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Original Research Article

EFFECT OF EXTENDING HOT WEATHER PERIODS ON APPROACH TO FLOOR CONSTRUCTION IN MODERATE CLIMATE RESIDENTIAL BUILDINGS

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Abstract

The effects of changes in Global climate on the prolonging time and the frequency of the periods of very high outside air temperature at summer were shown in the paper with particular emphasis on European moderate climate countries. In these countries, residential buildings, are usually equipped neither in air conditioning equipment, nor in ordinary window blinds. As the most promising solution it is suggested to resign completely or partially from ground slab thermal insulation, directly utilizing ground heat storage capacity. The paper includes detailed simulations on potential effect of various kind of floor construction and actions preventing high indoor air temperatures in building approach on air temperature inside the one-storey, passive residential buildings during consecutive days of very high outdoor temperature and total energy used yearly for additional heating and air conditioning.

Keywords: climate changes, heat waves, heat storage, slab on ground thermal insulation, energy consumption.

1. INTRODUCTION

Global warming significantly affects weather on both global and local scales. Some weather phenomena have become increasingly frequent and intense.

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Extreme heat waves become more frequent, more severe, and what particularly affects the climate in buildings, sustain for long time.

In summer 2003, the area of western and central Europe was affected by record-breaking heat waves [1]. The 2003 heat wave in Europe caused the increase in average July temperature by 20 - 30%. In many European countries extremely hot temperatures lasted over 20 consecutive days. The number of people who died because of 2003 heat stress in Europe is estimated for over 30 000. High temperatures centered over south-eastern France and extended from northern Spain to the Czech Republic and from Germany to Italy [2]. Such events happen more and more frequently all over the world [3], [4].

The events with unusually high temperatures lasting for long periods of time seem to affect particularly the regions with moderate climate which have never before been experienced by such phenomena. Gabriel and Endlicher [5] observed increase of human mortality rate in the north-eastern Germany province of Brandenburg by 32.3% and 16.0% respectively for 1994 and 2006 heat waves. Much higher increase in human mortality they observed in Berlin where in the center it increased to 67.2% due to heat island effect. In moderate temperature regions residential buildings are usually not equipped in air conditioning equipment, thus extended time of extremely hot weather can have very harmful effect on human life. It could be expected that the new circumstances should significantly affect the approach to building thermal design.

Even with the most optimistic Intergovernmental Panel on Climate Change scenarios, the damaging effect of extreme heat waves will be only worsening in coming decades. Instead of focusing on forcing at any cost the law according to which all the buildings in European Union countries should be close to zero energy (important for heating season mostly), we should also consider the summer effects on the design of the building. The option is to look for solutions which would provide for the best thermal environment all the year around, minimally affecting the total energy consumption.

On the other side, applying the phenomena of heat sinking to the ground below un-insulated floor has been not currently recognized as a promising possibility to reduce the indoor temperature in the building during long lasting summer heat waves [6], [7], [8]. The possibilities of using ground cooling is mentioned in context of buildings coupled with earth to air heat exchangers [8], [9]. On the other hand most of published research results in this area relate to modernization of existing houses what practically exclude any interventions in existing floor thermal insulation systems [6], [7], [8], [9].

The main goal of the paper was to demonstrate that applying ground slab with no thermal insulation or partially insulated makes a very promising approach of passive cooling method to efficiently decrease the indoor air temperature in one-storey residential buildings at moderate climate regions during heat waves. Using solar energy for warming up the un-insulated floor would make the consequences on total energy used in buildings, negligible.

2. RESEARCH METHODOLOGY

2.1. Calculation tool and assumptions

The thermal performance of the buildings was calculated using the WUFI®plus software, which was developed in Fraunhofer Institute for Building Physics IBP in Holzkirchen, Germany. WUFI®plus is a dynamic whole building simulation model which enables detailed analysis of transient hygrothermal processes in building components exposed to real climate conditions. The software contains weather database including outdoor air temperature, relative humidity, wind speed and direction, precipitation rate and solar radiation.

The 1-dimensional coupled heat and moisture transfer in opaque building components was developed and validated by Künzel [10]. Then zone model was developed [11] and validated via cross-validation with other tools, experiments and ASHRAE standard 140 [12]. In this model components are coupled to a whole building model, where the hygrothermal behavior of the building envelope affects the overall performance of a building. Ground coupled heat transfer through multilayer floor has been already extensively verified [13].

In the paper 3-dimensional heat exchange between building and the ground is considered. To solve this problem, the software was supplemented by so called “3D objects”. At certain distance from the building (at least half of a width and at least half of a length) a vertical adiabatic surface (with no horizontal heat flow) is assumed. Horizontal adiabatic surface (with no vertical heat flow) is assumed at 10m below floor level (at this level ground temperature is assumed to be equal to average outdoor air temperature).

Finite volume method [14] was used to solve differential equations. This method is based on the thermodynamic law of energy conservation. Heat transferring space is divided into small control volumes with nodes inside their centres of gravity. Division of heat conducting space into balance-differential elements with variable grid is performed automatically by the program. Parameters of outdoor climate define first kind boundary conditions on the upper surface of modeled ground. Heat exchange on the internal surface of the assemblies (wall, ceiling, floor) defines indoor boundary conditions (third kind boundary condition). Values of internal surface coefficient were assumed according to EN ISO 6946 [15].

To obtain realistic predictions of the indoor air temperature, the buildings were calculated with full thermal coupling with the ground. Indoor air temperature was obtained iteratively from heat balance of conditioned zone. The energy balance consists of heat exchange with thermal envelope including floor, ventilation, solar and internal gains according to EN-ISO 13790 [16]. Thermal coupling is established by defining of indoor air as a boundary condition for floor inside the building. Heat exchange with this assembly is attributed to zone air node. 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.

The 3D Objects model has been recently validated by Antretter et al. [13]. Four cases of thermal bridges given in the standard EN ISO 10211 [17] were analyzed. The validation was fully successful for all above mentioned cases and the model can be regarded as an accurate one.

It was noticed, that ground building thermal coupling can be regarded as a large scale thermal bridge under special assumptions. Thus, the obtained validation results refer to a case of 3D heat exchange between building and ground [13].

2.2. Scenarios

Four scenarios of slab on ground constructions were considered:

- *Scenario A*: 15 cm concrete slab on ground without thermal insulation,
- *Scenario B*: 15 cm concrete slab on ground with thermal insulation (30 cm EPS) under the slab - 1m strip along outer walls inside the building,
- *Scenario C*: 15 cm concrete slab on ground with thermal insulation (30 cm EPS) under the whole slab area,
- *Scenario D*: 15 slab concrete slab on ground with thermal insulation (30 cm EPS) over the whole slab area.

In each scenarios 1m of vertical thermal insulation of foundation walls were applied (15 cm concrete and 30 cm EPS).

2.3. Building and ground characteristics

For simplicity of calculations one-storey passive residential building was considered in this paper. In the Table 1 and 2 construction assemblies and windows are presented respectively.

Floor area of analyzed building is 108 m^2, net volume 300 m^3 and A/V factor is 0.85 1/m. Depth of foundation wall below ground surface is 1 m. According to EN ISO 13370 [18] recommendation, thermal conductivity for ground (λ) 2.0 $Wm^{-1}\cdot K^{-1}$ and thermal capacity ($\rho\cdot c$) $2.0\cdot 10^6$ $Jm^{-3}\cdot K^{-1}$ were used. Set point of indoor air temperature of 20°C and minimal air exchange rate of 0.5 ACH were assumed.

Table 1. Construction assemblies and windows

Building component	Construction	Thickness [m]	U-value [$Wm^{-2}K^{-1}$]
Outer wall / Internal wall	Lightweight timber framed wall (OSB plate + mineral wool)	0.45/0.22	0.10/0.22
Slab on ground	Concrete + EPS	0.45	0.13
Foundation wall - 1m deep	Concrete + EPS	0.27	0.13
Ceiling up to unheated attic	Lightweight ceiling (OSB plate + mineral wool	0.23	0.14

Table 2. Windows*

Orientation	Total area [m^2]
N	-
S	4.80
W	5.40
E	8.04

* Triple glazing windows SHGC (av.) = 0.53, U = 0.80 $Wm^{-2}K^{-1}$

2.4. Weather data analysis

The average temperatures of July, the warmest month in Poland, are within a range from approximately 17 ^{0}C in Baltic Coast to 19.3^{0}C at its hottest part, the Silesian Lowland and Tarnow. The Polish cities with the longest periods of summer high temperature are Tarnow, Wroclaw, and Słubice with statistically 8 days in a month when maximum temperature exceeds 30^{0}C. Słubice is a small city located just at the western Polish border with Brandenburg, Germany. The period selected for analysis was described above [5], assuming a heat wave which took place in July 2006. At this month the maximum temperature at Słubice, measured at local meteorological station exceeded 30^{0}C for 19 days and 33^{0}C for 7 days. The average monthly air temperatures at Słubice in July was 23.8^{0}C ± 5.6^{0}C.

3. RESULTS AND DISCUSSION

In the paper the impact of slab on ground construction solution on indoor air temperature during the hottest period of 9 consecutive days in July 2006 at Słubice was analyzed.

In Figure 1, 2 and 3 indoor air temperature obtained with WUFI®plus software for 4 considered scenarios: A, B, C and D are presented.

Three cases of actions preventing high indoor air temperatures in building were considered:

- *Case 1*: minimum air exchange 0.5 ACH for all day; no blinds in windows,
- *Case 2*: minimum air exchange 0.5 ACH for all day; blinds in windows,
- *Case 3*: minimum air exchange 0.5 ACH from 6 a.m. to midnight and night ventilation 2.0 ACH from midnight to 6 a.m.; blinds in windows.

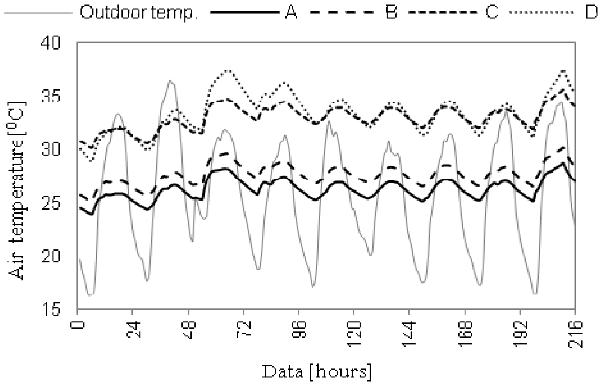

Fig. 1. Indoor air temperature in analyzed building for the hottest period of 9 days in July, 2006 at Słubice, including four scenarios of slab on ground constructions. *Case 1.*

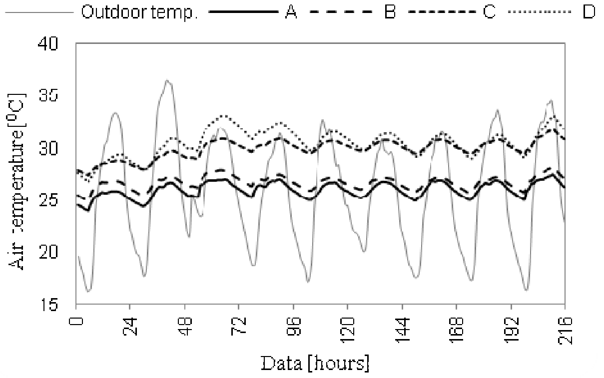

Fig. 2. Indoor air temperature in analyzed building for the hottest period of 9 days in July, 2006 at Słubice, including four scenarios of slab on ground constructions. *Case 2.*

In the Table 3 average indoor air temperatures (t) and standard deviations (σ) for 9 consecutive days in July 2006 at Słubice for the hottest part of the day (from 10 a.m. to 10 p.m.) for all considered scenarios and cases are presented. The most interesting relations were obtained for case 3. For the conditions: min. air exchange 0.5 ACH from 6 a.m. to midnight; night ventilation 2.0 ACH from midnight to 6 a.m.; blinds in windows, the highest average indoor air temperature was for building with thermal insulation over the floor and amounted to 29.5 ±1.1^{0}C. By placing thermal insulation under the floor which allowed for using thermal mass of the floor for daily cooling, the average indoor temperature dropped down by near 1.0^{0}C.

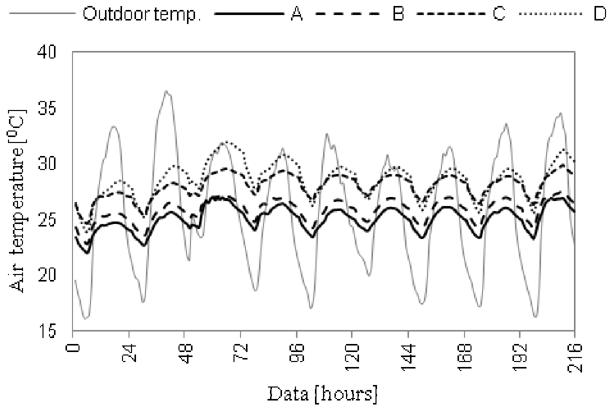

Fig. 3. Indoor air temperature in analyzed building for the hottest period of 9 days in July, 2006 at Słubice, including four scenarios of slab on ground constructions. *Case 3.*

Table 3. Average indoor air temperature in building.

Scenario	Case 1		Case 2		Case 3	
	t [^{0}C]	σ [^{0}C]	t [^{0}C]	σ [^{0}C]	t [^{0}C]	σ [^{0}C]
A	26.8	0.8	26.5	0.4	25.8	0.7
B	28.2	0.8	27.1	0.4	26.5	0.6
C	33.5	0.9	30.3	0.8	28.6	0.7
D	34.3	1.6	31.2	1.1	29.5	1.1

For the same case, extremely efficient appeared to be solutions with the slab with no thermal insulation and with thermal insulation under the slab - 1m strip along outer walls inside the building, with respective reductions in average indoor temperature by 3.7^{0}C and 3.0^{0}C comparing to scenario with thermal insulation over the floor.

The data in the Table 3 give information on average efficiency of introducing blinds in windows and night ventilation for all slab insulation solutions analyzed in the paper. Thus, introduction of the blinds in windows reduced the average indoor air temperature in the time of a day 10a.m. to 10p.m. by 3.1^{0}C from 34.3±1.6^{0}C to 31.2±1.1^{0}C for scenario D with thermal insulation over the floor. Additional introduction of night ventilation at a level 2.0 ACH from midnight to 6 a.m. lowered the average indoor air temperature by farther 1.7^{0}C. Similar results observed for scenario C with thermal insulation under the whole floor area.

The detailed analysis of the data illustrated in Figure 1-3 shows that such an approach would go too far in simplifying the obtained in simulation results. In case of the solution with insulated floor the effect of introduction night ventilation is much more significant than for fully un-insulated floor. There is also significant effect of blinds in windows on efficiency of night ventilation.

Because of complexity of processes which take place in using various approaches in attempt to cool down the indoor air temperature during heat waves, the full explanation can be obtained only experimentally.

As it was stated in &2.3, one-storey passive residential building was considered in the paper, just to show the potentials for summer cooling in building without ground slab thermal insulation and with partial one. Such an analysis for much popular, two-storey passive residential building would need application of CFD modeling and is planned in the near future. The main differences in these two types residential houses are supposed to be caused mostly by the significant difference in relation of the floor area to the net building volume, but also by lower floor room arrangement and location of staircase in relation to the rooms in which we want particularly keep as cold temperature as possible.

Respectively in the Table 4 and 5 heat losses for heating season and cooling demand for hot season (assuming $t_{max}=25^0C$) for all assumed scenarios are presented. The heat losses through floor during heating season were highest for scenario A and equalled 2896 kWh (case 3).

There was significant reduction for scenario B down to 2070 kWh. Much lower heat losses through floor area were for scenarios C and D, equalling respectively 638 and 654 kWh. The differences in heat losses for scenarios A and B are quite significant. For scenario B it is lower by approximately 30%.

The differences between scenarios C and D are negligible. Scenarios A and B consume respectively 4.5 and 3.2 times more of heating energy than scenario C.

Table 4. Heat losses from building to ground, Q [kWh]

Scenario	Case 1	Case 2	Case 3
A	2855	2860	2896
B	2033	2043	2070
C	632	636	638
D	649	652	654

Table 5. Cooling demand for building, Q [kWh]

Scenario	Case 1	Case 2	Case 3
A	257	56	27
B	443	138	68
C	1274	597	375
D	1422	662	485

Yearly cooling demand with assumption that the indoor air temperature should not increase above 25^0C were very low for scenarios A and B, equaling 27 kWh and 68 kWh respectively (case 3) and much higher for two remaining scenarios: C - 375 kWh and D - 485 kWh.

The reduction in cooling demand for scenarios A and B doesn't compensate scenarios C and D for heating losses during heating season. It should be taken into account however that energy for cooling which must be electricity is at least three times more expensive than energy for warming up which is usually from gas, oil or coal.

Not considering energy cost, the amount of total yearly energy (for heating and cooling) assuming actions preventing high indoor air temperatures in building in case 3, for scenario B is approximately only 10 kWh/m^2/year higher comparing to slab solution with full 30 cm insulation and it seems to be significantly more competitive than applying scenario A.

One approach could be a thorough statistical analysis which could at least suggest the areas for farther experimental procedure. Another one is full experimental procedure to be carried out.

Since the differences in using energy is relatively small (10 kWh/m^2/year), it seems to be interesting to consider the application of solar collectors to compensate for heat losses for the un-insulated floors in winter time. Although Chuangchid and Krarti [19] came to conclusion that when using additional pipe floor heating and cooling the slab should be insulated, it should be mentioned, that in case when the slab heating is only at a level of 1100 kWh for all heating season lasting approximately 7 months, the lack of insulation below the slab should not make a real problem with gaining this amount of solar energy which in 5 other months could be used for warming up the water. Additionally using floor heating could be helpful in reduction of possible cold floor effect.

4. CONCLUSIONS

1. The effect of persistent heat extreme events in moderate climate countries on indoor air temperature in buildings is very serious and seems to justify the changes in approach to the thermal design of the buildings.
2. Various configurations of building slab solutions, without, and with partial insulation seem to be very promising as an efficient options of approach to reduce heat stress in summer without losing too much energy.
3. Building slab solutions, without, and with partial insulation, the second one seems to be more efficient when all other actions preventing high indoor air temperatures are used, i.e. blinds in windows and increased night ventilation.
4. Building slab solution with partial insulation is particularly attractive, because it reduces the amount of total yearly energy (for heating and cooling) by close to 30 % comparing to the solutions with slab without ventilation.

5. The amount of total yearly energy (for heating and cooling) for building slab solution with partial insulation is approximately 10 kWh/m^2/year higher comparing to slab solutions with full 30 cm insulation.
6. Solutions of concrete ground floor slabs in conjunction with various solutions of its thermal insulation should be analyzed with all relations with the other methods of cooling down the indoor air temperature in summer.
7. It is worth to consider the application of solar collectors to compensate for heat losses for the non-insulated floors in winter time.

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WPŁYW PRZEDŁUŻAJĄCYCH SIĘ OKRESÓW WYSTĘPOWANIA WYSOKICH TEMPERATUR LETNICH NA PODEJŚCIE DO PROJEKTOWANIA PODŁOGI NA GRUNCIE W BUDYNKACH MIESZKALNYCH W KRAJACH KLIMATU UMIARKOWANEGO

Streszczenie

W artykule przedstawiono analizę wpływu wysokich temperatur zewnętrznych na kształtowanie się temperatur wewnątrz jednokondygnacyjnego budynku mieszkalnego, charakteryzującego się wysokim poziomem izolacyjności termicznej obudowy. W celu poprawy mikroklimatu pomieszczeń, autorzy proponują całkowitą bądź częściową rezygnację z izolacji termicznej podłóg na gruncie, wykorzystując pojemność cieplną gruntu jako naturalnego źródło chłodu. W artykule przedstawiono wyniki obliczeń numerycznych z zastosowaniem programu komputerowego WUFI$^{®}$plus dla różnych wariantów izolacji termicznej podłogi na gruncie, jak również innych niż proponowane przez autorów, sposobów zapobiegania przegrzewaniu się budynków w okresie pojawiających się fal upałów. Dla każdego z wariantów przeprowadzono obliczenia temperatury wewnętrznej, strat ciepła do gruntu oraz zapotrzebowania na chłód.

Słowa kluczowe: zmiany klimatu, fale upałów, podłoga na gruncie, magazynowanie ciepła w gruncie, zapotrzebowanie na chłód.

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