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RESEARCH ARTICLE

The Influence of Thermal Mass on the Cooling off Process of Buildings

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Abstract
In the paper the authors have investigated the influence of thermal mass of the building envelope on the alignment of temperatures between the external and internal environments without the input of either heating or cooling sources. It is commonly known that when the source of thermal energy is no longer active and the temperature difference between the inside and outside of the building is positive, the building envelope starts to transfer the heat outside. Such a process is repeated until the temperatures in both environments become equal. Hence, the decision to undertake such an analysis in the present paper. In the work the authors have attempted to investigate the impact of thermal mass of the building envelope on the cooling process of the whole internal air. Also, the influence of the shape of the investigated object on the cooling process of the internal zone has been analyzed.

Keywords
thermal mass, cooling process, ESP-r, heat retention rate, heat resistance, Krischer solution

1 Introduction

Thermal mass of the envelope is to be understood as its heat capacity. It means that the envelope with large thermal mass needs to absorb a lot of heat energy before the temperature on the surface of the envelope changes. And the envelope of small thermal mass reaches the surrounding temperature reasonably fast. The impact of heat retention rate on the thermal load of the zones ventilated by night in the climate of China was investigated in the work [1]. The works on thermal comfort had been already carried out for many years. In the publication [2], the authors were considering thermal inertia in terms of the experienced thermal comfort, and more specifically, the impact of thermal inertia on the total thermal load of the system. The investigation studies were carried out with the application of numerical analyses, using the Fourier equation.

Many works involve also the impact of temperature distribution in the room on thermal comfort. Such research works were carried out among others in the work [3]. The authors demonstrated that thermal comfort of rooms depends on the temperature of the outdoor environment. They also divided the rooms into thermal comfort zones, and they determined the minimum and maximum temperatures for thermal comfort. Research studies involving the influence of temperature loss of the room as a time function on energy savings have been carried out worldwide. Even the most recent literature is still occupied with this problem [4]. It is also quite significant in terms of energy savings in the building engineering industry to understand the role of heat accumulation of the envelope. The consumption of heating, cooling or ventilation energy is still rising, and therefore the systems of energy storage are becoming more and more apparent for researchers. In the work [5] the researchers found out that in the areas of high temperature difference between day and night, thermal insulation mounted on the external surface of the envelope yields better results than that mounted on the internal surface. As they explained, it was caused by a different heat accumulation of the envelope with external insulation than that with the internal one. The subject of heat accumulation of the envelopes and its influence on energy efficiency of buildings has been undertaken by many

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researchers who have published a lot of research studies covering that problem. In the work [6] the authors investigated the influence of heat capacity and thermal resistance on the thermal behavior of a wall with the application of the theory of distributed parameter continuum.

A very comprehensive literature review was presented in the publication [7]. The authors emphasize the significance of phase-changing materials for energy savings in building construction. Such materials are of great importance for the creation of thermal comfort of the interior through an appropriate storage of heat in the building envelope.

In another work [8], 150 different materials used in the research studies as PCM and 45 materials used commercially as PCM were tested.

Apart from research studies involving the influence of heat accumulation of building envelopes on energy efficiency of buildings, research studies are being carried out on new measurement methods of heat accumulation [9].

Thermal performance of walls has been investigated both by means of response functions [10, 11], Fourier transforms [12], and numerical methods [13, 14]. Numerical methods by means of computer simulations have been also applied to investigate heat comfort in buildings [15].

Another approach involves the application of radiant time series for testing the cooling process with the use of heat balance, which was interestingly presented in the work [16]. The authors of that paper describe the radiant time series method, the generation of the response factors as well as the radiant time series coefficients, and they also present a brief comparison to the heat balance method.

In the literature published worldwide, we can also find works [17] whereof findings indicate that the maintenance of a constant temperature in the room can provide the inhabitants with the feeling of heat comfort, and it surely generates high energy costs and higher production of CO_2.

All the research studies mentioned above encouraged the authors of the present publication to investigate the influence of heat accumulation of the building envelope on the cooling process of air inside a given building object. The studies covered the cases with insulation being applied (inside, outside), the type of insulation, or the structure of the building.

The analyses were carried out with the application of the ESP-r software. The application of this software has been discussed in many publications [18, 19, 20]. As we can read in the said publications, the ESP-r software facilitates an integrated approach to the simulation of an object, which enables to carry out all analyses involving building physics or energy systems. It is commonly known that very good thermal insulation is obtained by cupola-shaped structures. Due to such a shape, a convectional air flow is taking place without any accumulation of air in corners. It is one of the reasons why a copula is regarded as an energy-efficient building. Therefore, we found it reasonable to determine how the copula is cooling-off, depending on the thermal mass of the envelopes, and to compare it with the cuboid-shaped structure. Since the research necessitated access to structures of that type, which was a problem, therefore the studies were carried out by means of the ESP-r simulation. And the pilot tests on the real structure have already begun and are being in the realization stage.

2 Methodology

2.1 Assumptions involving the system of layers for the analysis of steady-state solutions of the Fourier equation

The solution of Fourier equation in the external wall with the ordered in time temperature distribution, with a rapid drop of heat flow rate to zero due to heat cut-off is very important when testing the thermal stability of building envelopes. This theory is based on the steady-state theory. The steady-state solution of the Fourier equation was offered among others by Krischer, and his equation was quoted in the work [21]. In his solution, by introducing order time and by determining the amount of the accumulated heat and the intensity of heat flow transferred to the outside at a given moment, and then assuming that the ratio of the accumulated heat amount at a given moment to the initially accumulated heat amount is equal to 1, we obtain:

$$t(0,\tau) = t_0 e^{-\frac{\tau}{z}}. \tag{1}$$

where: τ – cooling time, [h], t_0 – initial temperature of the body, [°C], z – heat retention rate, [h].

Ignoring the values of surface resistance, in the case of multilayer wall, the heat retention rate can be calculated as:

$$z = \sum_i R_i C_i. \tag{2}$$

where: R_i – thermal resistance from the middle of the layer i to the outside air, C_i – heat capacity of the layer i of the wall

The equation (1) was applied to analyze the setup of walls, which were below arranged as variants V1–V10. Table 1 presents the properties of materials which were used to set up the particular wall variants for cuboid rooms.

Table 1 Properties of materials used for the construction of walls V1–V10.

Layer Material	Mat. Vol. capacity [kg/m^3]	Design thermal conductivity [W/(m×K)]	Specific heat [kJ/(kg×K)]
lime plaster	1700	0.7	0.84
lime plaster on glass fiber mesh	1700	0.7	0.84
clinker brick wall	1900	1.05	0.88
ceramic brick wall	1800	0.77	0.88
hollow brick wall	810	0.58	0.75
cellular concrete blocks wall	600	0.16	0.84
reinforced concrete	2500	1.7	0.84
polystyrene EPS040	12.5	0.04	1.46
polystyrene EPS038	13.5	0.038	1.46
polystyrene EPS042	11	0.042	1.46
mineral wool	135	0.037	0.75

The behavior of the following envelope variants was analyzed:

- Envelopes built from the same materials but arranged in a different order. The analysis involved a full brick wall 25cm thick with a Styrofoam insulation layer covered with plaster 1cm thick on both sides.
- Envelopes having different material of face layer. We analyzed the wall from hollow bricks with Styrofoam insulation and plaster where the face layer was selected either as lime plaster on glass fiber mesh 1cm thick, or as clinker brick 12 cm thick.
- Envelopes having different material of the insulation layer. Two variants of hollow brick wall were considered, with the insulation from Styrofoam of the thermal conductivities $\lambda = 0.038, 0.040, 0.042$ W/(m×K) and from mineral wool $\lambda = 0.037$ W/(m×K) with plaster on both sides 1cm thick.
- Envelopes having different material of the structural layer: a wall from full ceramic bricks 25 cm thick, a wall from cellular concrete blocks 24 cm thick, a wall from hollow bricks 24 cm thick and reinforced concrete 15 cm thick with a Styrofoam insulation layer and plaster 1 cm thick.
- Envelopes of different structural solutions. We compared the envelopes made in the monolithic technology as a reinforced concrete structure 10 cm thick covered with polyurethane foam and PE fiber coated with PVC and finished from the inside with plaster 1 cm thick. (the envelope used for the construction of cupola-shaped objects).

During the construction works of the envelope each wall was ascribed a theoretical thickness of insulation layer in order to maintain $U = 0.2$ W/(m^{2}K).

As presented in the Table 1 and in line with the general description of the variants, the following wall systems were investigated:

V1: lime plaster (1cm) → ceramic brick wall (25cm) → polystyrene EPS040 (17.91cm) → lime plaster on glass fiber mesh (1cm)

heat retention rate [h]	533.075
total wall thickness [cm]	44.9
U of the envelope [W/(m^{2}K)]	0.20

V2: lime plaster (1cm) → polystyrene EPS040 (17.91cm) → ceramic brick wall (25cm) → lime plaster on glass fiber mesh (1cm)

heat retention rate [h]	40.927
total wall thickness [cm]	44.9
U of the envelope [W/(m^{2}K)]	0.20

V3: lime plaster (1cm) → hollow brick wall(24cm) → polystyrene EPS038(16.29) → clinker brick wall (1cm)

heat retention rate [h]	210.987
total wall thickness [cm]	53.3
U of the envelope [W/(m^{2}K)]	0.20

V4: lime plaster (1cm) → hollow brick wall (24cm) → polystyrene EPS038 (16.67cm) → lime plaster on glass fiber mesh (1cm)

heat retention rate [h]	207.832
total wall thickness [cm]	42.7
U of the envelope [W/(m^{2}K)]	0.20

V5: lime plaster (1cm) → hollow brick wall (24cm) → polystyrene EPS040 (17.55cm)→ lime plaster on glass fiber mesh (1cm)

heat retention rate [h]	207.781
total wall thickness [cm]	43.6
U of the envelope [W/(m^{2}K)]	0.20

V6: lime plaster (1cm) → hollow brick wall (24cm) → polystyrene EPS042 (18.43cm) → lime plaster on glass fiber mesh (1cm)

heat retention rate [h]	207.631
total wall thickness [cm]	44.4
U of the envelope [W/(m^{2}K)]	0.20

V7: lime plaster (1cm) → hollow brick wall (24cm) → mineral wool (16.23cm) → lime plaster on glass fiber mesh (1cm)

heat retention rate [h]	215.898
total wall thickness [cm]	42.2
U of the envelope [W/(m^{2}K)]	0.20

V8: lime plaster (1cm) → cellular concrete blocks wall (24cm) → polystyrene EPS040 (13.21cm) → lime plaster on glass fiber mesh (1cm)

heat retention rate [h]	156.882
total wall thickness [cm]	39.2
U of the envelope [W/(m^{2}K)]	0.20

V9: lime plaster (1cm) → reinforced concrete (10cm) → polyurethane foam (11.88cm) → non-woven PE coated with PCV (0.1cm)

heat retention rate [h]	301.774
total wall thickness [cm]	23.0
U of the envelope [W/(m^{2}K)]	0.20

V10: lime plaster (1cm) → reinforced concrete (15cm) → polystyrene EPS040 (18.85cm)→ lime plaster on glass fiber mesh (1cm)

heat retention rate [h]	438.940
total wall thickness [cm]	35.9
U of the envelope [W/(m^{2}K)]	0.20

Additionally, the analysis involved the variants K1-K4 of the envelopes which encircle a cupola-shaped room. In order to carry out their analysis, we accepted the cuboid-shaped variants K1a-K4a and cupola-shaped ones K1b-K4b as presented in Fig.1.

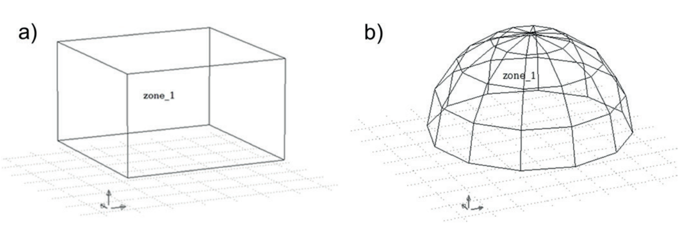

Fig. 1 Models of single-zone object investigated in the program ESP-r
a) cuboid model, b) cupola-shaped model

The investigated variants have different heat retention rate. The differences are attributed to the application of different thermal insulation.

K1: heat retention rate [h]	K2: heat retention rate [h]
301.774	90.974
K3: heat retention rate [h]	K4: heat retention rate [h]
49.220	31.366

The structure of the envelopes limiting the investigated rooms for variants K1-K4 was as follows:

K1: lime plaster → reinforced concrete → polyurethane foam → non-woven PE coated with PCV

heat retention rate [h]	301.774
total wall thickness [cm]	23.0
U of the envelope [W/(m^{2}K)]	0.20

K2: lime plaster → reinforced concrete → polyurethane foam → non-woven PE coated with PCV

heat retention rate [h]	90.974
total wall thickness [cm]	14.6
U of the envelope [W/(m^{2}K)]	0.60

K3: lime plaster → reinforced concrete → polyurethane foam → non-woven PE coated with PCV

heat retention rate [h]	49.220
total wall thickness [cm]	13.0
U of the envelope [W/(m^{2}K)]	1.00

K4: lime plaster → reinforced concrete → polyurethane foam → non-woven PE coated with PCV

heat retention rate [h]	31.366
total wall thickness [cm]	12.3
U of the envelope [W/(m^{2}K)]	1.40

The investigated cases were simulated by means of the simulation program ESP-r, and then they were modeled using the Gauss-Newton least square method.

The obtained runs of cooling-off time of the envelope and zone were subjected to the correlation analysis in the program STATISTICA. The objective of such an approach was to determine the level of their similarity and the level of their correlation.

2.2 Computer simulations

Computer simulations involved cooling the zone, that is cooling the air in a virtual room built from the building envelopes described above. The task was carried out by means of the simulation program *Environmental Systems Performance* ESP-r which makes it possible to model the flow of mass and energy in the building. In the program, the discretization of space is effected by means of the finite volume method. It consists in dividing the building, or its part into finite volumes whereof boundaries are combined with the surrounding through mathematical dependencies. Each volume contains a node in the center. The nodes are combined with one another by means of the equation $\mathrm{A}\hat{I}_{n+1} = \mathrm{B}\hat{I}_{n} + \mathrm{C}$, where **A** is the matrix describing the time step, **B** is the current time step and **C** contains the known boundary conditions. The matrix equation is solved using the Clark-Nicolson method [22]. The multilayer structure is represented by one node in the center and one node on each surface. It means that the structure N of the layer is representing 2n+1 nodes [23]. Fig.2 presents the example of such a volume combined with the surrounding by means of mathematical dependencies. The connection with the surrounding can be effected by heat transport, e.g. conduction in the wall.

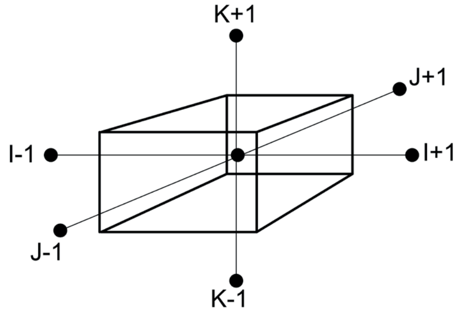

Fig. 2 A block with numerical connections to its surroundings [22]

The basic equation used to describe heat flow in the program ESP-r is the equation of energy conservation in the control node and corresponding to the control volume. In the present work two room models were investigated (Fig.1). The model of a cuboid-shaped object of the known dimensions 10.0 × 10.0 × 6.0 m (Fig.1a) and different envelopes as in the variants V1–V10. The second model was cupola-shaped (Fig. 1b). The cooling process was proceeded by heating the object to the temperature $\theta_i = 24^\circ\mathrm{C}$ and stabilizing the heat exchange process in the envelopes. The temperature $\theta_e = 0^\circ\mathrm{C}$ was accepted as that reflecting external conditions. Internal gains from the equipment, lighting or users were ignored to avoid measurement disturbances.

3 Results

Fig.3 presents the results of the research studies involving the cooling process of the envelopes and zones (air inside the buildings) limited on all sides with the same envelopes. The zone under investigation is the interior of a cuboid of the dimensions 10.0 × 10.0 × 6.0 m. The cuboid is located in a virtual environment, untouched by any other object to avoid heat transport between the bodies. Additionally, a homogeneous temperature was preset in the external virtual environment as well as the condition of no wind or sunlight was ensured.

Another research problem involved the answer to the question in what way the shape of an object can influence its cooling process. To answer the question, the objects of the shape presented in Fig.1 were subjected to investigation studies. They were described as variants K1, K2, K3 and K4.

In order to provide more comprehensive analysis, we presented cupola_volume situation (cupola has the same cubature as cuboid) and cupola_ area situation (cupola has the same limit area as the cuboid). The results are presented in Fig.4.

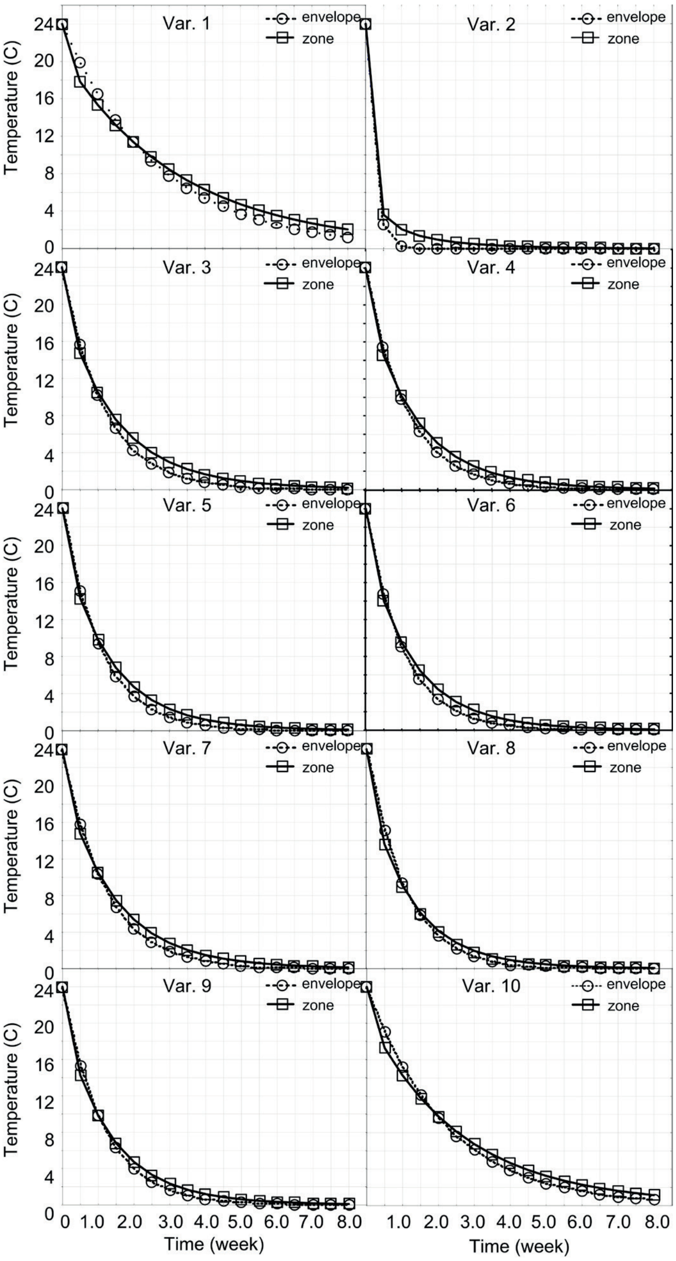

Fig. 3 Curves describing the cooling process of envelopes and zones (air inside the buildings)

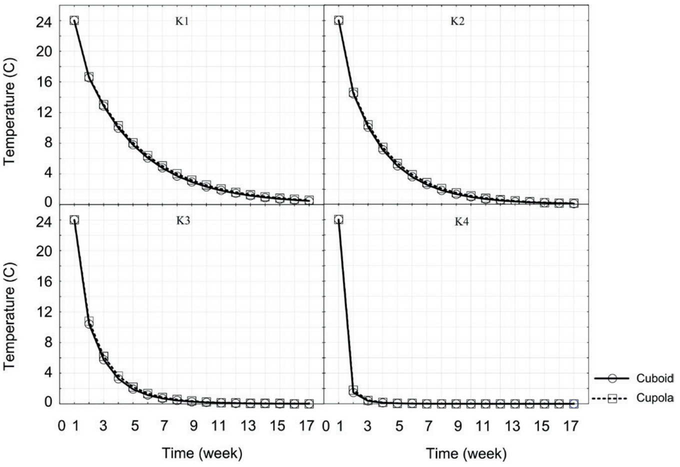

Fig. 4 Curves describing the cooling process of zones having different shapes

4 Analysis of the results

The curves describing the envelope were obtained using the equation (1), so they are described with exponential functions. And the curves describing the zone were generated by means of the results obtained from the simulation in ESP-r. As we can observe in Fig.3, the curves obtained from the simulation have also a similar run to the graph of the exponential function. The equations describing these curves were obtained with the application of the non-linear least square method, using the Gauss-Newton algorithm. The general form of the exponential function for which the said algorithm was applied to estimate the structural parameters of non-linear models is presented by the following equation (3)

$$y_t = a \cdot e^{b \cdot x_t} + \xi_t, \quad t = 1, \ldots, N \tag{3}$$

where: y_t – observations of the explained variable,

$\mathbf{x}_t$ - observation vector of the explaining variables,

$\mathbf{a}$,$\mathbf{b}$ - vectors of structural parameters,

ξ_t - realization of random components.

But we must assume here that the random components ξ_t are uncorrelated, their average value is zero and they have the same positive and finite variance. The application of the least square method for the non-linear Gauss-Newton model consists in the determination of the estimators a and b of the vectors of the parameters α and β in such a way that

$$\min S(\alpha, \beta) = \min \sum_t \left[y_t - a \cdot e^{b \cdot x_t}\right]^2 = S(a, b) \tag{4}$$

leads to the non-linear system of normal equations which is solved by means of numerical iteration procedures.

Now, we can investigate the cooling time of the envelopes and rooms limited by these envelopes.

For the envelope constructed as in V1, its cooling equation based on the Kricher solution (1) has the form $t_{Kr} = 24\,e^{-\frac{\tau}{533.075}}$. The cooling equation of the room limited by the envelopes constructed as in V1, obtained from the approximation with the Gauss-Newton method, assuming that $t_0 = 24$, has the form $t_{G-N} = 24\,e^{-\frac{\tau}{561.25}}$. We also note down the 95% confidence interval $z \in \langle 526.7, 595.8 \rangle$.The matching correlation coefficient of the curve $t_{G-N}$to the computer simulation is 0.99.

We can observe that $z \approx 533$h determined on the basis of equation (1) for the envelope is contained in the determined interval. Therefore, we can conclude that with the certainty of 95% the cooling process of the whole interior will be carried out in the same way as for a single envelope. The heat retention coefficient for the whole interior will be the same as for a single envelope.

Similar analyses were carried out for all variants, as presented below, with r standing for the correlation coefficient between the results obtained from the equation t_{G-N} and the computer simulations:

V2: cooling time $t_{Kr} = 24e^{-\frac{\tau}{40.93}}$, $t_{G-N} = 24e^{-\frac{\tau}{48.87}}$ for $r = 0.995$ and $z = 40.93 \notin \langle 41.2, 56.6 \rangle$

V3: cooling time $t_{Kr} = 24e^{-\frac{\tau}{210.99}}$, $t_{G-N} = 24e^{-\frac{\tau}{235.65}}$ for $r = 0.997$ and $z = 210.99 \notin \langle 221.6, 249.7 \rangle$

V4: cooling time $t_{Kr} = 24e^{-\frac{\tau}{207.83}}$ $t_{G-N} = 24e^{-\frac{\tau}{226.15}}$ for $r = 0.997$ and $z = 207.8 \notin \langle 214.52, 237.8 \rangle$

V5: cooling time $t_{Kr} = 24e^{-\frac{\tau}{207.78}}$ $t_{G-N} = 24e^{-\frac{\tau}{226.15}}$ for $r = 0.997$ and $z = 207.8 \notin \langle 214.5, 237.8 \rangle$

V6: cooling time $t_{Kr} = 24e^{-\frac{\tau}{207.63}}$ $t_{G-N} = 24e^{-\frac{\tau}{226.08}}$ for $r = 0.997$ and $z = 207.6 \notin \langle 214.4, 237.7 \rangle$

V7: cooling time $t_{Kr} = 24e^{-\frac{\tau}{215.90}}$ $t_{G-N} = 24e^{-\frac{\tau}{233.24}}$ for $r = 0.997$ and $z = 215.9 \notin \langle 221.0, 245.5 \rangle$

V8: cooling time $t_{Kr} = 24e^{-\frac{\tau}{156.88}}$ $t_{G-N} = 24e^{-\frac{\tau}{179.3}}$ for $r = 0.998$ and $z = 156.9 \notin \langle 153.3, 171.8 \rangle$

V9: cooling time $t_{Kr} = 24e^{-\frac{\tau}{301.77}}$ $t_{G-N} = 24e^{-\frac{\tau}{331.63}}$ for $r = 0.996$ and $301.8 \notin \langle 314.8, 348.5 \rangle$

V10: cooling time $t_{Kr} = 24e^{-\frac{\tau}{438.94}}$ $t_{G-N} = 24e^{-\frac{\tau}{475.48}}$ for $r = 0.994$ and $438.9 \notin \langle 449.5, 501.5 \rangle$

Basing on the carried out investigation studies, it seems evident that the cooling time of the zone is longer than the cooling time of the envelope.

Furthermore, for the heat retention rate being neither long nor short (in this case about 156h) the cooling time is within the 95% confidence interval of the cooling time zone. It seems advisable to confirm the said effect in future, the more so since it is also possible for very short cooling times.

We can then approximate the cooling time of the zone, using the information on the heat retention rate of the envelope. Interestingly enough, the cooling process of the zone is not much longer than the cooling time of the envelope. After the next statistical analysis, it turned out that the heat retention rate of the envelope was contained in the 90% interval of zone cooling determined with the Gauss-Newton least square method for the results obtained by means of the simulation in ESP-r.

Fig.4 presents the results of the cooling time of zones having different shapes, i.e. cuboid and cupola. As we can see from the graphs, the shape of the zone obtained in ESP-r has, in fact, no influence on the time of temperature loss by the zone. We can observe that such influence is not existing either for the zones having the same cubature or the same limit area.

The above fact was confirmed on scatter plots presented in Fig.5, which is illustrating the results for cuboid and cupola of the same cubature.

We can clearly see that the results for both zones have the correlation almost equal to 1. Additionally, we can read out from the regression equation that these results are lying almost on the straight line of the equation$y = x$.The above bespeaks of the fact that on the significance level of 0.05, the cooling time of the investigated zones is the same.

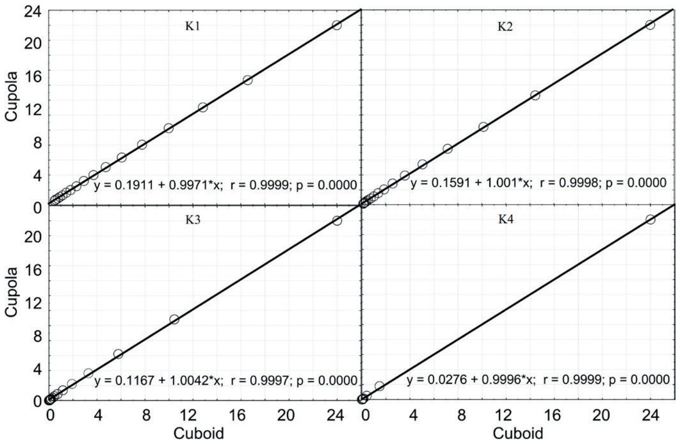

Fig. 5 Scatter plots and the result of the linear regression of the results for zones having different shapes

5 Conclusions

In the paper the authors are attempting to determine the impact of thermal envelope on the cooling process of air in buildings. In the first stage of the works, in Fig.3, the cooling processes of walls and buildings limited by those walls were presented. The analysis involved ten variants of wall structures. Already at that stage, we could observe apparent similarities between the processes. The equations involving wall cooling were obtained with the application of equation (1). Then, in the program ESP-r, the cooling time of the building limited by those building envelopes was determined. Having obtained the results from ESP-r, the Gauss-Newton least square method was applied and cooling equations of the rooms were determined.

- We could observe that the cooling time of the room was longer than the cooling time of building envelopes.
- But we could also notice a close relationship between the cooling process of walls and the cooling process of the zones limited by them.
- We can state that the cooling time of zones is similar to the cooling time of the envelopes limiting these zones.
- Another analysis involved the cooling process of zones having different shapes. We investigated the cuboid-shaped object and an object shaped like a cupola or hemisphere. We investigated two options: cuboid and cupola having the same cubature, and cuboid and copula having the same limit area. It turned out that when homogeneous external conditions are ensured, without any influence (wind or sunshine), the cooling time of both zones was the same. It can be effected both by the simulation conditions and the calculation algorithm alone. The studies carried out on a real object can verify this conclusion.
- Fig. 5 presents scatter plots and regression results between the results for both shapes. It turns out that the correlation of cooling time between both shapes is close to 1 for each investigated variant of wall structure limiting these zones. What is more, the results are arranged almost along a straight line y=x, which bespeaks of the fact that the cooling time is the same.

- The results obtained for the two zones having totally different shapes seem to be surprising and provoking to undertake further studies which would also allow for the influence of external factors such as wind, sunshine, incidence angle of sunrays, etc, as well as the internal factors such as: heating, ventilation, air conditioning, etc.
- The work is also looking into a less popular solution with the application of internal thermal insulation (V2). Such an option is applied e.g. in Poland for the modernization of thermal insulation of historical objects. The pros and cons of such a solution can be found in the work [24]. In the present paper the authors described a considerable drop of thermal mass of the wall with the internal thermal insulation as compared to the solution with external thermal insulation.

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