Influence of the new generation heating system on the greenhouse heat balance.

Greenhouse production carried out in a closed cycle requires a significant amount of heat. Many authors state that, depending on the type of the crop being cultivated, the share of heat in the structure of production inputs may exceed 50%. Hence, a lot of attention is paid to this issue. The new generation heating elements introduced to the greenhouse market several years ago meet a number of expectations, both in terms of energy as well as health and quality effects. Heating elements with a star cross-section called the "Walczak" pipe have a number of positive features. They are characterized primarily by a small water capacity which makes the control easier and contributes to heat savings because they allow quick adaptation of the heating system to external conditions and allow maintaining optimal microclimatic conditions having a decisive impact on the quantity and quality of production. In addition to the mentioned above features, they have even a few times less heat capacity of the greenhouse heating comosition. Moreover, the "Walczak" pipes have a different temperature on the surface of the heating element, which allows for changing the form of heat transfer to the cultivated plants (share of radiation and convection). The form of energy transfer has an impact on the growth and physiological status of plants and their health (reduction of fungi growth - higher temperature of plants in relation to the environment). The microclimate, which is a derivative of the heating system, has a huge impact on production efficiency. Maintaining the right conditions in a greenhouse, especially in the morning and evening hours means both, energy saving and meeting growing conditions. The heating installation made of "Walczak" pipes meets many of the above-mentioned expectations, also it was noted during the preliminary tests, it fits well in air drying systems and in heat recovery and management systems, therefore it fits into the energy-saving systems of the economy.

Comparison of the basic parameters of the φ 51 pipe with a round shape and an asterisk

Table 1. Parameters of a round tube and star shape size φ 51 mm

L.p	Parameter	Round shape	Star shape
1.	External diameter [mm]	51	Around the outer contour. 48
2.	Wall thickness [mm]	2,2	2,2
3.	External surface 1 rm. [cm^2]	1616,7	1728,0
4.	Own mass 1 rm. [kg]	2,65	2,80
5.	Water capacity 1 rm. [dm^3]	1,76	0,84
6.	Weight 1 rm. heating tube filled with water at temperature 30°C [kg]	4,41	3,63
7.	Equation describing heating efficiency as a function of temperature difference dT [W/m]	$y=2{,}08\cdot dT-6{,}2$	$y=2{,}16\cdot dT-5{,}5$
8.	Heating capacity 1rm heating element at 50/20 °C [W/m]	56,2	59,3
9.	Cross-section area [cm^2]	20,43	11,42
10.	Internal cross-section area [cm^2]	17,64	8,63
I. Endurance parameters			
I.1	Moment of inertness I_x, I_y [mm^4]	$I_{x,y}$ = 66315,74	I_x = 51241,45 I_y = 51241,45
I.2	Cross-section strength index for bending W_x, W_y [mm^3]	$W^{x,y}$ = 2764,55	W_x = 2394,46 W_y = 2135,06
I.3	The equivalent diameter [mm]	-	35,65
II. Change of parameters of the heating element			
II.1	Change in water capacity 1rm. [%]	100	49
II.2	Change in weight 1rm [%]	100	82
II.3	Change of the cross-section area [%]	100	56
II.4	Change of the internal cross-section area [%]	100	49
II.5	Change in moment of inertness I_x, I_y [%]	100	77
II.6	Change of cross-section strength index for bending W_x, W_y [%]	100 100	W_x – 87 W_y – 77
II.7	Reduction of the water capacity of 1rm heating element [dm^3]	–	0,9
II.8	Weight reduction 1rm [kg]	–	0,78
II.9	Reduction of the cross-section area [cm^2]	–	9,1
II.10	Reduction of the internal cross-section [cm^2]	–	9,1
II.1	Reduction of heat capacity 1rm [kJ/K]	–	3,8

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II.12	Reduction of thermal efficiency [%]	−	no change
III. Changing the exploitation parameters of the lower and upper heating system in the greenhouse in relation to 1 ha, with the installation consisting of 1.28 rm. bottom heating and 0.96mb heating of the upper pipe φ 51 per m2 of surface under glass.			
III.1	Reduction of the water capacity of the lower and upper heating systems respectively [m^3]	−	20,5 (11,52/8,96)
III.2	Reduction of the load on the bearing structure of the lower and upper heating systems, respectively [kN]	−	200 (112,45/87,46)
III.3	Reduction of the heat capacity of the lower and upper heating systems, respectively [MJ/K]	−	85,1 (48,6/36,5)
III.4	Heat loss when stopping the lower and upper heating systems, respectively, at a temperature 45^{O}C [MJ]	−	2298 (1313/985)
III.5	Gross heat loss when stopping the lower and upper heating systems, respectively, at a temperature [MJ]	−	3283 (1876/1407)
III.6	Heat loss calculated on coal with calorific value 21 MJ [kg]	−	157 (90/67)
III.7	Heat loss calculated on natural gas GZ50 at heat conversion with efficiency 0,85% [m^3]	−	75 (43/32)

Explanations for table 1:

In tab. 1, 2, 3, 4 are presented the basic thermal-geometric parameters of which values differ slightly in the analysis of selected heating elements. The "Walczak" pipe is made of a round pipe Ø 55, and the comparative pipe with a circular cross-section has a nominal dimension of 51 mm and is a standard element heating in a greenhouse. Hence, weight and external surface of heat exchange differ slightly. Position 1 is the nominal size which is significantly smaller for the "Walczak" pipe. In positions 5 and 6, the values of hydraulic parameters related to the water capacity of the pipes are included. The water capacity of the Walczak pipe in question is 2.04 times smaller than the round pipe. With a reduced water capacity, no changes in heating capacity were detected, as described in positions 7 and 8 respectively. For example, heating capacity 1 rm. assuming the temperature difference between the medium and the environment of 50/20 ^{O}C is at the level of 60 [W / m], while for the "Walczak" pipe it is slightly higher - by 6% - due to the larger surface area. Significant differences occur in the cross-section area, which around the outer contour is less than 2 times smaller (item 9), while on the inside the area is less than 2.04 times smaller.

A smaller surface area in the cross-section implies lower endurance indicators, i.e. moment of innerness (item I.1) and cross-section strength index for bending (item I.2). The decrease of these ratios is presented in items II.5 and II.6, respectively, which range from 77% to 87%. In items II.1 to II.4, a percentage comparison is made between the basic parameters of ‘’Walczak” pipe and the round pipe. All the comparisons show the benefits of the "Walczak" pipe, the most important is the change in the internal cross-section area (item II.4), which implies a change in the water capacity to 49% (item II.1). Changes of few parameters entail a quantitative reduction of many others parameters that have been set in items II.7 to II.11. The most important feature for thermal reasons is a reduction in thermal capacity of 1rm. by 3.8 kJ / K, in the context of controlling the heating system. Of course, it is not insignificant to reduce the weight of the elements as that may impact with the lower load on the bearing structure of the heating system.

The most important thermal and operational features of the “Walczak” pipe are contained in part III, in which the comparison of the parameters of the lower and upper heating system in the greenhouse is presented in relation to 1 ha, with the installation of bottom (1,28 rm) and upper (0.96rb) heating on 1 m^2 of area under glass (pipes φ 51). The savings resulting from the smaller unit water capacity are significant. The capacity of the heating system smaller by 20.5 m^3 (item III.1), will highly reduce the load on the bearing structure of the heating system - in total over 200 kN (item III.2). However, the most important are the energy effects resulting from the reduction of the total thermal capacity by 85.1 [MJ / K] per 1ha (item III.3), which allow to save original energy by 3283 MJ (item III.5). If converted to coal with a calorific value of 21 MJ that gives around 156 [kg] (item III.6), or if converted to GZ50 it gives over 67 m^3 – the results are only during one stop of the heating circuit when the solar conditions change rapidly and there is a need to open the ventilators.

Comparison of basic parameters of the φ 40 pipe with a round shape and an asterisk

Table 2: Parameters of a round tube and star shape size φ 40 mm

L.p	Parameter	Round shape	Star shape
1.	External diameter [mm]	40	Around the outer contour. 34
2.	Wall thickness [mm]	1,6	1,6
3.	External surface 1 rm. [cm^2]	1256,6	1256,6
4.	Own mass 1 rm. [kg]	1,52	1,52
5.	Water capacity 1 rm. [dm^3]	1,064	0,528
6.	Weight 1 rm. heating tube filled with water at temperature 30^{O}C [kg]	2,58	2,05
7.	Equation describing heating efficiency as a function of temperature difference dT [W/m]	$y=1{,}26\cdot dT-5{,}4$	$y=1{,}3\cdot dT-5{,}2$
8.	Heating capacity 1rm heating element at 50/20 ^{O}C [W/m]	32,5	33,9
9.	Cross-section area [cm^2]	12,56	7,21
10.	Internal cross-section area [cm^2]	10,64	5,27
I. Endurance parameters			
I.1	Moment of inertness I_x, I_y [mm^4]	$I_{x,y}$ = 33405	I_x = 13290,84 I_y = 13290,84
I.2	Cross-section strength index for bending W_x, W_y [mm^3]	$W_{x,y}$ = 2765	W_x = 863,6 W_y = 770,5
I.3	The equivalent diameter [mm]	-	30,2
II. Change of parameters of the heating element			
II.1	Change in water capacity 1rm. [%]	100	50
II.2	Change in weight 1rm [%]	100	79
II.3	Change of the cross-section area [%]	100	57
II.4	Change of the internal cross-section area [%]	100	50
II.5	Change in moment of inertness I_x, I_y [%]	100	40
II.6	Change of cross-section strength index for bending W_x, W_y [%]	100 100	W_x – 48 W_y – 43
II.7	Reduction of the water capacity of 1rm heating element [dm^3]	–	0,536
II.8	Weight reduction 1rm [kg]	–	0,53
II.9	Reduction of the cross-section area [cm^2]	–	5,36
II.10	Reduction of the internal cross-section [cm^2]	–	5,37
II.11	Reduction of heat capacity 1rm [kJ/K]	–	2,24

II.12	Reduction of thermal efficiency [%]	−	no change
III. Change in the parameters of the vegetative heating system in the greenhouse in relation to 1 ha, assuming 2.52rm. φ 40 pipes per 1 m^2 of area under glass.			
III.1	Reduction of the water capacity [m^3]	−	13,5
III.2	Reduction of the load on the bearing structure of the heating system [kN]	−	131
III.3	Reduction of the heat capacity [MJ/K]	−	56,5
III.4	Heat loss when stopping the heating system, at a temperature 45^{O}C [MJ]	−	1690
III.5	Gross heat loss when stopping the heating system, at a temperature 45^{O}C [MJ]	−	2450
III.6	Heat loss calculated on coal with calorific value 21 MJ [kg]	−	117
III.7	Heat loss calculated on natural gas GZ50 at heat conversion with efficiency 0,95% [m^3]	−	55

Explanations for table 2:

Similarly as for the pipe φ51 (table 1), the parameters were compared for the system with use of the "Walczak" pipe φ40 – those are summarized in table 2. Correspondingly in positions I, 2, 3, 4 (Table 2) contains the basic thermal and geometric parameters whose values do not differ in the analysis of selected heating elements (the star shape of the “Walczak” pipe and circular pipe) such as wall thickness, own mass and external surface (surface of the heat exchange). Position 1 is the nominal size which is significantly smaller in the case of the "Walczak" pipe (40mm / 35mm). In positions 5 and 6, the values of hydraulic parameters relating to the water capacity of the pipes have been included. The water capacity of the tested "Walczak" pipe is 2 times smaller than the round pipe. With a reduced water capacity, no changes in heating capacity were detected, as described in positions 7 and 8 respectively. For example, heating capacity 1rm. assuming a temperature difference between the medium and the environment of 50/20 ^{O}C, it is around 34 [W / m], however, for the “Walczak” pipe is slightly higher (about 4%), which may be within the error limits. Significant differences occur in the cross-section area, for the "Walczak" pipe- at the inner side- the cross-section area is twice smaller (item 10).

A smaller surface area in the cross-section implies lower endurance indicators, i.e. moment of inertness (item I.1) and cross-section strength index for bending (item I.2). The decrease of these ratios is presented in items II.5 and II.6, respectively, which range from 40% to 45%. Smaller values of these indicators do not affect the usefulness of this element in the heating system. In items II.1 to II.4, a percentage comparison is made between the basic parameters of both pipes. All the comparisons show the benefits of the "Walczak" pipe, the most important is the change in the internal cross-section area (item II.4), which implies a change in water capacity to 50% (item II.1). Changes in these parameters entail the reduction of many others parameters - that have been set in items II.7 to II.11. The most important for thermal reasons is a reduction in thermal capacity of 1rm. about 2.24 kJ / K (item II.11), in the context of controlling the heating system. Of course, it is not insignificant to reduce the weight, which may impact with the lower load on the bearing structure of the heating system as well as the greenhouse construction.

The most important thermal and operational features of the “Walczak” pipe are contained in part III, in which a comparison of greenhouse heating system parameters is presented in relation to 1 ha, assuming 2.52 rm. φ 51 pipe per m^2 area under glass. The savings resulting from the smaller unit water capacity are significant. The capacity of the vegetation heating system smaller by 13.5 m^3 (item III.1), will reduce the load on the bearing structure of the greenhouse by 131 kN per ha (item III.2). However, the most important are the energy effects resulting from the reduction of the total thermal capacity by 56,5 [MJ / K] per 1ha (item III.3), which allow to save original energy by 2450 MJ (item III.5). If converted to coal with a calorific value of 21 MJ that gives around 117 [kg] (item III.6), or if converted to GZ50 it gives over 55 m^3 – the results are only during one stop of the heating circuit when the solar conditions change rapidly and there is a need to open the ventilators.

Cnclusions

The presented effects resulting from the use of "Walczak" pipes in greenhouse heating systems, both, in the description and their quantitative characteristics contained in Tables 1 and 2 are summing up. Such operational and energy effects include:

1. Reduction of heat consumption in production under covers.

2. Decreasing the water capacity of the heating system.

3. Reducing the load on the greenhouse construction.

The most important effect of using “Walczak” pipes is to reduce the heat consumption in crop production under covers, which is directly related to the reduction of production costs as currently energy accounts for around 50% of these costs. This raises the question: *How the shape of the cross-section of heating elements can reduce heat consumption?* The answer can be included in one sentence - *Thanks to the reduced thermal capacity of individual heating elements in a greenhouse heating system*. The reduction of the thermal capacity of the heating system for the tested pipes is 50%. However, this does not fully explain the heat saving mechanism itself.

Biological and technical factors determine the effects of production under cover. Technical factors play an important role, their impact and settings should enable the growth, yielding and quality of cultivated plants. The construction, technical equipment of the greenhouse and the microclimate determine the production and economic effects. Temperature, humidity, light and air composition in the greenhouse system should meet the requirements of cultivated plants. Particularly important parameters in the cultivation of, for example, greenhouse tomato, are temperature and humidity, which are interrelated. Hence, very important moments in cultivation under cover are periods of significant changes in solar radiation, i.e. the amount of energy reaching the reception area. The first such critical moment is the sunrise, of course known in term of time but not known in term of energetic. After the night when the greenhouse is chilled (fruit and plants), but before sunrise, the heating should be turned on to preheat the plants and fruits, to a temperature which allow to prevent the condensation of water vapor at the moment, when the greenhouse effect appears. The occurrence of water vapor condensation is very harmful for both plants and fruit (often cause to the destruction of cultivated plants by diseases). This is why, before the sunrise, the greenhouse should be heated, even if after the sunrise (the appearance of the greenhouse effect) it will be needed to ventilate the greenhouse, in order to lower or keep the set up temperature. In this case, the large heat capacity of the heating system is harmful because we need to lose by ventilation the collected heat. Another daily phenomenon - a unfavorable from the energy point of view - is the so-called "Pranight" consisting in a rapid cooling of the greenhouse after a temperature peak, so that the plant will retain its food in fruits (tomato cultivation). The effect of rapid cooling is beneficial for the growth of fruit and its quality, but it is disadvantageous energetically because cooling down to the night temperature is again carried out by ventilation. This is another moment when heat capacity is harmful. Each reduction in thermal capacity allows for reduced heat losses in such moments, (the best solution is the zero heat capacity of the heating system). The next moment in which heat capacity is harmful and contributes to heat loss is a sudden change in solar radiation from a low order of 100 ÷ 300 W / m2 to a relatively high 500 ÷ 900 W / m2, that forces the control system to stop heating and turn on the ventilation to keep a constant set up of temperature optimal for plant growth. The described phenomena of heat loss resulting from the capacity of the heating system obviously occur on days characterized by high dynamics, i.e. transient cloudiness. It may occur several times a day, but may also not take place over a few cloudy or sunny days. This can only be described by probability by estimating that such phenomena will appear with a frequency no greater than 1 to 2 times a day. At the same time, it should be noted that the intensity of unfavorable moments when we lose heat due to the harmful heat capacity of the greenhouse heating system is the highest during early spring, spring, early autumn and autumn. Assuming the daily occurrence of the morning and evening appearing of unfavorable temperature changes in the greenhouse, and also 1 to 2 times of rapid changes in radiation intensity, we can estimate how much we can reduce losses of primary energy when using the "Walczak" pipe in the greenhouse heating system. Based on the section III.6 in table 1 and 2 and the cultivation period of 330 days, the seasonal reduction in primary energy consumption is 5675,67 GJ per hectare, resulting in a saving on coal of 270 tones. By taking into consideration the uncertainty associated with the stochastic occurrence of weather phenomena, it can be assumed that these savings will not be less than 200 tons of coal and not more than 330 tons of this fuel (with a calorific value of 21 MJ / kg). By transferring this to dimensionless energy savings, in the case of seasonal consumption at the level of 1000 tons of coal per hectare, these savings will range from 20 to 33%. The presented energy saving effect is a direct financial result. However, attention should also be paid to the effect of reducing carbon dioxide emissions to the atmosphere, which is an important ecological impact of environmental protection.

It can be stated that the use of the “Walczak” pipes in the greenhouse heating system, regardless of the heating system, will reduce the water capacity of this heating system by $34m^3$ on an area of 1 hectare. Of course, in this case, more important than saving water is the speed of the heating system. Twice less water capacity will allow reduce two times the response time of the heating system. Faster heat delivery to the greenhouse heating systems, will allow a more equal temperature distribution in both the vertical and horizontal layout.

One of the most important advantage of using "Walczak" pipes is to reduce the load on the greenhouse construction. The change of load of the upper and vegetative heating system has a direct effect on overall construction load. The lower heating system does not directly affect the greenhouse construction because it is placed on the ground. The total reduction of the load of greenhouse constructions resulting from the change of the heating system is 218.5 kN per hectare.

The presented test results (items 5 to 8), in conjunction with the calculations contained in the third part of tables 1 and 2, and with the analysis of reduction of energy consumption, allow noticing the significant advantage of use of the "Walczak" pipes as basic elements of central greenhouse heating systems.

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