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Research Paper

Combined Building Energy Systems/Active Thermal Protection (ATP)/Calculation of ATP in the Function of Thermal Barrier, Wall Heating and Wall Cooling

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ABSTRACT: *Combined building energy systems with active thermal protection (ATP) represent the optimal and most comprehensive technical solution for buildings within the meaning of Directive 2018/844/EU [1] amending Directive 2010/31/EU on the energy performance of buildings and Directive 2012/27/EU on energy efficiency, which introduced the new concept of "nearly Zero Energy Building (nZEB)" into our legal system. From the point of view of thermal protection of buildings, structures with an internal energy source represent progressive enveloping structures of a building with active control of heat transfer (thermal barrier). From an energy point of view, they are multifunctional with individual or combined functions of low-temperature radiant heating/high-temperature cooling, heat/cold storage, heat recovery, collectors for absorption of solar energy or ambient energy in combination with heat pumps. New, investigated variants of building structures with an internal energy source using exhaust air can also have the function of recuperative heat exchangers in forced ventilation of buildings. From an environmental point of view, building and energy systems with ATP have optimal use in the application of RES and waste heat. In applications of electricity generation, for example by photovoltaic power plants on or near buildings, buildings with combined building energy systems with ATP may be a suitable alternative for energy self-sufficient (zero) to plus buildings. Research focused on an evaluation of the ATP application was the subject of the dissertation of Ing. Peter Janík, PhD. titled: "Optimization of energy systems with long-term heat accumulation." [13], (supervisor: Kalús), and at the same time of the research project HZ PG 73/2011 titled: "Experimental measurements, analysis, and determination of the optimal rate of use of renewable energy sources on a prototype of a family house EB2020 with nearly zero energy demand "[10], (responsible researcher: Kalús). This paper focuses on the basic calculations of ATP in the function of thermal barrier, wall heating, and wall cooling. The results of our ATP research carried out at the Faculty of Civil Engineering, Department of Building Services, STU in Bratislava since 2005 are still part of three utility models and one European patent. [3, 4, 5, 6]*

KEYWORDS: *Heat accumulation, combined building-energy systems, active thermal protection (ATP), building structures with internal energy source, active heat transfer control, thermal barrier, wall heating/cooling*

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I. INTRODUCTION

Active thermal protection of buildings (ATP) is built-in pipe systems in building structures, to which a heat transfer medium is supplied, which can be air or liquid. In most cases, the working medium is water, but it can also be air. This represents a combined building-energy system, building structures with an internal energy source, and active heat transfer control. Depending on the temperature of the working medium, the system has mostly the following functions:

- thermal barrier,
- low temperature heating,
- high temperature cooling,

- accumulation of heat or cold.

Figure 1 shows the aforementioned functions for a perimeter wall, which is formed from the inside: plaster, thermal insulation, ATP layer in the mortar layer, load-bearing wall made of reinforced concrete and external plaster.

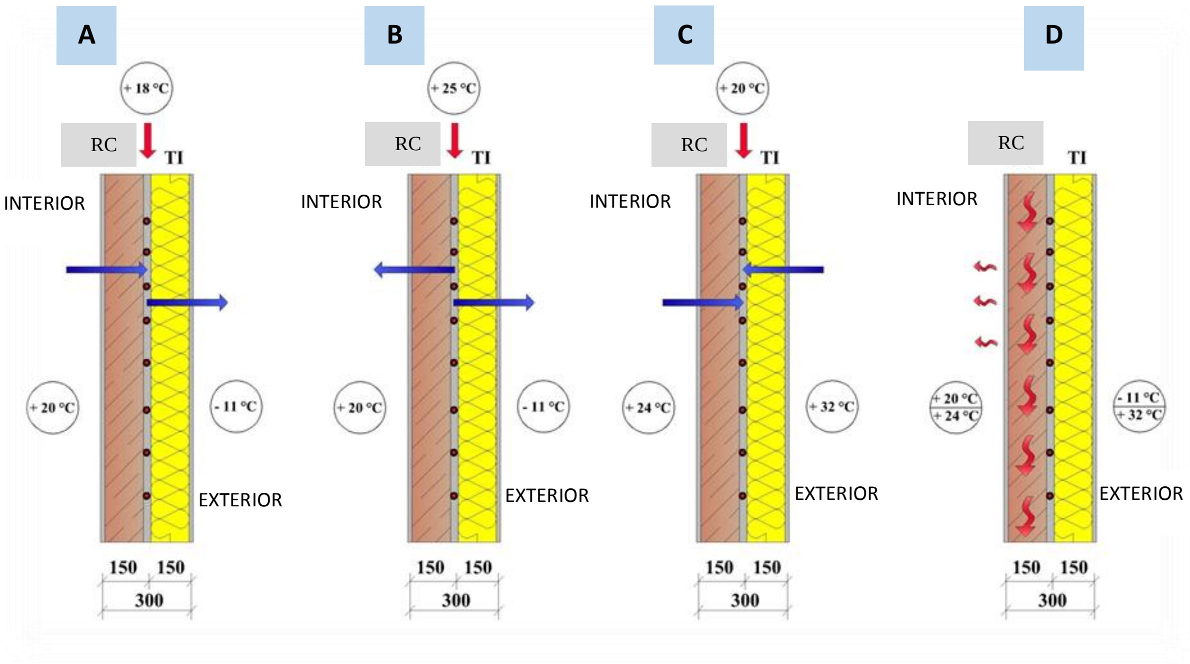

Figure 1: ATP functions: from left: thermal barrier (A), low temperature heating (B), high temperature cooling (C) and accumulation of heat/cold (D) [10, 13]
RC – reinforced concrete, TI – thermal insulation

There are several options for placing the ATP in the structure. In the case of perimeter masonry, it can be placed between the load bearing structure and the thermal insulation, as in Figure 1. For the perimeter structure, the recommended axial distance between the pipes is 20 to 25 mm, for the roof 10 to 20 mm [2], [55], [56]. In Spain, the recommended length of the plastic pipe laid in the ATP, roof, ground storage, and the cooling circuit according to [55] is: according to the "Isomax climate zones" I, II, III and IV, multiplication by 1, 2, 3 or 4 times the area of the building in m^2 can be considered taking into account the type of building. If it is a family house in climate area III with an area of 100 m^2, it is necessary to place 300 m in the perimeter walls, in the roof structure, in the ground storage, and in the cooling circuit. If it is an apartment building with 5 floors, where there are 4 apartments on each floor with an area of 100 m^2, considered for the calculation is 100% value at the highest floor and 70% for the rest of the floors. The result will be 1.0*400 + (0.7* 4 *400) = 1520 m of pipeline at climatic zone I. Polypropylene pipe 20 x 1.9 mm is considered. If the given area is insufficient to accommodate the calculated pipe length, it is possible to reduce the mutual axial distance.

II. DETERMINING THE TEMPERATURE IN THE ACTIVE THERMAL PROTECTION LAYER

Before designing the system, it is necessary to determine the temperature in the layer in which the ATP will be located. The calculation must be performed under various external and internal conditions. For correct function of the system, it is necessary to know the change in temperature in this layer under influence of changes in external conditions. It is advisable to create a dependence curve. Not knowing the conditions can lead to unnecessary waste of energy, or even discharging of the heat storage. An example was performed on perimeter structures. The assessment was processed for indoor air temperature 20°C (heating season) and 26°C (summer season) and outdoor air temperature -18°C, -11°C and 0°C. In summer, outdoor air temperature of +32°C was considered.

As an example, three structures will be examined:

- Structure A consists of a reinforced concrete load bearing structure 200 mm thick (reinforced concrete), which is insulated from the outside with polystyrene 120 mm thick. The ATP would be placed in a layer of mortar bed between the load-bearing wall and the insulation,
- Structure B consists of a reinforced concrete load bearing structure 200 mm thick, which is insulated on the exterior and interior side with polystyrene 60 mm thick. The ATP would be located in the middle of the load bearing structure,
- Structure C consists of aerated concrete blocks (PBT) 300 mm thick and insulated from the exterior with polystyrene 50 mm thick. The ATP would be placed in between.

Structure A. Figure 2 to 3 show the outputs from the Heat program. The structure has a heat transfer coefficient U = 0.29 W/(m^2.K). Composition of the structure from the interior:

- interior plaster, 5 mm thick, λ = 0.88 W/(m.K),
- reinforced concrete, 200 mm thick, λ = 1.74 W/(m.K),
- mortar bed, 20 mm thick, λ = 1.16 W/(m.K),
- polystyrene, 120 mm thick, λ = 0.038 W/(m.K),
- external plaster, 5 mm thick, λ = 0.20 W/(m.K).

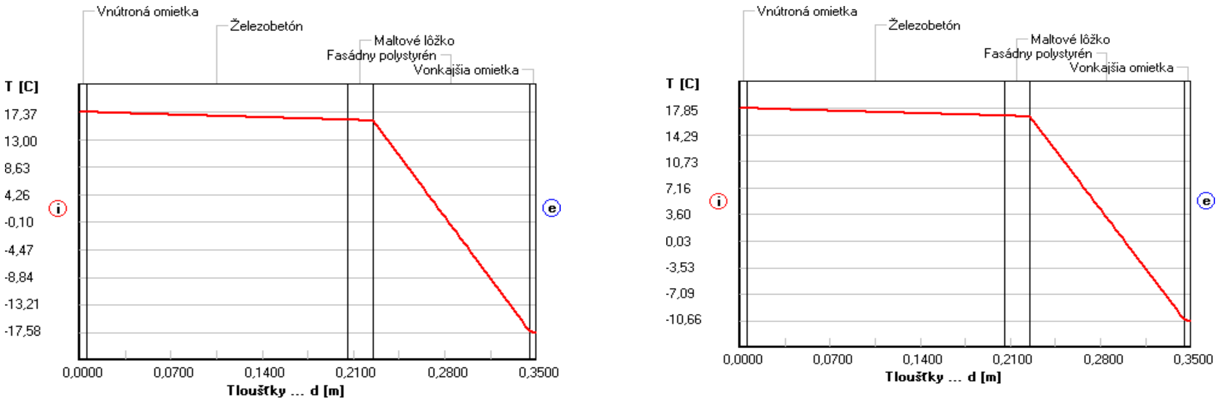

Figure 2: Temperature profile in structure A: Θ_i = 20°C, Θ_e = -18°C, temperature in the ATP layer = 16.0°C (left), temperature profile in structure A: Θ_i = 20°C, Θ_e = -11°C, temperature in the ATP layer = 16.8°C (right) [10, 13]

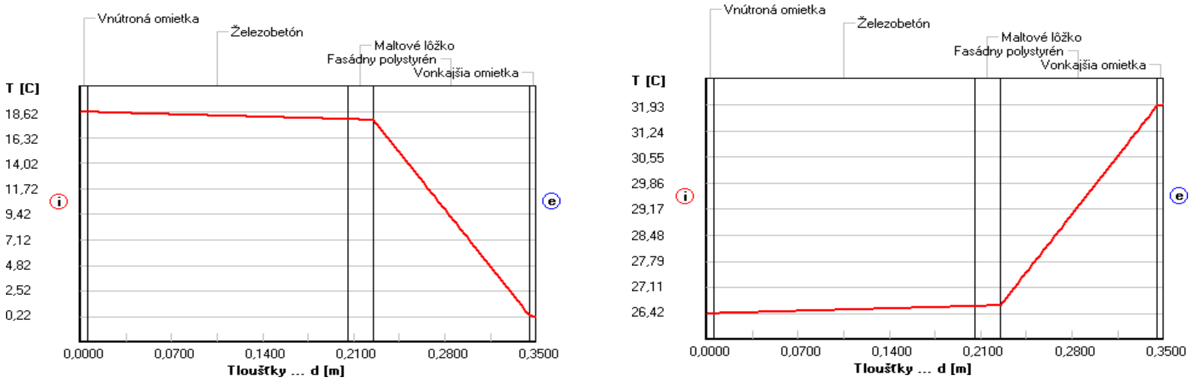

Figure 3: Temperature profile in structure A: Θ_i = 20°C, Θ_e = 0°C, temperature in the ATP layer = 17.9°C (left), temperature profile in structure A: Θ_i = 26°C, Θ_e = 32°C, temperature in the ATP layer = 26.6°C (right) [10, 13]

Structure B. Figure 4 to 5 show the outputs from the Heat program. The structure has a heat transfer coefficient U = 0.29 W/(m^2.K). Composition of the structure from the interior:

- interior plaster, 5 mm thick, λ = 0.88 W/(m.K),
- polystyrene, 60 mm thick, λ = 0.038 W/(m.K),
- reinforced concrete, 200 mm thick, λ = 1.74 W/(m.K),
- polystyrene, 60 mm thick, λ = 0.038 W/(m.K),
- exterior plaster, 5 mm thick, λ = 0.20 W/(m.K).

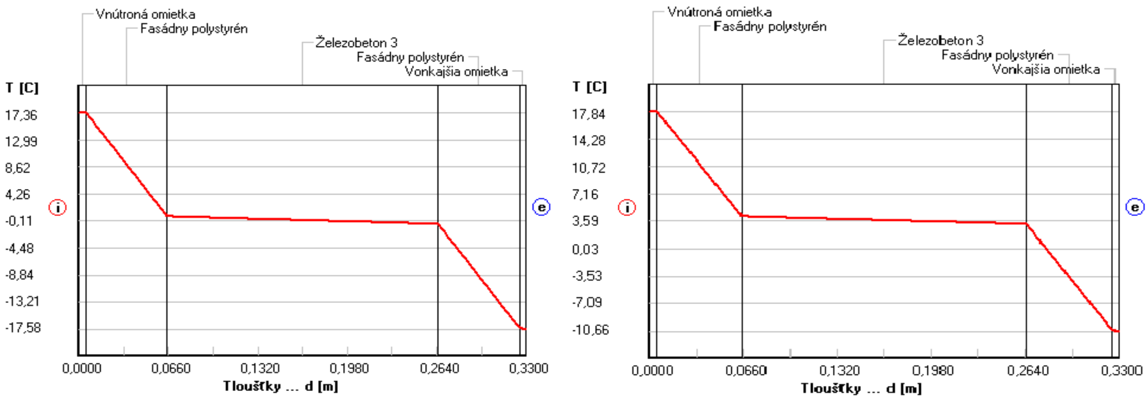

Figure 4: Temperature profile in structure B: Θ_i = 20°C, Θ_e = -18°C, temperature in the ATP layer = 0.0°C (left), temperature profile in structure B: Θ_i = 20°C, Θ_e = -11°C, temperature in the ATP layer = 3.7°C (right) [10, 13]

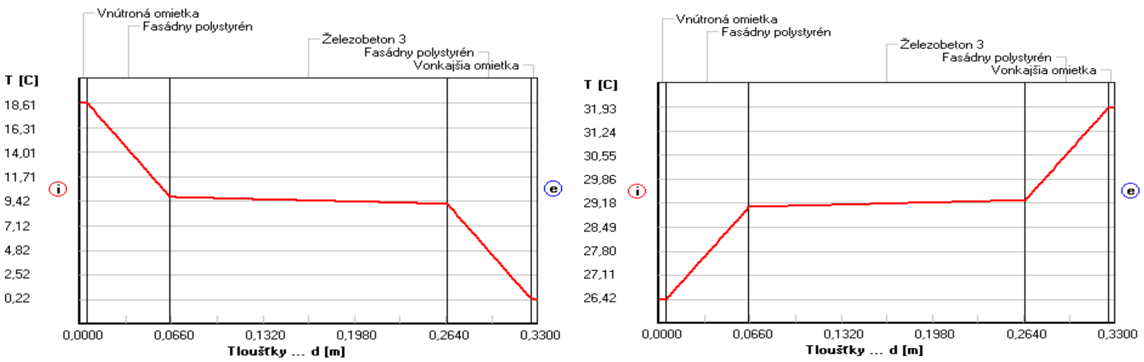

Figure 5: Temperature profile in structure B: θ_i = 20°C, θ_e = 0°C, temperature in the ATP layer = 9.5°C (left), temperature profile in structure B: θ_i = 26°C, θ_e = 32°C, temperature in the ATP layer = 29.2°C (right) [10, 13]

Structure C. Figure 6 to 7 show the outputs from the Heat program. The structure has a heat transfer coefficient U = 0.29 W/(m^2.K). Composition of the structure from the interior:

- interior plaster, hr. 5 mm thick, λ = 0.88 W/(m.K),
- aerated concrete block, hr. 300 mm thick, λ = 0.16 W/(m.K),
- mortar bed, hr. 20 mm thick, λ = 1.16 W/(m.K),
- polystyrene, hr. 50 mm thick, λ = 0.038 W/(m.K),
- exterior plaster, hr. 5 mm thick, λ = 0.20 W/(m.K).

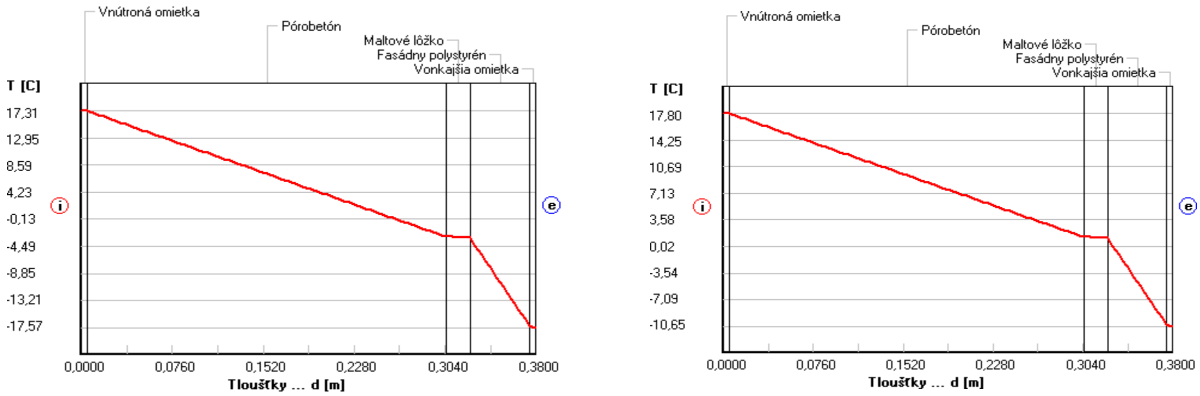

Figure 6: Temperature profile in structure C: ϴi = 20°C, ϴe = -18°C, temperature in the ATO layer = -3.0°C (left), temperature profile in structure C: ϴi = 20°C, ϴe = -11°C, temperature in the ATO layer = 1.2°C (right) [10, 13]

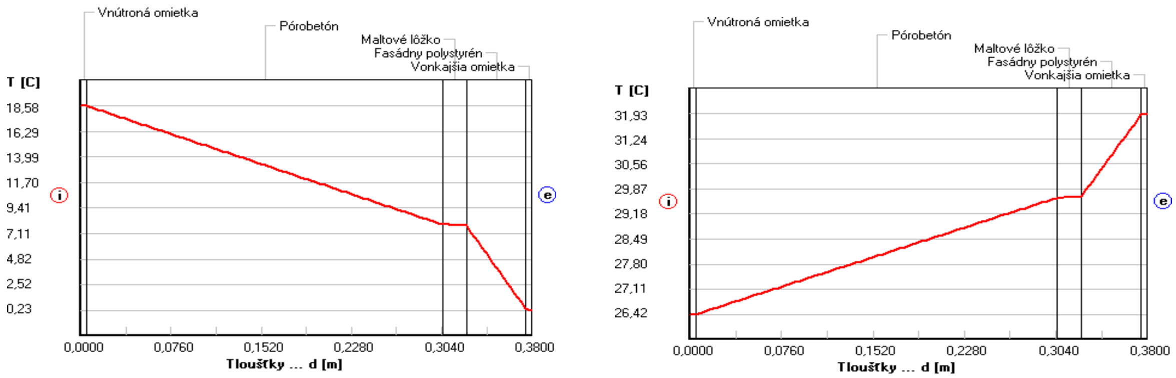

Figure 7: Temperature profile in structure C: ϴi = 20°C, ϴe = 0°C, temperature in the ATO layer = 7.9°C (left), temperature profile in structure C: ϴi = 26°C, ϴe = 32°C, temperature in the ATO layer = 29.6°C (right) [10, 13]

Structures with the same heat transfer coefficient have diametrically different temperatures at the ATP location. For structure A, it ranges from 16°C (at θ_e = -18°C) to 17.9°C (at θ_e = 0°C). The temperature in the ATP pipe as a thermal barrier must therefore be higher. For structure B, the ATP would be located in the middle of the reinforced concrete structure, where the temperature ranges from 0°C (at θ_e = -18°C) to 9.5°C (at θ_e = 0°C). For structure C, the temperature ranges from -3.0°C (at θ_e = -18°C) to 7.9°C (at θ_e = 0°C). A building structure that would have inverted layers like structure A, i.e. thermal insulation from the interior and reinforced concrete from the exterior, has not been assessed. Such a structure would have the highest heat fluxes to the exterior and the temperature in the ATP layer would be below 0°C. The circulating medium should not be water. The task will be to further calculate the heat flux from the interior and the heat flux from the ATP to the exterior, so that the system can be evaluated in more detail.

III. HEAT TRANSMISSION METHOD - CALCULATION OF ATP IN THE FUNCTION OF HEAT BARRIER, WALL HEATING, AND WALL COOLING

Heat exchange in the ATP system represents combined heat transfer by convection and radiation. Heat transfer occurs on the inside and outside of the building structure. On the inside of the building structure there is:

- air flow, as the air is warmer in the higher positions and colder in the lower positions,
- radiation as a consequence of the heat exchange of a given structure with all other room structures.

On the outside of the building structure there is:

- air flow mostly along the structure due to wind,
- radiation between a given surface of a structure and the sky, between surrounding buildings and terrain. [34]

The following relations will be used to calculate the heat flow from the ATO: Average temperature of the structure in the axis of the pipes:

$$\theta_d - \theta_i = (\theta_m - \theta_i).\frac{tgh\left(m.\frac{L}{2}\right)}{m.\frac{L}{2}} \quad (K)$$ [28, 57] (1)

θ_d is the average temperature of the structure in the axis of the pipes (°C),
θ_i calculated internal room temperature (°C),
θ_m average heating water temperature (°C),
L axial distance of pipes (m),
m coefficient characterizing the heating plate in terms of heat dissipation (m^{-1}).

Coefficient characterizing the heating plate in terms of heat dissipation:

$$m = \sqrt{\frac{2.(\Lambda_a + \Lambda_b)}{\pi^2.\lambda_d.d}} \quad (m^{-1})$$ [28, 57] (2)

Λ_a thermal permeability of the layer in front of the pipes toward the interior ($W/(m^2.K)$),
Λ_b thermal permeability of the layer behind the pipes toward the exterior ($W/(m^2.K)$),
λ_d thermal conductivity of the material into which the tubes are inserted (W (/m.K)),
d pipe diameter (m).

Thermal permeability of the layer in front of the pipes toward the interior:

$$\Lambda_a = \sqrt{\frac{1}{\sum\frac{a}{\lambda_a} + \frac{1}{\alpha_p}}} \quad (W/(m^2.K))$$ [28, 57] (3)

Thermal permeability of the layer behind the pipes toward the exterior:

$$\Lambda_b = \sqrt{\frac{1}{\sum\frac{b}{\lambda_b} + \frac{1}{\alpha'_p}}} \quad (W/(m^2.K))$$ [28, 57] (4)

a thickness of the layer in front of the pipes (m),
b thickness of the layer behind the pipes (m),
λ_a, λ_b thermal conductivity of the material of the respective layer (W/(m.K)),
α_p heat transfer coefficient toward the interior ($W/(m^2.K)$),
α'_p heat transfer coefficient toward exterior ($W/(m^2.K)$).

Average surface temperature of the structure:

$$\theta_p - \theta_i = \frac{\Lambda_a}{\alpha_p}.(\theta_d - \theta_i) = \frac{\Lambda_a}{\alpha_p}.(\theta_m - \theta_i).\frac{tgh\left(m.\frac{L}{2}\right)}{m.\frac{L}{2}} \quad (K)$$ [28, 57] (5)

Specific heat output (flow) from the structure toward the interior:

$$q = \Lambda_a .(\theta_d - \theta_i) = \alpha_p .\left(\theta_p - \theta_i\right) \quad (W/m^2)$$ [28, 57] (6)

Specific heat output (flow) from the structure toward the exterior:

$$q'' = \Lambda_b .(\theta_d - \theta_i) = \Lambda_b .\frac{\alpha_p}{\Lambda_a}.\left(\theta_p - \theta_i\right) + \Lambda_b .\ (\theta_i - \theta_e) \ (W/m^2)$$ [28, 57] (7)

The following values were calculated for structures A, B and C: θ_d - average temperature of the structure in the axis of pipes (°C), θ_p - average surface temperature of the structure in the interior (°C), q - heat flow from the structure toward the interior (W/m^2) and q´´ - heat flow from the structure toward the exterior (W/m^2). The calculation was performed for the winter (ATP as a wall heating and thermal barrier) and the summer (ATP as a wall cooling function). Boundary conditions: external dimension of the ATP pipe = 16 mm, spacing between the pipes = 0.20 m, heat transfer coefficient toward the interior = 8 W/(m^2.K) (in accordance with STN EN 15377-1 and ČSN 730548), heat transfer coefficient toward the exterior = 15 W/(m^2.K) (in accordance with ČSN 730548). In simplified calculation relations, the same air temperature in front of and behind the pipes was considered when calculating the average structure temperature in the pipe axis and the average surface temperature in accordance with [30, 60]. The results of the calculations for winter are shown in TAB. 4.8. Outside air temperature θ_e = -11°C was considered, internal air temperature θ_i = 20°C and mean working medium temperature in the ATO pipeline θ_m = 20 to 45°C. The calculation was processed in Excel.

Table 1: Average temperature in the pipe axis θ_d (°C), average surface temperature θ_p (°C), heat flux toward the interior q (W/m^2) and heat flux toward the exterior q´´ (W/m^2) for structures A, B and C (wall heating, thermal barrier) [10, 13]

	θ_e (°C)	θ_i (°C)	θ_m (°C)	θ_d (°C)	θ_p (°C)	q (W/m^2)	q´´ (W/m^2)
Structure A	-11	20	20	20.00	20.00	0.000	3.390
	-11	20	25	24.33	22.20	17.632	4.723
	-11	20	30	28.66	24.41	35.264	6.055
	-11	20	35	32.99	26.61	52.896	7.388
	-11	20	40	37.32	28.82	70.528	8.721
	-11	20	45	41.65	31.02	88.160	10.054
Structure B	-11	20	20	20.00	20.00	0.000	6.375
	-11	20	25	24.87	20.34	2.753	9.190
	-11	20	30	29.73	20.69	5.507	12.006
	-11	20	35	34.60	21.03	8.260	14.822
	-11	20	40	39.46	21.38	11.014	17.637
	-11	20	45	44.33	21.72	13.767	20.453
Structure C	-11	20	20	20.00	20.00	0.000	7.827
	-11	20	25	24.79	20.30	2.389	11.231
	-11	20	30	29.58	20.60	4.777	14.635
	-11	20	35	34.37	20.90	7.166	18.039
	-11	20	40	39.16	21.19	9.555	21.443
	-11	20	45	43.96	21.49	11.944	24.847

Comparison of structures brings the following results:

1. Building structure A consists of the interior in front of the ATP made of a material with high thermal conductivity and low thermal resistance (reinforced concrete) and behind the ATP towards the exterior made of a material with low thermal conductivity and high thermal resistance (polystyrene). As a result, a higher surface temperature in the interior, a higher heat flux toward the interior and a lower heat flux toward the exterior are achieved compared to structures B and C. Surface temperature θ_p e.g. at mean temperature of the working medium θ_m = 35°C in the ATP pipe starts at 26.61°C, while at structure B = 21.03°C and structure C = 20.90°C. The heat flux toward the interior at θ_m = 35°C is 52.896 W/m^2. Compared to structure B (8,260 W/m^2), this value is more than 6 times higher and compared to structure C (7,166 W/m^2) more than 7 times higher. The heat flux toward the exterior is by almost half lower than with structure B. The difference is even greater compared to structure C.

2, Building structures B and C consist of materials with low thermal conductivity and high thermal resistance in front of and behind the ATP. The heat flow toward the interior is considerably limited, compared to structure A the values are significantly lower. A higher average temperature in the pipe axis (θ_d) is generated in the layer where the ATP is located. However, as the temperature in the ATP pipe increases, the surface temperature in the interior increases only minimally. For example, in structure C, at the mean temperature of the working medium θm = 25°C the surface temperature is θ_p = 20.30°C, at θm = 45°C θ_p = 21.49°C. The heat flux toward the exterior is higher.

For a better comparison of the individual structures, charts were created that are shown in Figure 8 to 10. The average temperatures in the pipe axis, the average surface temperatures in the interior, and the heat fluxes toward the interior and exterior are shown for each structure.

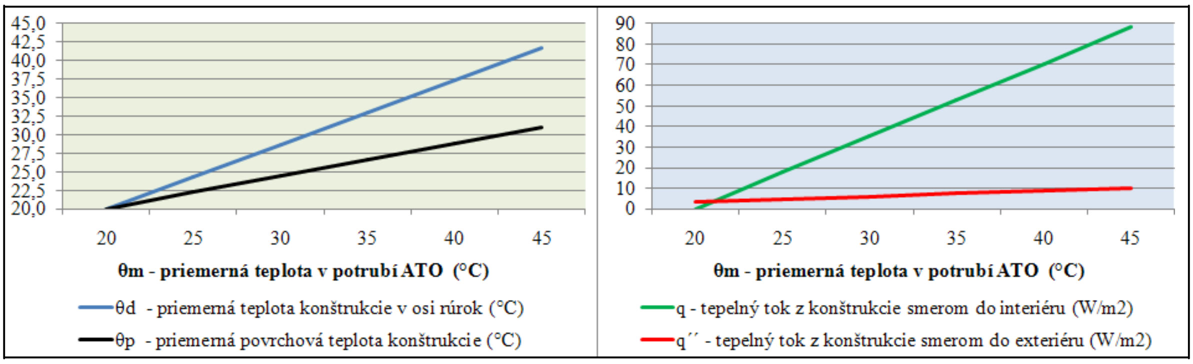

Figure 8: Structure A - ATP as a thermal barrier and wall heating, *θ_m average temperature in ATP pipes (°C), θ_d average temperature in pipe axis (°C), θ_p average structure surface temperature (°C), q heat flow from the structure toward the interior (W/m^2), q" heat flow from the structure toward the exterior (W/m^2)* [10, 13]

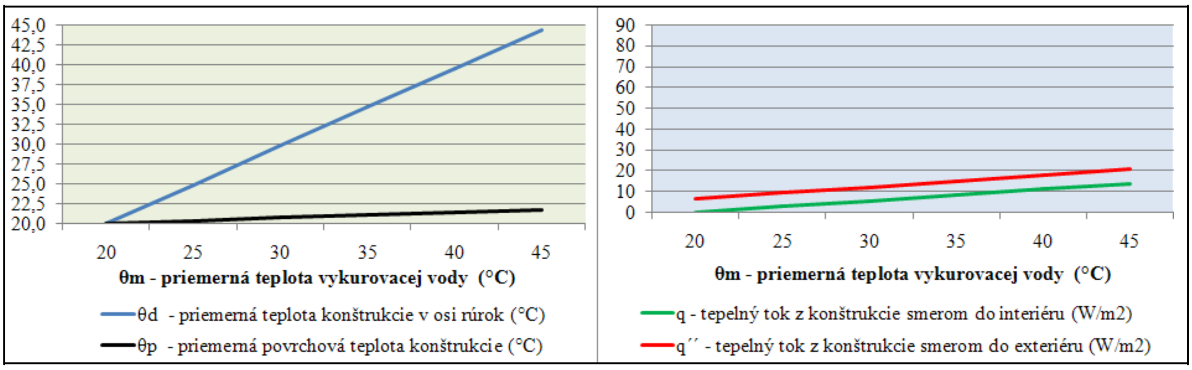

Figure 9: Structure B - ATP as a thermal barrier and wall heating, *θ_m average temperature in ATP pipes (°C), θ_d average temperature in pipe axis (°C), θ_p average structure surface temperature (°C), q heat flow from the structure toward the interior (W/m^2), q" heat flow from the structure toward the exterior (W/m^2)* [10, 13]

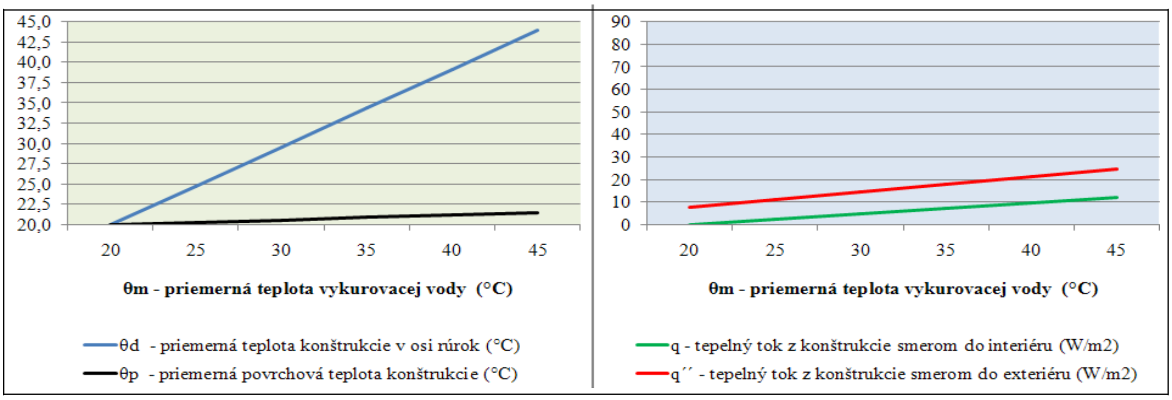

Figure 10: Structure C – ATP as a thermal barrier and wall heating, *θ_m average temperature in ATP pipes (°C), θ_d average temperature in pipe axis (°C), θ_p average structure surface temperature (°C), q heat flow from the structure toward the interior (W/m^2), q" heat flow from the structure toward the exterior (W/m^2)* [10, 13]

The ATP was further assessed in a wall cooling function. The results are shown in Table 2. Outside air temperature θ_e = 32°C, indoor air temperature θ_i = 26°C and mean working fluid temperature θ_m = 16°C to 21°C were considered.

Heat fluxes are negative, because the temperature of the working medium in the pipe is lower than the air temperature in the exterior and interior. It is clear that the wall cooling is of the greatest importance in structure A, i.e. in the structure which has high thermal conductivity and low thermal resistance from the pipes toward the interior. Due to the fact that behind the ATP towards the exterior there is a material with high thermal resistance, the heat flux toward the exterior is significantly lower. The surface temperature in the interior of structure A decreases significantly from 23.80°C (at θ_m = 21°C) to 21.59°C (at θ_m = 16°C).

In structures B and C, the heat flow (cold) toward the interior is considerably limited and, conversely, the heat flow (cold) to the exterior is significantly higher. This means that the temperature in the return pipe will be higher. The surface temperature in the interior changes only minimally - e.g. for structure B from 25.66°C (at θ_m = 21°C) to 25.31°C (at θ_m = 16°C). Wall cooling in building structures that have low thermal conductivity and high thermal resistance towards the interior in front of the ATP is considerably limited. In principle, it is only possible to cover heat gains through non-transparent structures. For better comparison, charts are shown in Figure 11 to Figure 13. They show average temperatures in the pipe axis, average surface temperatures in the interior, and heat fluxes to the interior and exterior.

Table 2: Average temperature in the pipe axis θ_d (°C), average surface temperature θ_p (°C), heat flow toward the interior q (W/m^2) and heat flow toward the exterior q´´ (W/m^2) for structures A, B and C (wall cooling) [10, 13]

	θ_e (°C)	θ_i (°C)	θ_m (°C)	θ_d (°C)	θ_p (°C)	q (W/m^2)	q´´ (W/m^2)
Structure A	32	26	16	17.34	21.59	-35.264	-12.508
	32	26	17	18.20	22.03	-31.738	-12.242
	32	26	18	19.07	22.47	-28.211	-11.975
	32	26	19	19.94	22.91	-24.685	-11.708
	32	26	20	20.80	23.36	-21.164	-11.101
	32	26	21	21.67	23.80	-17.632	-11.175
Structure B	32	26	16	16.27	25.31	-5.507	-24.140
	32	26	17	17.24	25.38	-4.956	-23.576
	32	26	18	18.22	25.45	-4.406	-23.013
	32	26	19	19.19	25.52	-3.855	-22.450
	32	26	20	20.16	25.59	-3.304	-21.887
	32	26	21	21.13	25.66	-2.753	-21.324

Structure C	32	26	16	16.42	25.40	-4.777	-29.533
	32	26	17	17.38	25.46	-4.300	-28.852
	32	26	18	18.33	25.52	-3.822	-28.171
	32	26	19	19.29	25.58	-3.344	-27.490
	32	26	20	20.25	25.64	-2.866	-26.810
	32	26	21	21.21	25.70	-2.389	-26.129

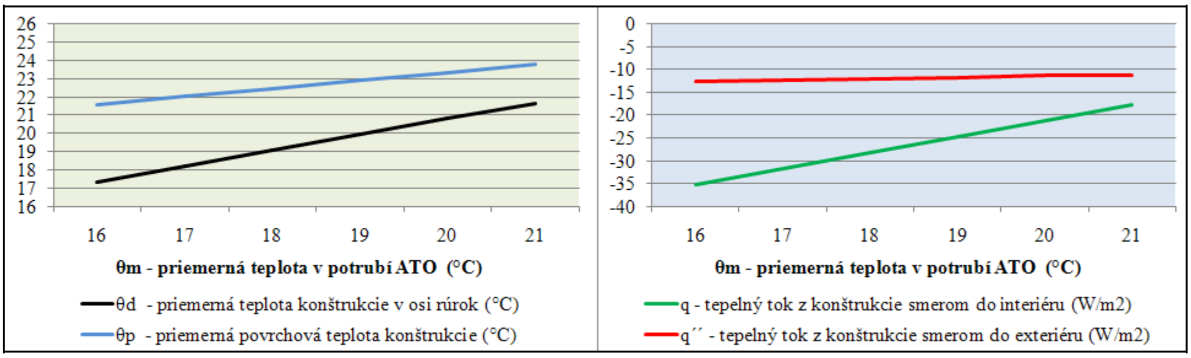

Figure 11: Structure A - ATP in the function of wall cooling, θ_m *average temperature in ATP pipes (°C),* θ_d *average temperature in pipe axis (°C),* θ_p *average structure surface temperature (°C), q heat flow from the structure toward the interior (W/m²), q" heat flow from the structure toward the exterior (W/m²)* [10, 13]

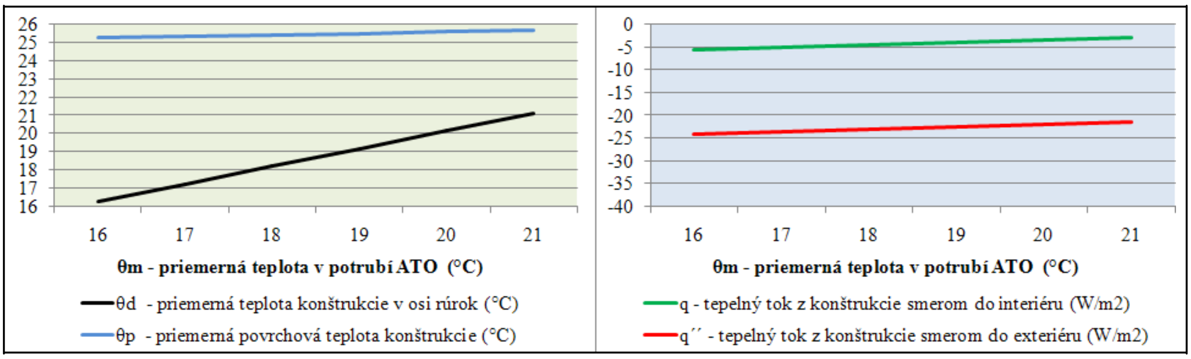

Figure 12: Structure B - ATP in the function of wall cooling, θ_m *average temperature in ATP pipes (°C),* θ_d *average temperature in pipe axis (°C),* θ_p *average structure surface temperature (°C), q heat flow from the structure toward the interior (W/m²), q" heat flow from the structure toward the exterior (W/m²)* [10, 13]

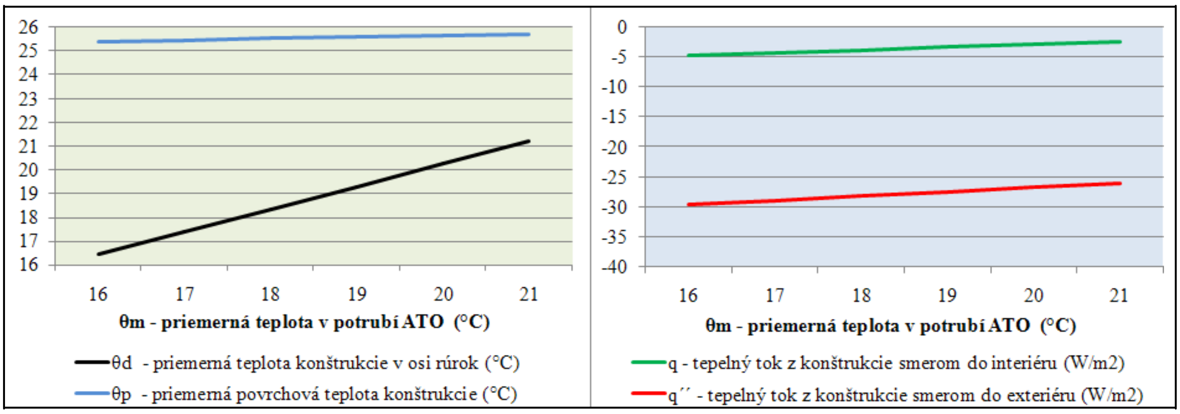

Figure 13: Structure C - ATP in the function of wall cooling, θ_m *average temperature in ATP pipes (°C),* θ_d *average temperature in pipe axis (°C),* θ_p *average structure surface temperature (°C), q heat flow from the structure toward the interior (W/m²), q" heat flow from the structure toward the exterior (W/m²)* [10, 13]

IV. CONCLUSION

Based on previous calculations, in which, as already mentioned, some simplifications have been applied, several conclusions can be drawn:

- The ATP in the function of wall heating and wall cooling is more suitable for use in building structures consisting of a material with high thermal conductivity and low thermal resistance before the ATP toward the interior and behind the ATP toward the exterior from a material with low thermal conductivity and high thermal resistance. A higher surface temperature in the interior will be achieved with wall heating and a lower one with wall cooling, a higher heat flux toward the interior and a lower heat flux towards the exterior.

- In building structures that have a material with low thermal conductivity and high thermal resistance in front of and behind the ATP, the operation of the ATP in the function of wall heating and wall cooling is limited - increasing the temperature of the working medium in the ATP in the function of wall heating increases in the interior temperature only minimally, during wall cooling, the heat flow (cold) toward the interior is considerably limited and the surface temperature decreases only minimally. In such structures, the average temperature of the structure in the ATP layer is higher and more balanced, because the heat flow toward the interior and partly also to the exterior is limited. A thermal barrier is created, which makes it possible to reduce or eliminate heat losses through non-transparent structures, but further increasing the temperature in the ATP pipeline is of no practical significance. With wall cooling, it is possible to cover the heat gains through the structure, but further reducing the temperature in the ATP piping is of no practical significance.

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