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SOME THERMAL PROPERTIES OF ROOT VEGETABLES

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Key words: thermal conductivity, thermal diffusivity, thermal properties of vegetable.

The thermal conductivity and thermal diffusivity of sugar beet, carrot, red beet, celery and parsley were measured with the use of the heat impulse method. Linear regression was used to calculate thermal properties data as a function of water content. There were no substantial differences in the thermal properties among varieties of the same vegetable and among vegetables having similar water content, except for parsley which had lower thermal properties than other products.

Thermal properties such as thermal conductivity and thermal diffusivity are necessary to predict heat transfer rates during processing and storage of food materials. There are not enough thermal properties data for agricultural and food products; also not enough is known about factors influencing thermal properties and the correlation between these factors and thermal properties. Several workers have reported data on thermal properties of some vegetables such as sugar beet, carrot, red beet, onion, turnip and cucumber [1, 2, 8, 9, 10, 11]. Most reported data concerning these properties did not take into consideration the temperature of tested samples, the varietal differentiations, and there is little data available as to the relation between thermal properties and water content. Thus, the values of thermal properties of the same materials often vary. Sometimes this variation is due to the methods used, some of which are reported not to be suited to materials with high water content [7].

The objective of this study was to determine the thermal conductivity and thermal diffusivity of selected root vegetables such as sugar beet and red beet, carrot, celery and parsley as well as the relation between these properties and water content. Another objective of the study was to demonstrate a method which can be used for measuring the thermal properties of high water content products.

MATERIALS AND METHODS

VEGETABLE SAMPLES

Two varieties of sugar beet: AJ-3 and Trimono and two varieties of carrot: Pierwszy Zbiór and Perfekcja, red beet: Czerwona Kula, celery: Jabłkowy, and parsley: Berlińska were tested in this work. The products were stored in 2-10°C room in wet sand during experiments. The water content of each sample was determined succesively immediately before experimental run. The experiments were conducted during 3 months after harvest.

THEORY OF THE METHOD

The theory of the method used in this work is based on the relationship between thermal properties and the temperature rise in an infinite homogonous medium caused by an infinitely short heat impulse of an infinitesimally thin planar heat source. If Q is the total heat produced by the heat source, the temperature distribution is given by the following function [5].

$$T(x,\tau) = T_o + \frac{Q\sqrt{a}}{2A\,k\sqrt{\pi\tau}}\exp\left(\frac{x^2}{4a\tau}\right) \tag{1}$$

where: T_0 is the initial temperature, k is the thermal conductivity, a the thermal diffusivity, τ the time, x the distance from the heat source and A is the area of the planar heat source.

The time of maximal temperature rise τ_m can be obtained from the partial derivative of equation (1).

$$\tau_m = \frac{x^2}{2\cdot a} \tag{2}$$

Thus, the maximal temperature rise is given by equation:

$$\Delta T_m = 0.121\,\frac{Q\cdot x}{A\cdot k\cdot \tau_m} \tag{3}$$

The time τ_m and the temperature rise ΔT_m at distance x from the heat source can be obtained from the time-temperature chart when a sample of material is heated by a short heat impulse. Hence, if temperature rise ΔT_m, time τ_m, distance x and heat value Q are known, thermal conductivity and thermal diffusivity can be calculated from the relations (2) and (3).

Equations (2) and (3) are valid for a sample of infinite dimensions, infinitely short heat impulse and infinitesimally thin planar heater. In this work the experimental system was composed of two cuboidal pieces of vegetable with the square planar heater between them (Fig. 1). Then, criteria had to be found for choosing sufficiently large dimensions of the sample, thickness of the heater, and the heat impulse duration in order to be able to use the theory presented above.

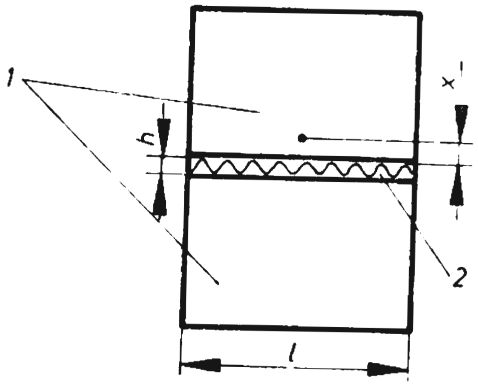

Fig. 1. Schematic of the heat impulse method; 1 — vegetable sample, 2 — planar heat source

According to the method presented by Krempasky [6] for cylindrical samples of finite diameter it was calculated that the edge of the sample 1 must be greater than $4x^2$ (mm) [3]. Thus, the error caused by the side heat losses and nonlinear heat flow is smaller than 1 percent.

The heat produced by the planar heater is partly accumulated inside the heater during an experimental run. Assuming that the accumulated heat is only 1 percent of the total heat produced, the following expression for the maximal thickness of the heater $h < 0.4 \frac{c\varrho}{c_0\varrho_0} x$ (mm) was obtained from the heat balance of the heater and sample, where $c\varrho$ and $c_0\varrho_0$ are specific heat capacities of vegetable and material of the heater respectively [3].

Another error due to the finitely short impulse was discussed by Kaganow [4]. It was assumed that the heat impulse may be concidered to be infinitely short when $\tau_0 < 0.02\,\tau_m$ (s), where τ_0 is heat impulse duration.

APPARATUS AND PROCEDURE

The apparatus used in this work is shown in Fig. 2. The infinite system was simulated by the square flat sample of thickness x surrounded by two pieces of the same material as the sample. The planar heat source of 2 cm^2 area, giving onedirectional homogenous heat flow was made with 0.05 mm in diam. copper wire as a square net and it corresponded to the conditions discussed above. The heat source was supplied by a low-voltage dc power supply switched by a time-regulated electronic switch.

The heat produced was measured with a specially designed integrating unit (electrical charge value) and a digital voltmeter (voltage drop across the heater). The temperature change was measured with a 0.1 mm in diam. copper-constantan differential thermocouple located at a precisely defined distance x from the heat source. The other weld of the thermocouple was in a differential sample cut from the same vegetable but with no heat source. Electric potential of the thermocouple was measured with the potentiometer strip chart recorder EZ-10 (accuracy 1 μV)

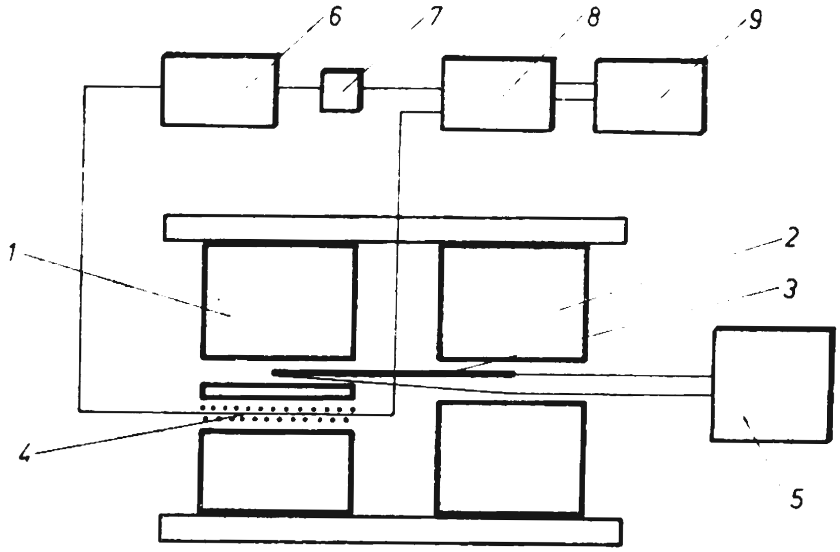

Fig. 2. Schematic diagram of experimental apparatus; 1 — sample, 2 — differential sample, 3 — differential thermocouple, 4 — planar heater, 5 — recorder, 6 — power supply, 7 — switch, 8 — integrating unit, 9 — voltmeter

Vegetables were cut into four 20×20×10 mm cuboidal pieces. The flat sample of 1-2 mm thickness was cut off of one piece of vegetable and precisely measured. The whole experimental system was located between two discs as in Fig. 2, and lightly pressed to insure good thermal contact. At the start of the test the temperature of the sample was established at 20°C. Then, the heat source was switched on for rectangular impulse of about 0.2 s duration and the temperature curve was recorded. The time of maximal temperature rise τ_m taken from the chart varied between 5 and 15 s according to thickness and thermal properties of the sample, and the maximal temperature rise was smaller then 1.5 K.

The thermal diffusivity and the thermal conductivity of the sample were calculated from the equations (2) and (3) respectively, where Q was taken as the product of the voltage drop across the heater (U) and the electrical charge value ($I \cdot \tau_o$).

Three separate tests were made in each sample and the average value was calculated.

RESULTS AND DISCUSSION

THERMAL CONDUCTIVITY

Results of the thermal conductivity determinations are shown in Fig. 3. A regression analysis was applied to the data of each product. The regresion equations are presented in Table 1.

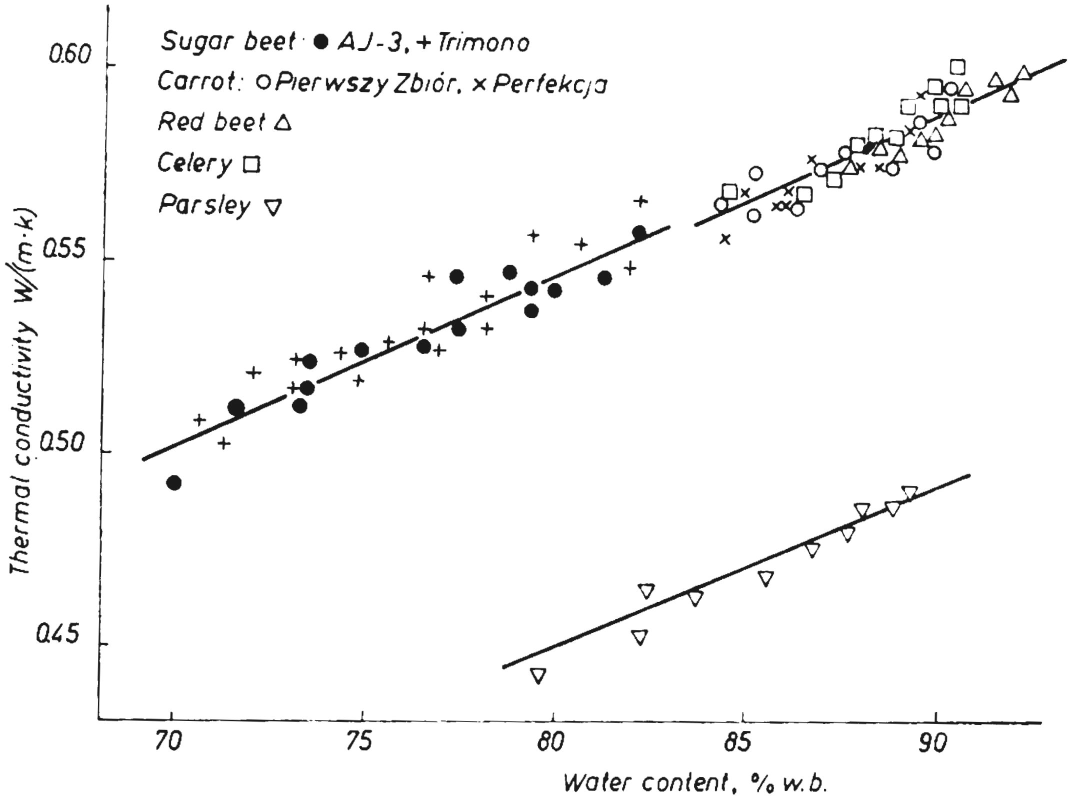

Fig. 3. Thermal conductivity versus water content for tested vegetables

Table 1. Regression equations representing the thermal conductivity of the tested products

Product	Number of tested samples	Water content range % w.b. W	Regression equation k	Standard deviation s, W/(mK)	Correlation coefficient r
Sugar beet AJ-3	15	70.0-82.0	$k = 0.174 + 0.0047\ W$	0.022	0.94
Trimono	17	70.6-82.0	$k = 0.180 + 0.0046\ W$	0.022	0.94
Carrot Pierwszy Zbiór	11	84.1-90.0	$k = 0.193 + 0.0044\ W$	0.014	0.88
Perfekcja	10	84.2-89.2	$k = 0.101 + 0.0054\ W$	0.017	0.89
Red Beet	10	87.4-91.9	$k = 0.103 + 0.0051\ W$	0.012	0.91
Celery	10	84.6-90.2	$k = 0.135 + 0.0051\ W$	0.018	0.87
Parsley	10	79.6-89.2	$k = 0.106 + 0.0043\ W$	0.038	0.98

There was strong correlation between water content and thermal conductivity of all products and there was significant difference between the thermal conductivity of parsley and that of the other products. The lower values of the thermal conductivity of parsley could be due to a higher cellulose content and a higher tissue porosity of this product.

By using the t-test with 95 percent confidence it has been indicated that there were no differences between regression equations of the two varieties of sugar beet and the two varieties of carrot. Thus, the regression equations determined for both varieties of sugar beet are:

$$k = 0.187 + 0.0045\ \mathrm{W}, \quad s = 0.028, \quad r = 0.94 \tag{4}$$

and for both varieties of carrot:

$$k = 0.172 + 0.0046\ \mathrm{W}, \quad s = 0.017, \quad r = 0.89 \tag{5}$$

The same procedure, applied for thermal conductivity of the three vegetables similar in the thermal conductivity values and in relation to water content, i.e., carrot, red beet, and celery, gives one regression equation represented by:

$$k = 0.176 = 0.0046\ \mathrm{W}, \quad s = 0.022 \quad r = 0.89 \tag{6}$$

which is limited to water content greater than 80%.

The relations obtained in this work are plotted in Fig. 4 together with the results of other investigators. The equation obtained by Gromow [2] for sugar beet, carrot, and potato, and Sweat's [9] equations for more then 20 different fruits and vegetables are quite similar to those obtained in this study. The results presented by Żadan and Chelemski [11] for the thermal conductivity of sugar beet are somewhat questionable.

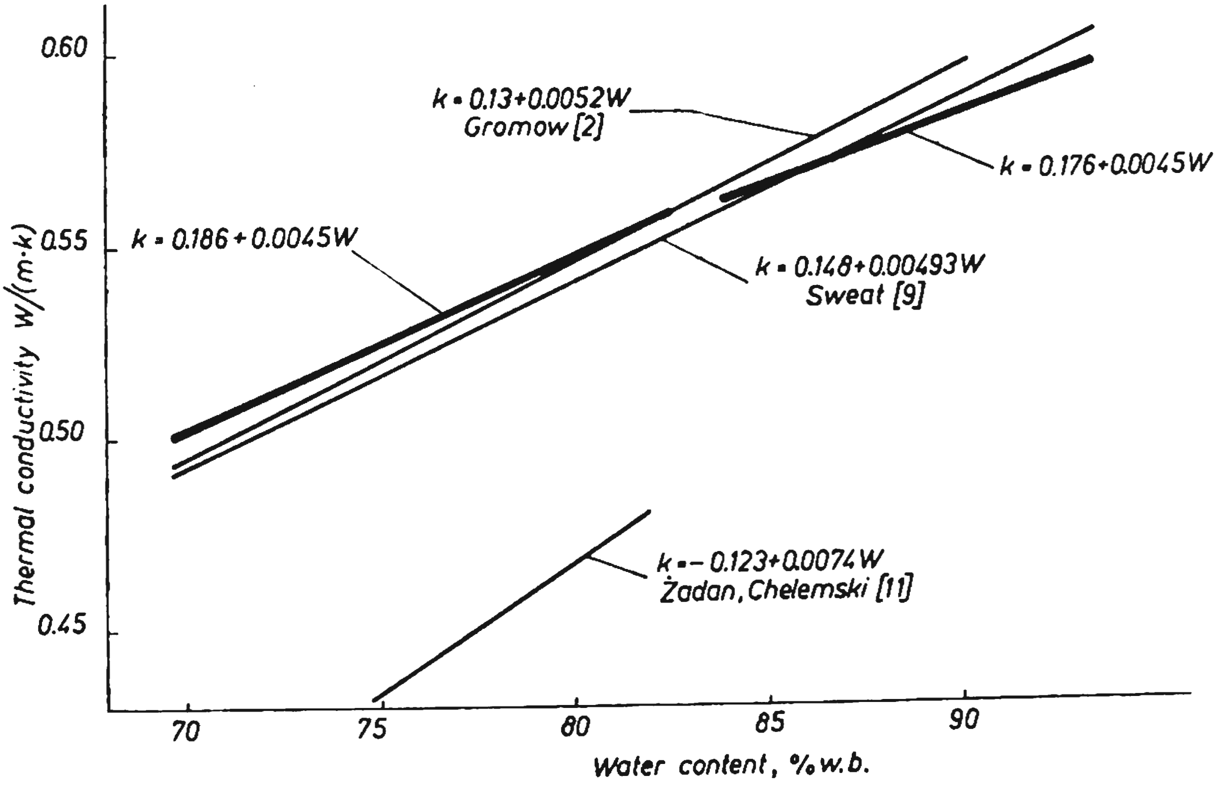

Fig. 4. Thermal conductivity versus water content: comparison of equations

THERMAL DIFFUSIVITY

Results of the thermal diffusivity determinations are shown in Fig. 5. The regression equations of each product are presented in Table 2.

There was also strong correlation between water content and thermal diffusivity of all products and the data of parsley was quite different from that of other products.

By comparison of the regression equations of the two varieties of sugar beet and carrot, it was assumed that the variety did not affect the therm-

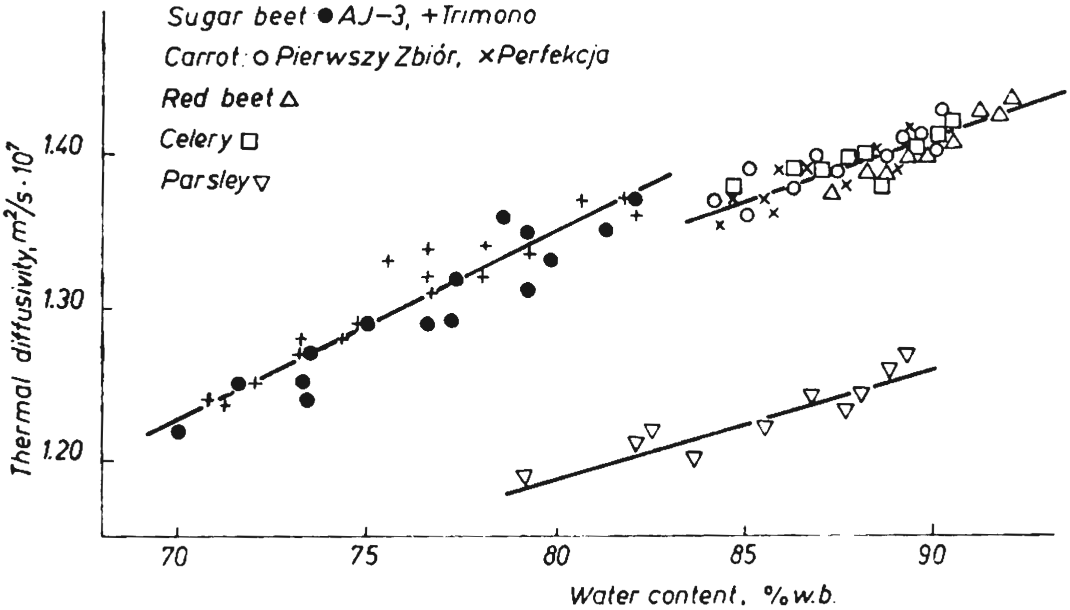

Fig. 5. Thermal diffusivity versus water content for tested vegetables

Table 2. Regression equations representing the thermal diffusivity of the tested products

Product	Number of tested samples	Water content range % w.b. W	Regression equation $a \cdot 10^7$	Standard deviation $s \cdot 10^7$, m²/s	Regression coefficient r
Sugar beet AJ-3	15	70.0-82.0	a = 0.34+ 0.0126 W	0.014	0.95
Trimono	17	70.6-82.0	a = 0.39+ 0.0119 W	0.014	0.96
Carrot					
Pierwszy Zbiór	11	84.1-90.0	a = 0.67+ 0.0087 W	0.010	0.91
Perfekcja	10	84.2-89.2	a = 0.61+ 0.0089 W	0.011	0.87
Red beet	10	87.4-91.9	a = 0.63+ 0.0089 W	0.011	0.91
Celery	10	84.6-90.2	a = 0.61+ 0.0088 W	0.011	0.94
Parsley	10	79.6-89.2	a = 0.61+ 0.0072 W	0.012	0.89

al diffusivity values. It was also assumed that the differences between regression equations of the carrot, red beet and celery appear to be very small. Thus, the equations resulting were as follows:

$$a = (0.35 + 0.0125\,W) \cdot 10^{-7}, \qquad s = 0.014 \cdot 10^{-7}, \qquad r = 0.95 \tag{7}$$

for sugar beet and

$$a = (0.66 + 0.0085\,W) \cdot 10^{-7}, \qquad s = 0.016 \cdot 10^{-7}, \qquad r = 0.97 \tag{8}$$

for carrot, red beet and celery.

For comparison the thermal diffusivity equations from Gromow [2] and Żadan and Chelemski [11] are shown in Fig. 6 together with those obtained in the present study. The equation of Żadan and Chelemski for sugar beet, limited to water contents between 70% and 80%, indicate lower values of thermal diffusivity, but the data of Gromow for sugar beet, carrot and potato with water content ranging from 60-90%, appears to be very high and are greater than the thermal diffusivity of water. It probably results from the "regular regime" method used by Gromow over a wide temperature range (cooling from 90 to 20°C).

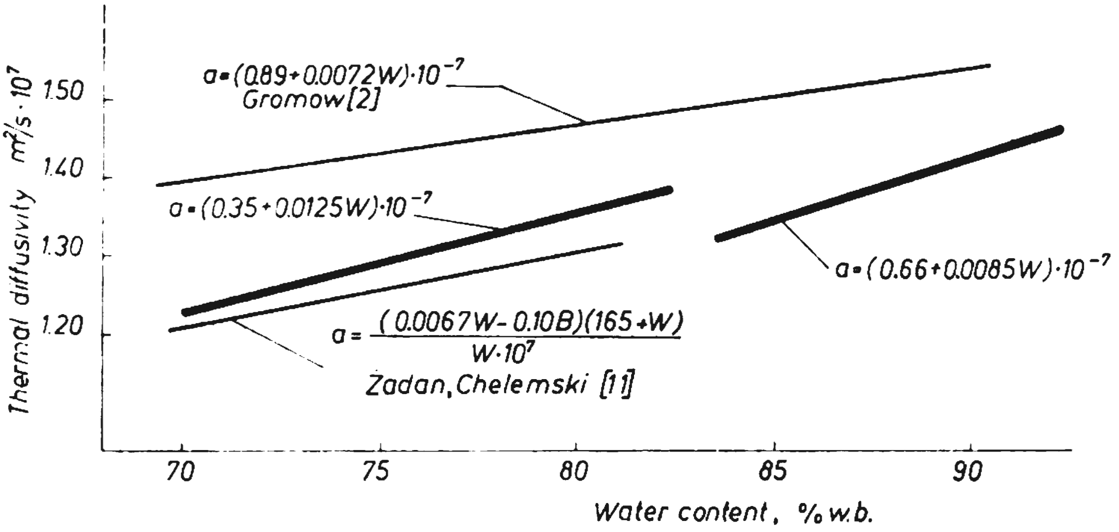

Fig. 6. Thermal diffusivity versus water content: comparison of equations

CONCLUSIONS

1. The impulse method has been successfully used for the simultaneous determination of the thermal conductivity and thermal diffusivity of root vegetables.
2. The thermal conductivity and thermal diffusivity values of two varieties of sugar beet and carrot studied in this work were not found to be different in the water content range characteristic of fresh vegetables.
3. There are no substantial differences in the thermal properties

among root vegetables which have the same water content at the same temperature except for parsley.

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LITERATURE

1. Gogół W.: Roczn. Nauk. Roln. 1973, 70-C-3, 55.
2. Gromow M. A.: Kons. owoszcz. prom. 1971, (6), 33.
3. Jankowski T.: Charakterystyka właściwości cieplnych płodów rolnych o dużej zawartości wody za pomocą metody ogrzewania impulsowego. Ph Thesis. AR Poznań, 1979.
4. Kaganow M. A.: Żurn. Techn. Fiz. 1956, **26**, 674.
5. Kącki E.: Termokinetyka. WNT. Warszawa, 1967.
6. Krempasky J.: Meranie termofizykalnych velicin. Slov. Akad. Vied. Bratislava, 1969.
7. Reidy G. A., Rippen A. L.: Trans. ASAE, 1971, **14**, 248.
8. Sawina N. J.: Kons. owoszcz. prom. 1963, (4), 15.
9. Sweat V. E.: J. Food Sci. 1974, **39**, 1080.
10. Wyszeleski A. N., Gromow M. A.: Kons. owoszcz. prom. 1963, (11), 25.
11. Żadan W. Z., Chelemski M. Z.: Sacharn prom. 1963, **37**, 54.

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NIEKTÓRE WŁAŚCIWOŚCI CIEPLNE WARZYW KORZENIOWYCH

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Streszczenie

Właściwości cieplne artykułów żywnościowych nie są jeszcze w pełni znane; niewiele wiadomo o czynnikach wpływających na te właściwości i związku właściwości cieplnych z tymi czynnikami.

W tej pracy wyznaczano przewodność cieplną właściwą i współczynnik wyrównywania temperatury buraków cukrowych, marchwi, buraków ćwikłowych, selera i pietruszki, biorąc pod uwagę wilgotność tych produktów w stanie świeżym i po krótkim okresie przechowywania. Pod uwagę wzięto także różnice odmianowe w dwóch materiałach — burakach cukrowych i marchwi. Pomiary właściwości cieplnych wykonywano przy użyciu metody polegającej na ogrzewaniu próbki materiału krótkim impulsem ciepła. Badany materiał w postaci dwóch prostopadłościennych kawałków z płaskim grzejnikiem pomiędzy nimi (rys. 2) i termoelementem różnicowym do pomiaru przyrostu temperatury umieszczonym w odległości x od grzejnika, ogrzewano impulsem ciepła trwającym około 0.2 s. Z krzywej wzrostu temperatury zapisywanej rejestratorem odczytywano czas, w którym temperatura osiągnęła wartość maksy-

malną — τ_m oraz maksymalny przyrost temperatury ΔT_m. Na podstawie tych dwu wielkości oraz grubości warstwy materiału x, ilości ciepła wydzielonej przez grzejnik — Q i powierzchni grzejnika A, obliczano właściwości cieplne z równań (2) i (3). Wyniki pomiarów opracowano metodą analizy regresji prostoliniowej i podano w postaci równań wyrażających zależność właściwości cieplnych od wilgotności materiału.

Przewodność cieplna właściwa i współczynnik wyrównywania temperatury dwóch odmian buraków cukrowych i dwóch odmian marchwi nie różniły się w badanym zakresie wilgotności. Nie stwierdzono istotnych różnic w badanych właściwościach cieplnych warzyw korzeniowych mających taką samą wilgotność w tej samej temperaturze za wyjątkiem pietruszki wykazującej niższe niż w pozostałych materiałach wartości liczbowe właściwości cieplnych przy podobnej wilgotności. Wyniki pomiarów porównano z danymi liczbowymi pochodzącymi z innych prac.