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Estimation of Heat Retention Index Basing on Temperature Measurements

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Abstract. Heat retention index is a function of thermal resistance and thermal capacity of the wall. When we know this index, we can accept the solution of Fourier equation in the form of Krisher equation. On that basis, the cooling time of the building envelope or the whole building is determined. In the paper, the authors have attempted to present the solution reverse to the presented problem. The estimation of heat retention index was precisely carried out by means of temperature measurements. For this purpose, a research stand in the form of a cube made of homogeneous material was built in a laboratory room. The measurement of temperature was carried out both inside the cube and on its surfaces. At the same time, the temperature of the external environment was monitored. Basing on the equalization time of temperatures of the internal and external environments of the cube, the index of heat retention was determined. To supplement the experiment and expand it onto other materials, the whole experiment was simulated in a virtual laboratory. The virtual laboratory was simulated in the ESP-r program.

1. Introduction

In recent times, an increasingly greater emphasis has been placed on the rational use of energy. Consequently, more and more significance has been attributed to proper design of external envelopes in terms of heat and humidity. In order to reduce energy consumption, thermal resistance of building envelopes should be increased, or the influence of thermal bridges [1], including point thermal bridges, should be minimized [2].

The design process of buildings which allows for thermal parameters of envelopes can contribute to a significant improvement of their energy balance. Taking into account the masonry material and its thickness, we can improve thermal resistance of the wall [3]. New modifications of insulating materials [4, 5] are being developed, affecting thermal insulation of the walls. The performance of buildings in the dynamically changing local climate conditions, and thus the comfort of their use, is affected not only by thermal conductivity of the materials from which the envelopes are built, but also by their thermal capacity [6]. The ability of an envelope to accumulate heat depends principally on its thermal capacity, C [J/K]. Material is able to accumulate more heat progressively with the rise of its volumetric density, but usually involves the deterioration of thermal insulation parameters [7]. The said issues are related with the so-called thermal mass of buildings. The thermal mass of the walls is used to control the temperature inside the building [8]. When we know the heat retention index, we



can model the equalization of temperature inside and outside the building [6]. However, a reverse approach may be interesting. Anyway, the estimation of thermal indexes by means of temperature measurement was already applied in the work [9]. Therefore, the authors of the article have attempted to estimate the heat retention index z with the use of temperature measurements. In addition, the error of such an estimation will allow us to determine the impact level of the heat retention index on the equalization of temperatures. This quality will allow us to determine if there are other factors equally affecting the equalization of temperatures.

2. Methodology

The carried out laboratory experiment involved the cooling-off process of a single-zone research object (a test chamber). The studies comprised:

- cooling-off tests of a single-zone object carried out in the laboratory of the Faculty of Civil Engineering of the Silesian University of Technology,
- infrared measurements of the created single-zone object in terms of thermal homogeneity of the envelopes,
- calculations of the heat retention index of the envelope,
- numerical analyses of the objects having different heat retention coefficients and different cubature,
- analyses of the obtained research results.

For the calculations of heat retention index z for a multilayer wall, the following equation was used:

$$z = \sum_i R_i C_i \quad (1)$$

where:

R_i – thermal resistance from the center of the layer i to the outside air [$\text{m}^2\text{K/W}$],

C_i – thermal capacity of the layer i of the wall [$\text{kJ/m}^2\text{K}$].

The cooling-off process and the equation (1) were quoted in the works [6], [10]. Throughout the work, cooling-off process should be understood as the equalization time of temperature inside and outside the tested sample (room).

Numerical analyzes were carried out in the ESP-r program. The parameters of the envelopes were determined using the equation (1) by modifying the material properties of the initial variant. The initial material properties of the envelope, for which the heat retention index z is 7.525 h, are summarized in Table 1.

Table 1. Properties of envelope materials

	Material	Density [kg/m^3]	Heat conductivity index [$\text{W/m}^2\text{K}$]	Thickness [cm]	Heat resistance [$\text{m}^2\text{K/W}$]	Specific heat [kJ/kgK]	Thermal capacity [$\text{kJ/m}^2\text{K}$]
1	Plasterboard	1000	0.23	1.25	0.054	1.00	12.5
2	EPS polystyrene	15	0.04	8.00	2.000	1.46	1.8

2.1. Description of the experiment

In the cooling-off test of a single-zone object, we applied a chamber of the dimensions in axes of 109.25 cm x 109.25 cm x 109.25 cm (internal dimension 1.0 x 1.0 x 1.0 m) with identical two-layer envelopes (EPS polystyrene 8.0cm + plasterboard 1.25cm). Inside the object, a point heat source was centrally installed, which served to heat the object to an suitably higher temperature, anticipating in that way the cooling-off process.

During the measurement, the temperature was recorded in the center of the chamber (point 2) and outside it at a distance of 1 m (point 1) from the chamber, as well as by means of additional sensors to control the stability of hygrothermal conditions of the laboratory room. The view of the test bench and the layout of the installed temperature sensors are shown in Figure 1.

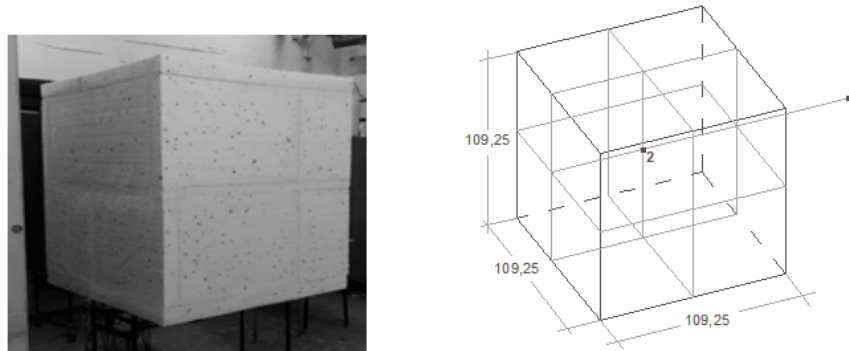


Figure 1. View of the test bench - test chamber under constant ambient conditions and the layout of the installed temperature sensors

The following measuring equipment was used in the cooling-off measurements:

- Pt100 resistance sensors (2x2mm) of the measuring range from -50 to + 500°C and accuracy of 0.15°C - temperature measurement at points 1 and 2,
- a multi-channel recorder Skaner MPI-16-00-R,
- USB st-171 temperature and humidity recorders with the measuring range for temperatures from -40 to +70°C, for humidity from 0 to 100% and with the measurement accuracy class of 0.5°C and 3% - additional temperature and humidity measurements of the laboratory room.

In order to obtain reliable results, the heating and cooling-off process was repeated several times. In the course of the heating and cooling processes in the laboratory room, possibly steady-state conditions of temperature and humidity were maintained, i.e. air temperature 14.6 - 15.1°C and relative humidity of air 43.2 - 56.2%. The measurements were carried out at the temperature difference (the interior of the chamber p2 - laboratory p1) of 15 ° C.

The assessment of the homogeneity of the envelopes of the test chamber, and hence the construction accuracy of the chamber, was carried out by infrared measurements. The measurements were carried out using a Flir B200 infrared imaging camera, with the temperature measurement range from -20 to 1200 ° C. An exemplary thermogram of the envelope with selected temperature values is presented in Figure 2.

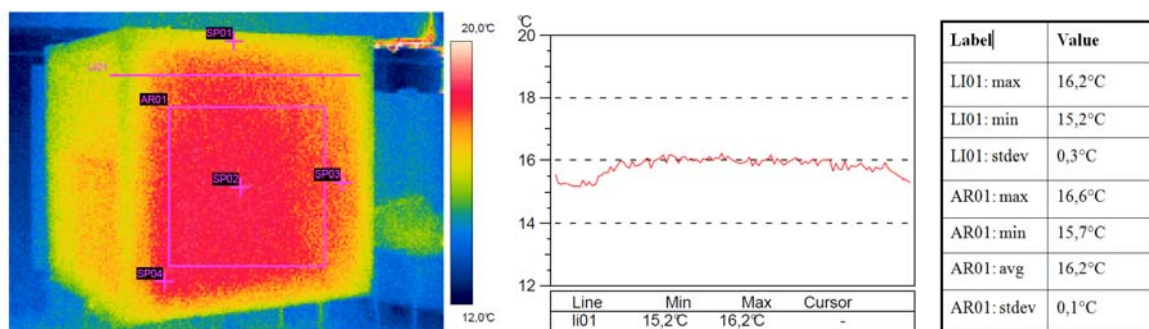


Figure 2. Thermogram with data labels

The maximum difference in temperatures in the investigated area AR01 was 0.9°C, and the standard uncertainty was 0.1°C. For the analyzed line LI01, the maximum difference was 1.0°C and the standard uncertainty was 0.3°C. The maximum temperature differences of the envelopes in the analyzed area and in the line did not exceed 1.0°C, and the distribution of temperatures in the envelopes can be considered close to homogeneous.

2.2. Computer simulations

The virtual test chamber corresponds to the actual chamber. Numerical analyses were carried out in the program Environmental Systems Performance ESP-r, in which the cooling-off process of the chamber subjected to laboratory tests was copied. The ESP-r program permits to model the flow of mass and energy, giving results reflecting the actual building environment [11]. In this program the discretization of space is carried out using the finite volume method.

The development of a complete numerical model had to be firstly preceded by the determination of the geometry of the object, boundary conditions, physical properties of the materials from which the chamber was built and the introduction of a heating system.

The parameters of the envelopes were determined using the equation (1). The numerical simulations were carried out for the cases where the object had the total cubature of limiting areas from 6 to 27.85 m² (Tab.1) and heat retention index from 10 to 100 h. The thermal transmittance coefficient U of the envelopes in each variant was equal to 0.45 W/(m²·K). The selected heat retention indexes were theoretical (not related to specific materials), to ensure that the analysis of the unit step of 10 hours could be carried out.

3. Results and discussions

In order to determine the influence of heat retention index and that of surfaces limiting the interior on the equalization time of temperatures, computer simulations were carried out. The results are summarized in Table 2.

Table 2. Results of computer simulations for various surfaces limiting the heated room as a function of heat retention index

Heat retention index	Area of envelopes, m ²									
	6.00	9.52	12.48	15.12	17.54	19.81	21.96	24.00	25.96	27.85
	Volume, m ³									
	1.00	2.00	3.00	4.00	5.00	6.00	7.00	8.00	9.00	10.00
Equalization time of temperatures, h										
10.000	58.7	59.5	60.3	61.0	62.0	62.7	63.5	64.3	65.2	66.2
20.000	113.5	115.3	116.8	118.3	120.0	121.5	123.2	125.0	126.8	128.5
30.000	166.2	168.8	171.3	173.3	176.0	178.3	181.0	183.7	186.5	189.0
40.000	216.7	220.0	223.5	226.5	229.8	233.2	236.5	240.2	244.2	246.8
50.000	258.2	261.5	265.2	268.3	271.7	275.2	278.5	281.7	285.2	288.2
60.000	306.3	311.2	316.0	319.3	323.5	327.8	332.0	337.3	340.5	344.7
70.000	348.3	353.2	358.7	362.3	366.8	371.8	376.0	380.3	385.8	390.2
80.000	410.0	417.3	425.3	428.8	434.7	443.2	450.7	458.7	467.3	475.5
90.000	438.8	446.3	452.7	457.5	464.0	470.2	475.7	482.3	489.2	497.8
100.000	481.3	488.0	496.2	502.3	509.2	515.8	522.0	529.7	536.2	543.8

Basing on Table. 2, it can be observed that the equalization time of temperatures is increasing with the rise of the index z . However, the rate of this increase depends on the surfaces that limit the test room (Figure 3).

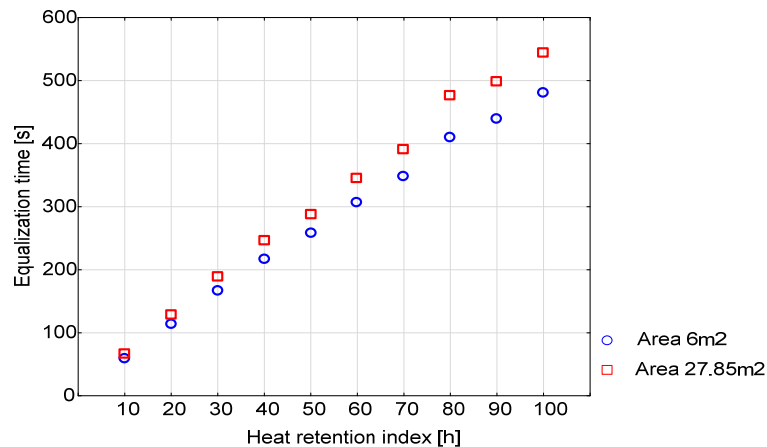


Figure 3. Equalization time of temperatures as a function of index z for two surfaces limiting the room

As it can be observed in Fig.3, the equalization time of temperatures is directly proportional to the index of heat retention. However, the rate of the increase depends on the total area limiting the room. Therefore, the investigation involving the equalization time of temperatures was carried out not only as a function of heat retention index but also as a function of surface limiting the room. The results are shown in Figure 4.

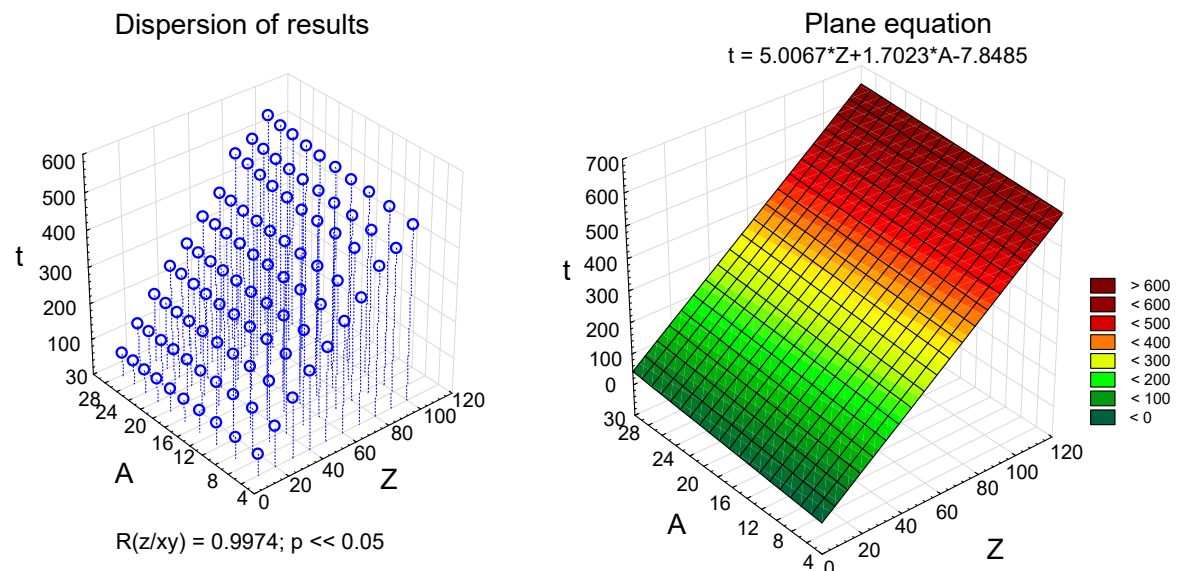


Figure 4. Time of temperature equalization as a function of heat retention index and surfaces limiting the room

The results presented in Table 2 and Figure 4 clearly indicate a linear relation $t(z, A)$. In order to verify the obtained equation and determine the scope of influence exerted by the analyzed factors (z, A) on temperature equalization time, the experiment described in Chapter 2.1 was carried out.

The results of that experiment are shown in Fig 5, with Fig. 5a. presenting the results of the cooling-off test of a single-zone object and Fig. 5b. showing the regression model of the simulation results with the measurements results. Obviously, the simulation involved the same object as the one examined in the laboratory together with the conditions existing in the laboratory. The calculated test probability p indicates that the obtained results are statistically significant.

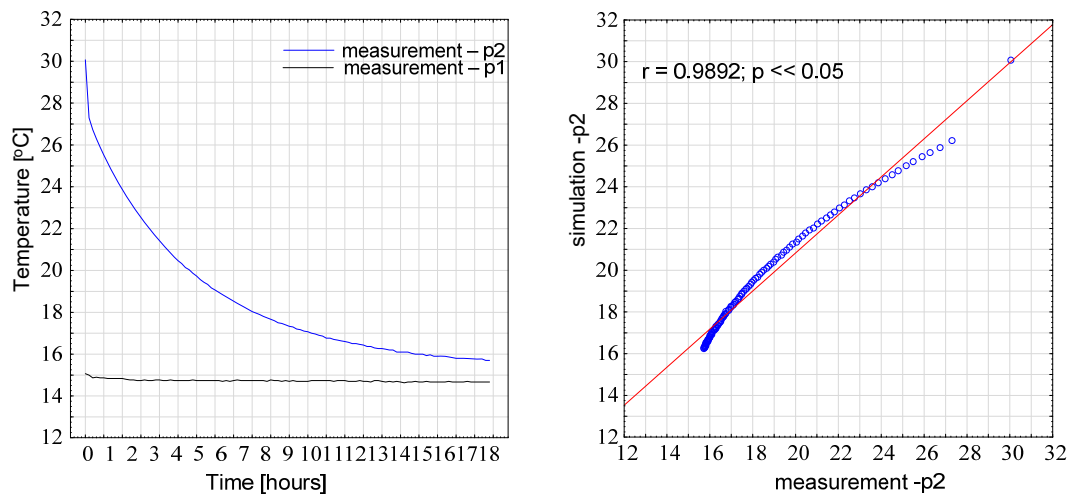


Figure 5. Diagram of the cooling-off temperatures of the object from the measurements and the scatter plot and linear regression result of the simulation-measurement temperatures

The equalization time involving the temperature of the laboratory test sample described in Table 1 of the total limiting area of 7.16 m² and heat retention index of 7.525h is $t=44.8$ h. Using the equation shown in Fig. 4 for the test sample, we obtained the temperature equalization time of $t=42.015$ h. It means that the relative error of the approximation is $\Delta t \approx 6\%$. Hence, we can conclude that the heat retention index and the surfaces limiting the sample are the factors determining the cooling-off time (equalization of temperatures). In addition, we confirmed the correctness of the virtual model of the sample and the virtual model of the laboratory. In order to further verify the model shown in Figure 4, a research sample having the parameters shown in Table 3 was built in the virtual laboratory.

Table 3. Research sample accepted for simulation

Material of the layer	Volumetric mass of material ρ [kg/m ³]	Heat conductivity index [W/(m ² K)]	Thickness [cm]	Thermal resistance R [(m ² K)/W]	Specific heat [kJ/(kg×K)]	Thermal capacity of the layer $C_v=c \times \rho \times d$ [kJ/(m ² K)]	$R_i \times C_i$
Plasterboard	1000	0.23	15.35096	0.6674	1.0000	153.5	99.513
EPS polystyrene	15	0.04	8	2.0000	1.4600	1.8	0.487
Heat retention index $z=\sum R_i C_i$ [h]							100
Total thickness of the wall [cm]							23.35
U of the envelope [W/(m ² K)]							0.35

It turned out that the simulation results for the sample (Table 3) having the total area limiting the sample of 6 m² provided the result of temperature equalization time of $t = 455.2$ h. However, the said time with the application of the model shown in Figure 4 was 503 h. The relative error of that approximation was $\Delta t \approx 10\%$. Similarly, for the same sample but with the area of 27.85 m², the simulations gave the result of $t = 503.3$ h, while the model in Fig.4 $t = 540.23$ h, which means the relative error of $\Delta t \approx 7\%$.

We can conclude from the presented simulations that the approximation error of the model presented in Fig.4 is getting smaller the larger is the sample. The approximation error with the model which takes into account two parameters (z , A) indicates that these parameters determine the time of temperature equalization, but they are not the only ones that have impact on that time.

4. Conclusions

In view of the analyses presented in this paper, we can make some conclusions regarding the equalization of temperature inside and outside the room (building).

- The main determinants that estimate the temperature equalization time inside and outside the room are heat retention index and the surfaces limiting the room.
- The temperature equalization time can be described by the equation $t = 5.0067 \cdot z + 1.7023 \cdot A - 7.8485$ where z is the temperature retention index while A is the surface limiting the room.
- Relative errors of the applied equation involving the measurement and simulation indicate that there are other factors having impact on the time of temperature equalization. However, these factors are not determining the entire process.

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