Temperatures and Heat Transfer beneath a Ground Floor Slab

Iveta Skotnicova, Lenka Lausova

***Abstract*—**This paper presents the results of one-year period in situ experiment designed to monitor the thermal performance of a real slab-on-ground floor. Experimental measurements of the subsoil temperatures were performed outside and under the foundation (at various depths and locations) of a timber frame passive house. The results of the experimental measurements of the subsoil temperatures under the foundation of the passive house showed higher temperatures than predicted in standard calculating procedures and moreover they are not included in the calculations at all. The results of the measurements of the heat flux over a slab-on-ground floor are presented only for a short period of time and will be the subject of further research. This paper also reports the results of the calculation procedures proposed by the standards for slab-on-ground heat transfer. In the following paragraphs, the analytical detailed calculation procedure of CSN EN ISO 13370:2009, the analytical simplified method of CSN EN 12831:2004 and the numerical simulation methods of CSN EN ISO 10211:2009 are described and compared. Different boundary conditions (external design temperatures and external measured temperatures) were used. The ground temperatures were not included in the calculation procedures; only the thermal conductivity of the ground was respected. In particular, a two-dimensional finite element model, was used to simulate the heat transfer beneath a ground floor slab into the soil. The results showed that this model is more suitable tools to predict the thermal performance of the slab-on-ground floor than simplified analytical methods.

***Keywords*—**Ground heat transfer, subsoil temperatures, ground floor slab, passive house, analytical methods, simulation methods, experimental measurements.

I. Introduction

IN accordance with the long-term strategic objectives of improving the energy efficiency of buildings, the adoption of Directive 2010/31/EU of 19 May 2010 on the energy performance of buildings raised the commitment to reduce overall greenhouse gas emissions by 2020 by at least 20%.

The directive requires Member States to design all new buildings with nearly zero energy by 31 December 2020 [1]. At the present time, the main environmental parameters of buildings are thermal comfort and energy savings, and therefore it is necessary to consider the energy consumption of buildings both in terms of the satisfaction of theirs users, and with minimal use of energy for heating and cooling [2]. The pursuit of better building energy performance has led to an increase in the thickness of the thermal insulation layer of the envelope. Therefore, ground heat losses have become more significant for the building energy balance assessment [3].

The purpose of this paper is to compare the calculation procedures proposed by the standards for slab-on-ground heat transfer and real measured data of the temperatures under a slab-on-ground floor.

II. Experimental measurements

A. Temperatures under a Slab-on-Ground Floor

Experimental measurements of the subsoil temperature performance were made under the foundation of a timber frame passive house situated at the site of the Faculty of Civil Engineering at the Technical University of Ostrava. Experimental measurements were performed outside and under the foundation (at various depths and locations) during a one-year measuring period [4]. In this paper, the slab-on-ground has been resolved. The assessed slab-on-ground floor is in contact with the ground over the whole area and is insulated over the whole of its area (Fig. 1).

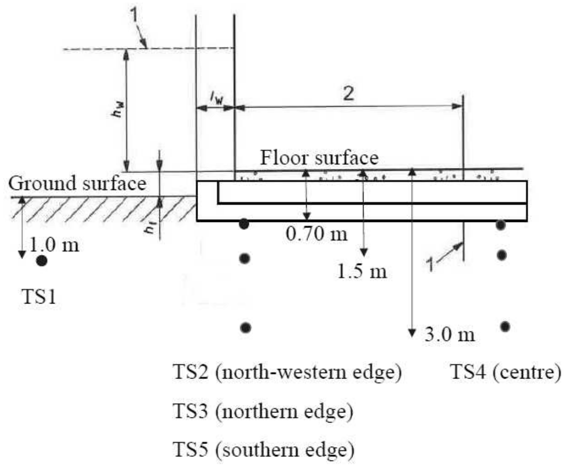

Fig. 1 Cross-section of the ground floor slab and location of the temperature sensors

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The thermal insulation layer is placed directly under the foundation slab and along its edges. It is laid on the 0.800 m compacted sub-base of crushed stones.

Under a fill from crushed stones is soil with a bearing capacity of more than 100 kPa. Sand was chosen as the kind of soil and has a thermal conductivity of 2 W/(m^{2}K) and volumetric heat capacity equal to 2.0 x 106 J/(m^{3}K). The thickness of the external wall l_w is 0.500 m. The total area of the floor A (from the external dimensions) is equal to 64 m^2. The exposed perimeter of the floor *P* is equal to 32 m.

The composition of the slab-on-ground floor is as follows:

1. Concrete paver
2. Concrete screed floor cover
3. Expanded polystyrene
4. Reinforced concrete foundation slab
5. Extruded polystyrene
6. Crushed stone
7. Ground soil

The thermal properties (d is thickness, ρ is density, λ is thermal conductivity, c is thermal capacity) of the materials are described in Table 1. The thermal resistance of this structure is R_f = 10.22 (m^2·K)/W, the U value is 0.096 W/(m^2·K).

Table 1 Thermal properties of the materials

Material	d [m]	ρ [kg/m^3]	λ [W/mK]	c [J/kgK]
1.	0.010	2000	1.010	840
2.	0.050	2100	1.230	1020
3.	0.140	30	0.034	1270
4.	0.300	2500	1.740	1020
5.	0.200	30	0.034	2060
6.	0.800	1650	2.000	1000
7.	-	1800	2.000	1000

The temperature sensors were placed in the subsoil at various depths and locations (Fig. 1). Five stacks are placed in different locations – outside the building (TS1), under the north-western edge of the foundation (TS2), under the northern edge of the foundation (TS3), under the centre of the foundation (TS4) and under the southern edge of the foundation (TS5). The stacks are placed at various depths ranging from 0.70 to 3.0 m beneath the slab-on-ground surface.

The experiment was designed to reveal the transient nature of the thermal behaviour of the site. It was therefore necessary to obtain data at relatively short time intervals. To record the measured temperatures in the ground and of the external air, a multi-channel dataTaker DT80G logger was used. It recorded all values at the set time period of 1 hour (in the ground) and 15 minutes (external air).

Fig. 2 and Fig. 3 shows the installation of ground temperature sensors outside and under the foundation of the building.

Fig. 2 Installation of ground temperature sensors under the foundation of the building

Fig. 3 Installation of ground temperature sensors outside the building

Fig. 4 shows the measured external daily average temperatures (during twelve months). The measured external temperatures followed a typical seasonal variation, ranging from winter lows of -13.0 °C to summer highs of approximately 38 °C.

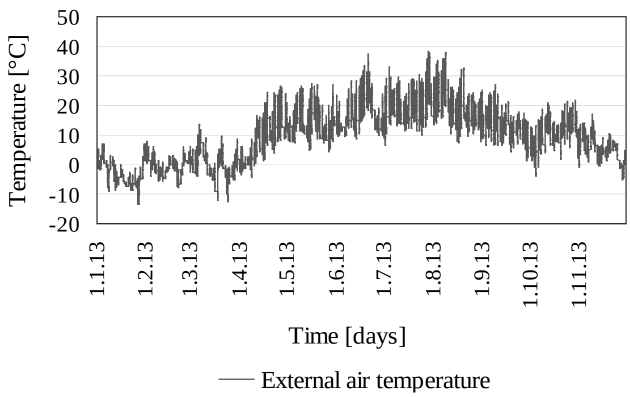

Fig. 4 External daily average temperatures

Fig. 5 shows the external monthly average temperatures and design external monthly average temperatures according to ČSN EN 12831:2004.

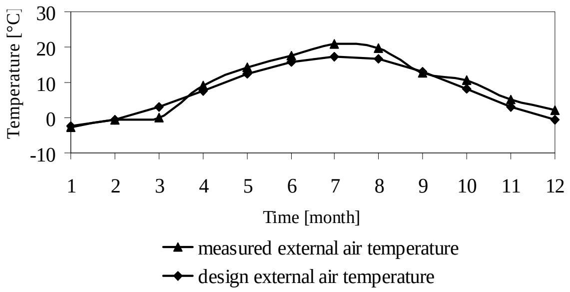

Fig. 5 External monthly average temperatures and external design (standard) monthly temperatures

Fig. 6, 7, 8 and 9 presents the ground temperature variation recorded at five temperature sensor locations. TS1 is located outside the building at a depth of 1.0 m under the ground surface. TS2, TS3, TS4 and TS5 are located directly under the foundation of the building at depths of 0.70 m, 1.5 m and 3.0 m (under the internal surface of the floor).

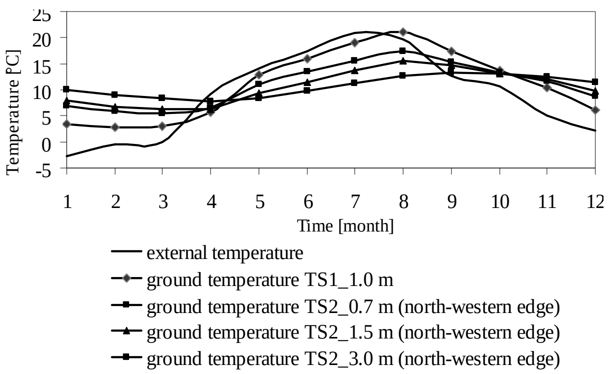

Fig. 6 Ground monthly average temperatures at stacks TS1 and TS2

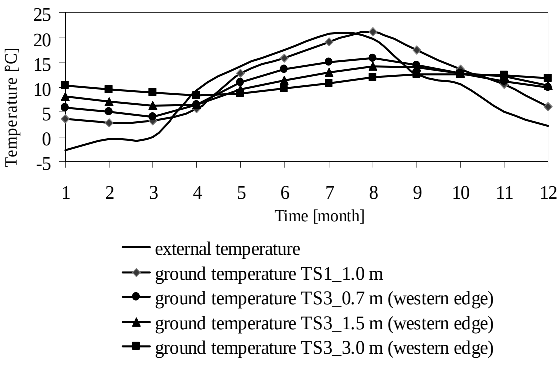

Fig. 7 Ground monthly average temperatures at stack TS1 and TS3

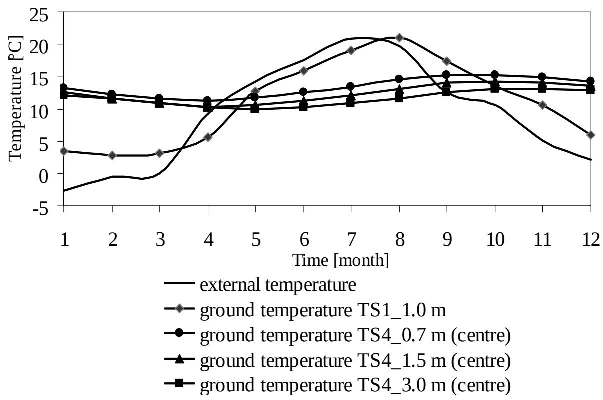

Fig. 8 Ground monthly average temperatures at stacks TS1 and TS4

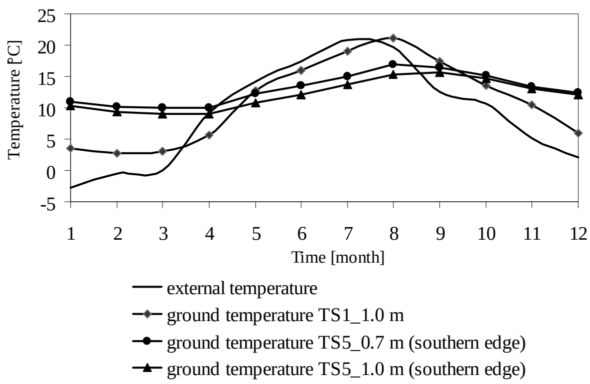

Fig. 9 Ground monthly average temperatures at stacks TS1 and TS5

Table 2 Monthly average temperatures (north-western edge under the foundation)

	Temperature [°C]				
Month	θe	TS1	TS2 (north-western edge)		
		1.0 m	0.7 m	1.5 m	3.0 m
1	**-2.7**	3.5	6.9	7.9	10.1
2	-0.5	2.8	5.9	6.8	9.0
3	0	**3.1**	**5.5**	**6.2**	8.3
4	9.2	5.6	6.6	6.3	**7.7**
5	14.2	12.8	11	9.3	8.4
6	17.5	15.9	13.5	11.5	9.7
7	**20.8**	19.0	15.6	13.6	11.2
8	19.7	**21.1**	**17.4**	**15.5**	12.6
9	12.6	17.4	15.4	14.8	**13.3**
10	10.6	13.6	13.2	13.1	13
11	5.1	10.5	11.6	12	12.4
12	2.1	6	8.8	9.7	11.4
ϕ	9.1	10.9	6.9	7.9	10.1

Tables 2, 3, 4 and 5 shows the monthly average temperatures measured in the soil throughout the year. Bold values indicate the minimum and maximum temperatures in the different measuring positions and depths in the soil. The measured results showed that the range of seasonal variation in ground temperature decreases as the depth below the ground surface increases.

Table 3 Monthly average temperatures (northern edge under the foundation)

	Temperature [°C]				
Month	θ_e	TS1	TS3 (northern edge)		
		1.0 m	0.7 m	1.5 m	3.0 m
1	**-2.7**	3.5	5.8	8.1	10.4
2	-0.5	2.8	4.9	7.0	9.5
3	0	**3.1**	**4.0**	**6.2**	8.8
4	9.2	5.6	6.4	6.5	**8.3**
5	14.2	12.8	11	9.4	8.7
6	17.5	15.9	13.6	11.3	9.7
7	**20.8**	19.0	15.0	12.9	10.8
8	19.7	**21.1**	**15.9**	**14.2**	11.9
9	12.6	17.4	14.3	13.9	**12.6**
10	10.6	13.6	12.7	12.8	12.6
11	5.1	10.5	11.1	12.1	12.4
12	2.1	6	9.9	10.4	11.7
ϕ	9.1	10.9	10.4	10.4	10.6

Table 4 Monthly average temperatures (centre under the foundation)

	Temperature [°C]				
Month	θ_e	TS1	TS4 (centre)		
		1.0 m	0.7 m	1.5 m	3.0 m
1	**-2.7**	3.5	13.3	12.6	12.1
2	-0.5	2.8	12.3	11.6	11.5
3	0	**3.1**	11.6	10.9	10.9
4	9.2	5.6	**11.2**	**10.3**	10.3
5	14.2	12.8	11.7	10.5	**10**
6	17.5	15.9	12.6	11.2	10.3
7	**20.8**	19.0	13.4	12.1	10.9
8	19.7	**21.1**	14.5	13.1	11.6
9	12.6	17.4	**15.3**	14.1	12.5
10	10.6	13.6	15.2	**14.3**	13
11	5.1	10.5	14.9	14.1	**13.1**
12	2.1	6	14.3	13.6	12.9
ϕ	9.1	10.9	13.4	12.4	11.6

Furthermore, the influence of short-term climatic temperature variations is clearly reflected in the near-surface temperature variation (TS1, TS2 and TS3 - 0.7 m depth). This effect is much reduced at a depth of 1.5 m, and was found to be negligible at 3.00 m, but this depends on the locations of the sensors under the foundation.

Table 5 Monthly average temperatures (southern edge under the foundation)

	Temperature [°C]				
Month	θ_e	TS1	TS5 (southern edge)		
		1.0 m	0.7 m	1.5 m	3.0 m
1	**-2.7**	3.5	3.5	11.0	10.4
2	-0.5	2.8	2.8	10.1	9.4
3	0	**3.1**	**3.1**	**10.0**	9.1
4	9.2	5.6	5.6	10.0	**9.0**
5	14.2	12.8	12.8	12.2	10.8
6	17.5	15.9	15.9	13.5	12.1
7	**20.8**	19.0	19.0	15.0	13.7
8	19.7	**21.1**	**21.1**	**17.0**	15.4
9	12.6	17.4	17.4	16.5	**15.6**
10	10.6	13.6	13.6	15.2	14.6
11	5.1	10.5	10.5	13.4	13.1
12	2.1	6	6.0	12.4	12.1
ϕ	9.1	10.9	10.9	13.0	12.1

The results of the experimental measurements of the subsoil temperatures under the foundation of the passive building showed higher temperatures than predicted in standard calculating procedures and moreover they are not included in the calculations at all.

B. Heat Flux over a Slab-on-Ground Floor

The results of the measurements of the heat flux over a slab-on-ground floor into the soil are presented on the Fig. 10 only for a short period of time and will be the subject of further research.

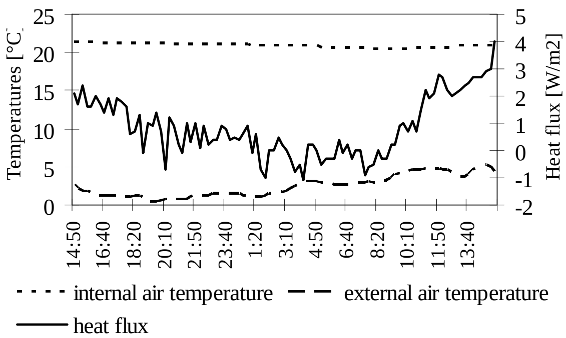

Fig. 10. Daily heat flux variation

III. CALCULATING METHODS OF THE SLAB-ON-GROUND HEAT TRANSFER

Two types of calculation methods appear in the literature [4]. They are based on analytical solutions and numerical solutions. The largest number of articles concerns the steady state heat loss for a two-dimensional case with an infinitely long slab. In the following paragraphs, the analytical detailed calculation procedure of CSN EN ISO 13370:2009 [5],[6], the analytical simplified method of CSN EN 12831:2004 and the numerical simulation methods of CSN EN ISO 10211:2009 are described.

In this article, attention is primarily focused on the temperature boundary conditions used in the calculation methods.

A. Analytical detailed method of CSN EN ISO 13370:2009

This technical standard provides methods for the calculation of heat transfer coefficients and heat flow rates for building components in thermal contact with the ground. The analytical detailed method depends of the type of foundation. There are three major types of foundations: slab-on-ground floors, suspended floors and basements. In this paper, the slab-on-ground was resolved. The assessed slab-on-ground floor is in contact with the ground over the whole area and is insulated over the whole of its area. The floor slab is situated near the level of the external ground surface.

The thermal transmittance *U* depends on the characteristic dimension of the floor *B´* and on the total equivalent thickness d_t, given by the equation:

$$d_t = w + \lambda \cdot (R_{si} + R_f + R_{se}) \tag{1}$$

where *A* is the area of the floor (m^2), *P* is the exposed perimeter of the floor (m), *w* is the thickness of the external wall (m), λ is the thermal conductivity of the ground (W/m·K), R_f is the thermal resistance of the floor slab (W/m^2·K), R_{si} is the internal thermal resistance, and R_{se} is the external thermal resistance (W/m^2·K).

In this case, $d_t > B'$, so the thermal transmittance *U* is computed using the equation (2):

$$U = \frac{\lambda}{0.457 \cdot B' + d_t}, \tag{2}$$

The steady-state ground heat transfer coefficient H_g (W/K) between the internal and external environments is given by the equation:

$$H_g = A \cdot U + P \cdot \psi_g, \tag{3}$$

where ψ_g is the linear thermal transmittance associated with the wall/floor junction, which computed by the finite element methods according to standard EN ISO 10211:2007 (see the paragraph Numerical simulation methods).

The heat flow Φ_m (W) for each month *m* can be calculated as:

$$\Phi_m = H_g(\bar{\theta}_i - \bar{\theta}_e) + H_{pe}(\bar{\theta}_e - \theta_{e,m}), \tag{4}$$

where $\bar{\theta}_i, \bar{\theta}_e$ are the yearly average internal and external air temperatures, $\theta_{e,m}$ is the monthly average external air temperature, and H_{pe} is the periodic specific heat flow (W/K). The ground temperature is not included in the calculation; only the thermal conductivity of the ground is respected.

Table 6 The heat flow Φ_m (W) for each month for different boundary conditions

Month	Design boundary conditions		Measured boundary conditions	
	θ_e [°C]	Φ_m [W]	θ_e [°C]	Φ_m [W]
1	-2.3	104.1	-2.7	103.5
2	-0.6	98.5	-0.5	96.2
3	3.3	85.5	0.0	94.5
4	8.2	69.3	9.2	64.0
5	13.3	52.4	14.2	47.4
6	16.4	42.1	17.5	36.5
7	17.8	37.4	20.8	25.5
8	17.3	39.1	19.7	29.2
9	13.6	51.4	12.6	52.7
10	9.0	66.6	10.6	59.4
11	3.8	83.9	5.1	77.6
12	-0.4	97.8	2.1	87.6
ϕ	**8.3**	**69.0**	**9.1**	**64.5**

The average heat flow for the heating season $\bar{\Phi}$ (W) is given by the equation:

$$\bar{\Phi} = H_g(\bar{\theta}_i - \bar{\theta}_e) + \gamma \cdot H_{pe} \cdot \hat{\theta}_e \tag{5}$$

where γ depends on the length of the heating season and is determined as:

$$\gamma = \frac{12}{n \cdot \pi} \sin\left(\frac{n \cdot \pi}{12}\right) \tag{6}$$

where *n* is the number of months in the heating period. For this case *n* = 7 months (for external design temperatures) and *n* = 8 months (for external measured temperatures).

The annual mean heat flow (for an approximate determination of the heat loss into the ground) $\bar{\Phi}$ (W) can be determined as:

$$\bar{\Phi} = H_g(\bar{\theta}_i - \bar{\theta}_e) \tag{7}$$

B. Analytical simplified method of CSN EN 12831:2004

The steady-state ground heat transfer coefficient H_g (W/K) between internal and external environments is given by the equation:

$$H_g = f_{g1} \cdot f_{g2} \cdot \left(\sum_k A_k \cdot U_{equiv,k} \right) \cdot G_w, \quad (8)$$

where f_{g1} is the correction factor reflecting the impact of the yearly changes of the external temperature (for this case f_{g1} = 1.45), f_{g2} is the temperature reduction factor reflecting the difference between the yearly average external temperature and the design external temperature (for this case f_{g2} = 0.33), A_k is the area of the floor (m^2), $U_{equiv,k}$ is the equivalent thermal transmittance of the floor (W/m^2·K), and G_w is the correction factor reflecting the impact of the ground water. The factors depend on the location of the house. In this case the location of the passive house is in Ostrava (Czech Republic). The equivalent thermal transmittance depends on the typology of the floor and is obtained from standard CSN EN 12831:2004.

The heat flow Φ (W) for the heating season is:

$$\Phi = H_g (\theta_i - \theta_e), \quad (9)$$

where θ_i, θ_e are the standard design internal and external air temperatures (for this case θ_i = 20 °C, θ_e = -15 °C).

C. Numerical simulation methods of CSN EN ISO 10211:2009

Numerical simulation by the finite element method [7]-[9] was used for calculation of the linear thermal transmittance ψ_g associated with the wall/floor junction and of the heat flow Φ through the floor slab on the internal side of the floor. The slab-on-ground can be discretized using 3-dimensional or 2-dimensional geometry (Fig. 10). In this case a 2-dimensional model was used, where the vertical plane of symmetry is placed in the middle of the floor (b = 8 m). All sectional planes create an adiabatic boundary.

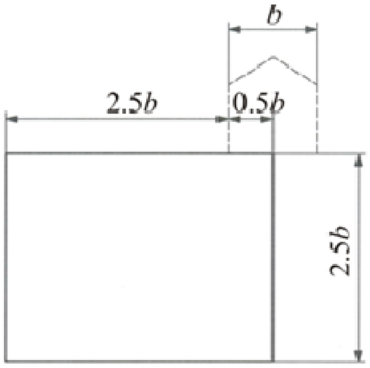

Fig. 10 2-dimensional geometry simulation model

In the steady state analysis the boundary temperatures were fixed at 8.28 °C for the external air (yearly average design external air temperatures) and at 20 °C for the internal air. The boundary ground temperature is not entered. Fig. 11 shows the results of the temperature field of the 2-dimensional geometry simulation model.

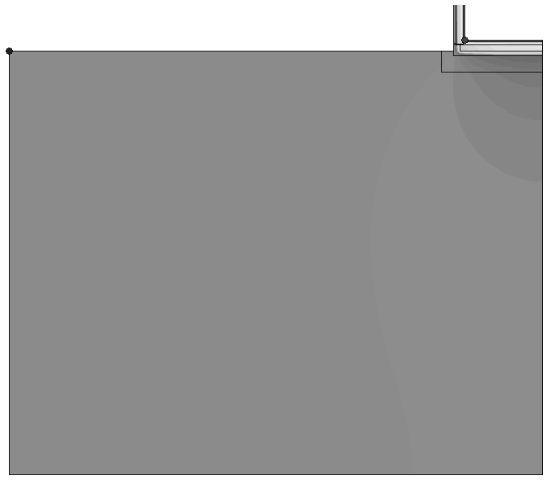

Fig. 11 Temperature field of the 2-dimensional geometry simulation model

In the transient analysis the boundary conditions were used by the average monthly temperatures for the external air.

Fig. 12 shows the heat flux profile for the steady state boundary condition.

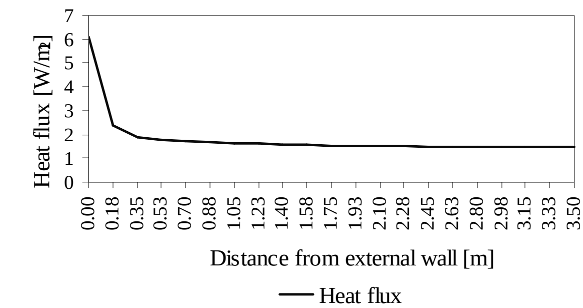

Fig. 12 Heat flux profile through the floor slab

D. Conclusion

The aim of this paper was to present detailed descriptions of the calculation procedures proposed by the standards for slab-on-ground heat transfer [10], [11] and the results of an in situ experiment designed to monitor the thermal behaviour of a real slab-on-ground floor. Tables 7 and 8 show the results of the analytical and numerical methods for different boundary conditions (external design temperatures and external measured temperatures).

Table 7 Comparison of the different methods of slab-on-ground heat transfer (for design boundary conditions)

Calculation procedures	CSN EN 12831	CSN EN ISO 13370	CSN EN ISO 10211
Annual mean heat flow	96.5	69.0	66.3
Heat flow for the heating period	96.5	86.6	-

Table 8 Comparison of the different methods of slab-on-ground heat transfer (for measured boundary conditions)

Calculation procedures	CSN EN 12831	CSN EN ISO 13370	CSN EN ISO 10211
Annual mean heat flow	96.5	64.5	62.0
Heat flow for the heating period	96.5	79.4	-

It has been shown that the numerical simulation methods are more suitable tools to predict the thermal performance of the slab-on-ground floor than simplified analytical methods.

The results of the experimental measurements of the subsoil temperature under the foundation of the passive building show higher temperatures than predicted in standard calculating procedures and moreover they are not included in the calculation.

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