THE INFLUENCE OF CLIMATE ON THE HEAT TRANSFER FROM EARTH-SHELTERED BUILDINGS

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ABSTRACT

The paper presents the results of the simulation of the energy performance of underground buildings variously insulated, in two different climates. The long-term unsteady thermal processes between the building and surrounding soil are considered together with the heat transfer at the ground surface throughout the year. Presented results include the time and space distribution of the heat flow between the building and surrounding soil at different time intervals and during the whole year for various insulation patterns, and the heat flows through the ground surfáce. The isotherms around the buildings in winter and summer, for various insulation patterns are also presented. The conclusions are drawn.

INTRODUCTION

Only since the mid-seventies has the subject of an accurate thermal analysis of underground heat transfer from buildings become an object of intensive research in the U.S.A.

Thermal utilization of the surrounding ground is the best way to maximize energy conservation in earth-sheltered structures when it is coupled with optimal insulation. Achieving this (optimization) goal depends on an adequate understanding of the thermal processes taking place between underground building and its surroundings. As it was demonstrated in [1], in certain climates improper placement of insulation to reduce winter heat losses can negatively affect the overall energy savings when the complete annual cycle of heating and cooling is analyzed. It is therefore important to evaluate the variations in heat losses and/or gains over the entire year. This effect is shown also in this paper.

Probably the first computer program dealing with earth contact heat transfer was developed by Kusuda and Achenbach [2]. Since the late 1970s, numerical modeling methods have become widely used for analyzing and solving earth-coupled heat transfer problems. The numerical models use finite-difference or finite-element methods what was reported in numerous works, for example in [3], [4], [5], [6], [7]. Numerical models vary based on their assumptions, boundary conditions, and numerical representations. Further variations result from the considered thermal properties of the ground, the solution method of the sets of algebraic equations, the time step, and the pattern of building insulation considered. Some of the works are characterized by extensive field measurement validation ([1], [6], [7], [8]). None of these methods, however, can handle a wide variety of insulation configurations as the simulation program developed and applied here.

Energy conservation in earth-sheltered buildings may be achieved because of the significant dynamic interaction between these buildings and the surrounding soil, decreased infiltration rates, passive solar features, and use of the ground as a thermal sink and source. The temperature gradient between the ground and the surface of the structure is significantly reduced compared to that of the above-grade buildings. Seasonal outside temperature effects are greatly attenuated by the ground cover and the large heat capacity added to the building by the surrounding earth. To a smaller extent though, the outside climate still influences the heat transfer between the underground building and surroundings. This influence is presented in this paper on the base of numerical analysis of the energy performance of earth-sheltered buildings located in two different climatic conditions. The first one (named Climate 1) is the same as used in the analysis reported in [9]. It was chosen for comparing the numerical results with those previously obtained by applying different method [10]. The second (Climate 2) simulates the outside climatic model for Warsaw which is representative for central Poland. The buildings analyzed in the paper use six different insulation configuration strategies. These are as follows:

- Roof insulation projected horizontally beyond the building envelope,
- Uniform roof insulation,

- Uniform insulation on the roof and the walls,
- Insulation placed uniformly on the roof and partially on the walls,
- Insulation placed uniformly on the whole external surface of the building, and
- An uninsulated underground building.

Below, the mathematical and computer modeling of the considered process are briefly described. They were presented more deeply in [9] together with analysis of the various insulation strategies of underground buildings insulation performance in Climate 1. The results of simulation reported here, were computed for Climate 1 and Climate 2, two different depths of underground building and two thicknesses of insulation.

MATHEMATICAL AND COMPUTER MODELING

Figure 1 schematically shows the configuration of the underground building, the region of interest, and the system of coordinates. The two cross sections of the building can be perpendicular, as is shown in Figure 1. They may be also parallel in order to simulate various sections of the building with different dimensions.

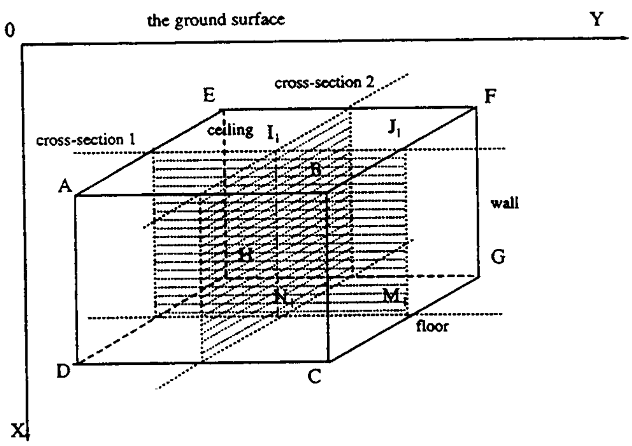


Figure 1 *Two cross sections of the underground building*

The mathematical model of the process consists of a heat conduction equation with appropriate boundary and initial conditions. A third boundary condition is assumed at the ground surface and at the internal wall surfaces. The variations in outside air temperature are driven by a harmonic function. The set of algebraic equations obtained by balancing the elementary heat flows into control elements is solved by an explicit scheme.

Program SHELTER

The program SHELTER developed to simulate the heat transfer between underground building and its surroundings enables a two-dimensional thermal analysis for an underground building of any size and situated at any depth; in two cross sections. It calculates the temperatures at all the nodes of both cross sections at each time step, employing the previously described algorithm. It also predicts the heat fluxes at all boundary nodes between the building and the surrounding soil and through the ground's surface. The summarized heat flow throughout the year, evaluated numerically for the undisturbed (by the building thermal influence) ground's surface, is compared with respective value evaluated analytically. This enables checking the actual accuracy of the algorithm in each program run.

Input data include the following:

1. Layout and dimensions of the building in both cross sections.
2. Thermal properties of the soil, concrete and insulation.
3. Configuration of insulation and it's length, the thickness of insulation and the concrete layers.
4. Total conductances at the internal surfaces of the building and at the ground's surface.
5. The internal air temperature in both cross sections of the building and outside temperature fluctuations.
6. The grid specification and the time step.
7. The period of time being simulated (without restrictions).
8. The geothermal gradient.
9. Output specification.

Output from the program covers all the input data, temperatures around the building and at the surfaces, as well as heat flows and sums. Some of the information summarized below may be printed as often as specified in the input data.
Output includes the following:

1. Input data.
2. Time (year, hour, day) and for both cross-sections:
   internal air temperature, the mean temperatures of the ceiling, walls, and floor, and sums

of the heat flow through the ceiling, floor and walls, in W/m.

3. Temperatures and/or heat fluxes in all boundary nodes placed at the internal surface of the building.

4. Temperatures in all nodal points of both cross sections, i.e. data regarding the ground's temperature fields at the dates of appearance of the maximum and minimum outside air temperature. The isotherms are calculated by a separate program, ISOT, which has to be applied to evaluate each temperature field.

5. Heat transferred through all boundary points during specified time intervals and for the whole year.

6. Mean heat fluxes in all boundary points during specified time intervals and for the whole year.

7. At the end of each simulated year: sums of the heat transferred through all internal boundary nodes and nodes placed at the ground surface.

8. Comparison of numerically and analytically evaluated heat transfer through the ground's surface.

9. Gross heat transfer through the ceiling, floor, walls and the whole building.

RESULTS AND DISCUSSION

Some simulation results of the transfer processes taking place between an earth-sheltered building constructed in two different climates and its surroundings are presented below.

Data

The building dimensions are as follows: height 3m, width 6 m and length 10 m. It is placed 1 m or

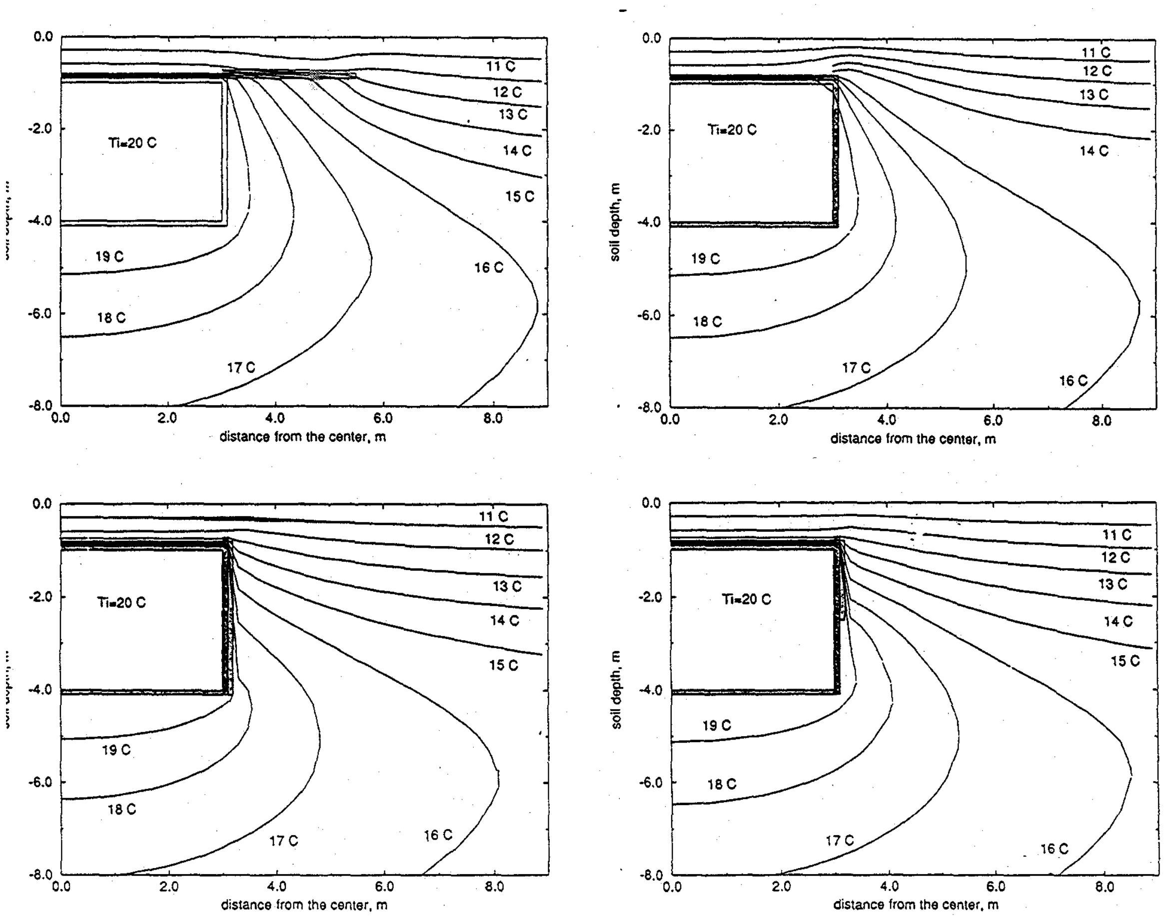


Figure 2 *The isotherms around the buried building insulated by different insulation configurations of thickness* $(d_i) = 0.10$ *m, in winter;*
a) configuration "aa", b) configuration "ab", c) configuration "ba", and d) configuration "bb".

2 m below the soil surface. The temperature of the internal air is kept at a constant level of 20^oC. The geothermal gradient is assumed to be zero, and there is no heat flow through the boundary nodes at the grid line below the building.

The thermal properties of soil were assumed to be a mid-range set of properties simulating a moist soil. They are as follows:

conductivity (k_g) = 1 W/(m K),
heat capacity (c_g) = 1550.4 $kJ/(m^3\ K)$,
diffusivity (a_g) = $6.45*10^{-7}\ m^2/s$.

The data regarding the concrete and insulation layers are as follows:

thickness of concrete layer around the building (d_c) = 0.10 m,
insulation thickness (d_i) = 0.05 m (2 inch) or 0.10 m (4 inches),
conductivity of insulation (k_i) = 0.05 W/(m K),
thermal diffusivity of insulation (a_i) = $13.81*10^{-7}\ m^2/s$,
heat capacity of insulation (c_i) = 36.2 $kJ/(m^3\ K)$,
conductivity of concrete (k_c) = 1.73 W/(m K),
diffusivity of concrete (a_c) = $9.18*10^{-7}\ m^2/s$,
heat capacity of concrete (c_c) = 1884.12 $kJ/(m^3\ K)$.

Surface convection film coefficients were taken from ASHRAE. They were the same values as used in [7] and were different for the ceiling, walls and floor, but the same numbers were assumed for both cross-sections. They are as follows:

ceiling (h_c) = 6.13 $W/(m^2\ K)$,
floor (h_f) = 9.26 $W/(m^2\ K)$,
walls (h_w) = 8.29 $W/(m^2\ K)$.

The convective film coefficient at the ground's surface, (h_g), was assumed to be constant throughout the year. Its value is calculated as a mean of the different values recommended by ASHRAE for different seasons and equals 28.4 $W/(m^2\ K)$.

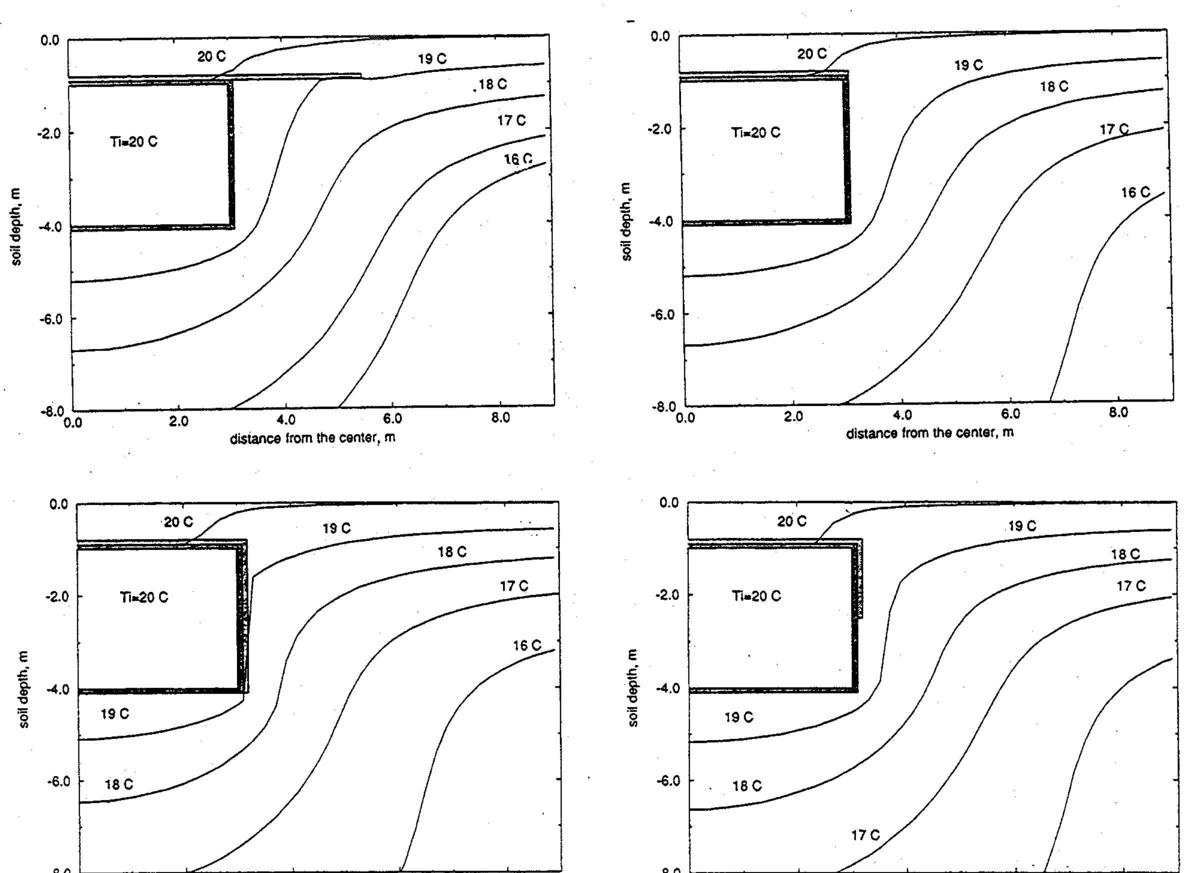


Figure 3 *The isotherms around the buried building insulated by different insulation configurations of thickness (d_i) = 0.10 m, in the summer;*
a) configuration "aa", b) configuration "ab", c) configuration "ba", and d) configuration "bb".

To check the effect of climate on the heat transfer two different climates were simulated referred as Climates 1 and 2. As it was mentioned before, Climate 1 is the same as assumed in [9] and in [10]; the variation of the outside air temperature, t_z, is given by:

$t_z = 15 + 5.1*\sin(om*t - 1.87)$.

The outside air temperature for Climate 2 simulating Warsaw climatic conditions is expressed as follows:

$t_z = 9.4 + 12.6*\sin(om*t - 1.80)$.

This temperature equals the sol-air temperature for Warsaw which was found [11] as best simulating the heat transfer conditions at the ground's surface.

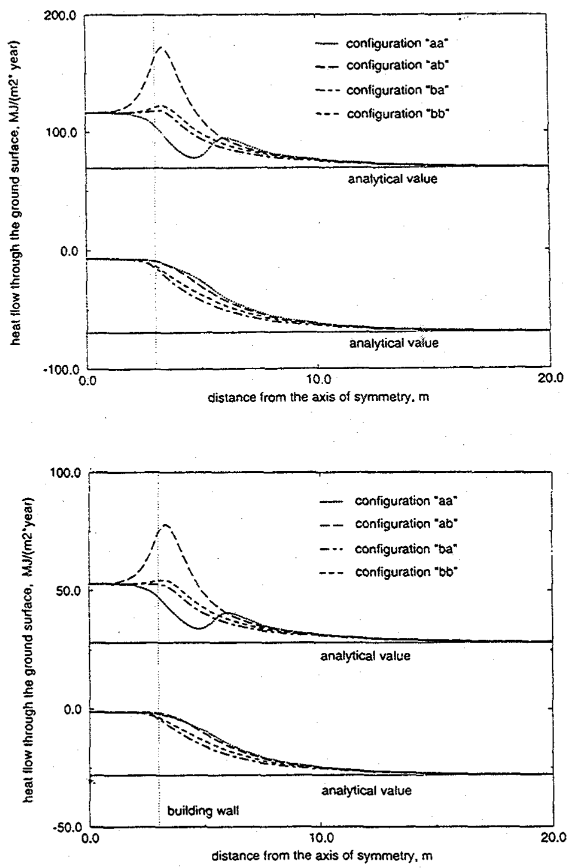


Figure 4 *The heat transferred through the ground's surface during a third year of the building operation in Climates 2 and 1 evaluated numerically for all configurations of insulation, and analytically without building thermal influence; insulation thickness (d_i) = 0.10 m,*
a) for Climate 2,
b) for Climate 1.

The comparative analysis of the energy performance of various insulation configurations for the earth-sheltered building included the five different

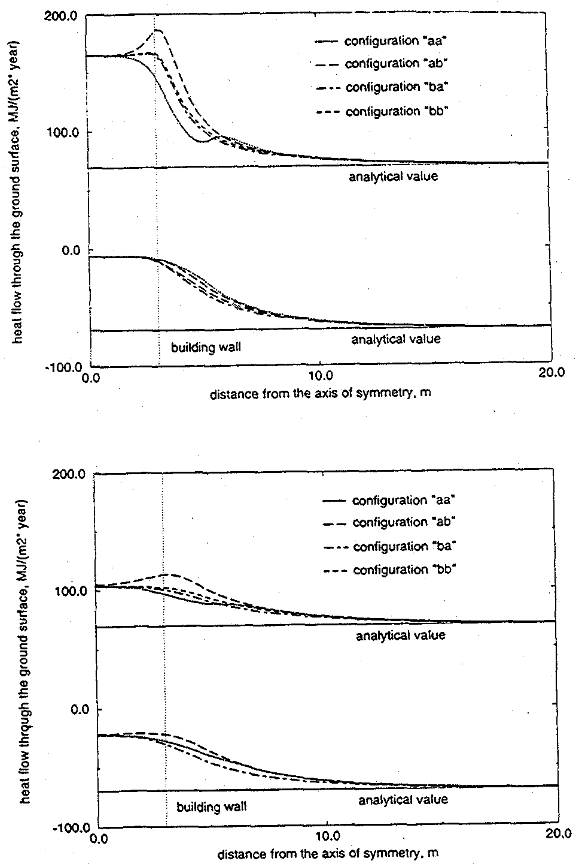


Figure 5 *The heat transferred through the ground's surface during a third year of the building operation in Climate 2 evaluated numerically for all configurations of insulation, and analytically without building thermal influence; building placed at two depths,*
a) the depth = 4 m, insulation thickness (d_i) = 0.05 m,
b) depth = 5 m, insulation thickness (d_i) = 0.10m.

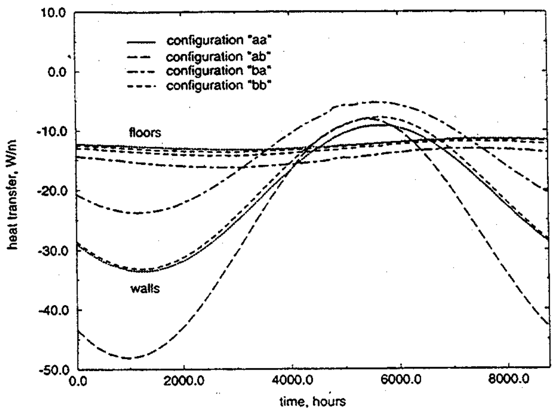
options described above, plus an uninsulated building. The length of insulation in the "aa" configuration (roof insulation projected horizontally) was assumed to be equal to 2.5 m. The length of insulation in the "bb" configuration (insulation placed on upper part of walls) was equal to 1.5 m, i.e. half of wall area was assumed to be insulated. These values were the same for all simulation runs.

Results

Figures 2 and 3 illustrate isotherms around a buried building which is insulated by all considered insulation patterns except full; in winter and in summer, respectively, in the second year after construction of the building. Figures 2a and 3a show isotherms for insulation configuration "aa", Figures 2b and 3b for the configuration "ab", Figures 2c and 3c for the insulation pattern "ba", and Figures 2d and 3d for the insulation configuration "bb". Isotherms shown in all the above mentioned figures were evaluated for the insulation thickness $(d_i) = 0.10$ m and Climate 1.

Comparing the isotherms shown in Figures 2a and 3a with those in Figures 2b and 3b, 2c and 3c, and 2d and 3d one can easily notice that the differences in isotherms for various insulation configurations are most pronounced in the ground surrounding the walls. They are identical above the building and in the whole region close to the ground surface where the influence of the heat transfer through the surface has a strong effect on the temperature of the soil. Comparing isotherms for both the summer and winter seasons one can also see that respective lines are very close to each other below the building. This is caused by the lack of an outside climatic thermal influence, maintaining a constant internal temperature, and the fact that all floors are uninsulated. This result also shows that the algorithm used does not produce systematic errors. Small differences in the ground temperature below the floor can be observed between the building insulated by configuration "ba" and the buildings with the other patterns of insulation; the temperature below this building is slightly lower. This effect is due to the insulation on the walls which lowers the temperature of the surrounding ground.
These results reflect the fact that all considered insulation patterns have fully and uniformly insulated ceilings; also none have insulated floors. The insulation configuration "ba" is the only one with fully and uniformly insulated walls; this results in lower temperatures in the surrounding ground.

Figures 4 and 5 illustrate the heat flow through the ground's surface as it is affected by the building placed below this surface for Climates 2 and 1, and Climate 2, respectively. Figure 4a and 4b shows summarized heat flows during the whole year through all boundary nodes at the ground surface for insulation configurations "aa", "ab", "ba" and "bb" and Climates 2 and 1, respectively; for insulation thickness $(d_i) = 0.10$ m.
Figure 5a and 5b shows also the heat flow through the ground surface but for the insulation thickness $(d_i) = 0.05$ m where the building is placed at the same depth of 4 m (Figure 5a) and at a depth of 5 m and the same thickness of insulation $(d_i) = 0.10$ m (Figure 5b). The horizontal solid lines at these figures show analytically calculated heat flows through the ground surface for both half-year long periods of time in which the heat flows in the same direction: out of the ground or into it. These values are calculated under assumption that there is no building thermal influence. The vertical dotted lines denote the placement of the building walls (3 m from the axis of symmetry).



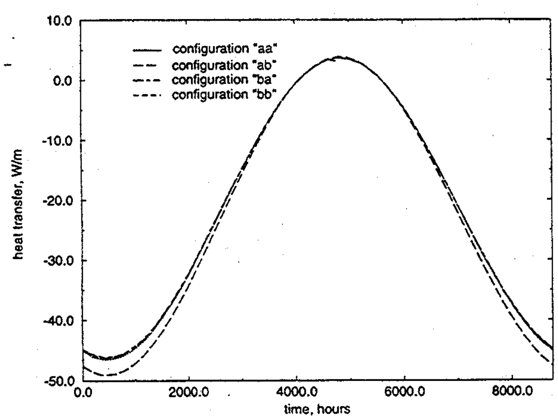


Figure 6 *Yearly variation of the heat losses through the ceiling, walls and floor of an earth-sheltered buildings situated in Climate 2 and insulated by all configurations of insulation; a) walls and floors heat losses, b) ceilings heat losses.*

As can be seen from the results of the simulations presented in Figures 4 and 5, the influence of climate on the heat flow through the ground surface has a different character than the influence of the insulation pattern, the insulation thickness, and the depth of the building placement. All lines show decreasing thermal influence by the building on the heat flow through the ground's surface with increasing distance from the walls so that the largest differences are produced in the surroundings of the upper corner. The respective lines in Figure 4a and 4b are identical in character. They differ only in quantities of the heat flow which are obviously larger for Climate 2, reflecting larger differences between outside and internal air temperatures. The differences between the heat flow through the ground's surface for various insulation patterns are larger for thicker insulation (see Figures 4a and 5a for Climate 2 and insulation thickness $(d_i) = 0.10$ m and $(d_i) = 0.05$ m, respectively) and for more shallowly placed buildings (see Figures 4a and 5b for insulation thickness $(d_i) = 0.10$ m, and depth of 4 m and 5 m, respectively). The differences in the heat flow through the ground's surface affected by various parameters considered above, decrease as the distance from the building increases. At the distance of about 5 m, these differences become practically negligible. At a distance of about 14 m, building's thermal influence on the heat flow through the ground surface approaches zero. This distance does not depend on the climate, the depth of building placement or the insulation thickness.

Figure 6 illustrates the yearly variation of heat transfer through the walls, ceilings and floors for various configurations of insulation thickness (d_i) =0.10 m for the building constructed in Climate 2. The results presented in Figure 6 reflect in character the respective results received for Climate 1 and reported in [9]. However, as can be seen in Figure 6a, in the summer the heat flows into the building. This was not the case in Climate 1, where the building was constantly losing heat. The building located in Climate 2 gains heat in summer; mainly through the ceiling but also through the upper walls insulated by all patterns except "aa". These effects are illustrated more clearly in Figures 7 and 8 which show, respectively, the heat gains for the underground building constructed in Climate 2 and insulated by patterns "aa", "ab", "ba" and "bb" as well as fully insulated (8b) and uninsulated (8a); in June, July and August. As can be seen in Figures 7 and 8 insulation configuration "aa" (roof insulation projected horizontally) is the only one which does not allow the heat to flow into the building through the walls. Insulation "ab" (uninsulated walls) causes step changes in the heat flow around the upper corners. The heat gains for uninsulated building in Climate 2

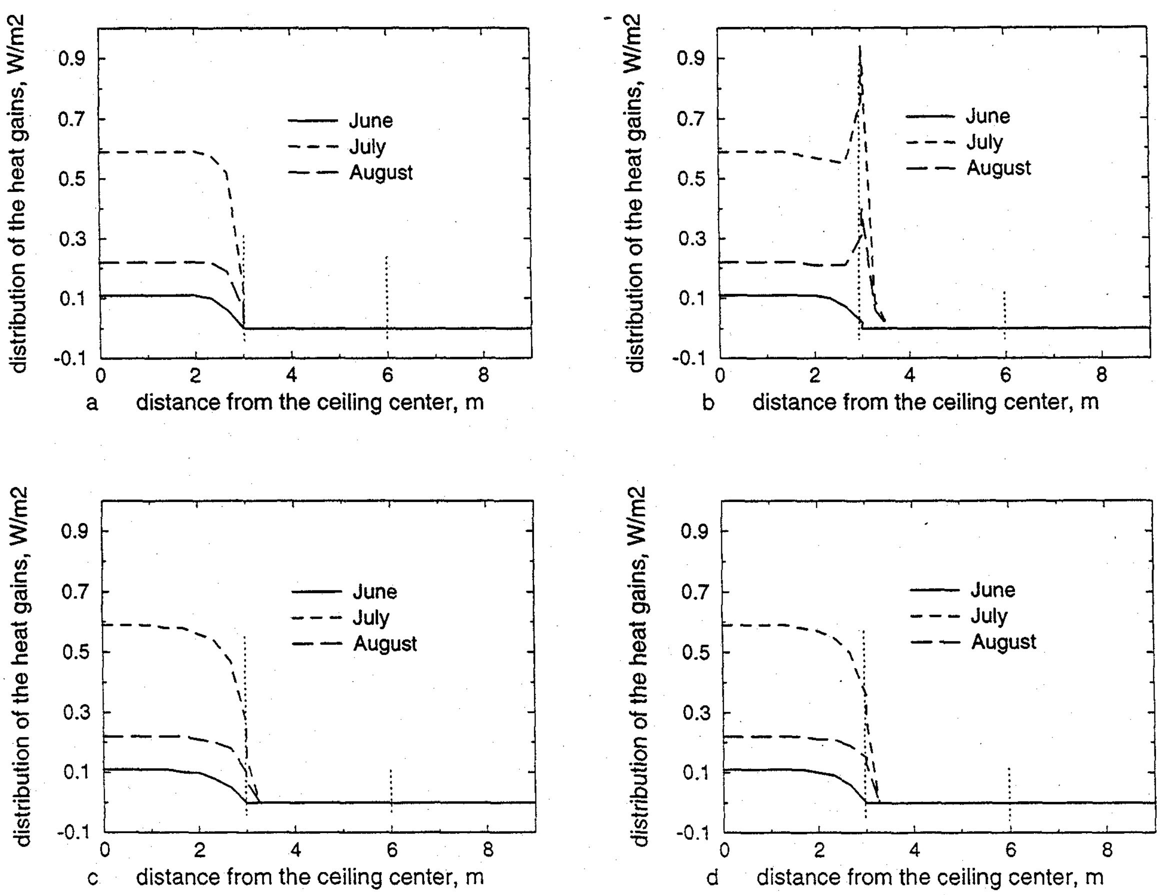


Figure 7 *The time and space distribution of the heat gains along the internal surface of an earth-sheltered building insulated by various insulation configurations, insulation thickness* (d_i) *= 0.10 m, Climate 2;*
a) configuration "aa", b) configuration "ab", c) configuration "ba", and d) configuration "bb".

are pronouncly larger than for the insulated one. This can be seen in Figure 8.

Figure 9 illustrates the distribution of the heat flow through the internal surface of the underground buildings constructed in Climate 2 and insulated by all six insulation patterns considered. There are very small differences between the distribution of the insulated ceilings heat losses except at the corners where they become more pronounced. In the center of the building, where the heat flow is one-dimensional and perpendicular to the building surface, the insulated ceilings heat losses are identical. These results are analogous to the respective results evaluated for the building located in Climate 1 and reported in [9]. They are also analogous to the conclusions regarding heat losses through walls and floors. The buildings constructed in Climate 2, however, also gain heat what was already stated above. This effect has been illustrated in Figures 6, 7, 8 and 9.

Figure 10 shows the monthly distribution of the heat flow through the internal surface of the underground buildings constructed in Climate 2 and insulated by the insulation configuration "bb" which was chosen from all six insulation strategies because of the "step" change in the heat flux at the end of the partial wall insulation. As can be seen in Figure 10 there are large differences between the heat flow through the ceiling in different months. The largest heat flow can be noticed in January, February and December. The smallest in June, July and August. In these summer months the heat flows in opposite direction - into the building, as is shown in Figure 7. The annual variation in heat transfer through the ceilings diminish along the walls, reaching almost identical and stable distribution at floors. This is due to the earth coupled effect on the heat transfer.

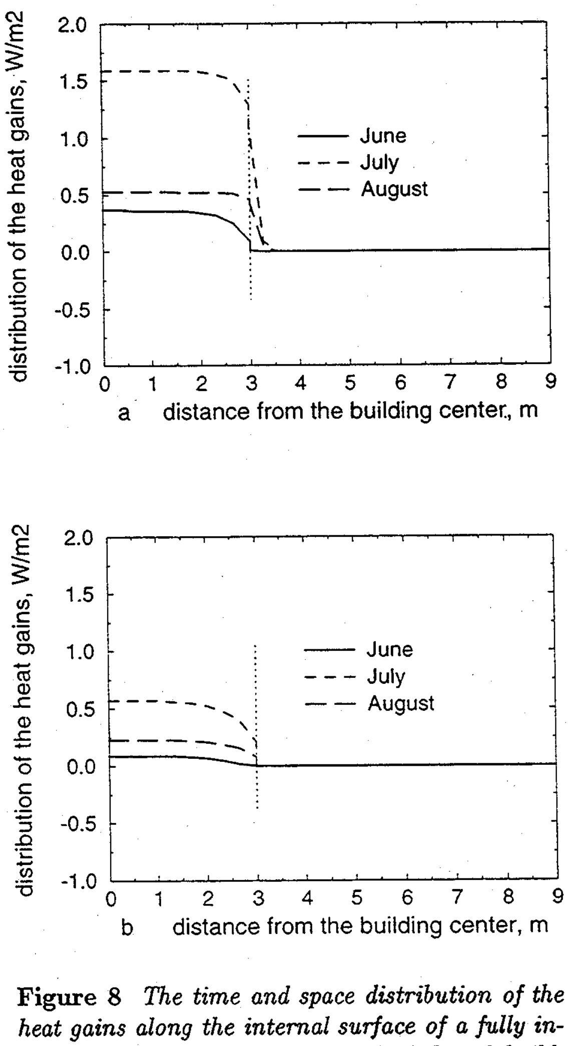


Figure 8 *The time and space distribution of the heat gains along the internal surface of a fully insulated and an uninsulated earth-sheltered building; insulation thickness (d_i) = 0.10 m, Climate 2.*

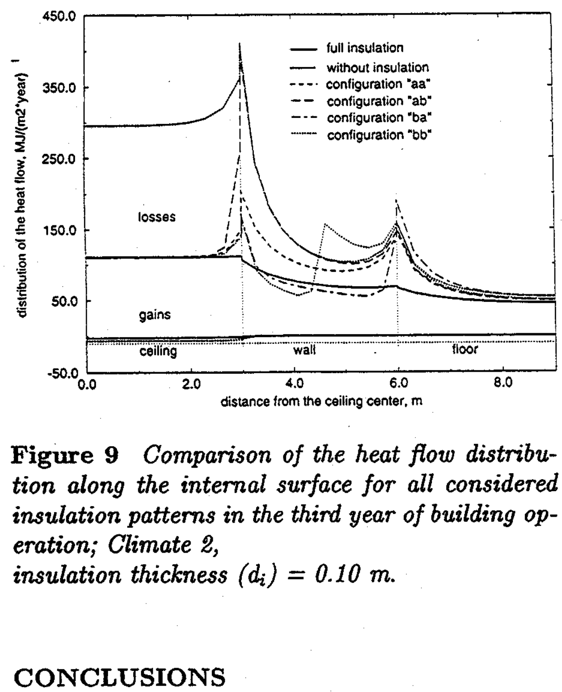


Figure 9 *Comparison of the heat flow distribution along the internal surface for all considered insulation patterns in the third year of building operation; Climate 2, insulation thickness (d_i) = 0.10 m.*

CONCLUSIONS

The results presented confirm the conclusions stated in [9] that the simulation program SHELTER is an effective tool for analyzing the energy performance of various insulation configurations for earth-sheltered buildings and the influence of different parameters on the ground-coupled heat transfer between these buildings and surroundings.

The above results provide evidence that the climate influences the mutual relationship between the building heat gains and losses; in Climate 1 buildings insulated by all patterns of insulation in question, are constantly losing heat. In Climate 2 the heat flows also towards the buildings interior through ceilings and upper walls except building insulated by configuration "aa" which protects walls against heat gains in summer. This may be important in certain climates when summer cooling is necessary, saving energy consumed for this purpose. This insulation pattern also provides the most uniform distribution of heat losses along the walls in winter. It confirms the conclusion from [9] that the pattern "aa" may be a good strategy of insulation, especially but not exclusively for retrofitting where it is easier and less expensive to apply than any other insulation. The results presented above show also that there is important to evaluate the variations in heat losses and/or gains over the entire year for a given climate. This is in agreement with the conclusions from an experimental study described in [1] which was already cited in the introduction.

The above presented results of simulations show that some of the heat flowing out from the underground building to the surroundings is accumulated in the surrounding mass of the soil but most of this heat is transferred out of the ground and is convected and radiated to the outside air. It means that all methods of evaluating the earth-coupled heat transfer which determine a priori the ground's surface temperature or the heat flux at the ground surface in the boundary condition (assuming the first or the second boundary condition at the ground's surface), neglect the heat flowing from the building out of the ground through the surface. This is a source of pronounced error which depends on the depth of the building, insulation pattern and thickness, the climate, and ground thermal properties.

All the numbers regarding heat losses that were reported in this paper should only be considered for comparative purposes to illustrate certain processes and tendencies and should not be taken as reliable and absolute data. There are many uncertainties, especially regarding the soil thermal properties which are still not adequately known.

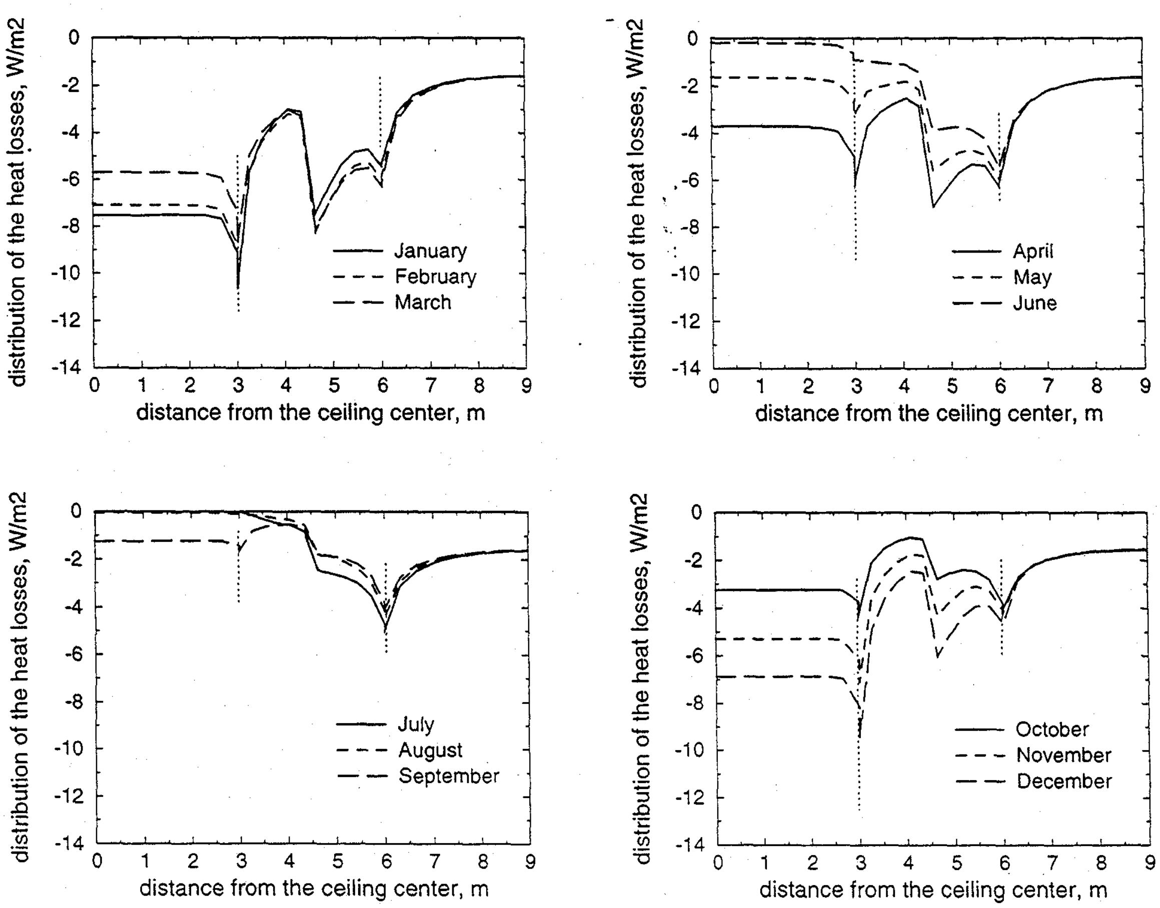


Figure 10 *The time and space distribution of the heat losses along the internal surface of an earth-sheltered building insulated by the configuration "bb" in the third year; insulation thickness (d_i) = 0.10 m, Climate 2.*

A variety of parameters should be considered. Further investigation and parametric study for different depths, shapes, sizes, insulation thicknesses, insulation properties, and climates in connection with heating and cooling requirements are needed to draw general conclusions. Especially important is the influence of the ground thermal properties on the heat transfer.
It will enable to study the effects of moisture migration in soil on the heat transfer.

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