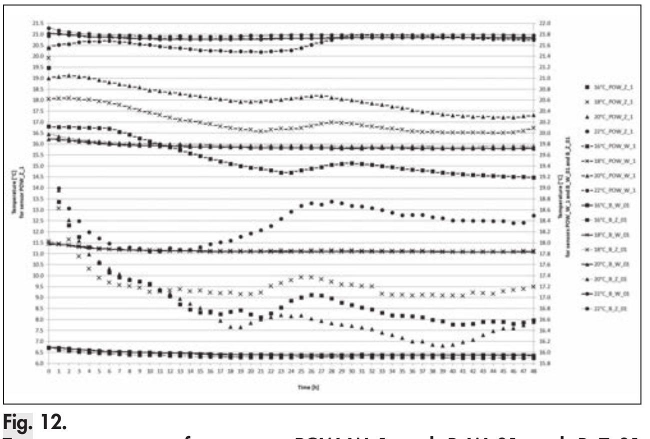

Fig. 12.
Temperature course for sensors POW_W_1 and B_W_01 and B_Z_01 for the settings: 16°C, 18°C, 20°C and 22°C for variable outside air temperature
Rys. 12. Przebieg temperatury dla czujników POW_W_1 oraz B_W_01 i B_Z_01 dla nastaw: 16°C, 18°C, 20°C i 22°C dla zmiennej temperatury powietrza zewnętrznego

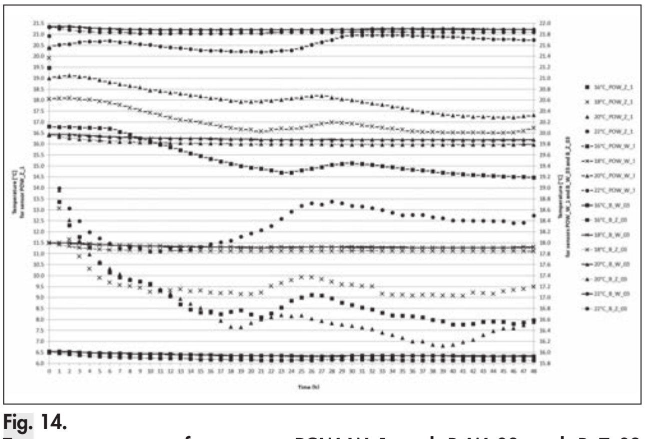

Fig. 14.
Temperature course for sensors POW_W_1 and B_W_03 and B_Z_03 for the settings: 16°C, 18°C, 20°C and 22°C for variable outside air temperature
Rys. 14. Przebieg temperatury dla czujników POW_W_1 oraz B_W_03 i B_Z_03 dla nastaw: 16°C, 18°C, 20°C i 22°C dla zmiennej temperatury powietrza zewnętrznego

from the fan start-up to the moment when the temperature changes by 0.02°C and 0.1°C. Concrete wall surface facing the internal air zone turned out to be almost resistant to the influence of different temperatures on its other side, i.e. in the outer zone. A change in the sensor indication by 0.1°C for all temperature settings occurred only for sensors located at extreme places on the partition surface, i.e. extreme upper B_W_14 and extreme lower B_W_01. For sensor B_W_07 located in the middle of the wall height (central) difference of 0.1°C occurred only for the 20°C setting after 31 hours and 57 minutes, similarly for sensor B_W_03 (located 30 cm below the central sensor). For second sensor located 30 cm above the central sensor, i.e. B_W_11 a change for the 16°C setting was also recorded. Again for the central sensor (B_W_07) and two sensors nearby (B_W_03 and B_W_11) in the case of change by 0.02°C change occurred at the latest. For sensor POW_W_1 located in the internal air zone temperature decrease by 0.1°C occurred after 6 hours for all temperature settings except 22°C, when temperature increased after 3 hours by 0.1°C.

Table 1. The reaction time of the measuring sensors followed by a temperature change of 0.02°C and 0.1°C [11]
Tablica 1. Czas reakcji czujników pomiarowych, po którym nastąpiła zmiana temperatury o 0,02°C i 0,1°C [11]

Cooling bath thermostat temperature setting [°C] / Sensor number [-]	16	18	20	22
	response time [hour and minutes] after which there was a change by:			
	0.02°C			
	0.1°C			
B_W_07	2 h 51 min	2 h 38 min	3 h 34 min	3 h 24 min
	-	-	31 h 57 min	-
B_W_14	1 h 21 min	2 h 2 min	3 h 34 min	3 h 29 min
	6 h 16 min	6 h 22 min	6 h 37 min	8 h 10 min
B_W_01	1 h 28 min	1 h 14 min	1 h 21 min	1 h 16 min
	10 h 24 min	6 h 1 min	6 h 26 min	8 h 36 min
B_W_11	2 h 25 min	2 h 20 min	2 h 33 min	3 h 44 min
	21 h 27 min	-	19 h 29 min	-
B_W_03	2 h 41 min	2 h 2 min	3 h 34 min	3 h 39 min
	-	-	41 h 29 min	-
POW_W_1	2 h 15 min	1 h 7 min	0 h 28 min	0 h 43 min
	6 h 58 min	6 h 35 min	6 h 35 min	3 h 38 min

The difference in the sensor readings for sensors located under the insulation layer from the side of the external (B_Z) and (B_W) internal air zones did not differ by more than 0.1°C.

In the case of extreme value of temperature in the external zone the lowest temperature was recorded for cooling bath thermostat temperature setting of 20°C and it was equal 6.76°C. Another sensors located on concrete surface indicated values not lower than 19.65°C, while in the internal zone it was 20.34°C. Continuing the analysis of temperature course for 20°C_POW_Z_1 16 hours earlier was recorded the highest temperature occurred after about the day from the moment the fan start-up and it was 8.25°C, at that time the temperature for sensor POW_W_1 was equal to 20.62°C, and for sensors B_W and B_Z was not lower than 19.69°C.

The highest temperature in the external zone was noted after 24 hours after the moment the fan start-up and cooling bath thermostat temperature setting was 22°C, then the temperature reached the value of 13.39°C. The remaining temperature values were respectively: 21.74°C in the inner zone, while for the measurement on the concrete surface, the temperature values did not drop below 21.73°C. For the minimum temperature presented in the line graph for 22°C_POW_Z_1 equal to 11.05°C similar values were obtained: 21.6°C for POW_W_1 and the temperature values did not drop below 21.72°C for sensors marked B.

For the lowest cooling bath thermostat setting temperature, equal to 16°C the highest temperature in the external zone was observed after the day after turning on the fan, was equal to 9.18°C, while the temperature in the inner zone was 19.35°C, and between the concrete and polystyrene layers it was 15.87°C. The minimum air temperature for sensor POW_Z_1 was recorded on the second day of measurements and it was a value of 7.73°C. At the same time, temperature for sensor POW_W_1 was 19.24°C, and for sensors marked B it was 15.86°C.

Conclusions

As a result of the conducted measurements, it was noticed that the time needed to stabilize the temperature on the surface of the pipe-embedded wall between the concrete and polystyrene layers is approximately 24 hours from the moment the cooling bath thermostat is turned on. Thus, it confirms one of the features of massive partitions – high thermal inertia.

The reason for using a partition made of materials with high heat capacity is to maintain temperature stability, additionally insert a thermally activated element (loop of pipe) to the structure promote to maintain the temperature at a certain level, regardless of the ambient temperature. The performed measurements and conclusions drawn from them confirmed this regularity. For the test stage based on a variable outside air temperature, it was found that the wall is characterized by a delayed response. On the concrete surface, the time after which the temperature changes by 0.02°C from the moment the fan is turned on, ranged from about 1 hour to about 4 hours. The temperature in the inner zone, i.e. with no airflow, changed by 0.02°C within 28 minutes for the 20°C setting and for the 16°C setting within 2 hours and 15 minutes. The reaction time increased when the temperature changed by 0.1°C. The change in air temperature is expected after about 7 hours, except for the 22°C setting when it takes about 4 hours. For sensors placed on the concrete surface, the time shift in some cases exceeded the measurement time, i.e. 48 hours. The temperature changed the fastest for the B_W_01 sensor and it was 6 hours and 1 minute for the setting of 18°C.

A more advantageous solution in terms of energy efficiency is to supply a pipe-embedded wall with a medium of the lowest possible temperature. During the tests for the lowest setting temperature, i.e. equal to 16°C, the temperature in the inner zone was 19.24°C. This value was recorded when the temperature in the outer zone was 7.73°C, thus only by 0.97°C higher than the minimum recorded during the entire measurement period (the case for the 20°C setting).

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