Thermal properties and temperature regime of champignon cultivation substrate

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Abstract. In designing and analysing the systems of automatic regulation of substrate temperature for champignon cultivation it is necessary to know substrate thermal properties (thermal conductivity and specific heat), intensity of substrate self-heating and the distribution of overtemperature caused by self-heating within a substrate briquette. It is proposed to estimate substrate thermal properties by the nonsteady method of combined determination of thermal characteristics using a flat constant power heat source. The scheme of experiments, mathematical expressions for calculating thermal indicators, examples of temperature variation, examples of thermal indicators calculations and the established mean thermal indicators for champignon cultivation substrate are presented.

An electrical analogy model of thermal process in substrate briquette was made for self-heating investigations. It was established by modelling that the distribution of overtemperature caused by self-heating within the thickness of a briquette is parabolic. The mean specific heat of substrate self-heating was established by comparison of modelling and experiments results. An equation to assess the overtemperature of substrate briquette centre in engineering calculations is presented.

Key words: champignons, cultivation substrate, thermal properties, self-heating.

INTRODUCTION

Technological requirements for champignon cultivation substrate and the microclimate of cultivation premises are known (Kmitienė & Kmitas, 1996; Szudyga, 2005; Morozov, 2006) and the best suitable parameters for a certain mushroom species are indicated in short instructions attached to substrate briquettes quite often.

In order to automate the temperature regime of cultivation environment optimally it is important to know its main thermal characteristics: thermal conductivity and specific heat. There are works published regarding the research of the thermal characteristics of greenhouse substrate (Kurpaska et al., 1996; Fernandez & Rodriguez, 2006). However, there are no more specific data on the thermal properties of champignon cultivation substrate.

In addition, it is important not to let substrate be heated over (29–30)^{o}C as in such temperature spawn stops growing and dies in longer time. Most often, when cultivating champignons it is not possible to regulate substrate temperature directly: there is no equipment to heat or cool substrate directly. Substrate temperature can be varied by regulating the air temperature in the premises of cultivation. In order to perform on time and relevant regulation of substrate temperature, one should know the intensity of substrate self-heating, and in order to avoid local overheats the distribution of temperature increase (overtemperature) within a substrate briquette caused by self-heating should be known.

The investigation objective is to estimate the mean thermal characteristics of the substrate that champignon cultivation briquettes are made of: specific heat and thermal conductivity, as well as to estimate self-heating intensity of substrate and the distribution of overtemperature induced by self-heating within a substrate briquette. The research is targeted at determine mean parameter values required and used in designing and analysing the systems for automatic control of substrate temperature.

MATERIALS AND METHODS

The thermal properties of champignon cultivation substrate are estimated by the nonsteady method of combined determination of thermal characteristics using a flat constant power heat source (Lykov, 1973). Measurement scheme is presented in Fig. 1.

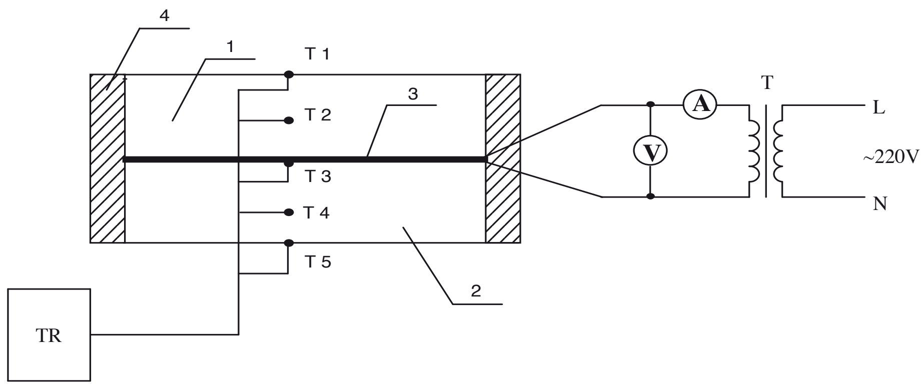

Figure 1. Scheme of measuring nonsteady temperature regime in substrate briquettes: 1, 2 – substrate briquettes, 3 – flat thin heater of constant power, 4 – thermal insulation, V, A – measuring devices, T – transformer, $T_1 – T_5$ – temperature sensors, TR – recording device.

It is considered that heat travels only perpendicularly to the heater and that heat spreading is the same into both briquettes. Then temperature change $\Delta T_x(\tau)$ at distance x from the heater and after time τ from heater switching-on can be calculated by equation (Lykov, 1973):

$$\Delta T_x(\tau) = T(x,\tau) - T_o = \frac{q\sqrt{a\,\tau}}{\lambda}\, ierfc\, \frac{x}{2\sqrt{a\,\tau}}\,, \qquad (1)$$

where: $\Delta T_x(\tau)$ – temperature change at distance x from heater in time moment τ, ^{o}C,

$T(x,\tau)$ – temperature at point x in time moment τ, °C,
T_o – initial temperature of sample, °C,
q – comparative power of heater, Wm^{-2},
a – temperature conductivity of substrate, m^2s^{-1},
λ – thermal conductivity of substrate, $Wm^{-1}K^{-1}$,
ierfc – integral of the complementary error function.

A change of heater temperature $\Delta T_s(\tau)$ can be calculated using equation (1):

$$\Delta T_s(\tau)=T(o,\tau)-T_o=\frac{q\sqrt{a\tau}}{\lambda\sqrt{\pi}}, \tag{2}$$

as *ierfc* $0 = 1/\sqrt{\pi}$ (Lykov, 1973).

Having divided (1) by (2) we obtain:

$$ierfc\ \frac{x}{2\sqrt{a\tau}}=\frac{\Delta T_x(\tau)}{\Delta T_s\sqrt{\pi}}. \tag{3}$$

Having put in inverse function $ierfc^{-1}z = y$, which is calculated from equation $ierfc\ y = z$ or it is obtained from *ierfc* function tables, thus we obtain:

$$a=\frac{x^2}{4\tau(ierfc^{-1}\dfrac{\Delta T_x(\tau)}{\Delta T_s(\tau)\sqrt{\pi}})^2}. \tag{4}$$

Having calculated temperature conductivity a using (4), heat conductivity λ is calculated using (2):

$$\lambda=\frac{q\sqrt{a\tau}}{\Delta T_s\sqrt{\pi}}=\frac{q\sqrt{a}}{\sqrt{\pi}\ tg\varphi}, \tag{5}$$

where φ – curve angle of heater temperature rise in system of axes $T_s = f(\sqrt{\tau})$.

When we know a and λ it is easy to calculate volumetric specific heat c_v:

$$c_v=\frac{\lambda}{a}. \tag{6}$$

It can be seen from (5) that the proof of experiment 'cleanliness' is a linear increase of heater temperature, when time scale $\sqrt{\tau}$ (Lykov, 1973).

A heater made of two plates of 0.8 mm thick glass textolite foiled from two sides with a copper wire of 0.12 mm^2 diameter traced between them at 5 mm spacing was used for the investigations. Heater area was 0.16 m^2 (0.4 m x 0.4 m). The electrical resistance of such a heater is about 4 Ω . In order to achieve the heating power of (10–20) W the voltage of (6.3–9) V is required.

When analysing the temperature regime of a substrate briquette, a mathematical model of steady temperature regime of the substrate briquette is created. When modelling it is taken that a briquette is a flat body of unlimited area (Fig. 2), i.e. heat exchange through side surfaces are not taken into account. The results achieved in such fashion are suitable for the boards of different width and briquettes of different dimensions. Practically, such assumption is acceptable as it is important to avoid substrate overheating and unassessed heat transmission through side surfaces only reduces the temperature of the briquettes on board edges.

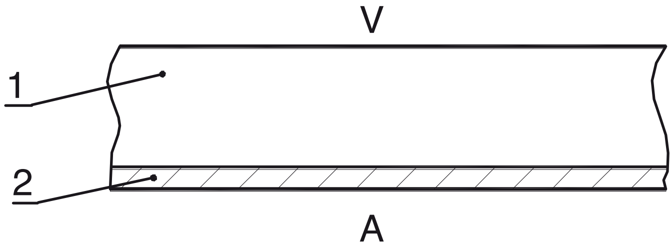

Figure 2. Scheme of modelling briquette. 1 – substrate briquette; 2 – board; V – surface of heat exchange with room air (briquette top); A – surface of heat exchange with room air through board (briquette bottom).

A board is regarded as a body of concentrated thermal parameters, and a briquette is modelled as a body of distributed thermal parameters. It is taken that heat emission is smooth within the entire volume of the briquette and the briquette, thermally, is made of homogeneous material.

In modelling a substrate briquette the electrical analogy of thermal processes (Marcus & Morris, 1985) is applied. Electrical equivalents of the thermal values used in this work are given in Table 1.

Table 1. Analogy of thermal and electrical values.

Heat		Electricity	
Value	Measure unit	Value	Measure unit
Heat flow	W	Current	A
Temperature	K	Voltage (emf)	V
Heat capacity	$Jkg^{-1}K^{-1}$	Comparative capacity	Fkg^{-1}
Thermal conductivity	$Wm^{-1}K^{-1}$	Specific conductivity	$\Omega^{-1}m^{-1}$
Heat transfer coefficient	$Wm^{-2}K^{-1}$	Comparative conductivity	$\Omega^{-1}m^{-2}$

While replacing the body – substrate briquette – of the distributed thermal parameters with electrical equivalents a circuit of the distributed electrical parameters is obtained. Having applied sampling in space, i.e. having divided the substrate briquette in elementary layers and replacing each layer with electric circuits of concentrated parameters, an electric circuit analogous to a substrate briquette is obtained. This circuitry consists of a finite number of electrical circuits connected in series.

The scheme of electric circuit, in which electrical processes are analogous to the steady thermal processes in the substrate briquette, is shown in Fig. 3.

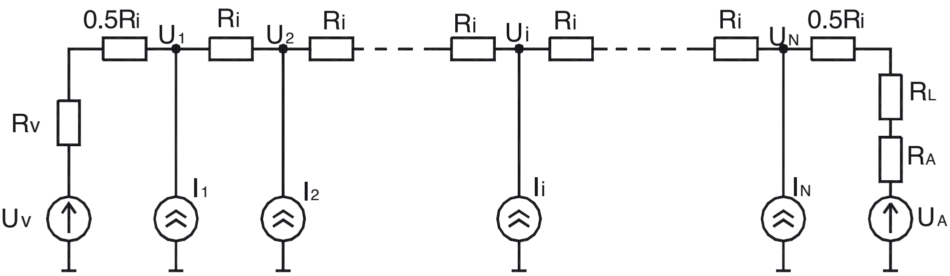

Figure 3. Scheme of electric circuit modelling temperature distribution within substrate briquette. U_A, U_V – electrical voltages modelling ambient air tmperature under and above the briquette; R_A, Rv – electrical resistances modelling the resistances of heat transfer from briquette to ambience at briquette top and bottom; R_L – electrical resistance modelling the resistance of board heat transfer; U_i, I_i, R_i – electrical voltage, current and resistance modelling the temperature, heat of self-heating and heat transfer resistance of elementary substrate briquette layer; N – number of elementary layers in substrate briquette.

The numerical expressions of electrical values equivalent to thermal values are calculated using the following equations:

$$U_A = K_U T_A \quad \text{and} \quad U_V = K_U\, T_V\,, \tag{7}$$

where: T_A , T_V – ambient air temperature below and above briquette, ^{o}C;
K_U – coefficient of dimension conversion: $K_U = 1$ VK^{-1};

$$R_A = K_R / \alpha_A \quad \text{and} \quad R_V = K_R / \alpha_V\,, \tag{8}$$

where α_A , α_V – heat transfer coefficients of briquette bottom surface (or board) and briquette top surface, Wm^{-2}K^{-1};
K_R – coefficient of dimension conversion: $K_R = 1$ ΩWK^{-1}m^{-2};

$$R_L = K_R\, d_L / \lambda_L\,, \tag{9}$$

where: d_L – board thickness, m;
λ_L – thermal conductivity of board material, $Wm^{-1}K^{-1}$;

$$R_i = (K_R\, d) / (N\, \lambda_S)\ , \tag{10}$$

where: d – briquette thickness, m;
λ_S – thermal conductivity of substrate, $Wm^{-1}K^{-1}$;

$$I_i = K_I\, Q_S\, d / N\ , \tag{11}$$

where: Q_S – comparative heat of substrate self-heating, Wm^{-3}.
K_I – coefficient of dimension conversion: K_I =1 $AW^{-1}m^2$;

To estimate comparative heat Q_S of substrate self-heating during growing experiments the temperature distribution within substrate briquettes was measured. The measurements were made in five points evenly spaced within the entire briquette thickness including the briquette centre and surfaces. The briquettes used for the experiments had substrate density of (500–600) kgm^{-3}. The modelling of temperature distribution within a substrate briquette was carried out for the regimes corresponding to experimental measurement conditions to establish the comparative heat of self-heating. By varying parameter Q_S the best matching of modelling and experimental results was achieved. The best matching criterion is the lowest mean square error of modelling and experimental results.

RESULTS AND DISCUSSION

Thermal characteristics of substrate

The thermal properties of 'fresh' substrate briquettes (before champignon cultivation) and after harvesting were measured. Briquette moisture ranged from 66% to 70%. In total 6 experiments were made. Three parameter values were calculated from each experiment taking different time moments. In total 17 values were calculated (one experiment was shorter due to accidental cutout of voltage).

The charts of temperature variations during one experiment are presented in Fig. 4 and Fig.5, and the results of thermal parameter calculations are given in Table 2.

Temperature regime of substrate briquette

Having taken that $U_A = U_V = U$, voltages U_i (Fig. 3) were calculated by the superposition method of electrical circuit calculation (Neiman & Demirchian, 1981). The voltages are equivalent to the elementary layer temperatures of a substrate briquette:

$$U_1=U+I_i N(R_A+0{,}5R_i N)(R_V+0{,}5R_i)/(R_A+R_V+R_i N) \text{ at } i=1. \tag{12}$$

$$U_i=U_{i-1}+R_i I_i((N-i+1)(R_A+0{,}5R_i(N-i+1))-(i-1)(R_V+0{,}5R_i(i-1)))/(R_A+R_V+R_i N),$$
$$\text{at } 2 \le i \le N.$$

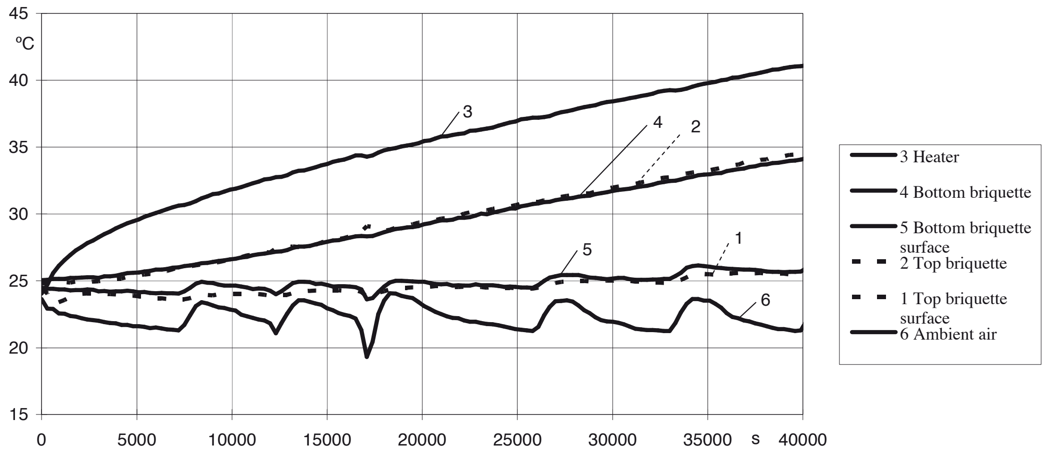

Figure 4. Temperature charts in linear time scale.

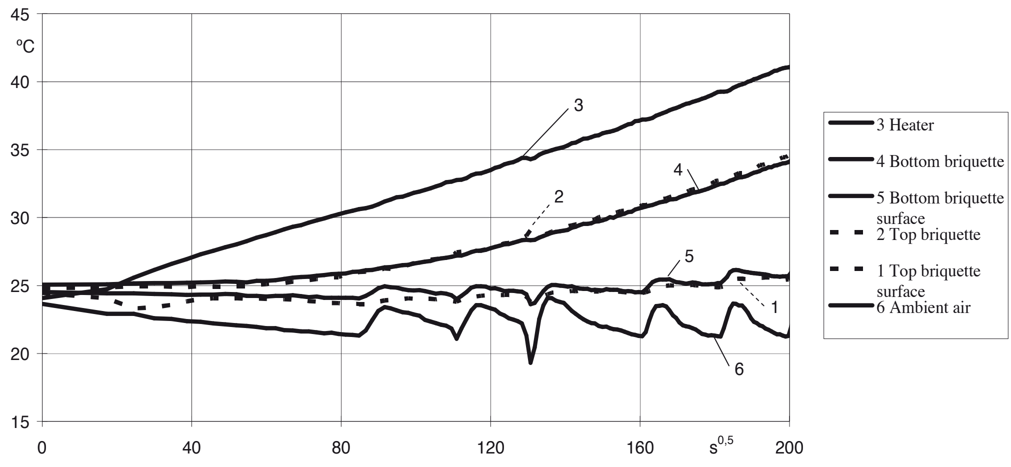

Figure 5. Temperature charts in time scale $\sqrt{\tau}$

Table 2. Calculation of thermal parameters of substrate. (q = 87 Wm^{-2}, x = 0.068 m)

Parameter	Measure unit	Parameter values		
Time τ	S	8,100	14,400	32,400
Time $\sqrt{\tau}$	s^{0,5}	90	120	180
Temperature change ΔT_x	K	1.2	2.5	7.5
Temperature change ΔT_s	K	7.0	9.5	15.5
$tg\ \varphi$	-	0.078	0.079	0.086
Temperature conductivity a	m^{2}s^{-1}	$0.23 \cdot 10^{-6}$	$0.21 \cdot 10^{-6}$	$0.26 \cdot 10^{-6}$
Thermal conductivity λ	Wm^{-1}K^{-1}	0.30	0.29	0.29
Volumetric specific heat c_v	Jm^{-3}K^{-1}	$1.3 \cdot 10^6$	$1.4 \cdot 10^6$	$1.2 \cdot 10^6$

The mean parameter values from all 17 calculations and their reliability indicators (Rumshiskij, 1971) are presented in Table 3.

Table 3. Mean thermal parameters of champignon cultivation substrate.

Parameter	a , m^{2}s^{-1}	λ, Wm^{-1}K^{-1}	c_v , Jm^{-3}K^{-1}
Mean value	$0.25 \cdot 10^{-6}$	0.35	$1.4 \cdot 10^6$
Standard deviation	$0.054 \cdot 10^{-6}$	0.081	$0.14 \cdot 10^6$
Confidence interval at P = 0.95	$0.026 \cdot 10^{-6}$	0.038	$0.067 \cdot 10^6$

In order to have one of the modelled voltages U_i corresponding to a briquette centre, number N of briquette division into elementary layers has to be odd, e.g., N=101. To have modelling results independent of a concrete briquette thickness and division number N it is appropriate to use a comparative coordinate of briquette thickness d^*, which is calculated as follows:

$$d^* = (N-i)/(N-1). \qquad (13)$$

Fig. 6 illustrates an example of the distribution curve of the modelled overtemperature created by substrate self-heating within a briquette. The modelling was carried out under the following initial conditions: $U_A = U_V = 0$ (increase of modelled temperature over ambient temperature), α_A = 5.9 Wm^{-2}K^{-1} and α_V = 10 Wm^{-2}K^{-1} (Barkauskas, 2000), N = 101, d_L = 0 (modelling without a board), d = 0.14 m, λ = 0.33 Wm^{-1}K^{-1}, Q_S = 316 Wm^{-3}. The marked experimental overtemperatures are equal to the mean values of comparative overtemperatures over five days, when substrate self-heating is the most intensive. The lowest mean square deviation of the experiment and modelling results (0.75°C) is achieved, when comparative power of self-heating is Q_S = 316 Wm^{-3}.

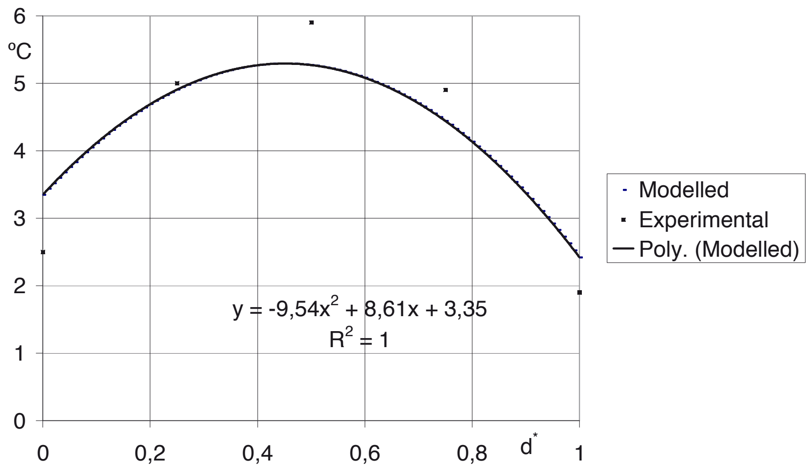

Figure 6. Distribution of self-heating overtemperature within a briquette (without board).

The mathematical equation and correlation coefficient (Fig. 6) describe the curve approximating the modelling results. The second degree equation and the correlation coefficient equal to one show that the distribution of the overtemperature created by substrate self-heating within briquette thickness is parabolic. The parabola top has a slight deviation from the briquette centre. A shift is caused by unequal transfer of heat from the briquette top and bottom.

The influence of the lower floor (board) on temperature distribution is minor: Fig. 7 shows briquette temperature distribution modelled under the same conditions as Fig. 6 at d_L=0.008 m and λ_L=0.87 $Wm^{-2}K^{-1}$ (corresponds to board made of 8 mm thick panel of concrete-shavings).

According to the measurements of three experimental champignon cultivations and the results of corresponding modellings it was established that the mean comparative heat of self-heating during the most intensive periods of self-heating was 308 Wm^{-3} with a variation interval (250–400) Wm^{-3}.

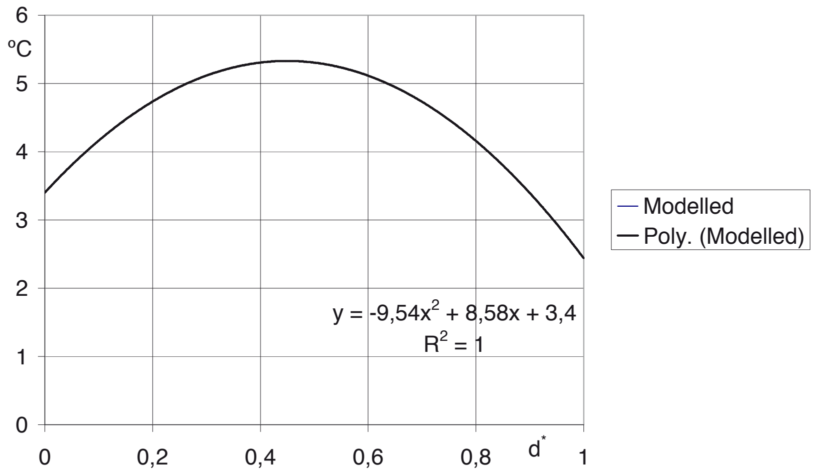

Fig. 7. Distribution of self-heating overtemperature within a briquette (with board).

Having carried out a range of modellings with the thermal briquette parameters obtained during the experiments there was a try to calculate dependency between the briquette centre overtemperature induced by self-heating and briquette thermal properties. The following dependency acceptable for engineering calculations was obtained:

$$T_C=1,14\ Q_S\ d\ \lambda^{-0,46}/(\alpha_A + \alpha_V)\ , \tag{14}$$

where: T_C – briquette centre overtemperature due to self-heating, °C;
α_A , α_V – heat transfer coefficients of briquette bottom and top surfaces, $Wm^{-2}K^{-1}$;
Q_S – comparative heat of substrate self-heating, Wm^{-3};
d – briquette thickness, m;
λ – thermal conductivity of substrate, $Wm^{-1}K^{-1}$.

According to the equation (14) it is possible to assess the increase of briquette centre temperature due to substrate self-heating with sufficient accuracy for engineering calculations (modelling and calculation results using equation (14) differ without exceeding 0.1°C).

It can be observed from the distribution of experimental and calculated overtemperatures given in Fig. 6 that the measured overtemperature in the briquette centre is higher than the modelled one. Such an increase was recorded during all experiments. This fact suggests an assumption that the comparative heat of substrate self-heating is not constant but increases with an increase of substrate temperature.

CONCLUSIONS

1. To establish thermal properties of champignon substrate briquettes an nonsteady method of combined determination of thermal characteristics using a flat constant power heat source may be used.

2. When designing or analysing temperature automatic control systems for champignon cultivation the following mean thermal parameters of substrate of (500–600) kgm^{-3} density can be used: temperature conductivity $0.25 \cdot 10^{-6}$ m^2s^{-1}, thermal conductivity 0.35 $Wm^{-1}K^{-1}$, volumetric specific heat $1.4 \cdot 10^6$ $Jm^{-3}K^{-1}$.

3. The distribution of overtemperature caused by substrate self-heating within the thickness of a briquette is parabolic. A slight deviation of the parabola top (maximum point of substrate temperature) from the briquette centre can be ignored in practice and it can be taken that the temperature sensor installed in the briquette centre measures the maximum briquette temperature.

4. The mean comparative heat of substrate self-heating during the most intensive heating is 308 Wm^{-3} with a variation interval of (250–400) Wm^{-3}.

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