

Parametric Study of Heating and Cooling Capacity of Interior Thermally Active Panels

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Abstract

ITAP panels - interior thermally active panels with an integrated active surface in an innovative way combine existing building and energy systems into one compact unit, and thus create combined building and energy systems. These are building structures with an internal energy source. Low heat losses, respectively, thermal gains predestine for energy-efficient buildings the application of low-temperature heating/high-temperature cooling systems such as large-area floor, wall, and ceiling heating/cooling. The main benefit of ITAP panels is the possibility of unified and prefabricated production. At the same time, they represent a reduction of production costs due to their technological process of production, a reduction of assembly costs due to a reduction of steps during implementation on the construction site and a reduction of implementation time due to their method of application.

Keywords

thermally active panels, integrated active surface, large-area radiant low-temperature heating temperature, high-temperature cooling, mathematical-physical model, parametric study

1 Introduction

ITAP panels - interior thermally active panels with an integrated active surface are formed by a tubular or capillary energy system integrated in the thermal insulation part of a panel and a thermally active surface formed by a thermally conductive material (e.g., thin layer plaster, plasterboard, or sheet metal). They are applied in the same way as previously known panels with integrated tubular or capillary systems (e.g., in SD boards). ITAP panels are protected by European patent EP 2 572 057 B1 [1] from 15.10.2014 [2]. We focused our research in this area on the possibilities of application of ITAP panels for large-area low-temperature heating and high-temperature cooling with heat/cold sources based on RES [1, 2, 3–6]. The subject of the research described in this paper is a parametric study of the method of heat/cold dissipation in a perimeter wall and interior wall fragment with concealed tube energy system and ITAP panels, optimization of appropriate thermal insulation thickness, tube dimensions and spacing of interior thermally active panels with an integrated active surface [1, 2, 3–6].

2 Research methodology and methods

To solve the given research questions we have chosen the method of a parametric study. A mathematical–physical model of the perimeter wall with an ITAP panel was created. Stationary (time-stabilized) parametric studies were performed, where the following parameters changed: thickness of the thermal insulation (ITAP panel), spacing and dimension of the tubes, temperature gradient of the heat transfer medium and temperature in the interior, exterior, and adjacent room, respectively. All these parametric studies were performed at boundary conditions representing both winter and summer, [2, 3, 7, 8].

2.1 Theory of calculation of large-area radiant heating

Calculation of the radiant heating surface is based on the assumption that the average surface temperature of the radiant heating surface does not exceed hygienically permissible values, while the heat output of the radiant heating surface will cover the heat losses of the heated space. Modified calculation for radiant hot water heating, [7, 9, 10]. Thermal permeability of the layer above/in front of the tubes Λ_a (W/(m².K)) is calculated as in Eq. (1):

$$\Lambda_a = \frac{1}{\sum \frac{a}{\lambda_a} + \frac{1}{h_p}}, \quad (1)$$

where: a is thickness of the layer above/in front of the tubes (m), λ_a is thermal conductivity coefficient of the material of the respective layer (W/(m².K)), h_p is heat transfer coefficient (W/(m².K)).

Thermal permeability of the layer under/behind the tubes Λ_b (W/(m².K)) is calculated as in Eq. (2):

$$\Lambda_b = \frac{1}{\sum \frac{b}{\lambda_b} + \frac{1}{h_p}}, \quad (2)$$

where: b is thickness of the layer under/behind the tubes (m), λ_b is thermal conductivity coefficient of the material of the respective layer (W/(m².K)), h_p is heat transfer coefficient (W/(m².K)).

Coefficient characterizing the heating plate in terms of heat dissipation m (m⁻¹) is calculated as in Eq. (3):

$$m = \sqrt{\frac{2 \cdot (\Lambda_a + \Lambda_b)}{\pi^2 \cdot \lambda_d \cdot d}}, \quad (3)$$

where: Λ_a is thermal permeability of the layer above/in front of the tubes (W/(m².K)), Λ_b is thermal permeability of the layer under/behind the tubes (W/(m².K)), λ_d is thermal conductivity of the material of the layer in which the tubes are embedded (W/(m².K)), d is tube diameter (m).

Surface temperature of the heating surface θ_p (°C) is calculated as in Eq. (4):

$$\theta_p - \theta_i = \frac{\Lambda_a}{h_p} (\theta_m - \theta_i) \frac{tgh\left(m \cdot \frac{L}{2}\right)}{m \cdot \frac{L}{2}}, \quad (4)$$

where: θ_p is floor surface temperature (°C), θ_i is calculated indoor room temperature (°C), Λ_a is thermal permeability of the layer above/in front of the tubes (W/(m².K)), h_p is heat transfer coefficient (W/(m².K)), θ_m is average temperature of heating water (°C), m is factor characterizing the heating plate in terms of heat dissipation (m⁻¹), L is axial distance of tubes (m).

Specific heat output of the heating surface upwards q (W/m²) is calculated as in Eq. (5):

$$q = h_p \cdot (\theta_p - \theta_i), \quad (5)$$

where: h_p is heat transfer coefficient from the floor upwards (W/(m².K)), θ_p is floor surface temperature (°C), θ_i is calculated indoor room temperature (°C).

Specific heat output of the heating surface downwards q' (W/m²) is calculated as in Eq. (6):

$$q' = \frac{\Lambda_b}{\Lambda_a} \cdot q, \quad (6)$$

where: Λ_b is thermal permeability of the layer under the tubes (W/(m².K)), Λ_a is thermal permeability of the layer above the tubes (W/(m².K)), q is specific heat output of the underfloor heating surface upwards (W/m²).

Heating area S (m²) is calculated as in Eq. (7):

$$S = \frac{Q_c}{h_p \cdot (\theta_p - \theta_i)} = \frac{Q_c}{q + q'}, \quad (7)$$

where: Q_c is total heat loss (W), h_p is heat transfer coefficient from the floor upwards (W/(m².K)), θ_p is floor surface temperature (°C), θ_i is calculated indoor room temperature (°C), q is heat output of the heating surface towards the interior (W/m²), q' is heat output of the heating surface towards the exterior (W/m²).

Heat output of the heating surface Q_s (W) is calculated as in Eq. (8):

$$Q_s = (q + q') \cdot S_p, \quad (8)$$

where: q is heat output of the heating surface towards the interior (W/m²), q' is heat output of the heating surface towards the exterior (W/m²), S_p is heating surface (m²).

2.2 Mathematical-physical model

As a basis for the parametric study, a mathematical-physical model for concealed large-area heating was made (Figs. 1 and 2) and a mathematical-physical model for ITAP panel (Figs. 3 and 4). Color-differentiated materials can be seen on mathematical-physical models, which consist of characteristic fragments of the perimeter wall and the inner wall with a concealed energy system and ITAP panels. Material characteristics were assigned to individual materials [2, 5–14].

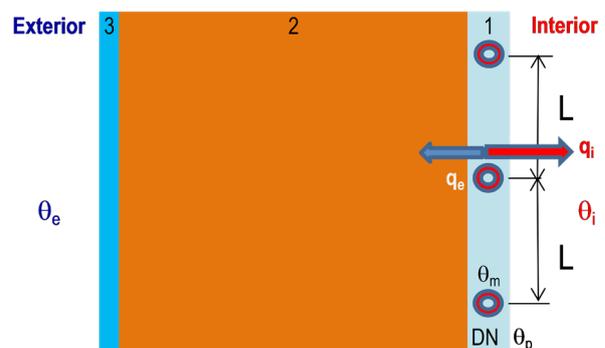


Fig. 1 Mathematical-physical model for concealed large-area heating on the perimeter wall and individual material characteristics according to STN 73 0540-3 [15]

2.2.1 Perimeter (external) wall

Legend for Fig. 1:

L is tube spacing (m), DN is tube dimension (m), θ_m is mean temperature of heating medium ($^{\circ}\text{C}$), θ_i is interior temperature ($^{\circ}\text{C}$), θ_e is exterior temperature ($^{\circ}\text{C}$), θ_p is surface temperature of heating/cooling surface ($^{\circ}\text{C}$), q_i is heat output of the heating surface towards the interior (W/m^2), q_e is heat output of the heating surface towards the exterior (W/m^2).

In Table 1 the values of physical quantities in individual layers of the building structure are given.

2.2.2 Inner (internal) wall

Legend for Fig. 2:

L is tube spacing (m), DN is tube dimension (m), θ_m is mean temperature of heating medium ($^{\circ}\text{C}$), θ_i is interior temperature ($^{\circ}\text{C}$), θ_{i2} is interior temperature in the adjacent room ($^{\circ}\text{C}$), θ_p is surface temperature of heating/cooling surface ($^{\circ}\text{C}$), q_i is heat output of the heating surface towards the interior (W/m^2), q_{i2} is heat output of the heating surface towards the adjacent room (W/m^2).

Table 1 Mathematical-physical model of large-area radiant heating for perimeter (external) wall [15]

Layer	Material	Thickness d (m)	Volumetric density ρ (kg/m^3)	Thermal conductivity coefficient λ ($\text{W}/(\text{m}\cdot\text{K})$)	Specific heat capacity c ($\text{J}/(\text{kg}\cdot\text{K})$)
1	Interior plaster	0.010*	1600	1.160	840
2	Thermal insul. masonry	0.500	650	0.058	1000
3	Exterior plaster	0.010	1300	0.800	840

* thickness of the layer in front of/behind tubes toward the interior

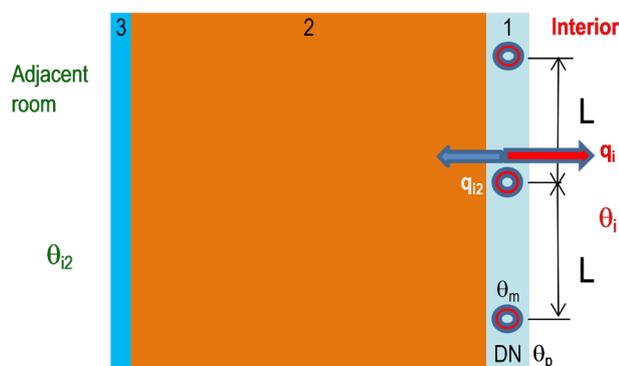


Fig. 2 Mathematical-physical model for concealed large-area heating on the inner wall and individual material characteristics according to STN 73 0540-3 [15]

Table 2 Mathematical-physical model of large-area radiant heating for inner (internal) wall [15]

Layer	Material	Thickness d (m)	Volumetric density ρ (kg/m^3)	Thermal conductivity coefficient λ ($\text{W}/(\text{m}\cdot\text{K})$)	Specific heat capacity c ($\text{J}/(\text{kg}\cdot\text{K})$)
1	Interior plaster	0.010*	1600	1.160	840
2	Brick masonry	0.240	1350	0.510	960
3	Exterior plaster	0.010	1300	0.800	840

* thickness of the layer in front of/behind tubes toward the interior

In Table 2 the values of physical quantities in individual layers of the building structure are given.

2.2.3 Perimeter (external) wall with ITAP panel

Legend for Fig. 3:

L is tube spacing (m), DN is tube dimension (m), θ_m is mean temperature of heating medium ($^{\circ}\text{C}$), θ_i is interior temperature ($^{\circ}\text{C}$), θ_e is exterior temperature ($^{\circ}\text{C}$), θ_p is surface temperature of heating/cooling surface ($^{\circ}\text{C}$), q_i is heat output of the heating surface towards the interior (W/m^2), q_e is heat output of the heating surface towards the exterior (W/m^2).

In Table 3 the values of physical quantities in individual layers of the building structure are given.

2.2.4 Inner (internal) wall with ITAP panel

Legend for Fig. 4:

L is tube spacing (m), DN is tube dimension (m), θ_m is mean temperature of heating medium ($^{\circ}\text{C}$), θ_i is interior temperature ($^{\circ}\text{C}$), θ_{i2} is interior temperature in the adjacent room ($^{\circ}\text{C}$), θ_p is surface temperature of heating/cooling surface ($^{\circ}\text{C}$), q_i is heat output of the heating surface towards the interior (W/m^2), q_{i2} is heat output of the heating surface towards the adjacent room (W/m^2).

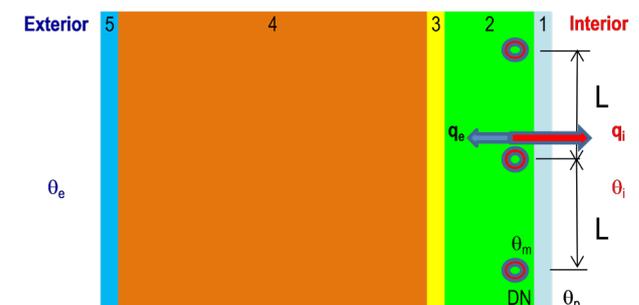


Fig. 3 Mathematical-physical model for a perimeter wall with ITAP panel and individual material characteristics according to STN 73 0540-3 [15]

Table 3 Mathematical-physical model of large-area radiant heating for perimeter (external) wall with ITAP panel [15]

Layer	Material	Thickness	Volumetric density	Thermal conductivity coefficient	Specific heat capacity
		d (m)	ρ (kg/m ³)	λ (W/(m.K))	c (J/(kg.K))
1	Interior plaster	0.010	1600	1.160	840
2	Thermal insulation EPS-F	0.050	30	0.040	1270
3	Adhesive mortar	0.005	1300	1.160	840
4	Thermal insul. masonry	0.500	650	0.058	1000
5	Exterior plaster	0.010	1300	0.800	840

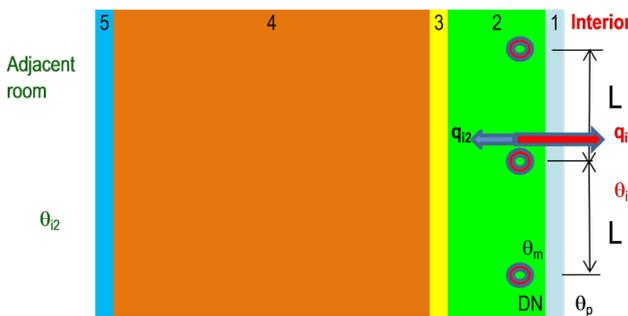


Fig. 4 Mathematical-physical model for a inner wall with ITAP panel and individual material characteristics according to STN 73 0540-3 [15]

Table 4 Mathematical-physical model of large-area radiant heating for inner (internal) wall with ITAP panel [15]

Layer	Material	Thickness	Volumetric density	Thermal conductivity coefficient	Specific heat capacity
		d (m)	ρ (kg/m ³)	λ (W/(m.K))	c (J/(kg.K))
1	Interior plaster	0.010	1600	1.160	840
2	Thermal insulation EPS-F	0.050	30	0.040	1270
3	Adhesive mortar	0.005	1300	1.160	840
4	Brick masonry	0.240	1350	0.510	960
5	Exterior plaster	0.010	1300	0.800	840

In Table 4 the values of physical quantities in individual layers of the building structure are given.

2.3 Parametric study

Parametric study for the described mathematical-physical model - fragment of an inner wall with ITAP panel (Fig.4) and a perimeter wall with ITAP panel (Fig. 3) was performed on a mathematical configurator - Calculation of

large-area radiant heating (VVSV) in MS Excel [15]. Input data that can be changed: thickness of thermal insulation (ITAP panel), spacing and dimensions of tubes, temperature gradient of heat transfer medium and temperature in the interior, exterior, or adjacent room, compositions and thicknesses of building structures in front of/above and behind/under tubes, thermal-technical properties of building materials (thermal conductivity of materials, heat transfer coefficient). Parametric calculations were performed at boundary conditions representing winter $\theta_e = -11$ °C and summer $\theta_e = +32$ °C.

Table 1 shows the input criteria for the parametric study of a perimeter wall with ITAP panels - heating period: thermal insulation thickness 50 mm, tube dimension 15 mm, interior temperature +20 °C, exterior temperature -11 °C, mean heat transfer medium temperature +35 °C and tube spacing 100 mm. Using the mathematical configurator, the following parameters of large-area wall heating with ITAP panels on the perimeter wall were calculated. Outputs from the mathematical configurator – parametric study of the ITAP panel – heating period are given in Tables 5 to 7.

2.3.1 Winter season (heating period)

These are important results excluded from Tables 5 to 7:

- heat flow to the interior $q_i = 99.685$ W/m²,
- heat flow to the exterior $q_e = 4.282$ W/m²,
- total heat flow 103.967 W/m²,
- total heat flow losses 4.12 %,
- surface temperature 30.310 °C.

Tables 8 to 10 shows the input criteria for the parametric study of a perimeter wall with ITAP panels - summer: thermal insulation thickness 50 mm, tube dimension 15 mm, interior temperature +26 °C, exterior temperature +32 °C, mean temperature of the heat transfer medium is +17 °C, tube spacing 100 mm. Using the mathematical configurator, the following parameters of large-area wall cooling with ITAP panels on the perimeter wall were calculated. Outputs from the mathematical configurator – parametric study of the ITAP panel – summer season are given in Table 8 to 10.

2.3.2 Summer season

These are important results excluded from Tables 8 to 10:

- heat flow to the interior $q_i = -59.811$ W/m²,
- heat flow to the exterior $q_e = -1.318$ W/m²,
- total heat flow -61.129 W/m²,
- total heat flow losses 2.16 %,
- surface temperature 19.814 °C.

Table 5 Calculation of thermal permeability of the layer above/in front of the tubes towards the interior [15]

Name of the quantity	Value	
Dimension of tubes d (m)	0.015	
Thickness of the layer before/above tubes toward the interior No.1 a_1 (m)	0.018	
Thermal conductivity of the material in front of/above the tubes of the respective layer toward the interior No.1 λ_{d1} (W/(m ² .K))	1.160	
Thickness of the layer before/above tubes toward the interior No.2 a_2 (m)	0.000	
Thermal conductivity of the material in front of/above the tubes of the respective layer toward the interior No.2 λ_{d2} (W/(m ² .K))	0.000	
Heat transfer coefficient in front of/above the tubes toward the interior floor heating h_{pi} (W/(m ² .K))	9.600	
Heat transfer coefficient in front of/above the tubes toward the interior ceiling heating h_{pi} (W/(m ² .K))	7.300	
Name of the quantity	Value	
Heat transfer coefficient in front of/above the tubes toward the interior wall heating h_{pi} (W/(m ² .K))	10.000	
Thermal permeability in front of/above the tubes towards the interior floor heating Λ_a (W/(m ² .K))	7.954	
Thermal permeability in front of/above the tubes towards the interior ceiling heating Λ_a (W/(m ² .K))	6.308	
Thermal permeability in front of/above the tubes towards the interior wall heating Λ_a (W/(m ² .K))	8.227	
Heat transfer efficiency		
	floor heating	95.73%
Ratio between the heat flow to the interior and the total heat flow, efficiency of transfer of the end radiant surfaces	ceiling heating	94.51%
	wall heating	95.88%
Heat loss		
	floor heating	4.27%
Ratio between heat flow to the exterior and total heat flow - loss	ceiling heating	5.49%
	wall heating	4.12%

Table 6 Calculation of thermal permeability of the layer under/behind the tubes towards the exterior [15]

Name of the quantity	Value	
Dimension of tubes d (m)	0.015	
Thickness of the layer behind the tubes toward the exterior No.1 b_1 (m)	0.050	
Thermal conductivity of the respective layer of material behind/under the tubes toward the exterior No.1 λ_1 (W/(m ² .K))	0.040	
Thickness of the layer behind the tubes toward the exterior No.2 b_2 (m)	0.005	
Thermal conductivity of the respective layer of material behind/under the tubes toward the exterior No.2 λ_2 (W/(m ² .K))	1.160	
Thickness of the layer behind the tubes toward the exterior No.3 b_3 (m)	0.500	
Thermal conductivity of the respective layer of material behind/under the tubes toward the exterior No.3 λ_3 (W/(m ² .K))	0.058	
Thickness of the layer behind the tubes toward the exterior No.4 b_4 (m)	0.005	
Thermal conductivity of the respective layer of material behind/under the tubes toward the exterior No.4 λ_4 (W/(m ² .K))	0.800	
Thickness of the layer behind the tubes toward the exterior No.5 b_5 (m)	-	
Thermal conductivity of the respective layer of material behind/under the tubes toward the exterior No.5 λ_5 (W/(m ² .K))	-	
Thickness of the layer behind the tubes toward the exterior No.6 b_6 (m)	-	
Thermal conductivity of the respective layer of material behind/under the tubes toward the exterior No.6 λ_6 (W/(m ² .K))	-	
Heat transfer coefficient behind the tubes toward the exterior floor heating h_{pe} (W/(m ² .K))	7.000	
Heat transfer coefficient behind the tubes toward the exterior ceiling heating h_{pe} (W/(m ² .K))	7.000	
heat transfer coefficient behind the tubes toward the exterior wall heating h_{pe} (W/(m ² .K))	7.000	
Thermal permeability behind/under the tubes toward the exterior floor heating Λ_b (W/(m ² .K))	0.099	
Thermal permeability behind/under the tubes toward the exterior ceiling heating Λ_b (W/(m ² .K))	0.099	
Thermal permeability behind/under the tubes toward the exterior wall heating Λ_b (W/(m ² .K))	0.099	

Table 7 Calculation of large-area radiant hot water heating [15]

Name of the quantity	Value
Coefficient characterizing the heating plate in terms of heat dissipation - floor heating m (m^{-1})	17.640
Coefficient characterizing the heating plate in terms of heat dissipation - ceiling heating m (m^{-1})	15.734
Coefficient characterizing the heating plate in terms of heat dissipation - wall heating m (m^{-1})	17.936
Mean heating water temperature θ_m ($^{\circ}C$)	35
Tube spacing L (m)	0.1
Interior temperature θ_i ($^{\circ}C$)	20
Temperature on the opposite side of the heated space (e.g. exterior temperature) θ_e ($^{\circ}C$)	-11
Surface temperature - floor heating θ_p ($^{\circ}C$)	29.968
Surface temperature - ceiling heating θ_p ($^{\circ}C$)	27.905
Surface temperature - wall heating θ_p ($^{\circ}C$)	30.310
Specific heat flow to the interior - floor heating q_i (W/m^2)	95.697
Specific heat flow to the interior - ceiling heating q_i (W/m^2)	72.770
Specific heat flow to the interior - wall heating q_i (W/m^2)	99.685
Specific heat flow toward the exterior - floor heating q_e (W/m^2)	4.274
Specific heat flow toward the exterior - ceiling heating q_e (W/m^2)	4.225
Specific heat flow toward the exterior - wall heating q_e (W/m^2)	4.282
Total specific heat flow toward the exterior - floor heating (W/m^2)	99.971
Total specific heat flow toward the exterior - ceiling heating (W/m^2)	76.995
Total specific heat flow toward the exterior - wall heating (W/m^2)	103.967

Table 8 Calculation of thermal permeability of the layer above/in front of the tubes towards the interior [15]

Name of the quantity	Value
Dimension of tubes d (m)	0.015
Thickness of the layer before/above tubes toward the interior No.1 a_1 (m)	0.018
Thermal conductivity of the material in front of/above the tubes of the respective layer toward the interior No.1 λ_{a1} ($W/(m^2.K)$)	1.160
Thickness of the layer before/above tubes toward the interior No.2 a_2 (m)	0.000
Thermal conductivity of the material in front of/above the tubes of the respective layer toward the interior No.2 λ_{a2} ($W/(m^2.K)$)	0.000
Heat transfer coefficient in front of/above the tubes toward the interior floor heating h_{pi} ($W/(m^2.K)$)	9.600
Heat transfer coefficient in front of/above the tubes toward the interior ceiling heating h_{pi} ($W/(m^2.K)$)	7.300
Heat transfer coefficient in front of/above the tubes toward the interior wall heating h_{pi} ($W/(m^2.K)$)	10.000
Thermal permeability in front of/above the tubes towards the interior floor heating Λ_a ($W/(m^2.K)$)	7.954
Thermal permeability in front of/above the tubes towards the interior ceiling heating Λ_a ($W/(m^2.K)$)	6.308
Thermal permeability in front of/above the tubes towards the interior wall heating Λ_a ($W/(m^2.K)$)	8.227
Heat transfer efficiency	
	floor heating 97.76%
Ratio between the heat flow to the interior and the total heat flow, efficiency of transfer of the end radiant surfaces	ceiling heating 97.14%
	wall heating 97.84%
Heat loss	
	floor heating 2.24%
Ratio between heat flow to the exterior and total heat flow - loss	ceiling heating 2.86%
	wall heating 2.16%

Table 9 Calculation of thermal permeability of the layer under/behind the tubes towards the exterior [15]

Name of the quantity	Value
Dimension of tubes d (m)	0.015
Thickness of the layer behind the tubes toward the exterior No.1 b_1 (m)	0.050
Thermal conductivity of the respective layer of material behind/under the tubes toward the exterior No.1 λ_1 (W/(m ² .K))	0.040
Thickness of the layer behind the tubes toward the exterior No.2 b_2 (m)	0.005
Thermal conductivity of the respective layer of material behind/under the tubes toward the exterior No.2 λ_2 (W/(m ² .K))	1.160
Thickness of the layer behind the tubes toward the exterior No.3 b_3 (m)	0.500
Thermal conductivity of the respective layer of material behind/under the tubes toward the exterior No.3 λ_3 (W/(m ² .K))	0.058
Thickness of the layer behind the tubes toward the exterior No.4 b_4 (m)	0.005
Thermal conductivity of the respective layer of material behind/under the tubes toward the exterior No.4 λ_4 (W/(m ² .K))	0.800
Thickness of the layer behind the tubes toward the exterior No.5 b_5 (m)	-
Thermal conductivity of the respective layer of material behind/under the tubes toward the exterior No.5 λ_5 (W/(m ² .K))	-
Thickness of the layer behind the tubes toward the exterior No.6 b_6 (m)	-
Thermal conductivity of the respective layer of material behind/under the tubes toward the exterior No.6 λ_6 (W/(m ² .K))	-
Heat transfer coefficient behind the tubes toward the exterior floor heating h_{pe} (W/(m ² .K))	7.000
Heat transfer coefficient behind the tubes toward the exterior ceiling heating h_{pe} (W/(m ² .K))	7.000
heat transfer coefficient behind the tubes toward the exterior wall heating h_{pe} (W/(m ² .K))	7.000
Thermal permeability behind/under the tubes toward the exterior floor heating Λ_b (W/(m ² .K))	0.099
Thermal permeability behind/under the tubes toward the exterior ceiling heating Λ_b (W/(m ² .K))	0.099
Thermal permeability behind/under the tubes toward the exterior wall heating Λ_b (W/(m ² .K))	0.099

Table 10 Calculation of large-area radiant cooling [15]

Name of the quantity	Value
Coefficient characterizing the heating plate in terms of heat dissipation - floor heating m (m ⁻¹)	17.640
Coefficient characterizing the heating plate in terms of heat dissipation - ceiling heating m (m ⁻¹)	15.734
Coefficient characterizing the heating plate in terms of heat dissipation - wall heating m (m ⁻¹)	17.936
Mean heating water temperature θ_m (°C)	17
Tube spacing L (m)	0.1
Interior temperature θ_i (°C)	26
Temperature on the opposite side of the heated space (e.g. exterior temperature) θ_e (°C)	+32
Surface temperature - floor heating θ_p (°C)	20.019
Surface temperature - ceiling heating θ_p (°C)	21.257
Surface temperature - wall heating θ_p (°C)	19.814
Specific heat flow to the interior - floor heating q_i (W/m ²)	-57.418
Specific heat flow to the interior - ceiling heating q_i (W/m ²)	-43.662
Specific heat flow to the interior - wall heating q_i (W/m ²)	-59.811
Specific heat flow toward the exterior - floor heating q_e (W/m ²)	-1.313
Specific heat flow toward the exterior - ceiling heating q_e (W/m ²)	-1.283
Specific heat flow toward the exterior - wall heating q_e (W/m ²)	-1.318
Total specific heat flow toward the exterior - floor heating (W/m ²)	-58.731
Total specific heat flow toward the exterior - ceiling heating (W/m ²)	-44.945
Total specific heat flow toward the exterior - wall heating (W/m ²)	-61.129

3 Heating and cooling capacities of ITAP panels

Using the mathematical configurator, the heating and cooling heat flows of ITAP panels made of thermal insulation expanded polystyrene EPS-F ($\lambda = 0.04 \text{ W}/(\text{m}^2 \cdot \text{K})$) with thickness 50 mm with tube spacing 100 mm were calculated (Tables 11 and 12).

When calculating the heating heat flows, we considered the mean temperature of the heating medium of 25 °C, 30 °C, 35 °C, 40 °C, indoor temperatures of 16 °C, 18 °C, 20 °C, 22 °C, 24 °C. When calculating the cooling heat flows, we considered the mean temperature of the heating medium of 15 °C, 16 °C, 17 °C, 18 °C, indoor temperatures of 20 °C, 22 °C, 24 °C, 25 °C, 26 °C. In addition to heat flows to the interior, exterior, and total heat flow, the surface temperature of ITAP panels was also determined.

Table 11 Heating and cooling heat flows of ITAP panels
 Heating period $\theta_e = -11 \text{ °C}$ [15]

Interior temperature θ_i (°C)		16	18	20	22	24
Mean temperature of heating medium $\theta_m = 25 \text{ °C}$	Heat flow to the interior q_i (W/m ²)	59.81	46.52	33.23	19.94	6.65
	Heat flow to the exterior q_e (W/m ²)	3.40	3.44	3.48	3.52	3.56
	Total heat flow q_{total} (W/m ²)	63.22	49.96	36.71	23.46	10.20
	Surface temperature θ_p (°C)	22.19	22.81	23.44	24.06	24.69
Mean temperature of heating medium $\theta_m = 30 \text{ °C}$	Heat flow to the interior q_i (W/m ²)	93.04	79.75	66.46	53.17	39.87
	Heat flow to the exterior q_e (W/m ²)	3.81	3.84	3.88	3.92	3.96
	Total heat flow q_{total} (W/m ²)	96.84	83.59	70.34	57.08	43.83
	Surface temperature θ_p (°C)	25.62	26.25	26.87	27.50	28.12
Mean temperature of heating medium $\theta_m = 35 \text{ °C}$	Heat flow to the interior q_i (W/m ²)	126.27	112.98	99.69	86.39	73.10
	Heat flow to the exterior q_e (W/m ²)	4.61	4.22	4.28	4.32	4.36
	Total heat flow q_{total} (W/m ²)	130.87	117.20	103.97	90.71	77.46
	Surface temperature θ_p (°C)	29.06	29.69	30.31	30.94	31.56
Mean temperature of heating medium $\theta_m = 40 \text{ °C}$	Heat flow to the interior q_i (W/m ²)	159.50	146.21	132.91	119.62	106.33
	Heat flow to the exterior q_e (W/m ²)	4.61	4.65	4.68	4.72	4.76
	Total heat flow q_{total} (W/m ²)	164.10	150.85	137.60	124.34	111.09
	Surface temperature θ_p (°C)	32.50	33.12	33.75	34.37	35.00

Table 12 Heating and cooling heat flows of ITAP panels
 Summer period $\theta_e = +32 \text{ °C}$ [15]

Interior temperature θ_i (°C)		20	22	24	25	26
Mean temperature of cooling medium $\theta_m = 15 \text{ °C}$	Heat flow to the interior q_i (W/m ²)	-33.23	-46.52	-59.81	-66.46	-73.10
	Heat flow to the exterior q_e (W/m ²)	-1.59	-1.56	-1.52	-1.50	-1.48
	Total heat flow q_{total} (W/m ²)	-34.82	-48.08	-61.33	-67.95	-74.58
	Surface temperature θ_p (°C)	16.56	17.19	17.81	18.13	18.44
Mean temperature of cooling medium $\theta_m = 16 \text{ °C}$	Heat flow to the interior q_i (W/m ²)	-26.58	-39.87	-53.17	-59.81	-66.46
	Heat flow to the exterior q_e (W/m ²)	-1.51	-1.48	-1.44	-1.42	-1.40
	Total heat flow q_{total} (W/m ²)	-28.10	-41.35	-54.60	-61.23	-67.86
	Surface temperature θ_p (°C)	17.25	17.88	18.50	18.81	19.13
Mean temperature of cooling medium $\theta_m = 17 \text{ °C}$	Heat flow to the interior q_i (W/m ²)	-19.94	-33.23	-46.52	-53.17	-59.81
	Heat flow to the exterior q_e (W/m ²)	-1.43	-1.39	-1.36	-1.34	-1.32
	Total heat flow q_{total} (W/m ²)	-21.37	-34.62	-47.88	-54.50	-61.13
	Surface temperature θ_p (°C)	17.94	18.56	19.19	19.50	19.81
Mean temperature of cooling medium $\theta_m = 18 \text{ °C}$	Heat flow to the interior q_i (W/m ²)	-13.29	-26.58	-39.87	-46.52	-53.17
	Heat flow to the exterior q_e (W/m ²)	-1.35	-1.31	-1.28	-1.26	-1.24
	Total heat flow q_{total} (W/m ²)	-14.64	-27.90	-41.15	-47.78	-54.40
	Surface temperature θ_p (°C)	18.63	19.25	19.88	20.19	20.50

4 Discussion

Based on mathematical-physical models for concealed large-area radiant heating/cooling and for ITAP panels, a comparison of these two energy systems on the perimeter wall and on the inner wall of a building was performed for the following boundary conditions: mean temperature of heat transfer medium for heating is +35 °C, for cooling medium it is +17 °C, indoor temperature in the heating season is +20 °C, in the summer it is +26 °C, outdoor temperature in the heating season is -11 °C, in the summer +32 °C, room temperature behind the inner wall is +18 °C (winter) and +26 °C (summer), tube spacing is $L = 100 \text{ mm}$, thickness of thermal insulation part of ITAP panel is 50 mm (EPS-F).

It can be stated (Tables 13 to 14), that the application of large-area radiant heating/cooling of under plaster and using ITAP panels on perimeter walls (the composition meets the requirements of STN EN 73 0540 [8], $U = 0.22 \text{ W}/(\text{m}^2\cdot\text{K})$) in terms of energy *show almost the same heating and cooling heat fluxes*.

When applying large-area concealed radiant heating/cooling and ITAP panels on internal walls (thickness of ceramic bricks 240 mm, thermal conductivity of the material $0.510 \text{ W}/(\text{m}^2\cdot\text{K})$), which have worse thermal resistance than perimeter walls, *ITAP panels show heating saving of approximately 13 % and for cooling of approximately 11 % compared to a concealed tube energy system* thanks to thermal insulation, which adjusts the thermal permeability of the wall layers behind the tubes towards the adjacent room Λ_b ($\text{W}/(\text{m}^2\cdot\text{K})$). In addition to these savings, it is clear from Tables 15 and 16 that the ratio of heat flow towards the heated/cooled space is 78:22 for concealed pipe system with heating and 81:19 for cooling. The heat flow ratio towards the heated/cooled space is 93:7 for ITAP panels for heating and 94:6 for cooling.

Legend for Tables 13 to 14:

Λ_a is thermal permeability in front of/above the tubes towards the interior ($\text{W}/(\text{m}^2\cdot\text{K})$), Λ_b is thermal permeability behind/under the tubes towards the exterior ($\text{W}/(\text{m}^2\cdot\text{K})$), θ_p is surface temperature of heating/cooling surface ($^\circ\text{C}$),

θ_i is specific heat flow to the interior (W/m^2), θ_e is specific heat flow to the exterior (W/m^2), q_{total} is total specific heat flow (W/m^2).

Legend for Tables 15 and 16:

Λ_a is thermal permeability in front of/above the tubes towards the interior ($\text{W}/(\text{m}^2\cdot\text{K})$), Λ_b is thermal permeability behind/under the tubes towards the exterior ($\text{W}/(\text{m}^2\cdot\text{K})$), θ_p is surface temperature of heating/cooling surface ($^\circ\text{C}$), θ_i is specific heat flow to the interior (W/m^2), θ_e is specific heat flow to the exterior (W/m^2), q_{total} is total specific heat flow (W/m^2).

5 Conclusions

Based on the parametric study of ITAP panels and the concealed tubular energy system on the perimeter wall and the inner wall between two rooms, it was determined that:

- The thickness of thermal insulation of ITAP panels when applied to perimeter walls (the composition meets the requirements of STN EN 73 0540 [8], max. $U = 0.22 \text{ W}/(\text{m}^2\cdot\text{K})$) has almost no effect in terms of energy requirements. Thermal heating and cooling flows are approximately the same as with the concealed tube system.
- When applying large-area radiant heating/cooling with a concealed tubular energy system and ITAP panels on interior walls that have worse thermal resistance than perimeter walls, ITAP panels show savings in heating and

Table 13 Comparison of heating and cooling heat flows – perimeter wall Wall heating [15]

Boundary conditions			Λ_a	Λ_b	θ_p	θ_i	θ_e	q_{total}
Interior temperature θ_i ($^\circ\text{C}$)	20	under the plaster heat system	8.227	0.116	30.30	99.64	4.99	104.63
Exterior temperature θ_e ($^\circ\text{C}$)	-11							
Mean temperature of heating medium θ_m ($^\circ\text{C}$)	35							
Tube spacing L (mm)	100	ITAP panel	8.227	0.099	30.31	99.68	4.28	103.96
Tube diameter (mm)	15							
Thermal insulation thickness - ITAP (mm)	50							

Table 14 Comparison of heating and cooling heat flows – perimeter wall Wall cooling [15]

Boundary conditions			Λ_a	Λ_b	θ_p	θ_i	θ_e	q_{total}
Interior temperature θ_i ($^\circ\text{C}$)	26	under the plaster cool system	8.227	0.116	19.81	-59.78	-1.53	-61.32
Exterior temperature θ_e ($^\circ\text{C}$)	+32							
Mean temperature of heating medium θ_m ($^\circ\text{C}$)	17							
Tube spacing L (mm)	100	ITAP panel	8.227	0.099	19.81	-59.81	-1.31	-61.12
Tube diameter (mm)	15							
Thermal insulation thickness - ITAP (mm)	50							

Table 15 Comparison of heating and cooling heat flows inner wall – Wall heating [15]

Boundary conditions			Λ_a	Λ_b	θ_p	θ_i	θ_e	q_{total}
Interior temperature θ_i (°C)	20	under the plaster heat. system	8.227	1.963	31.93	57.33	17.60	74.943
Exterior temperature θ_e (°C)	-11							
Mean temperature of heating medium θ_m (°C)	35							
Tube spacing L (mm)	100	ITAP panel	8.227	0.516	32.12	59.23	4.74	63.981
Tube diameter (mm)	15							
Thermal insulation thickness - ITAP (mm)	50							
								losses 23.50 %
								losses 7.42 %

Table 16 Comparison of heating and cooling heat flows inner wall – Wall cooling [15]

Boundary conditions			Λ_a	Λ_b	θ_p	θ_i	θ_e	q_{total}
Interior temperature θ_i (°C)	26	under the plaster cool. system	8.227	1.963	20.07	-57.33	-9.75	-67.09
Exterior temperature θ_e (°C)	+32							
Mean temperature of heating medium θ_m (°C)	17							
Tube spacing L (mm)	100	ITAP panel	8.227	0.516	19.87	-59.23	-2.68	-61.91
Tube diameter (mm)	15							
Thermal insulation thickness - ITAP (mm)	50							
								losses 14.54 %
								losses 4.33 %

cooling compared to a concealed tubular energy system due to thermal insulation that adjusts thermal permeability of layers of the wall behind the tubes towards the adjacent room Λ_b (W/(m².K)). In the case of the inner wall (thickness of ceramic bricks 240 mm, thermal conductivity of the material 0.510 W/(m².K), ITAP panels show savings of approximately 13 % in heating and approximately 11 % in cooling.

- The mean temperature of the heat transfer medium and the interior temperature of the heated/cooled space, has a significant effect on the heating and cooling capacity of ITAP panels, as well as the concealed tubular energy system.

- Tube spacing has significant influence on the heating and cooling capacity of ITAP panels, as well as of concealed tube energy system, e.g. when spacing is changed from $L = 100$ to 150 mm, capacity is reduced by about 15 to 20 % and to $L = 200$ mm capacity reduction is about 30 to 35 %.

- The influence of exterior temperature, respectively, temperature in the adjacent space for heating and cooling capacity of ITAP panels, as well as concealed tubular energy system, represents a deviation of about 5 % depending on the thermal insulation properties of building structures on which large-area radiant energy systems are applied.

- The effect of changing the tube dimensions of ITAP panels, as well as of the concealed tube energy system, from a diameter of $d = 15$ to 20 mm on the heating and cooling capacity represents a deviation of approximately 2.5 %.

The research will continue with parametric studies under other boundary conditions and search for optimal criteria for design, calculation, and assessment of energy-efficient, economically efficient and environmentally friendly large-area radiant energy systems. Another research task will be to establish criteria for ITAP panels with air as the heat-carrying medium in applications for floor, ceiling, and wall heating. After a mathematical-physical model is developed, parametric studies and mathematical simulations will be performed.

The research will also continue under laboratory conditions, where measurements will be performed on a fragment of a perimeter, interior wall, ceiling, and floor with ITAP panels and built-in tubular energy systems, as well as air ducts.

The main benefit of ITAP panels – interior thermally active panels with an integrated active area – is the possibility of unified and prefabricated production. At the same time, they represent a reduction of production costs due to their technologically simpler production process (DN of tubes for thermal insulation part of ITAP panels is not limited as for panels with pipes in SD), reduction of assembly costs due to fewer construction steps and less time needed for implementation with regard to their method of application.

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