

Numerical Analysis of the Impact of the Cooling Cycle Length in Vegetable Cold Stores on the Heat Exchange with Soil

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ABSTRACT

The paper includes an analysis of the impact of the cooling cycle length in vegetable cold stores on the heat exchange with soil. The scope involves the analysis of indoor and outdoor air temperature as well as soil temperature under the cold store and in its vicinity, specification and adaptation of the cold store-soil heat exchange model, model validation by comparison of the calculation results with experimental studies, choice of calculation variants, calculations for the used variants in non-stationary conditions, and a comparative analysis of the cold store-soil heat exchange for the used variants and of the soil temperature at selected solutions. The paper used the results of the field tests conducted in a vegetable cold store located in southern Poland. The building was used to store carrots from 1 October to 30 June. Four calculation variants were used for the in-depth study of the impact of selected factors on the heat exchange between the cold store and the soil. The calculations were performed based on the elementary balances method, using WUFI®plus software. The calculation model validation was based on the field measurements of indoor and outdoor air temperature as well as soil temperature in 5 measurement lines at the depth of 0.05, 0.50, 1.00 and 1.50 m. The obtained validation results showed a very good correlation between the measured and calculated data, in addition to an absence of significant differences. The calculation results for the 4 calculation variants showed significant differences in the heat exchange with soil.

Keywords: vegetable cold store, heat exchange, technological interruption, soil temperature

INTRODUCTION

The climatic and technological conditions in agricultural production necessitate storing fruit and vegetables for long periods of time. A significant development of the fruit and vegetable storage technology has been observed in recent years (Holsteijn and Kemna 2018, Richter and Bokelmann 2017, Tanner 2016). In order to reduce costs, growers are keener to form producer groups and cooperatives which have a significantly greater production potential than single farms (Nawalany et al. 2017, 2016). Currently, quality seems to be one of the most important criteria during the distribution of fruit and vegetables (Jha et al. 2019, Roupheal et al. 2018, Onwude et al. 2017). The quality of fruit and vegetables depends mainly on the storage conditions and methods (Ambaw et al. 2013, East et al. 2013, Liu et al. 2010).

Depending on the storage period and the type of product, it can be stored in traditional stores or cold stores. The appropriate storage method has a decisive impact on the shelf life of fruit and vegetables (Mazzeo et al. 2015, Jakubowski 2010, 2009, 2008, Łapczyńska-Kordon and Krzysztofik 2008). The basic threat for the product value deterioration is the water loss which causes a subsequent weight loss, and this in turn reduces the resistance to disease (Verboven et al. 2006, Adamicki 1997a, b). In addition to the quantity losses, the nutritional value is also reduced as a result of loss of vitamins (Ambaw et al. 2011, Ciećko 1993).

Depending on the type of stored crops, there are different types of stores and cold stores. Small farms usually have facilities used for most part of the year, with a technological interruption in summer (Chądzyński and Piróg 2013, Chądzyński

2000). The technological interruption is used to prepare the store for the next storage season. One of the tasks performed during such interruption is disinfection of the storage rooms. It should be noted that the storage rooms are kept open throughout the technological interruption. This particularly applies to the soil under the floor, which accumulates heat during high temperatures, and such heat increases the amount of energy used for cooling at the beginning of the storage season. Thus, the following research problem can be formulated: what is the impact of the technological interruption length on the heat exchange with soil?

The subject of heat exchange with soil is well researched. It was studied by, inter alia, Radoń et al. (2014), Nawalany et al. (2017, 2014), Staniec (2009), Martin and Canas (2006), Janssen (2002) and Deru (2001). The problem of soil temperature has been important during the design of heating and cooling facilities in recent years, a fact that has been reflected in studies (Erol and Francois 2018, Zhao 2016, Kupiec et al. 2015, Fidorów and Szulgowska-Zgrzywa 2015, Flaga-Maryanczyk et al. 2014, Bertram 2014). In the case of a vegetable cold store, the soil is a heat receiver during the cooling cycle. During the technological interruption, the soil heats up.

The purpose of the research was to study the heat exchange between the vegetable cold store and the soil for the chosen length variants of the technological interruption.

The scope included an analysis of the indoor and outdoor air temperature as well as soil temperature under the cold store and in its vicinity, specification and adaptation of the cold store-soil heat exchange model, model validation by comparison of the calculation results with experimental studies, choice of calculation variants for various storage cycle lengths, choice of the calculation method and its adaptation (calculation tool adaptation), calculations for the used variants under non-stationary conditions, and a comparative analysis of the cold store-soil heat exchange for the used variants and of the soil temperature at selected variants.

MATERIALS AND METHODS

The field studies were conducted in a vegetable cold store in southern Poland. The store has two cold rooms and a sorting and packing area.

The total surface area of the facility is 232 m², including 58 m² of the sorting and packing area, 96 m² of room A, and 78 m² of room B (Fig. 1). The building has a steel frame structure on a 30-cm wide concrete foundation located 1.0 m below the ground level. The fact that the foundation is not thermally insulated is important for the heat exchange with soil. The room floors are made of 10-cm thick cement screed and feature a 4-cm thick EPS thermal insulation. An organoleptic soil examination showed that the cold store surrounding includes a 40-cm thick humus layer, with a 1.5-m thick layer of silty clay below it. The outside walls and ceiling of the rooms are made of sandwich panels, comprising steel sheets galvanized and painted on both sides and a 15-cm thick EPS core. Polyurethane foam was used at the joints of panels to eliminate thermal bridges.

The storage cycle in the examined facility lasted from 15 October to 30 June, with a technological interruption from 1 July to 30 September. The optimum temperature was kept by a 20 kW refrigerating unit. The dimensions of cold rooms were adapted to multiple box pallets in which the carrots were kept. The distances between the box pallets and walls as well as between the box pallet rows were: 10 cm – 30 cm and 5 cm – 10 cm, respectively.

The field studies were conducted between 1 May 2009 and 30 June 2011. The studies included continuous measurements of the indoor and outdoor air temperature, floor temperature and soil temperature, in 1-hour intervals. The temperature was measured by twenty two APATOR TOP 168 sensors based on a PT100 platinum resistor (0.1 °C measurement resolution, 0.1 °C measurement error). The sensors were connected to an HP 34970A recorder. The measurement results were used to validate the calculation model.

Four calculation variants were used to study the impact of the technological interruption length on the indoor microclimate and the soil temperature under the cold store and in its vicinity: variant I – 3-month technological interruption, variant II – 2-month technological interruption, variant III – 1-month technological interruption, and variant IV – no technological interruption (all-year-long cooling).

The simulations were conducted in WUFI@plus software, which allows for calculating in a non-stationary approach using the method of elementary balances.

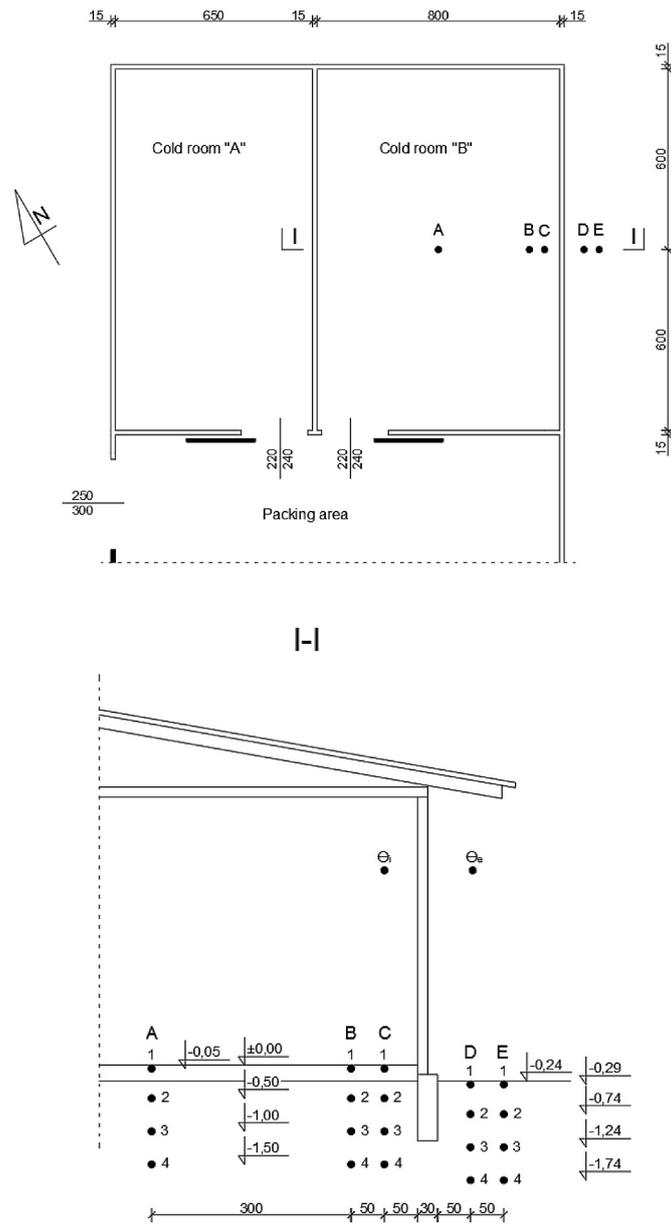


Fig. 1. Location of measurement points in the cold store: a) plan, b) section I-I: A, B, C, D, E – measuring lines, A1-A4, B1-B4, C1-C4, D1-D4, E1-E4 – soil temperature measurement points, Θ_i , Θ_e – air temperature measurement points

Prior to the calculation analysis for the chosen variants, the software had to be validated based on the actual measuring data. The starting point for the model validation was to build a discrete geometrical model divided into balance-differential elements. The model included the measuring points corresponding to their actual location in the field-studied facility (Fig. 2) and featured the same technical parameters of construction materials and soil as in the real facility (Table 1).

In addition, the minimum indoor air temperature used in all variants was $\Theta_{i,\min} = 0^\circ\text{C}$, maximum indoor air temperature $\Theta_{i,\max} = 4^\circ\text{C}$, minimum

indoor air relative humidity $Rh_{i,\min} = 80\%$, maximum indoor air relative humidity $Rh_{i,\max} = 99\%$. The natural air change was assumed at 0.3 h^{-1} and infiltration at 0.2 h^{-1} .

RESULTS AND DISCUSSION

The validation calculations were based on the measured indoor and outdoor temperatures (Fig.3). During the studied period, the indoor air temperature was kept between 0.0°C and 4.0°C . During the technological interruption in July,

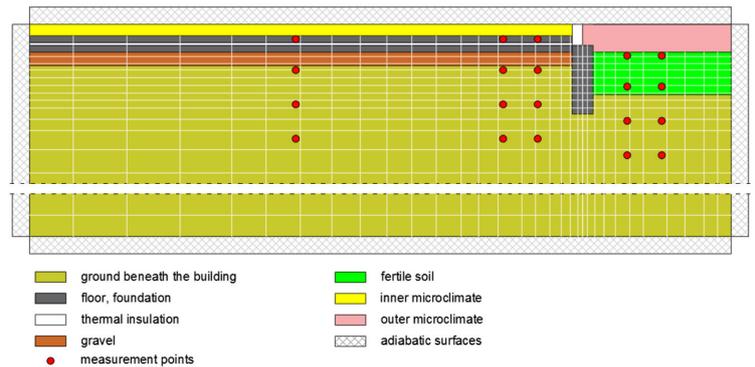


Fig. 2. Section of the modelled facility with the division network and layout of soil temperature calculation points (model from WUFI@plus software)

August, September and the first half of October, the building was not cooled and remained open. The indoor air temperature in that period was in the 6.0–24.5°C range. The outdoor air temperature during the year fluctuated between -15.4°C and 34.6°C.

The floor temperature analysis in point A1 showed 4.2°C on the last day of the cooling period. On the first day of the next cooling cycle, the floor temperature was 11.6°C and decreased gradually. It was determined that in the analysed calculation variant, the time necessary to reduce the floor temperature to the value from the end of the storage period is 18 days.

At points C1, B1 and A1 located in soil under the cold store, the annual soil temperature amplitude was in the 13.9°C – 14.3°C range. A

larger impact of soil on the stabilisation of thermal conditions is visible at the depth of 1.5 m. At the depth of 0.50 m, the annual temperature fluctuations were reduced almost twofold, compared to the depth of 0.05 m. The impact of the cold store on the soil temperature decreases with depth. At the points located in the facility surrounding, the annual soil temperature amplitude varied from 14.5°C (point D2) to 15.1°C (point E2), and at points under the cold store, the amplitude was from 7.5°C (A2), 6.5°C (B2) and 6.6°C in C2 (Fig. 4).

The calculation model was validated based on the temperature measured inside and outside the cold store. In relation to the soil temperature, the measured temperature was a boundary condition of the third kind. The initial soil temperature was

Table 1. Physical parameters of the soil and construction materials used in the calculations

	Specification	Unit	Value
Clay	density	kg·m ⁻³	1600
	specific heat	J·kg ⁻¹ ·K ⁻¹	1000
	thermal conductivity coefficient	W·m ⁻¹ ·K ⁻¹	1.80
Humus	density	kg·m ⁻³	1800
	specific heat	J·kg ⁻¹ ·K ⁻¹	1260
	thermal conductivity coefficient	W·m ⁻¹ ·K ⁻¹	0.90
Eps	density	kg·m ⁻³	20
	specific heat	J·kg ⁻¹ ·K ⁻¹	1500
	thermal conductivity coefficient	W·m ⁻¹ ·K ⁻¹	0.04
Concrete	density	kg·m ⁻³	2300
	specific heat	J·kg ⁻¹ ·K ⁻¹	1000
	thermal conductivity coefficient	W·m ⁻¹ ·K ⁻¹	2.30
Gravel bedding	density	kg·m ⁻³	1800
	specific heat	J·kg ⁻¹ ·K ⁻¹	840
	thermal conductivity coefficient	W·m ⁻¹ ·K ⁻¹	0.90
Steel	density	kg·m ⁻³	7900
	specific heat	J·kg ⁻¹ ·K ⁻¹	460
	thermal conductivity coefficient	W·m ⁻¹ ·K ⁻¹	17.00

Source: based on PN-EN ISO 6946:2008

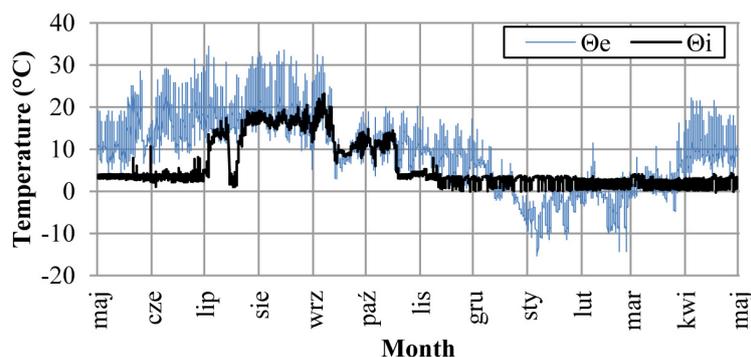


Fig. 3. Outdoor (Θ_e) and indoor (Θ_i) air temperatures from 1 May 2009 to 31 May 2010

assumed at 8.8°C , which corresponds to the average annual outdoor air temperature for Krakow (TRY).

A correlation analysis was performed for the results obtained from all the measuring points, based on the Spearman's Rank Test (the data distribution was not normal). The data distribution normality was previously tested using the Shapiro-Wilk Test. The highest correlation coefficient (0.95 – 0.99) was determined for measuring points E2, E3, E4, D2, D3, D4, C2, C3, C4, B2, B3, B4, and A2, A3 and A4. Consequently, the conformity of calculation and measurement data at the depth of 0.50 m, 1.00 m and 1.50 m can be considered full. In the case of the points E1 and D1, located 0.05 m below the ground level, and A1, B1 and C1, located under the floor, the correlation coefficient was 0.85–0.88, so the conformity of measurement and calculation data should be considered very high (Fig. 5).

It should be emphasized that in winter, the actual soil temperature at the depth of 0.10 m differed from the calculated values by 11.2°C in line E and 11.0°C in line D. The reason was the impossibility to account for the snow cover. The differences occurred, however, only for a short time and were not significant for the entire period of the study. The statistical significance of differences was tested using the Kruskal-Wallis ($p < 0.05$) test.

The analysis of the heat exchange intensity between the indoor air and the soil for **variant 1** showed that the soil share in the total cold store energy balance was 16.6%. The highest energy gains from the soil were found in October (478.5 kWh). As a result of technological interruption in the summer, there was an intensive heat flow to the soil in July (588.1 kWh). The simulation showed that the length of the cooling period during which the indoor air temperature

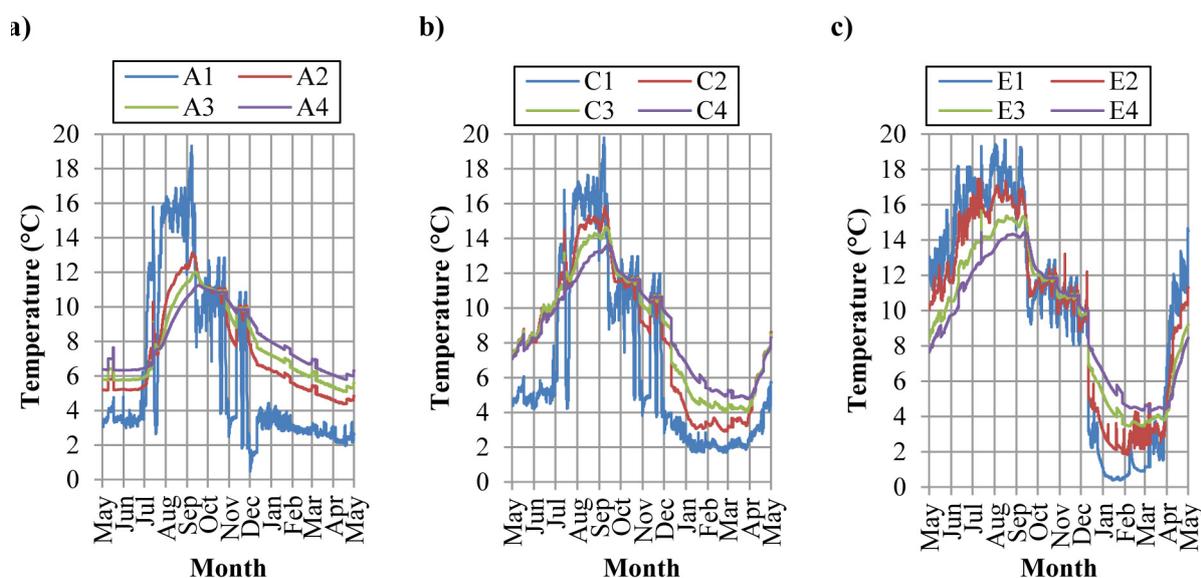


Fig. 4. Measured soil temperatures in lines A, B and E:

a) temperature points A1 – A4, b) points C1 – C4, c) points E1 – E4

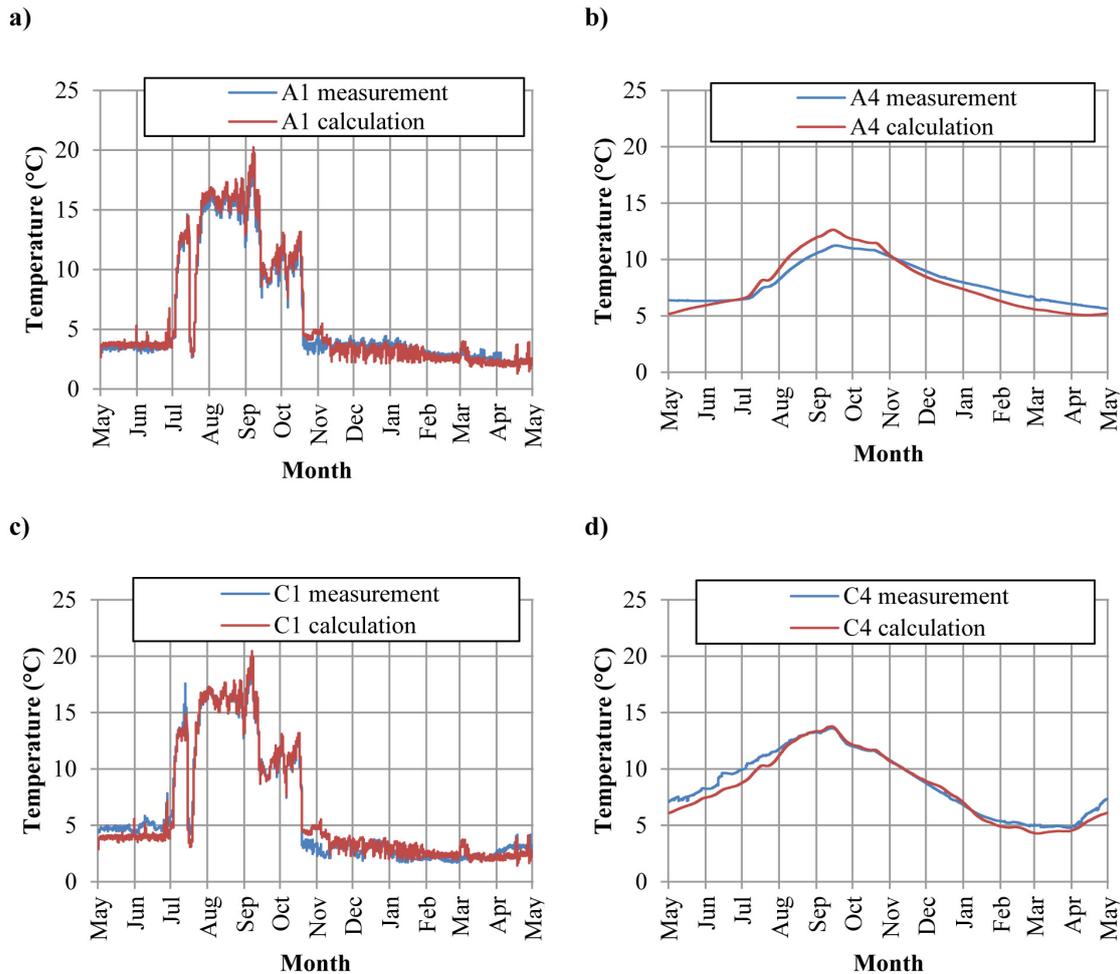


Fig. 5. Calculated and actual soil temperature: a) A1, b) A4, c) C1, d) C4

had to be reduced by a cooler was 155 days, and the period during which the air had to be heated was 27 days. The total energy demand for cooling in variant I was 5141.4 kWh, and for heating 527.2 kWh (Fig. 6a).

VARIANT II included a 2-month technological interruption. The maximum heat gains from soil in this case were 251.6 kWh and occurred in winter. The heat losses to the soil were found during the technological interruption, totalling 783.6 kWh in July and August (Fig. 6b). The soil share in the building energy balance was 6.7%. The simulation showed that 5842 kWh of energy during 183 days of active cooling would be necessary to ensure optimum thermal conditions inside the cold store. The total energy gains from the soil were 1523.5 kWh, and the losses – 1088.5 kWh.

The analysis of the result for a 1-month technological interruption for **variant III** showed an intensive heat outflow from the cold store to soil in July (436.2 kWh). The soil share in the annual cold store energy balance was 10.3%. The total

heat load was 653.6 kWh, and the cooling energy demand was 7649 kWh (Fig. 6c). The calculation results showed a negative balance of the heat flow to the soil in July and March. In the remaining months, the heat flow was from the soil to the cold store.

The absence of technological interruption significantly affected the annual heat exchange with the soil. The analysis results for **variant IV** showed that the soil share in the cold store energy balance was 13%. The indoor air cooling was required for 242 days in this variant. The heating period was 30 days. The cooling energy demand of the cold store was 9307 kWh, and the heating energy demand was 662 kWh (Fig. 6d). The energy gains from the soil were from 44.2 kWh to 236.2 kWh. The maximum heat gain from the soil took place in December, and the greatest heat losses to the soil occurred in February (63.6 kWh).

In the case of the absence of technological interruption, it was determined that the soil temperature under the floor at the depth on 0.50 m

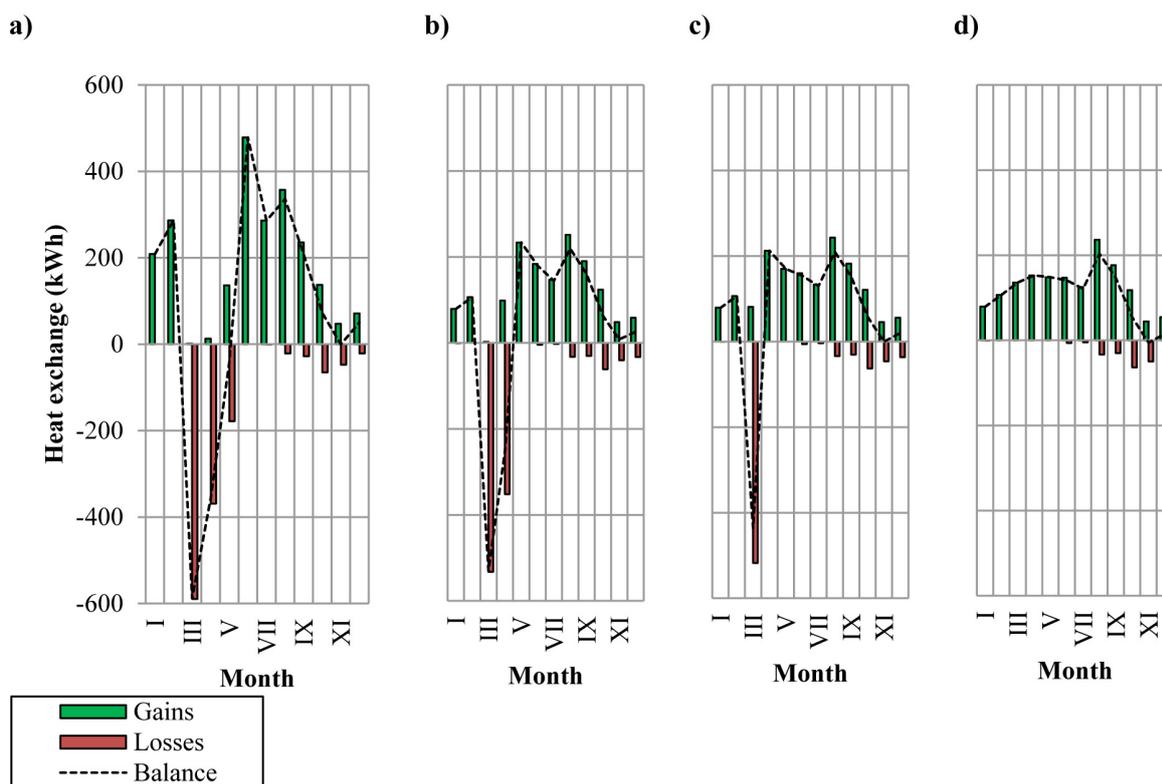


Fig. 6. Heat exchange between the cold store and soil: a) variant I, b) variant II, c) variant III, d) variant IV

on 1 October is 3.2 °C lower compared to the variants with technological interruptions. In the variants with technological interruptions, the soil temperature under the floor was similar to the variants with all-year-long cooling after 80 days from the start of the cooling season.

CONCLUSIONS

The heat exchange between the environment and the soil depends mainly on the soil physical parameters such as thermal conductivity coefficient, heat capacity and density. The size of the building envelopes in contact with the soil or surrounding air is also very important. In single-storey buildings, where the ratio of usable area to the footprint is almost one, the soil share is higher due to a large area of envelopes in contact with the soil. A lower percent soil share in the total energy balance can be observed in multi-storey buildings, with the same thermal insulation parameters.

The calculation model validation was based on the field measurements of the indoor and outdoor air temperature as well as soil temperature in 5 measurement lines at the depth of 0.05, 0.50,

1.00 and 1.50 m. The obtained validation results showed a very positive correlation between the measured and calculated data and an absence of significant differences.

The technological interruption (July-September) reduces the annual cold store energy demand by 4300 kWh, but contributes to a 30 kWh increase of energy demand in the first week of cooling. If the cold store is operated all year long (no technological interruption), the annual cooling energy demand increases more than twofold. The length of technological interruption has no significant effect on the heat exchange with soil. In terms of energy, only the fact of its presence or absence is important in the case of an all-year-long cooling cycle.

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