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COMPARISON OF THE CALCULATION RESULTS OF HEAT EXCHANGE BETWEEN A SINGLE-FAMILY BUILDING AND THE GROUND OBTAINED WITH THE QUASI-STATIONARY AND 3-D TRANSIENT MODELS. PART 1: CONTINUOUS HEATING MODE

Anna STASZCZUK*
University of Zielona Góra, Faculty of Civil and Environmental Engineering,
Institute of Building Engineering
Szafrana st 1, 65-516 Zielona Góra, Poland

The paper provides comparative results of calculations of heat exchange between ground and typical residential buildings using simplified (quasi-stationary) and more accurate (transient, three-dimensional) methods. Such characteristics as building's geometry, basement hollow and construction of ground touching assemblies were considered including continous heating mode. The calculations with simplified methods were conducted in accordance with currently valid norm: PN-EN ISO 13370:2008. *Thermal performance of buildings. Heat transfer via the ground. Calculation methods.* Comparative estimates concerning transient, 3D, heat flow were performed with computer software WUFI®plus. The differences of heat exchange obtained using more exact and simplified methods have been specified as a result of the analysis.

Keywords: heat transfer via the ground, quasi-stationary calculations, transient heat flow, continous heating mode

1. INTRODUCTION

The heat flow process in the ground is generally transient, three-dimensional and boundary conditions are very complicated.

Recent methods up to the current standard [12] and their derivatives [10], [11] regarding heat exchange between a building and a ground are based on

* Corresponding author. E-mail: A.Staszczuk@ib.uz.zgora.pl

quasi-stationary method developed in the eighties last century by Hagentoft [4], [5], [9] and completed by Anderson [2], [3].

This method assumes harmonic boundary conditions. Annual temperature course including both external and internal temperatures should be in the shape of sinusoid. Indeed, typical mean year pattern of outer air temperature for European location (see Figure 1) can well be approximated by sine curve. If the real conditions, however they are not compatible with this assumption, calculations results may become not accurate and not adequate to simulate heat flow between the building and the ground.

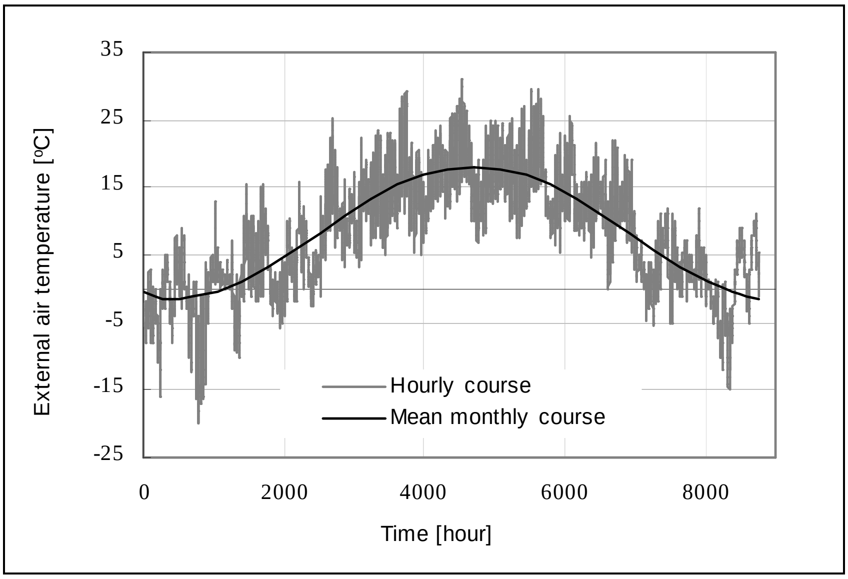

Fig. 1. Yearly pattern of air temperature in Cracow.

In this paper the impact of building's geometry, basement hollow, construction of ground touching assemblies were considered to asses the possible error using quasi-stationary calculation methods for heat exchange with the ground.

Calculations were done for buildings heated continuously according to assumptions in Hagentoft's method (internal air temperature is constant and amplitude of internal air temperature is assumed zero).

The other cases: intermittent heating (cut off 10 p.m – 6 a.m) and reduced heating (with long break e.g. holiday) will be treated (covered) in Part II of this article.

2. MATERIAL AND METHODS

2.1. Calculation tools

Calculations according to PN-EN ISO 13370:2008 [12] were carried out using Microsoft® Excel® software. For calculations of transient, 3D, heat flow through the ground the computer program WUFI®plus was used. The calculations are based on control volume heat balance method [7]. Division of heat conducting space into balance-differential elements with variable grid is done automatically by the program. To obtain realistic predictions of the internal air temperature (especially during intermittent heating), the buildings were calculated with full thermal coupling with the ground. The basement is considered as integral part of the heated building (1 zone model).

The example of modeling of surrounding ground and building for thermal calculation in WUFI®plus software is shown in Figure 2. Thermal coupling is established by defining of internal air temperature as boundary condition for floor and basement walls inside the building. Heat exchange with these assemblies is attributed to zone air node. At certain distance from the building (at least half of a width and at least of a lenght) a vertical adiabatic surface is assumed (no horizontal heat flow). Horizontal adiabatic surface (no vertical heat flow) is assumed at 10m below floor level (at this level ground temperature is assumed to be equal to average external air temperature).

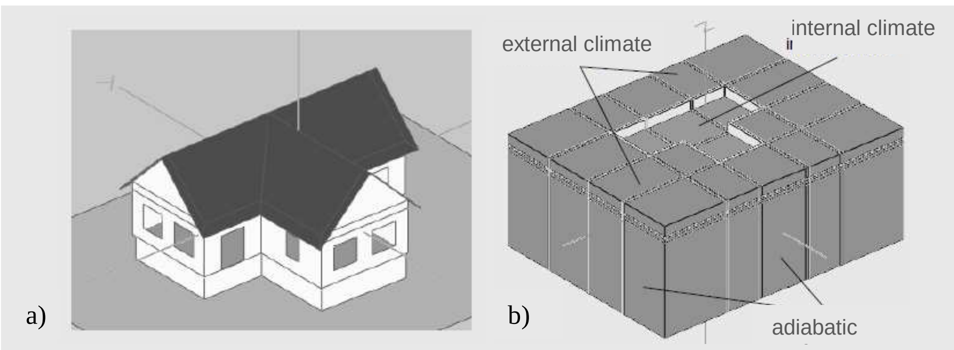

Fig. 2. Modelling of building and ground in WUFI®plus software:
a) building construction, b) 3-D model of surrounding ground.

2.2. Assumptions

The parameters of statistical climate recently developed for Cracow City by Gawin & Kossecka [8] were used as an external boundary condition for the building and ground. The buildings were calculated only thermally according to the WUFI®plus model (www.WUFI.de), using 1 hour time step. Inner air temperature was obtained iteratively from heat balance of conditioned zone. The heat balance consists of heat exchange with thermal envelope including floor and basement walls, ventilation, solar and internal gains according to EN-ISO 13790 standard [6]. Despite variable spatial division the number of differential ground elements extended from about 100 to 160 thousand. Set point of inner air temperature of 20°C and minimal air exchange rate of 1,0 ACH were assumed.

2.3. Cases

Three types of typical ground-floor residential buildings, characterized by different geometry (see Figure 3) were considered.

Observing tendency in the development of the modern single-family housing in Poland, small buildings about the footprints floor area not exceeding 100 m^2 were chosen for analysis. The shapes (footprints) and main dimensions are shown in Figure 3. Thermal insulation level of outside and inside components follows Polish regulations.

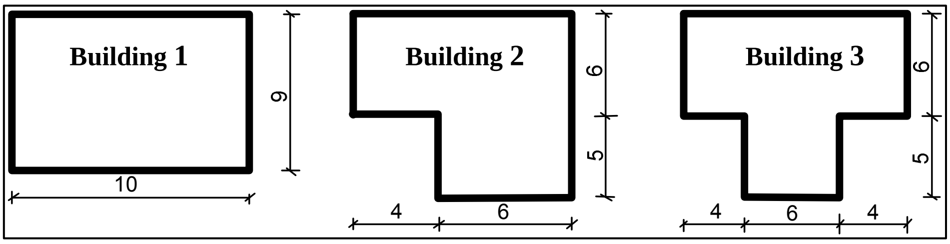

Fig. 3. Shapes of analyzed buildings.

For each building three cases of basement hollow were considered:

- slab on ground (z = 0 m),
- basement (height 2,2 m, z = 1.0 m),
- basement (height 2,2 m, z = 1.5 m),

where “z” means the depth of cellar floor below ground level.

In addition every case includes two scenarios of earth-contact construction:

a - thermally not insulated,
b - thermally insulated (slab on ground insulated with 10 cm EPS, edge vertical insulation 10 cm EPS - 0.7 m depth, floor and basement walls thermally insulated with 5 cm EPS).

3. NUMERICAL ANALYSIS

3.1. Building and ground characteristics

In the Tables 1 and 2 the geometry and assembly construction of exemplary buildings are presented. The same assemblies and material data were assumed in everyone of the presented buildings.

According to PN-EN ISO 13370 standard recommendation thermal conductivity for ground λ=2,0 W/(m·K) and thermal capacity ρ·c=2,0·10^6 J/(m3·K) were used.

Table 1. Building geometry

Specification	Building 1 Rectangular	Building 2 „L-shaped"	Building 3 „T-shaped"
Floor area [m^2]	74	74	94
Net volume [m^3]:			
- building with floor on ground	252	252	319
- building with basement	447	447	605
Floor perimeter [m]	35	39	47
Characteristic dimension* B'	4,32	3,79	4,03
A/V coefficient:			
- building with floor on ground	1,14	1,18	1,15
- building with basement	0,80	0,84	0,82

**B'* = floor area/(0,5·permieter lenght)*

Table 2. Assemblies and materials

Building component	Material	U [$Wm^{-2} K^{-1}$]
Outer wall	29 cm MAX hollow ceramic bricks + 10 cm EPS	0,29
Floor on ground	Concrete 10 cm	4,30
Foundation	Concrete 29 cm	3,13
Floor on ground thermally insulated	Concrete 10 cm + 10 cm EPS + Concrete 5 cm	0,36
Foundation thermally insulated	Concrete 29 cm + 10 cm EPS	0,35
Basement floor on ground	Concrete 10 cm	4,30
Basement floor on ground thermally insulated	Concrete 10 cm + 5 cm EPS + Concrete 5 cm	0,66

Table 2. Assemblies and materials

Building component	Material	U [$Wm^{-2} K^{-1}$]
Basement wall	Concrete bricks 24 cm	2,19
Basement wall thermally insulated	Concrete bricks 24 cm + 5 cm EPS	0,57
Ceiling up to unheated attic	OSB plate + 18 cm mineral wool + plywood 2 cm	0,20
Ceiling inside balanced zone	Reinforced concrete 15 cm + 5 cm EPS + 5 cm concrete + 2 cm hard wood (parquet floor)	0,55
Windows	Double glazing SHGC (average) = 0.53	1,99

3.2. Calculations

Transient heat flow calculations were made for 2 years period. First year of simulation was used only to define proper initial condition (temperature distribution) in the ground and was not taken into account.

Hourly pattern of both internal and external air temperature obtained with WUFI®plus (transient 3D) calculations was used to define mean year value and amplitude (sine curve for PN-EN ISO 13370 calculation) for every building type and case.

Due to summer overheating inner air temperature has no zero amplitude, even by constant heating throughout a year. Sometimes, however, inner air fluctuations are disregarded when calculating according to the PN-EN ISO 13370 standard. Therefore two kinds of comparative calculation were made, with and without considering the variation of monthly mean internal temperature.

4. RESULTS

To assess influence of the chosen factors on the calculations accuracy of heat exchange between building and the ground, transient heat flow Φ [kW] obtained with WUFI®plus (transient 3D method) was monthly averaged and compared with the results obtained according to the PN-EN ISO 13370 standard (quasi-stationary method).

As a results of analysis, heat exchange between building and the ground Q [kWh] for particular month and for the whole heating season were presented. Percentage value of difference between presented methods was calculated as:

$$\Delta Q_{1-3} = \frac{Q_1 - Q_3}{Q_3}$$

and

$$\Delta Q_{2-3} = \frac{Q_2 - Q_3}{Q_3}$$

where:

Q_1 – heat exchange according to quasi-stationary method without variation of monthly mean internal air temperature, internal air temperature assumed constant [kWh],

Q_2 – heat exchange according to quasi-stationary method with variation of monthly mean internal temperature adopted from WUFI®plus calculations [kWh],

Q_3 – heat exchange according to transient 3D method [kWh],

ΔQ_{1-3} – relative between quasi-stationary (Q_1) and transient 3D (Q_3) methods [%],

ΔQ_{1-2} – relative between quasi-stationary (Q_2) and transient 3D (Q_3) methods [%],

taking that into account transient 3D method is more accurate.

Additionaly, statistical parameters such as: standard deviation (*s*) and correlation coefficient (*r*) were calculated regarding 7 months of heating season. Graphical interpretation of obtained results in statistical approach was presented in box-plots.

As expected, adjustment of the internal temperature provided better results, i.e. ΔQ_{2-3} deviations are generally smaller then ΔQ_{1-3}. However differences between ΔQ_{1-3} and ΔQ_{2-3} are almost negligible. It means that in case of continuous heating internal temperature can be set constant with no effect on the heat loss to the ground. Therefore, in this paper, only differences ΔQ_{1-3} were presented and indicated later on as ΔQ.

In Table 3 calculation results of heat exchange between a building and the ground in heating season for the all considered buildings and cases were presented including both quasi-stationary and transient 3D method.

The most comparable results can be noticed in the case of insulated slab on ground and both not insulated and insulated basement (differences are not greater than ±10%) in the all considered types of buildings. However, heat losses through not insulated slab on ground calculated with simplified method varies from 20% in the case of Building 1 (Rectangular) and Building 2 (L-shaped) to 30 % in the case of Building 3 (T-shaped).

Table 3. Calculation results of heat exchange (Q_1 and Q_3) between the building and the ground in the heating season in Cracow.

Scenario	**Heat exchange between building and the ground**		**Differences in calculations of heat exchange between building and the ground**			
	Quasi-stationary method	Transient 3D method				
	Q_1	Q_3	ΔQ			
	kWh		kWh	**%**	s	r
BUILDING 1						
Slab on the ground						
a	4231,00	3552,11	678,89	19,11	58,15	0,996
b	1086,75	1065,67	21,07	1,98	32,19	0,991
Basement z = 1,0 m						
a	6782,06	6487,09	294,98	4,55	69,62	0,967
b	3220,79	3255,96	-35,17	-1,08	14,98	0,995
Basement z = 1,5 m						
a	7152,45	7243,33	-90,88	-1,25	66,58	0,968
b	3499,10	3688,19	-189,09	-5,13	13,74	0,993
BUILDING 2						
Slab on the ground						
a	4517,71	3651,92	865,79	23,71	72,65	0,995
b	1091,93	1073,28	18,65	1,74	38,02	0,990
Basement z = 1,0 m						
a	7367,71	6924,71	443,00	6,40	85,21	0,986
b	3430,73	3450,50	-19,77	-0,57	20,56	0,994
Basement z = 1,5 m						
a	7783,58	7749,23	34,35	0,44	82,59	0,964
b	3744,50	3924,81	-180,31	-4,59	18,89	0,992
BUILDING 3						
Slab on the ground						
a	5563,29	4354,25	1209,04	27,77	90,45	0,993
b	1383,27	1335,67	47,60	3,56	46,29	0,988
Basement z = 1,0 m						
a	9000,10	8136,18	863,91	10,06	106,77	0,965
b	4228,85	4096,62	132,22	3,2	23,99	0,994
Basement z = 1,5 m						
a	9500,31	9193,78	306,53	3,33	105,07	0,962
b	4605,57	4692,01	-86,44	-1,8	21,96	0,992

Statistical analysis confirms above considerations (see Figure 4). Distribution of differences between analyzed methods (quasi-stationary and transient) is approximately zero in the case of insulated assemblies touching ground.

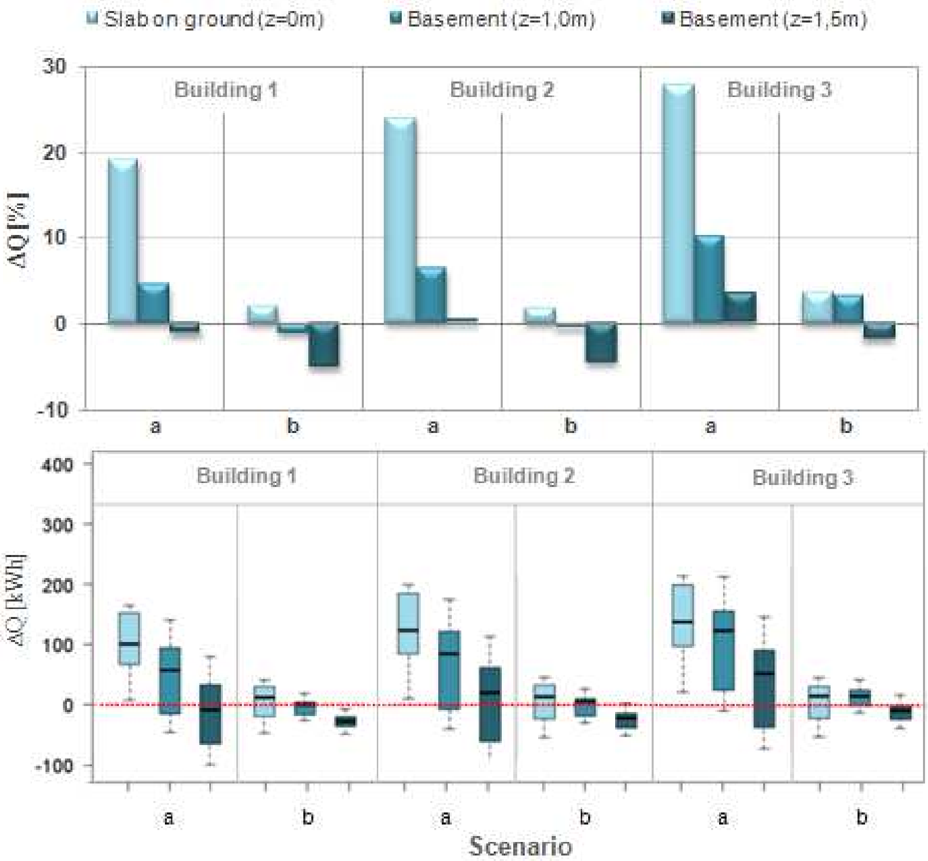

Fig. 4. Differences in heat exchange calculations ΔQ [%] in heating season and their statistical interpretation (*box-plots*).

5. CONCLUSIONS

All considered in the paper factors such as building's geometry, basement hollow and construction of ground touching assemblies have some (less or more) influence on calculation accuracy of quasi-stationary method according to Hagentoft assumptions including continous heating mode.

The highest differences (up to 30%) independent of building type occur in the case of uninsulated slab on ground. However, comparative analysis of different calculation methods carried out by Adjali et all [1] have shown, that calculations according to simplified methods can bring under- or overestimation on such level.

Thermal insulation of assemblies touching ground and building hollow caused incresase of the quasi-stationary calculation accuracy. It is to be supposed that thermal insulation of slab on ground, foundations, basement floor and walls, and building hollow decrease influence of boundary conditions on heat exchange between building and the ground. Especially significant in the case of slab on the ground. Furthermore, thermal insulation doesn't only reduce both 2-D heat flow at the floor perimeter and 3-D heat flow in the corners, but according to quasi-stationary method it additionally decreases the impact of building's geometry on calculation accuracy. The differences between rectangular L-shaped and T-shaped building are small in comparison with the general accuracy.

Taking into account the above mentioned, as well as more and more restrictive requirements concerning thermal protection of buildings, the analysis of uninsulated assemblies seems to be useless. It also concerns assemblies touching ground. However, the results of research [13] carried out by the author of this paper have shown, that complete or partial resign from ground thermal insulation, directly utilizing ground heat storage capacity, seems to be the most promising solution for decreasing internal air temperature in one-storey residential buildings during the long periods of very high summer temperatures in moderate climate regions.

Generally, differences between analyzed methods considered not exceed ±10% and quasi-stationary calculations according to PN-EN ISO 13370 standard (Hagentoft assumptions) may be useful in enginerring practice.

Appropriate method and calculation tools for assessment of heat loss to the ground come into prominence in energy-saving and proecological building design according to sustainable development paradigm.

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PORÓWNANIE WYNIKÓW OBLICZEŃ WYMIANY CIEPŁA JEDNORODZINNEGO BUDYNKU MIESZKALNEGO Z GRUNTEM UZYSKANYCH ZA POMOCĄ METODY QUASI-STACJONARNEJ ORAZ MODELU NIESTACJONARNEGO TRÓJWYMIAROWEGO. CZĘŚĆ I: OGRZEWANIE CIĄGŁE

Streszczenie

W artykule przedstawiono porównanie wyników obliczeń wymiany ciepła typowego budynku mieszkalnego z gruntem z zastosowaniem metody quasi-stacjonarnej i metody uwzględniającej w pełni niestacjonarny, trójwymiarowy przepływ ciepła w gruncie. Celem analizy obliczeniowej było określenie wpływu wybranych czynników takich jak: geometria budynku, poziom zagłębienia budynku w gruncie oraz konstrukcja przegród stykających się z gruntem na dokładność obliczeń wymiany ciepła za pomocą metod quasi-stacjonarnych uwzględniając ciągły tryb ogrzewania budynku. Obliczenia z zastosowaniem metody uproszczonej przeprowadzono zgodnie z aktualnie obowiązującą normą: PN-EN ISO 13370:2008. W celu przeprowadzenia szczegółowych obliczeń numerycznych opracowano model wymiany ciepła budynku z termicznym sprzężeniem z gruntem, oparty na metodzie bilansów elementarnych i stanowiący integralną część programu komputerowego "WUFI®plus". Rezultatem analizy porównawczej są różnice w wymianie ciepła określonej z zastosowaniem obu metod obliczeniowych.