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DOPRINOS SPREMNIKA TOPLINE URAVNOTEŽENJU I STABILNOSTI GRIJANJA NISKOAKUMULATIVNIH OBJEKATA

CONTRIBUTION OF A HEAT TANK TO BALANCING AND STABILITY OF HEATING LOW-ACCUMULATION OBJECTS

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Izvorni znanstveni članak

Sažetak: *Mala vremenska konstanta i termofizikalna karakteristika niskoakumulativnih objekata izrazito povećavaju osjetljivost unutarnje temperature zraka u zoni uzgoja agro kultura na vanjske, naročito nagle, mikroklimatske promjene. Obrnuto proporcionalna brzina grijanja i hlađenja objekta značajno smanjuje učinkovitost toplifikacijskog sustava i ekonomičnost proizvodnje. Uz prilagođenu softversku podršku provedena su eksperimentalna istraživanja u ograničenom vremenskom intervalu na tri objekta (GH1, GH2 i GH3) na različitim lokacijama te je analiziran i uspoređen utjecaj toplifikacijskog sustava sa i bez spremnika topline na brzinu postizanja srednje dnevne unutarnje temperature zraka pri prosječnim vanjskim mikroklimatskim uvjetima u zimskom periodu i tehnološki najosjetljivijem uzgojnom periodu biljaka. Korištenjem akumulirane toplinske energije iz spremnika topline postižu se za oko 50 % brže srednje vrijednosti dnevne unutarnje temperature zraka od minimalno dopuštene unutarnje temperature zraka. Potrošnja toplinske energije i biomase je za oko 23 % do 28 % veća pri pogonu termoenergetskog postrojenja bez spremnika topline i veće toplinske snage za oko 25 % po jedinici površine grijanog prostora iste namjene. Izravna primjena rezultata provedenih istraživanja doprinosi svrhovitijem dimenzioniranju i oblikovanju akumulacijskih spremnika topline te većoj učinkovitosti i ekonomičnosti toplifikacijskih sustava niskoakumulativnih objekata različitih i strogih tehnoloških zahtjeva.*

Ključne riječi: *niskoakumulativni objekti, akumulacijski spremnik topline, biomasa, unutarnja temperatura zraka, brzina grijanja, stabilnost grijanja.*

Original scientific paper

Abstract: *A low time constant and thermophysical characteristic of low-accumulation objects significantly increases the sensitivity of the inside air temperature in the area of cultivation of agricultural products to external, especially sudden, microclimate changes. Inversely proportional rate of heating and cooling an object considerably reduces the efficiency of the district heating system and the production cost-effectiveness. With custom software support experimental research was conducted in a limited period of time at three objects (GH1, GH2 and GH3) in different locations and the impact of the district heating system on the rate of achieving the mean daily internal air temperature under average external microclimate conditions in the winter period and the technologically most sensitive period for plant cultivation was analyzed and compared with and without a heat tank. By using the accumulated thermal energy from the heat tank, around 50% faster mean values of daily inside air temperature are achieved as compared to the minimally allowed inside air temperature. The consumption of thermal energy and biomass is about 23 % to 28 % higher in the operation of thermal power plants without heat tank, while thermal capacity is about 25 % higher per unit area of the heated area for the same purpose. Direct application of research results contributes to more appropriate sizing and shaping of accumulation heat tanks and a greater efficiency and cost-effectiveness of heat energy systems of low-accumulation objects of various and strict technological requirements.*

Key words: *low-accumulation objects, accumulation heat tank, biomass, internal air temperature, heating rate, heating stability.*

1. INTRODUCTION

Geometrical shape, technical characteristics and construction quality of low-accumulation agrotechnology objects (greenhouses) must be adapted to climate conditions for year-long production at the location where they are constructed. Along with agrotechnology conditions, the rate of achieving and the stability of maintaining a suitable air temperature in the zone of plant cultivation in all of its biological stages directly affect the product quality and the expected yield. Due to strong sensitivity of low-accumulation objects to the changes in outside microclimate conditions, along with maintaining the set inside air temperature, it is not possible to achieve stationary heating under all conditions and carry out an exact thermodynamic calculation. Optimal adjustment of the rate of heating and preventing sudden cooling of a low-accumulation object within a technologically acceptable time interval requires a balance between a low thermophysical characteristic ($\lambda \cdot c \cdot \rho$) of the object and a rational district heating system. Time, cause and frequency of the reduction or discontinuance of heating, thermophysical characteristic of the surface material, windiness, orientation and reflection degree – absorption of external surfaces exposed to solar activity, represent factors that directly affect the thermal reaction of a greenhouse (temporal constant = accumulated heat/heat loss). Temporal constant is very low and significantly affects the efficiency of district heating systems, especially during rapid changes of microclimate conditions at low temperatures of the external air. Additionally, by as much as 10 % – 60 % heat losses increase if the system is exposed to wind, and especially if exposed to rain at the external air temperature between – 2 °C and + 10 °C when higher wind speeds are the most frequent. Due to low temporal constant and thermophysical characteristic of objects, as well as high inertia of the secondary hot-water system, in frequently expressed, sometimes even sudden, changes in microclimate conditions in morning and/or evening hours, greater responsiveness and aptitude of the thermal power plant for achieving, maintaining and stability of different inside air temperatures in the heating zones are required. Slower achieving of the required temperature of the heating medium is more expressed in district heating systems with a large proportion of water amount in the secondary circle as compared to the primary circle, which is a feature of greenhouses with larger and large surfaces for intensive plant growth. Accumulation – compensation heat tank is used for diminishing or removing sudden air temperature changes and maintaining thermal and hydraulic balance between the heat source and the secondary heating circle (consumer) [1, 2, 3, 4].

Experimental research was conducted regarding the influence of the heat tank on the rate of achieving inside air temperature, heating balance and stability, as well as the consumption of drive fuel under variable microclimate conditions in the winter period and technologically most sensitive plant growth period.

2. RESEARCH OBJECT AND METHOD

Research was conducted at three low-accumulation objects (greenhouses) constructed in different regions of the continental part of the Republic of Croatia.

(GH1) P_1 = 10000 m^2, hot-water thermal power plant of thermal capacity Q_1 = 1.5 MW, insulated vertical cylindrical heat tank V_1 = 50000 liters, zone hot-water heating of the cultivation area.

(GH2) P_2 = 5000 m^2, hot-water thermal power plant of thermal capacity Q_2 = 0.7 MW, insulated vertical cylindrical heat tank V_2 = 25000 liters, zone hot-water heating of the cultivation area.

(GH3) P_3 = 5000 m^2, hot-water thermal power plant of thermal capacity Q_3 = 1.0 MW, zone hot-water heating of the cultivation area, without a heat tank.

Drive fuel of each thermal power plant of the installed thermal capacity is biomass – wood chips. Between the primary and secondary heat circle there is a cylindrical heat tank (V_1, V_2), each of a different diameter, height and accumulation heat capacity. Biomass (wood chips) is a mixture of chipped beech and oak wood with granulation up to 5 cm, average moisture 28 % and 35 % and bulk density of around ρ_{bm} = 385 kg/m^3. The average lower heating value of biomass amounted to around H_{d} = 2800 Wh/kg to 3100 Wh/kg. The useful volume of the drive cylindrical biomass container at the thermal power plant GH1 amounts to V_{bm}(GH1) = 40 m^3, thermal power plant GH2 V_{bm}(GH2) = 27 m^3, and thermal power plant GH3 V_{bm}(GH3) = 30 m^3. According to consumption each container was filled with new amounts of biomass within the range of minimal and maximal level inside the container [5, 6]. The product of the useful volume of each container V_{bm} and the number of replenishments n during experimental trials, the consumed amount of biomass was determined for each thermal power plant individually;

$$V_{\mathrm{bm}(1,2,3)} = \frac{D^2_{(1,2,3)} \cdot \pi}{4} \cdot h_{\mathrm{K}(1,2,3)} \cdot n_{(1,2,3)} \quad \mathrm{m}^3 \qquad [1]$$

where at:

D – diameter of cylindrical biomass container, m

h_{K} – useful height of the container ($h_{\max} - h_{\min}$), m.

Biomass mass was determined according to the following expression:

$$m_{\mathrm{bm}(1,2,3)} = \frac{V_{\mathrm{bm}(1,2,3)} \cdot \rho_{\mathrm{bm}}}{1000} \quad \text{tons.} \qquad [2]$$

The objects are used for intensive, year-long tomato cultivation under controlled technological and microclimate conditions with the regime of changing the inside daily air temperature in the zone of plant cultivation $\vartheta_{\mathrm{gh,day}}$ = 20 °C to 24 °C, $\vartheta_{\mathrm{gh,night}}$ = 16 °C to 18 °C. The automated regulation and control system continually and with variable work mode maintained the set values of technological and microclimate parameters in the objects, which was connected with drive devices of thermotechnical and technological installations and facilities.

The ratio of the heating medium mass within a hot-water system between the primary and the secondary circle (without the heat tank) amounted to around 1 : (15 – 18). Experimental trials were conducted in the winter period from 20th January to 20th February 2014. In this period thermal load is usually the greatest, and technological conditions of plant growth and development are very strict. The trial equipment for testing influential parameters included: measurement probes and additional instruments, collection and communication assembly, suitable wiring, central system for receiving and processing measurement signals and practical measurements and notes made by operators at each facility and thermotechnical system. Six temperature sensors distributed inside the greenhouse were used for measuring the inside air temperature ϑ_{gh} at the height 0.6 – 1.0 m above the cultivation surface, while outside microclimate changes were recorded by an internal meteorological station of each object GH1, GH2 and GH3 (outside air temperature ϑ_o, relative air humidity φ_o, wind speed w). The block diagram of the district heating systems (GH1, GH2, GH3) is shown in Figure 1. Measurement locations were selected in the way that allows as precise monitoring of status and changes of influential parameters during trial measurements as possible.

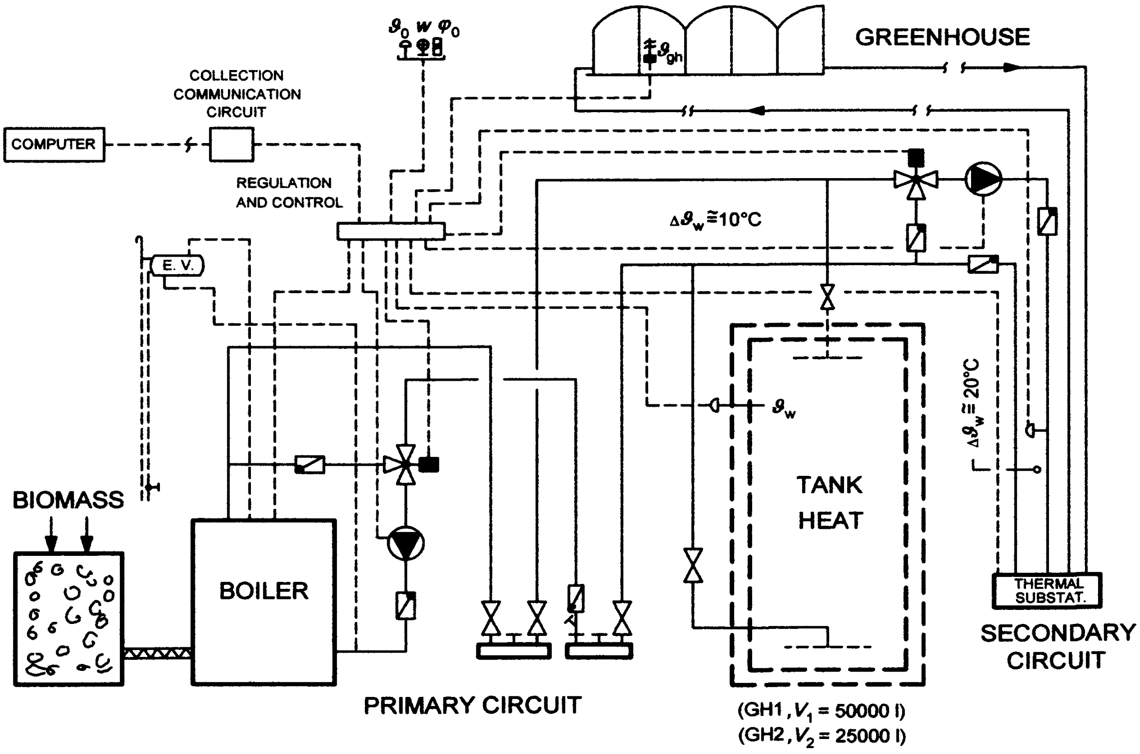

Figure 1. District heating system (GH1, GH2, GH3)

The day interval of maintaining the inside air temperature was between 07:00 to 17:00 o'clock, while the night interval was between 17:00 to 07:00 o'clock on the following day. The recorded measuring of inside and outside air temperature was carried out in the day mode at 08:00, 12:00, 14:00 and 16:00 o'clock, and in the night mode at 17:00, 19:00, 21:00, 23:00, 01:00, 03:00, 05:00 and 07:00 o'clock. Mean day and night temperatures of inside and outside air were determined as arithmetic mean values of measured data according to the following relations:

- Mean outside day air temperature

$$\vartheta_{\mathrm{o,day}} = \frac{\sum_{i=1}^{N} \vartheta_{\mathrm{o,i}}}{N} \quad °\mathrm{C}, \quad N = 5 \qquad [3]$$

- Mean outside night air temperature

$$\vartheta_{\mathrm{o,night}} = \frac{\sum_{i=1}^{N_1} \vartheta_{\mathrm{o,i}}}{N_1} \quad °\mathrm{C}, \quad N_1 = 7 \qquad [4]$$

- Mean inside day air temperature

$$\vartheta_{\mathrm{gh,day}} = \frac{\sum_{i=1}^{N} \vartheta_{\mathrm{gh,i}}}{N} \quad °\mathrm{C}, \quad N = 5 \qquad [5]$$

- Mean inside night air temperature

$$\vartheta_{\mathrm{gh,night}} = \frac{\sum_{i=1}^{N_1} \vartheta_{\mathrm{gh,i}}}{N_1} \quad °\mathrm{C}, \quad N_1 = 7\,. \qquad [6]$$

The reduction of heating intensity or switching off the thermal power plant is carried out during the day when it is allowed by microclimate conditions at a certain location, often accompanied by a somewhat higher air temperature, clear atmosphere and expressed insolation.

Characteristic time intervals of reducing thermal needs and smaller heat losses at objects are between 11:00 and 15:00 o'clock. According to technological conditions in the defined vegetative plant stage and slower heat loss from the object, the allowed drop of the inside air temperature reached the values between $\vartheta_{gh,min}$ = 17 °C to 18 °C, which is the limit value for switching on the district heating system and increasing and maintaining the operative air temperature in the zone of plant cultivation ϑ_{gh}. For objects GH1, GH2 and GH3 measurements were carried out regarding the rate at which the district heating system affects the achieving of the inside air temperature ϑ_{gh} under similar microclimate conditions at different locations of the constructed objects.

3. MEASUREMENT RESULTS

The trends and changes of the outside mean air temperature values ϑ_o during day and night in the time interval in which trials were carried out are shown in Figure 2 during district heating of low-accumulation objects (greenhouses) GH1, GH2 and GH3 constructed at different locations in the continental part of the Republic of Croatia. In the same time intervals the trends of the inside air temperature ϑ_{gh} was measured and recorded in the zone of plant cultivation at objects GH1, GH2 and GH3. Its values for day and night work modes are shown in Figure 3.

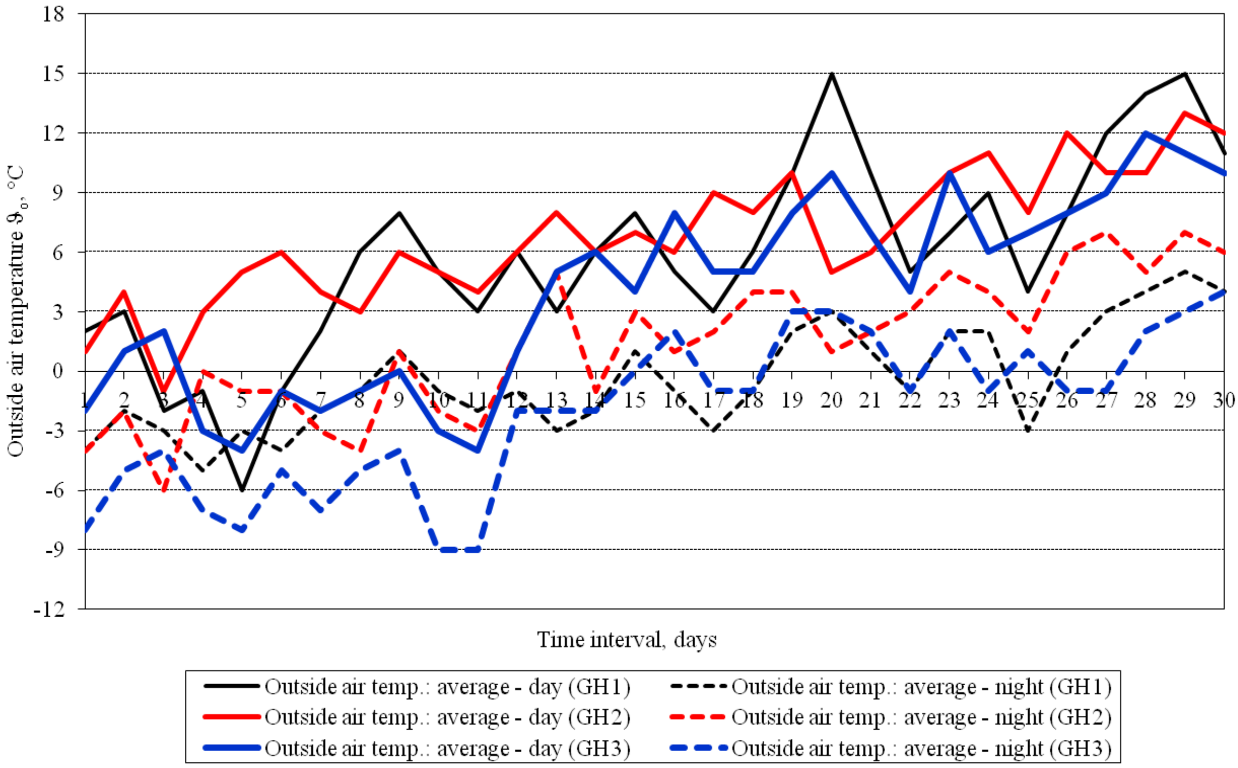

Figure 2. Mean values of outside air temperature (day, night) in the test interval

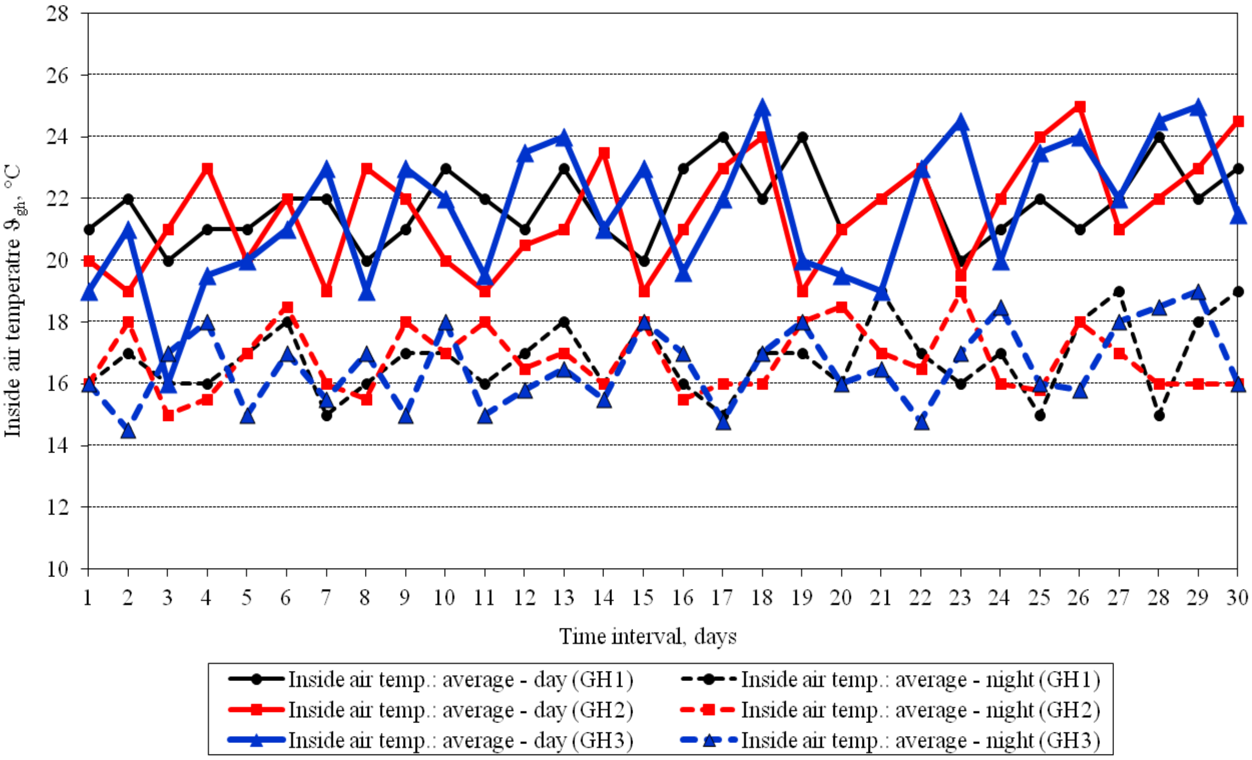

Figure 3. Mean values of inside air temperature (day, night) in the test interval

Under favorable microclimate conditions during the ten day time intervals, heating intensity was reduced or the thermal power plant was switched off, which in practical technical and technological conditions contributes to energy saving without lowering the quality of intensive plant growth. The maximal difference of inside air temperature $\Delta\vartheta_{gh}$ between the technologically conditioned day value and the minimally allowed values amounted to 3 °C to 6 °C, usually 5 °C to 6 °C. The average time $t_{H,av}$ of achieving the inside air temperature in the plant grwoth zone from the minimally allowed temperature $\vartheta_{gh,min}$ to the set day value of inside temperature $\vartheta_{gh,day}$ is shown in Table 1.

Table 1. Values of experimental trial parameters

Object	Trial	$\vartheta_{gh,day}$, °C	$\vartheta_{gh,min}$, °C	$\Delta\vartheta_{gh}$, °C	ϑ_o, °C	$t_{H,av}$, min	$t_{H,av}/\Delta\vartheta_{gh}$, min/°C	District heating system
GH1	1	22	18	4	-1	32	8	P_1 = 10000 m^2, Q_1 = 1.5 MW, V_1 = 50000 liters, zone hot-water heating of the cultivation area.
	2	23	18	5	5	20	4	
	3	23	18	5	3	27	5.4	
	4	23	18	5	5	18	3.6	
	5	24	19	5	3	30	6	
	6	24	19	5	10	14	2.8	
	7	23	18	5	5	17	3.4	
	8	21	18	3	9	13	4.33	
	9	24	19	5	14	12	2.4	
	10	22	18	4	15	12	3	
GH2	1	23	17	6	3	31	5.16	P_2 = 5000 m^2, Q_2 = 0.7 MW, V_2 = 25000 liters, zone hot-water heating of the cultivation area.
	2	23	17	6	3	30	5	
	3	23.5	17.5	6	6	24	4	
	4	23	17	6	9	20	3.33	
	5	24	18	6	8	23	3.83	
	6	22	17	5	10	18	3.6	
	7	24	18	6	8	21	3.5	
	8	25	19	6	12	17	2.83	
	9	23	18	5	15	15	3	
	10	24.5	18.5	6	12	18	3	
GH3	1	21	18	3	1	38	12.66	P_3 = 5000 m^2, Q_3 = 1.0 MW, without a tank, zone hot-water heating of the cultivation area.
	2	23	18	5	-2	68	13.6	
	3	23	18	5	0	48	9.6	
	4	23.5	18.5	5	1	55	11	
	5	24	18	6	5	48	8	
	6	25	19	6	5	43	7.2	
	7	24.5	18.5	6	10	37	6.16	
	8	24.5	18.5	6	7	42	7	
	9	24	18	6	8	35	5.83	
	10	25	19	6	11	24	4	

4. ANALYSIS OF RESULTS

Under similar microclimate conditions during time intervals of trials, the mean outside day air temperature was usually between 0 °C and 8 °C with maximal oscillation in some intervals from – 6 °C to 15 °C. In the same time intervals the mean night temperature of outside air was usually between – 3 °C and 3 °C, while in some intervals it was around– 9 °C i.e. 6 °C, Figure 2. At the same time, in the plant cultivation zone the mean day temperature of inside air was within the technologically allowed limits from 18 °C to 24 °C, and the mean night temperature of inside air was between 15 °C and 18 °C, Figure 3.

Within the ten time intervals at higher day temperature, clear atmosphere and expressed insolation heat losses at objects were reduced and the reduction of the inside air temperature was slowed down to the minimally allowed limit. For each low-accumulation object the following was measured: time $t_{H,av}$ of achieving the mean day inside air temperature $\vartheta_{gh,day}$ from the minimally allowed value $\vartheta_{gh,min}$, which affects the technological growth parameters, efficiency and cost-effectiveness of the district heating system. The time required for achieving the inside air temperature at objects GH1, GH2 and GH3 in the intervals of switching on the district heating system is shown in Figure 4.

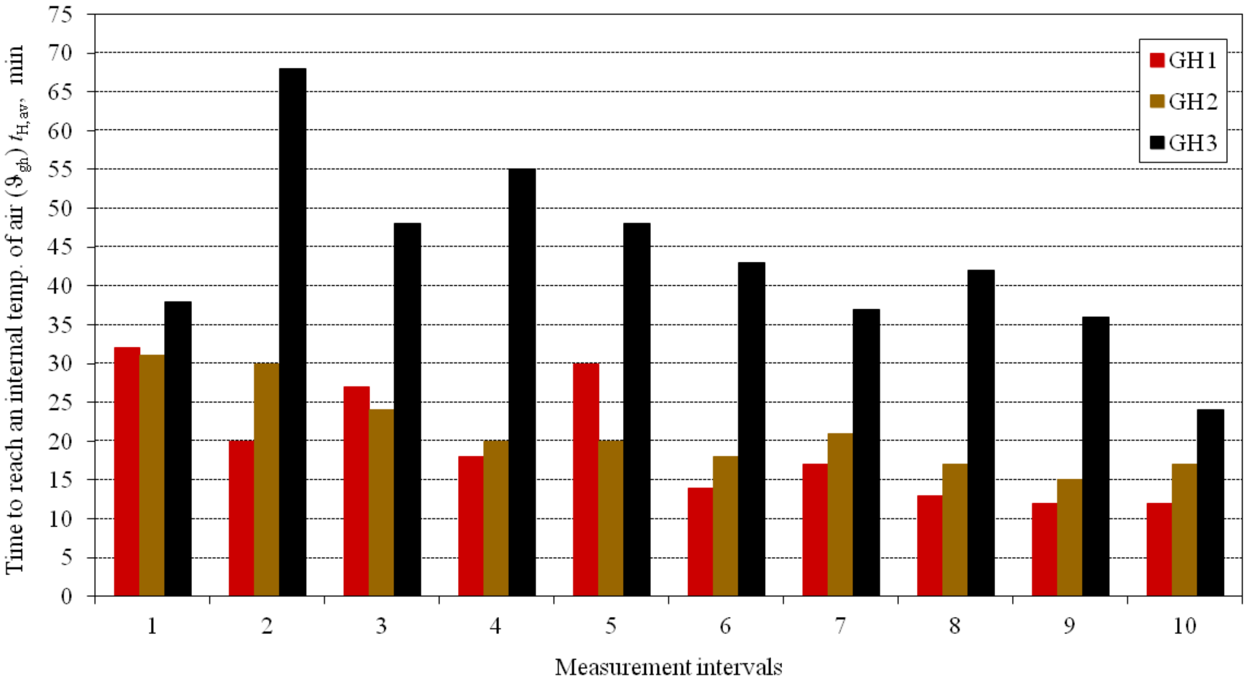

Figure 4. Time required for achieving the mean day inside air temperature $\vartheta_{\text{gh,day}}$ ($\Delta\vartheta = \vartheta_{\text{gh,day}} - \vartheta_{\text{gh,min}}$)

By switching on a thermal power plant with an accumulation heat tank (GH1 and GH2) it is possible to achieve the mean day inside air temperature significantly faster as compared to a thermal power plant without a heat tank (GH3), with lower consumption of biomass (wood chips) per unit of the heated area surface. In average, the time required for achieving the mean inside day air temperature $\vartheta_{\text{gh,day}}$ is around 50 % shorter when using a heat tank as compared to a district heating system without one. By lowering the average outside air temperature, the influence of the heat tank on the duration of achieving the mean inside day air temperature is more expressed (Figure 5) and it contributes to a more precise sustainability of technological conditions and higher efficiency and stability of district heating systems and the low-accumulation object.

The determined consumption of biomass (wood chips) and the calculated consumption of thermal energy in the intervals of test measurements are shown in Table 2.

Thermal power plant without a heat tank (GH3) has approximately 25 % higher nominal heat capacity as compared to the thermal power plants of objects GH1 and GH2. The consumption of biomass (wood chips) and thermal energy per unit of the heated area surface is by around 23 % to 28 % greater as compared to thermal power plants with a heat tank, which affects the cost-effectiveness of the technological process and the efficiency of the district heating system.

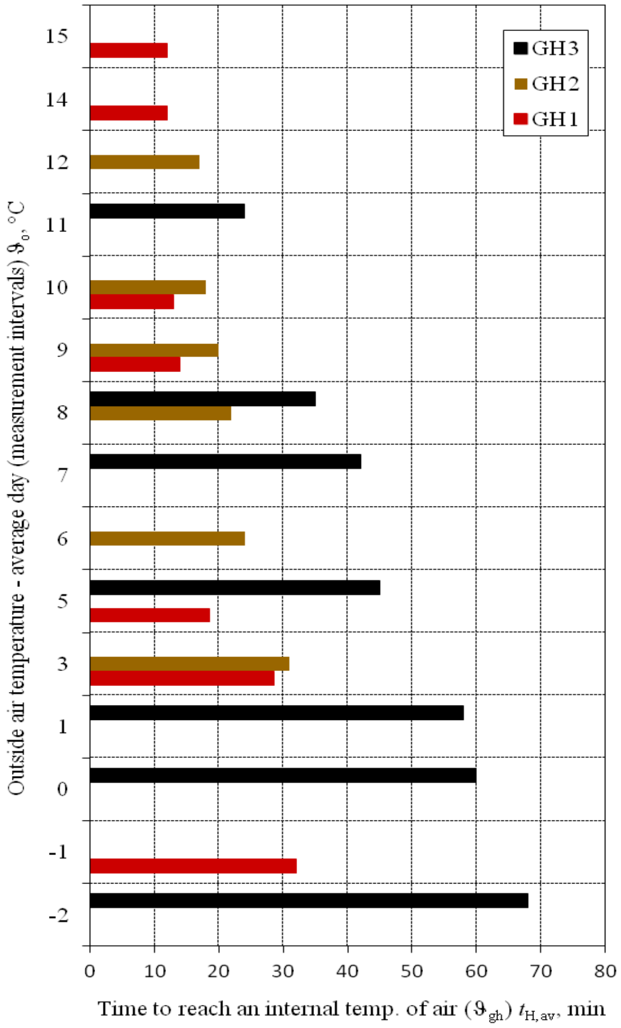

Figure 5. Time required for achieving the mean day inside air temperature $\vartheta_{\text{gh,day}}$ at different mean day outside air temperature

Table 2. Biomass consumption and thermotechnical parameters

Low-accum. object	GH1 (10000 m^2)	GH2 (5000 m^2)	GH3 (5000 m^2)
Consumed biomass m_{bm}, t	212	124	142
Unit biomass m_{bm}/m^2, kg/m^2	21.2	24.8	28.4
Unit nominal thermal load q, W/m^2	150	140	200
Nominal heat capacity Q, kW	1500	700	1000
Consumed thermal energy Q_1, MWh	540.6	323	392
Actual heat loss q_1, W/m^2	75	89.8	109

5. CONCLUSION

Heat tank significantly contributes to the stability and efficiency of low-accumulation objects with discontinued thermal loads during the heating season in the intensive production of agricultural products. Trials were conducted within a limited time interval at three objects (GH1, GH2 and GH3) under similar microclimate and technological conditions at different locations for the purpose of analyzing and comparing the influence of a district heating system with and without a heat tank on the rate of achieving the mean day inside air temperature under average microclimate conditions in the winter period. There is a significant contribution of the heat tank to a lower consumption of thermal energy and drive fuel (wood chips), higher efficiency and stability of the district heating system within zone heating of low-accumulation objects of low thermophysical characteristic and temporal constant. Usage of accumulated thermal energy from the heat tank allows for achieving around 50 % faster mean values of day inside air temperature as compared to the minimally allowed air temperature. The consumption of thermal energy and biomass is around 23 % to 28 % greater at thermal power plants without a heat tank, while the heat capacity is around 25 % higher per surface unit of heated area used for the same purpose. By reducing the outside air temperature the accumulation aptitude of the heat tank increases the efficiency and stability of the district heating system, especially when the thermal power plant used biomass – wood chips of variable quality and heating value as the drive fuel. By additional numerical simulation and software adjustments, the results of trial measurements may contribute to optimal geometrical and thermal sizing of the heat tank with a direct application in rational design and greater efficiency and cost-effectiveness of thermal power plants and district heating systems.

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