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EFFECT OF DEPTH AND INSULATION OF A FRUIT COLD STORAGE PLANT FLOOR ON HEAT EXCHANGE WITH THE GROUND

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ABSTRACT

The method of 3-dimensional, transient heat transfer calculation through partitions touching the ground (floor and walls) was presented. The effect of a fruit cold storage plant floor depth and thermal insulation on heat gains during storage period was analysed. Results of calculations show the great disadvantage of partly underground location and lack of floor insulation of cold storage in comparison with traditional fruit stores. Insulating the floor with foamed polystyrene 10 cm thick reduces total heat gains during the whole cold storage season by as much as about 40% and several times lowers demand of necessary power of cold-storage plant at the beginning of storage period.

Key words: cold-storage plant, ground, thermal insulation, heat transfer

INTRODUCTION

Over 80% of the storage base in the fruit-growing regions of the Carpathian Foothills are formed by traditional, partly underground fruit stores [1]. The construction of partly underground fruit stores was favored by the layout of the land and the opinion widespread in 1965-1985, when fruit-growing experienced a peak, that such stores are most suitable for Poland’s climatic conditions [2, 3].

The ability of partly underground facilities, which thanks to their large heat storage capacity can withstand rapid changes of external air temperature and have a stabilizing effect on the interior microclimate, has been known and taken advantage of for a long time. This phenomenon is due to the accumulation of surplus heat when the internal air temperature increases and to the partial giving up of heat when the temperature becomes lower. The intensity of this process is proportional to the depth of a building in the ground, and the thermal resistance of partitions touching the ground is low. For this reason, the floors of traditional fruit stores have no thermal insulation.

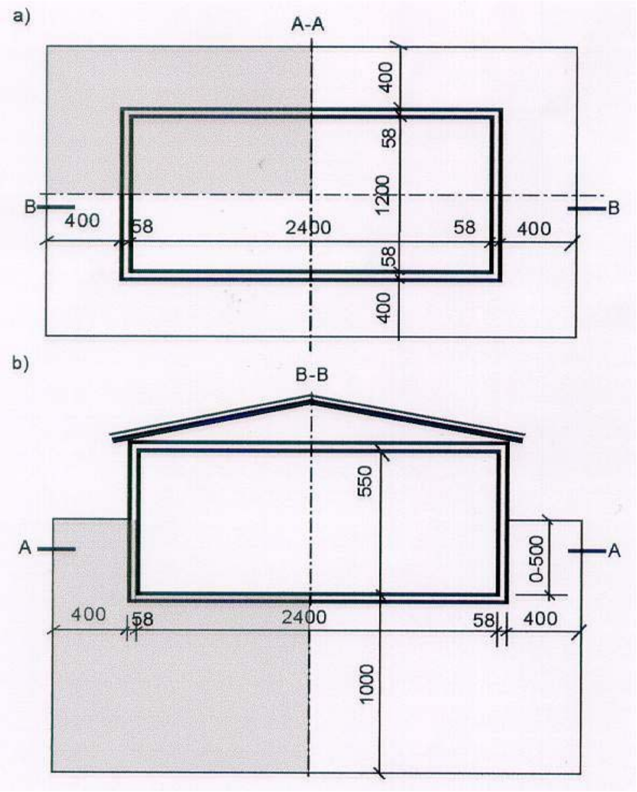
The rapid cooling of fruit after harvesting and maintenance of the required air temperature and humidity in storage chambers are the most important factors affecting the long storage of fruit. However, the optimum microclimatic conditions (temperature close to 0°C, relative air humidity of 90-94%) can only be ensured in facilities equipped with a ventilation system, i.e. in cold storage plants.

The aim of the present paper was to determine the effects of cold storage plant depth below the ground surface and thermal insulation of the floor on heat exchange with the ground and answer on the question whether partly underground location could be, in comparison to traditional storage, beneficial for their energy balance.

MATERIAL AND METHODS

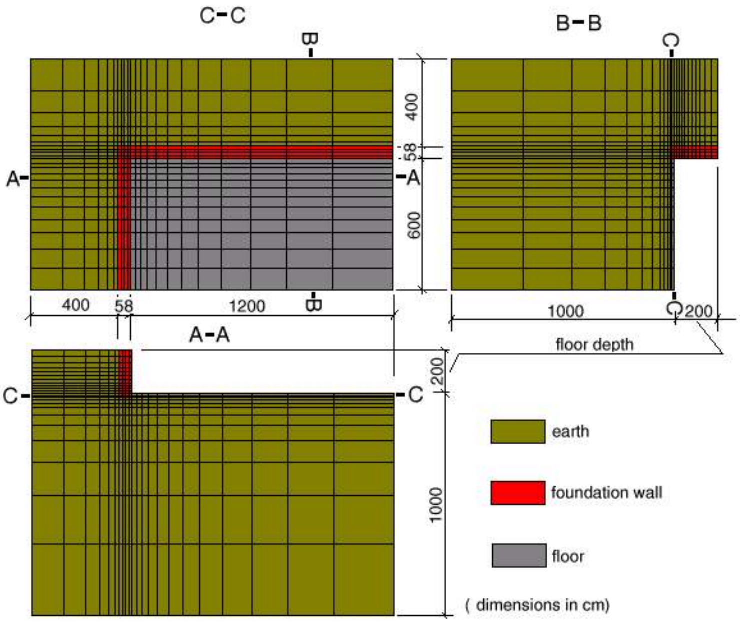
A typical fruit cold storage plant (internal dimensions 12×24 m, height 5.5 m) was taken to analyse the role of partitions touching the ground (floor and walls) depending on their depth below the ground surface. The building was considered in 6 variants of the zero level position in relation to the area surface – location at ground surface and at floor depths of 1, 2, 3, 4 and 5 m below the ground. Due to the specific nature of heat flow in the ground (large heat accumulation, three-dimensionality of the flows) it was assumed that there is a vertical adiabatic plane (horizontal flow disappears) 4 m off the walls and the vertical flow disappears 10 m below the floor (fig. 1).

Fig. 1. Dimensions of cold storage and attached ground assumed in the calculations. Grayed area denotes part of the ground, floor and foundation walls taken into calculation because of object-symmetry: a – horizontal cross section A-A, b – vertical cross section B-B



The calculations were made using a dedicated software which analyses three-dimensional, non-stationary heat flows in the ground. The program is based on the method of elementary balances [6]. This is a universal method for generating energy equations for differential elements, which due to the geometry of the building and the ground are rectangular prisms. The program has been thoroughly validated by comparing the calculations with long-term measurements made on specific facilities, including a fruit store [7]. Due to the symmetry of the analyzed building, a fourth part of the system (building and ground) was used in the calculations. To reduce the number of elements while maintaining the highest possible accuracy of the calculations, a variable distribution of the division grid was applied. Within the foundation walls and the floor was applied a maximum density of the division grid, which gradually decreases according to successive terms of a geometric series (fig. 2). Owing to a large number of elements (9,500-10,000 depending on floor depth), an explicit time scheme (forward difference quotient) was assumed. This algorithm makes it possible to determine temperature in the next time step without the need to solve complex systems of linear equations. However, the stability and physical correctness of the model are conditional on considerably limiting the time step. In the analyzed cases, it was about 3 minutes, which is 20 time steps per hour.

Fig. 2. Division of cold storage and attached ground in cubed differential elements



The basic parameters of the system assumed in the calculations were determined based on the standards PN-91/B-02020 [8] and PN-EN ISO 6946 [9] and are given in table 1. For outer and foundation walls and the floor, the coefficients of heat conductance, heat storage capacity and density were averaged. Although this simplification may have had some influence on the local distribution of temperatures, it did not affect the flow of heat. It was also assumed that thermal parameters of the walls, the floor and the ground do not change in time. On the whole, these assumptions conform to the recommendations of the European standard EN ISO 13370 [4] for calculating heat lost to the ground.

The storage season for stone fruit, mainly apples, usually lasts from 1 October to 31 May, i.e. about 8 months. During that period, temperature in the cold store is maintained close to 0°C. From the end of one storage season to the beginning of the next, temperature in the cold store is not adjusted. It follows a random pattern due to the effects of external climate and ground on the building. In particular, this temperature becomes set at the level of thermal equilibrium determined by the balance of ventilation heat, transmission flow through external walls touching external air, through foundation walls and through the floor. To determine the external temperature pattern between storage seasons, the mean multiplication factor of heat exchange was assumed to be 0.5 exchanges per hour. Because the effect of heat accumulation in the external partitions touching external air (ceiling, external walls) on the accuracy of the calculations is small, it was disregarded.

Table 1. Basic parameters of the system assumed in the calculations

Specification/Unit	Value
Cold storage	
Length, width, height (internal dimensions) (m)	24; 12; 5.5
Depth of floor (m)	0; 1; 2; 3; 4; 5
Foundation and outer walls (mean values)	
Thermal conductivity (W/m·K)	0.183
Specific heat (kJ/kg·K)	1
Bulk density (kg/m^3)	1991
Thickness (m)	0.58
Thermal transmittance of outer walls (W/m^2·K)	0.3
Thermal transmittance of foundation walls (W/m^2·K)	0.3
Non insulated floor	
Thermal conductivity (W/m·K)	2
Specific heat (kJ/kg·K)	1
Bulk density (kg/m^3)	2400
Thickness (m)	0.1
Insulated floor (mean values)	
Thermal conductivity (W/m·K)	0.069
Specific heat (kJ/kg·K)	1
Bulk density (kg/m^3)	1215
Thickness (m)	0.2
Ground	
Thermal conductivity (W/m·K)	1.8
Specific heat (kJ/kg·K)	1
Bulk density (kg/m^3)	1800
Remaining values	
Thermal resistance on the inner surface of foundation walls (m^2·K/W)	0.13
Thermal resistance on the floor-surface (m^2·K/W)	0.17
Thermal resistance on the ground surface (outside building) (m^2·K/W)	0.05
Thermal transmittance of flat roof (W/m^2·K)	0.2

Due to thermal inertia of the ground, the initial condition, i.e. the distribution of temperatures in the ground during the beginning of the storage season, acquires a great importance. For this reason, calculations were made for the two successive years, assuming that the calculated distributions of temperatures in the ground for the 2nd year will be reliable (reproducible). The results of calculations in the third year showed that they are identical to those in the second year, which leads us to conclude that the assumed time period of “advancing” the calculations to obtain the initial condition was sufficient. Individual calculation periods and their assumptions are given in table 2. The last storage season (V period of calculation) was assumed to be reliable for calculation results.

Table 2. Calculation periods and their assumptions

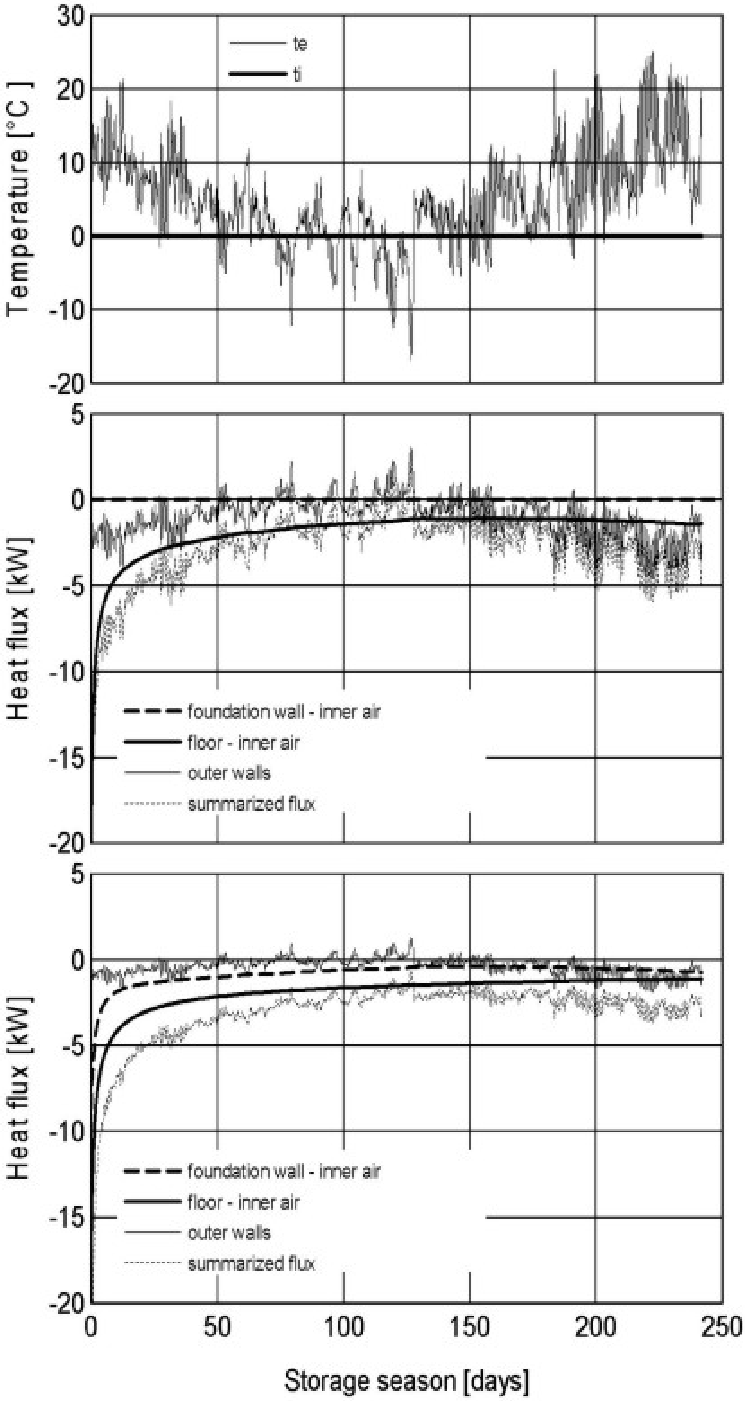
Period of calculation	Year	Date	Assumptions
I	1	1 June	Temperature of the ground const.= 10°C
II	1	1 June to 30 September, break between storage seasons	Non controlled inner air temperature determined by thermal balance
III	1	1 October to 31 May, storage season	Inner air temperature maintained at 0°C
IV	2	1 June to 30 September, break between storage seasons	Non controlled inner air temperature determined by thermal balance
V	2	1 October to 31 May, storage season	Inner air temperature maintained at 0°C

In the whole period analyzed, the external boundary condition is determined by the course of external air temperature characteristic of a given place and time. Due to the non-stationary nature of the heat flows, a statistical, annual pattern of external air temperature at 1-hour intervals would be the most suitable for the calculations. The statistical climate of Poland has not been elaborated yet. For this reason, and due to climatic similarities, the statistical climate TRY for the region of Wűrzburg (Germany) was used in the calculations [5]. The effect of solar radiation was disregarded.

RESULTS OF THE CALCULATIONS

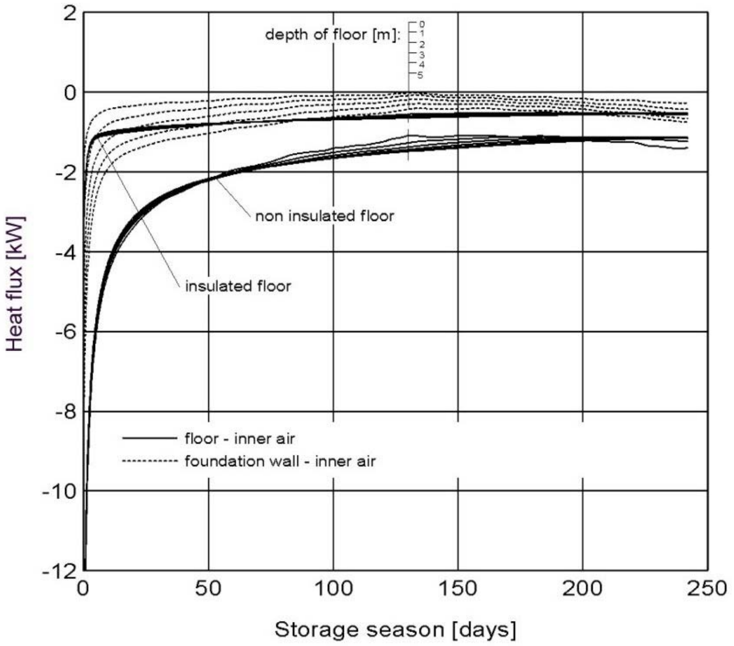
For the periods described in table 2, heat flows through the cold store partitions were calculated for 6 variants of floor depth. The last of the storage seasons was assumed to be representative (repeatable) during the year. Figure 3 shows the boundary condition (pattern of external air temperature) and patterns of total heat flux through uninsulated floor, foundation walls and external walls for an above-ground building and for a floor depth of 5 m below the ground. In the above-ground building heat flux through foundation walls was zero during the whole period, while heat exchange with the ground took place via the floor. With increasing floor depth (variants 2-6), the proportion of foundation walls in total heat exchange increased, while the proportion of external partitions (touching the external air), characterized by a large amplitude of heat flux variations, decreased. This resulted in a reduced amplitude of total heat flux with increasing depth of the building.

Fig. 3. Course of outer air temperature (top diagram), heat fluxes by floor depth of 0 m (middle diagram) and by floor depth of 5 m (lower diagram)



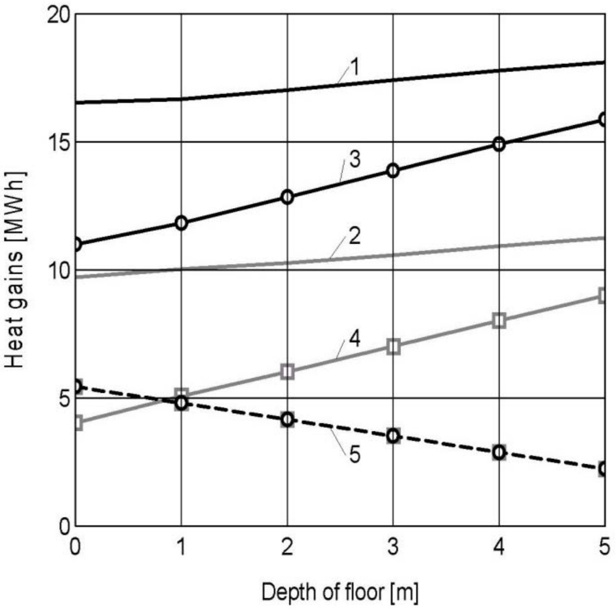
Maintenance of constant internal air temperature at 0°C at the beginning of the storage season causes a rapid flow of heat flux from the ground to the storage chamber regardless of the zero position variant. The heat flows through the walls touching the ground and through the floor are similar in character, but the flow curve is more flat for the floor (fig. 4). Within 10 to 20 days (depending on depth), heat flow through the foundation walls inside rapidly decreases. This period is followed by a very slow decrease of the heat flux. After about 130 days, a slight increase in the flow is observed, resulting from the inflow of external air (further cooling of the ground is inhibited by the inflow of heat from the air). A similar effect occurs for the above-ground floor and for the floor about 1 m deep.

Fig. 4. Courses of heat flux through floor and foundation walls



Flow of the heat flux through the uninsulated floor decreases almost exponentially, reaching about 20% of the initial value after several days and from about 1 month to the beginning of the storage season, the flow stabilizes at about 10% of the initial value. During the whole calculation period, there are slight differences in the flow of heat through the floor situated at different depths. The nature of the heat flow through the insulated floor is generally different. The initial heat flow is many times lower and is much shorter than in the case of the uninsulated floor. After about 3-5 days, the heat flow stabilizes and begins to decrease very slowly. Large thermal resistance of the heat insulation under the floor causes only the floor and not the ground to be cooled. After 5 days, the flow of heat flux is almost stationary, and the effect of depth on its volume almost disappears.

Fig. 5. Heat gains through particular partitions of cold storage during the storage season: 1 – summarized heat gain (non insulated floor), 2 – summarized heat gain (insulated floor), 3 – ground touching partitions (non insulated floor), 4 – ground touching partitions (insulated floor), 5 – partitions touching outer air



In the storage season, total heat gains through the partitions touching the ground increase almost linearly with depth (fig. 5). At a depth of 5 m, the gains increase by about 5.0 MWh compared to the above-ground floor. Because the proportion of walls touching the external air decreases with depth, the curve of gains obtained by all the partitions of the cold storage plant is more flat. However, total gains also increase with depth, by about 2.0 MWh for the uninsulated floor and by about 1.6 MWh for the insulated floor. The difference in total gains between the building with insulated and uninsulated floor is about 6.8 MWh and is almost completely dependent on the depth. For the above-ground building with insulated floor, gains are reduced by about 40% compared to the cold storage plant with the uninsulated floor.

CONCLUSIONS

Heat flow through the partitions touching the ground is directed into the cold store during the whole storage season. At the beginning, the heat flow is rapid, especially with uninsulated floor, but then gradually decreases. The effect of depth on the size of heat flux is small. The amplitude of variations in the heat flux coming to the building decreases with the depth.

Total heat gains per season rise by about 0.4 MWh (3.6%) per 1 meter of depth of uninsulated floor and by about 0.32 MWh/m (8.0%) for the insulated floor. Unlike the traditional cold store, sinking of the cold storage plant in the ground is unfavorable technically (more earthwork and insulation work necessary, greater weight of construction), but also in terms of energy.

At the beginning of the storage season, maintenance of about 0°C inside the cold store with uninsulated floor requires the use of high-power cold-storage appliances or an adequately earlier cooling of the chambers. In the case of insulated floor, the necessary power of cold-storage plants is about 4 times less and demand for it lasts much longer. Earlier cooling of the chamber may even be unnecessary.

Insulating the floor with foamed polystyrene 10 cm thick reduced total heat gains during the whole cold storage season by as much as about 40%. Consumption of energy per cooling will be accordingly lower.

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