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Influence of temperature and variety on the thermal properties of apples

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A b s t r a c t. The influence of temperature within the range 273 to 333 K (0-60°C) on the thermal properties of four apple varieties has (Jonathan Red, Golden Delicious, Idared, Jonagold) been studied. An impulse method to measure thermal properties in which a linear source of heat generates a short-term heat impulse was worked out in the model of an infinite cylinder. Temperature and variety exert a significant influence on the values of thermal conductivity coefficient and thermal diffusion. In each case the influence was at the level of significance α=0.01. In the case of volumetric specific heat ($c\rho$) no statistically significant differences were found other than for the varieties Jonagold and Idared. With a temperature increase in the range 273-333 K (0-60°C) the values of apple thermal properties increased linearly.

K e y w o r d s: thermal properties of apples, impulse method

BASIC NOTATIONS

$a, \bar{a}$ - coefficient of thermal diffusion, mean value (m^2s^{-1}),
b - coefficient characterising the device used in the Volkenstein method,
c, c_p - specific mass heat capacity (for gas under constant pressure) (J $kg^{-1}K^{-1}$),
$c\rho, \bar{c}\rho$ - specific volumetric heat capacity, mean value (kJ m^{-1} K^{-1},
d,s - auxiliary variables,
δ - relative error (%),
$E_1(\beta)$ - integral characteristic function of parameter,
Fo - Fourier criterion for heat conductivity in the undetermined state,
I - current intensity (A),
l - length of resistance wire (m),
q - intensity of heat stream (W m^{-2}),
q_1 - linear intensity of heat stream (W m^{-1})
Q - heat (J),
Q_1 - linear heat pulse (J m^{-1}),
r - variable in the radial direction (m),
r_o - distance from the linear heat source (m),
R - electrical resistance (Ω)
$\lambda, \bar{\lambda}$ - coefficient of thermal conductivity, its mean value (W m^{-1} K^{-1}),
$\varphi_o, \varphi_\lambda, \varphi_a, \varphi_{cp}$ - coefficients used in the impulse method with the linear heat source,
$\theta_{(x,y,z,\tau)}$ - increase in temperature at a point with coordinates (x,y,z,τ) after τ from the beginning of heat pulse (K),
t - temperature (°C),
T - absolute temperature (K),
T_o - initial temperature (K),
ΔT - temperature difference (K),
ΔT_{max} - maximum temperature increase (K),
∇T - temperature gradient (K m^{-1}),
τ - time (s),
τ_i - time interval from the beginning to the end of the heat impulse,
$\tau_{\kappa o}$ - correction coefficient (s),
τ_o - duration of pulse (s),
τ_l - time from beginning of pulse to end,
τ_{max} - time for reaching maximum temperature increase ΔT_{max},
u - absolute humidity or water content (kg water · kg dry matter^{-1}),
w - relative moisture (kg water · kg^{-1})·100,
x,y,z - auxiliary variables in direction x, y, z; β - auxiliary variable.

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INTRODUCTION

Data on apple thermal properties (such as coefficient of thermal conductivity, specific heat capacity, and coefficient of thermal diffusion) found in literature often differs considerably from author to author. In the same conditions (T=313 K, moisture of 88%), according to Jljasowa *et al.* [2] the coefficient of thermal conductivity λ is 0.537 for apples in general; for var. Granny Smith according to Lozano *et al.* [4] it is 0.490 and according to Ramaswamy and Tunga [7] it is 0.467. For var. Golden Delicious according to Ramaswamy and Tunga [7] it is 0.479; and for var. Jonagold according to our own studies it is 0.463 [4].

In the above conditions, specific heat capacity *c* for apples in general is 3829 J kg^{-1}K^{-1} according to Ratti and Mujumdara [8]. Ramaswamy and Tunga [7] quote the figure of 3596 for var. Granny Smith, and 3660 for var. Golden Delicious. The very figure according to our own studies [4] is equal to c=3657 J kg^{-1}K^{-1}, and volumetric heat capacity is ($c\rho$)=3.4454 MJm^{-3}K^{-1}.

In the same conditions, the coefficient of thermal diffusion (a, 10^{7}m^{2}s^{-1}) for apples in general is 1.784 according to Jljasow *et al.* [2]; for var. For Granny Smith according to Ramaswamy and Tunga [7], it is 1.5324 and according to our studies [4] for var. Jonagold it is 1.3459. The above differences are big enough to be significant since the coefficient in question is related to the remaining thermo-physical properties of apples and the relation takes the form of $a=\lambda/c\rho$. Above freezing point, the relations between apple thermal properties and temperature are expressed with linear equations with positive directional coefficients.

The aim of the current study was to elaborate a pulse method for the determination of the thermal properties of uniform bodies with a high moisture content with the use of linear source of heat.

MATERIALS AND METHODS

The influence of temperature on the thermal properties of fresh apples was studied in the temperature range from 273 to 333 K (0-60°C) in twelve repetitions. The study material consisted of four apple varieties (Jonathan Red, Golden Delicious, Idared, and Jonagold). The following parameters were experimentally determined: thermal diffusion coefficient (a), thermal conductivity (λ) and specific volumetric heat capacity ($c\rho$), i.e., specific heat. Due to the high moisture content of apples, their properties were compared to the thermo-physical properties of water.

The method of the non-stationary flow of heat in Volkenstein's [10] unlimited plate served to determine the thermal properties of agricultural raw materials because of the relatively short time of measurement (5-10 min) and not very high values of heating temperature but it is characterised by difficulties in the accurate determination of the amounts of heat taken up by the sample from the flowing water since the intensity of the process is influenced by many factors. However, the pulse method allows shortening of measurement time to one minute as well the taking of measurements with imperceptible changes in the moisture content of a given body. The pulse method with a flat heat source was introduced by Lykow [6] and followed up by Ginsburg *et al.* [1] and in the range of limited relative measurement error through the choice of optimum temperature, distance between the heat source and the thermoelement as well as measurement time by Lisowa *et al.* [3]. It is based on the solution of the equation for the thermal conductivity for an unrestricted body. The body studied is subjected to the short action of a thermal stream coming from a flat heat source. According to Ginsburg *et al.* [1] the values of the coefficient of thermal diffusion, thermal conductivity and specific volumetric heat capacity can be determined from the following formulas:

$$a = \frac{x^2}{2\tau_o}\varphi_a, \tag{1}$$

$$\lambda = \frac{q \cdot x}{\Delta T_{\max}}\varphi'_\lambda, \tag{2}$$

$$c\rho = \frac{2q \cdot \tau_o}{x \cdot \Delta T_{\max}}\frac{\varphi'_\lambda}{\varphi_a}, \tag{3}$$

where: x - distance between the hot joint of the thermoelement and flat heat source (m), φ_a, φ_l - coefficients whose values depend on the value of coefficient φ_o, when $\varphi_o = \tau_o / \tau_{\max}$, values φ'_λ and φ_α are given in the table in the paper by Ginsburg *et al.* [1], $\tau_{\max}$ - time which the increase of temperature at point x from the heat source equals $\Delta T_{\max}$ (s).

The use of a linear source of heat instead of a flat one (Eqs 1-3) ensures good contact between the electrical heater and the body studied and enables the accurate determination of the intensity of the heat stream. The goal of the study was realised through the use of the equation of thermal diffusivity for the case of a uni-dimensional flow of heat, with a linear source generating a short thermal pulse and the design and building of an experimental station for determining thermal characteristics by the pulse method. We experimentally determined: thermal diffusivity, thermal conductivity, specific volumetric heat and density.

Lykow's [6] solution for thermal diffusivity equation was employed:

$$\rho \cdot c \cdot \frac{\partial T}{\partial \tau} = \nabla(\lambda \cdot \nabla T), \tag{4}$$

for its flow in unrestricted cylinder with following type II initial-boundary conditions:

$$q_1 = \text{const} \quad \text{for } 0 < \tau \le \tau_o \tag{5}$$

$$T(r=\infty,\tau)=T_o, \tag{6}$$

$$T(r,\tau=0)=T_o. \tag{7}$$

In the case of a tri-dimensional temperature field $\theta(x, y, z, \tau) = T(x, y, z, \tau) - T_o$, whose distribution is caused by thermal pulse Q emitted at a point with the co-ordinates (x_1,y_1,z_1) in time $\tau=\tau_1$ the general solution of Eq. (4) is:

$$\theta(x,y,z,\tau)=T(x,y,z,\tau)-T_o=$$

$$\frac{Q}{8\cdot c\cdot\rho\left[\Pi\cdot a\left(\tau-\tau_1\right)\right]^{3/2}}\cdot$$

$$\exp\left[-\frac{\left(x-x_1\right)^2+\left(y-y_1\right)^2+\left(z-z_1\right)^2}{4\cdot a\cdot\left(\tau-\tau_1\right)}\right], \tag{8}$$

where: Q - heat emitted at a point with the co-ordinates (x_1, y_1, z_1) in time $\tau=\tau_1$,

$$\tau_1\in<0,\tau_o>.$$

Heat is determined from the equation:

$$Q=\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}c\cdot\rho\cdot\theta\left(x,y,z\right)\,dx\,dy\,dz\,. \tag{9}$$

The temperature distribution in a two-dimensional temperature field $\theta_1(x,y,\tau)$ created by a linear thermal pulse Q_1, acting at moment $\tau=\tau_1$ along a straight line parallel to the straight line z and passing through point (x_1, y_1) is arrived at by integrating Eq. (8) after dz_1, in the interval $(-\infty,+\infty)$:

$$\theta(x,y,\tau)=T(x,y,\tau)-T_o=\int_{-\infty}^{\infty}\theta\left(x,y,z,\tau\right)dz_1=$$

$$\frac{Q_1}{4\cdot\Pi\cdot\lambda\cdot\left(\tau-\tau_1\right)}\cdot\exp\left[-\frac{\left(x-x_1\right)^2+\left(y-y_1\right)^2}{4\cdot a\cdot\left(\tau-\tau_1\right)}\right], \tag*{[10]}$$

where: Q_1 - amount of heat temporarily emitted by linear heat source unit.

The method is based on the solving Eq. (10) after $d\tau_1$ in the interval from '0' to τ_o whereas the temperature distribution in time is determined for a point at a distance $r_o = \sqrt{x^2+y^2}$ from the heat source passing through point (x_1, y_1), where $x_1 = y_1 = 0$. Maximum temperature increase $\Delta T_{\max}=\left[T(r_o,\tau_{\max})-T_o\right]$ can be described as: $\tau=\tau_{\max}$,

$$\Delta T_{\max}=\frac{q_1}{4\cdot\Pi\cdot\lambda}\cdot\int_0^{\tau_o}\exp\left[-\frac{r_o^2}{4\cdot a\cdot\left(\tau_{\max}-\tau_1\right)}\right]\cdot$$

$$\frac{d\tau_1}{\left(\tau_{\max}-\tau_1\right)}. \tag{11}$$

By integrating Eq. (11) after $\tau_{\max}$ and equating the derivative to zero:

$$\frac{d\left(\Delta T_{\max}\right)}{d\,\tau_{\max}}=0, \tag{12}$$

we obtain a quotient at which the condition of extremum maximum function $\Delta T=f(\tau)$ at a given point at a distance r_o from the heater is met:

$$\ln\frac{\tau_{\max}}{\tau_{\max}-\tau_o}=\frac{r_o^2}{4a}\cdot\left[\frac{1}{\tau_{\max}-\tau_o}-\frac{1}{\tau_{\max}}\right]. \tag{13}$$

The joint solving of Eqs (10) and (13) gives simple relationships in the forms:

$$a=\frac{r_o^2}{4\cdot\tau_o}\cdot\varphi_a\,, \tag{14}$$

$$\lambda=\frac{q_1}{4\cdot\Pi\cdot\Delta T_{\max}}\cdot\varphi_\lambda\,, \tag{15}$$

where: φ_a and φ_λ are coefficients dependent on φ_o, the values of which can be found in Table 1 [1], whereas:

$$\varphi_o=\frac{\tau_o}{\tau_{\max}}, \tag{16}$$

$$\varphi_a=\frac{\varphi_o}{\frac{1-\varphi_o}{\varphi_o}\cdot\ln\frac{1}{1-\varphi_o}}, \tag{17}$$

$$\varphi_\lambda=E_1\left(\frac{1}{\varphi_o}\cdot\ln\frac{1}{1-\varphi_o}\right)-E_1\left(\frac{1-\varphi_o}{\varphi_o}\cdot\ln\frac{1}{1-\varphi_o}\right), \tag{18}$$

where: $E_1(\beta)$ - integral characteristic function, β - auxiliary variable.

The integral characteristic function $E_1(\beta)$ has the form:

$$-E_1(-\beta)=\int_\beta^\infty\frac{\exp(-s)}{s}\,ds, \tag{19}$$

where: s - auxiliary variable. Taking into account the relationship $c\rho=\frac{\lambda}{a}$ we get:

T a b l e 1. Values of coefficients φ_λ and φ_α dependent to φ_o used in pulse method with liner heat source

φ_o	φ_λ	φ_α	φ_o	φ_λ	φ_α
0.01	0.0037	0.0100	0.46	0.2302	0.6359
0.02	0.0074	0.0202	0.47	0.2374	0.6565
0.03	0.0113	0.0305	0.48	0.2449	0.6776
0.04	0.0150	0.0408	0.49	0.2523	0.6992
0.05	0.0188	0.0513	0.50	0.2601	0.7213
0.06	0.0228	0.0619	0.51	0.2678	0.7441
0.07	0.0267	0.0727	0.52	0.2760	0.7675
0.08	0.0307	0.0834	0.53	0.2842	0.7916
0.09	0.0347	0.0944	0.54	0.2927	0.8163
0.10	0.0389	0.1055	0.55	0.3014	0.8418
0.11	0.0429	0.1167	0.56	0.3102	0.8681
0.12	0.0471	0.1280	0.57	0.3195	0.8953
0.13	0.0513	0.1395	0.58	0.3290	0.9233
0.14	0.0556	0.1511	0.59	0.3385	0.9523
0.15	0.0599	0.1629	0.60	0.3486	0.9822
0.16	0.0642	0.1748	0.61	0.3588	1.0133
0.17	0.0687	0.1869	0.62	0.3694	1.0455
0.18	0.0732	0.1991	0.63	0.3803	1.0789
0.19	0.0777	0.2115	0.64	0.3915	1.1137
0.20	0.0822	0.2241	0.65	0.4033	1.1499
0.21	0.0869	0.2369	0.66	0.4153	1.1876
0.22	0.0916	0.2497	0.67	0.4279	1.2270
0.23	0.0965	0.2629	0.68	0.4408	1.2682
0.24	0.1013	0.2762	0.69	0.4544	1.3113
0.25	0.1062	0.2897	0.70	0.4683	1.3566
0.26	0.1122	0.3034	0.71	0.4829	1.4042
0.27	0.1163	0.3173	0.72	0.4982	1.4544
0.28	0.1214	0.3315	0.73	0.5139	1.5074
0.29	0.1266	0.3459	0.74	0.5306	1.5635
0.30	0.1319	0.3605	0.75	0.5483	1.6230
0.31	0.1373	0.3753	0.76	0.5664	1.6864
0.32	0.1427	0.3905	0.77	0.5858	1.7540
0.33	0.1483	0.4059	0.78	0.6060	1.8264
0.34	0.1540	0.4215	0.79	0.6276	1.9043
0.35	0.1597	0.4375	0.80	0.6503	1.9883
0.36	0.1655	0.4537	0.81	0.6746	2.0793
0.37	0.1714	0.4703	0.82	0.7002	2.1784
0.38	0.1776	0.4872	0.83	0.7283	2.2869
0.39	0.1837	0.5044	0.84	0.7580	2.4064
0.40	0.1900	0.5220	0.85	0.7902	2.5389
0.41	0.1964	0.5400	0.86	0.8249	2.6870
0.42	0.2028	0.5583	0.87	0.8632	2.8538
0.43	0.2095	0.5771	0.88	0.9044	3. 0436
0.44	0.2163	0.5962	0.89	0.9508	3.2624
0.45	0.2233	0.6159	0.90	1.0020	3.6170

$$c\rho = \frac{q_1 \cdot \tau_o}{\Pi \cdot r_o^2 \cdot \Delta T_{\max}} \cdot \varphi_{c\rho}; \quad \varphi_{c\rho} = \frac{\varphi_\lambda}{\varphi_\alpha} \quad . \tag{20}$$

A heating element in the form of a resistance wire was placed inside a cylinder-shaped sample, at a known distance r_o from the 'hot end' of a thermoelement. The thermal pulse generated by the heating element by means of an electric current caused a change of the temperature of the sample which was measured with the use of the thermoelement and registered with a recording device. By measuring $\Delta T_{\max}$ (maximum increase of temperature caused by thermal pulse) and time $\tau_{\max}$ (after which the maximum temperature increase occurred) we determined the thermal properties of, for instance, apples.

Due to the high moisture of apples, the impulse method can be used to study their thermal properties since the measuring period is short (1 min). In order to determine apple dry mass, a vacuum drier was used. Weight measurements were carried out with the accuracy of ± 0.001 g.

Evaluation of errors in the determination of thermal properties

We employed the method of logarithmic integration, taking the following possible measurement errors into account: temperature - $\left|\Delta\left(\Delta T_{\max}\right)\right| = 0.01\text{K}$, distance between thermal element from linear source of heat $\left|\Delta r_o\right| = 0.02$ mm, time after which maximum temperature increase occurred - $\Delta T_{\max} - \left|\Delta\tau_{\max}\right| = 0.5$ s, duration of pulse $\left|\Delta\tau_o\right| = 0.05$ s, electric resistance $\left|\Delta R\right| = 0.05\,\Omega$ and length $\left|\Delta l\right| = 1\text{mm}$. By finding the logarithm and then integrating the Eq. (14) we arrived at a formula for maximum relative error of measurement of coefficient of thermal diffusivity:

$$\frac{\Delta a}{a} = 2\left|\frac{\Delta r_o}{r_o}\right| + 2\left|\frac{\Delta\tau_o}{\tau_o}\right| + \left|\frac{\Delta\tau_{\max}}{\tau_{\max}}\right|, \tag{21}$$

which was:

$$\delta_{\max} = \frac{\Delta a}{a} \cdot 100\% = 4.6\%. \tag{22}$$

The form of the formula for maximum relative error of the coefficient of thermal conductivity is:

$$\frac{\Delta\lambda}{\lambda} = \left|\frac{\Delta q_1}{q_1}\right| + \left|\frac{\Delta\left(\Delta \mathrm{T}_{\max}\right)}{\Delta \mathrm{T}_{\max}}\right| + \left|\frac{\Delta\tau_o}{\tau_o}\right| + \left|\frac{\Delta\tau_{\max}}{\tau_{\max}}\right|. \tag{23}$$

The linear thermal stream in Eq. (22) was determined from the formula $q_1 = \frac{I^2 R}{l}$, and the relative error made in the course of its determination was:

$$\left|\frac{\Delta q_1}{q_1}\right| = \left[2\left|\frac{\Delta I}{I}\right| + \left|\frac{\Delta R}{R}\right| + \left|\frac{\Delta l}{l}\right|\right] = 0.017, \tag{24}$$

relative error made when reading temperature:

$$\left|\frac{\Delta\left(\Delta T_{\max}\right)}{\Delta T_{\max}}\right| = \left|\frac{0.01}{1.8K}\right| = 0.004, \tag{25}$$

relative error of measurement of length of pulse:

$$\left|\frac{\Delta\tau_o}{\tau_o}\right| = 0.003, \tag{26}$$

relative error of time measurement ($\tau_{\max}$):

$$\left|\frac{\Delta\tau_{\max}}{\tau_{\max}}\right| = \left|\frac{1}{24}\right| = 0.021. \tag{27}$$

Finally, the maximum error of determination of coefficient of thermal conductivity was:

$$\delta_{\max}(\lambda) = \frac{\Delta\lambda}{\lambda} \cdot 100\% = 4.6\%. \tag{28}$$

Maximum relative error of measurement of volume heat capacity calculated from formula:

$$\frac{\Delta(c\rho)}{c\rho} = \left|\frac{\Delta q_1}{q_1}\right| + 2\left|\frac{\Delta\tau_o}{\tau_o}\right| + \left|\frac{\Delta\tau_{\max}}{\tau_{\max}}\right| + \left|\frac{\Delta\left(\Delta T_{\max}\right)}{\Delta T_{\max}}\right| + 2\left(\frac{\Delta r_o}{r_o}\right) \tag{29}$$

was $\delta_{\max}(c\rho) \cdot 100\% = 6.8\%$.

RESULTS AND DISCUSSION

Influence of temperature on the thermal properties of four varieties of fresh apples

In order to study the significance of the influence of water fraction and variety on the values of heat coefficients, the method of analysis of variance for double cross classification with various numbers of observations of the properties studied in the sub-class (Table 2) was applied. Temperature exerts a significant influence on the values of the thermal properties studied and for each of these values, the influence is at the level of significance of α=0.01. Significant differences were found for the coefficient of thermal conductivity and thermal diffusion for all the studied varieties, and no significant differences were found for the specific volumetric heat other than in the case of vars. Jonagold and Idared. Only in the case of thermal diffusion interaction between variety and temperature was the level of significance α=0.01. Relations between apple thermal properties and temperature can be expressed as linear equations. The graphs of these functions are straight lines

T a b l e 2. Analysis of thermal variance of the fresh apple coefficients

Size and source of variability	Degrees of freedom	$F_{calculated}$	F_o		Significance
			$F_{0.05}$	$F_{0.01}$	
		Thermal conductivity (λ)			
Variety	3	186.366	2.63	3.85	**
Temperature	7	228.739	2.04	2.70	**
Variety x temperature	21	0.858	1.83	2.40	—
Error	339				
		Thermal diffusion (a)			
Variety	3	204. 928	2.63	3.85	**
Temperature	7	208.857	2.04	2.70	**
Variety x temperature	21	2.168	1.60	1.92	**
Error	339				
		Specific heat ($c\rho$)			
Variety	3	26.356	2.63	3.85	**
Temperature	7	41.221	2.04	2.70	**
Variety x temperature	21	0.621	1.83	2.40	—
Error	339				

F - test of probability, $F_{0.05}$, $F_{0.01}$ - limit value of test-function from table of F-Snedecor distribution for level $a = 0.05$ and $a = 0.01$.
** significance at the level of α=0.01, — no significance found.

with positive directional coefficients. With increasing temperature, the values of thermal conductivity coefficients and thermal diffusion and volumetric heat capacity of all the apple varieties studied also increased as in the case of water, see Figs 1-3.

Relative moisture of fresh apples was differentiated (Jonathan 84.3%, Golden Delicious 84.5%, Idared 85.2%, and Jonagold 87.6%). At the same temperature level apples with lower moisture content had lower values of all the thermal properties studied (Table 3). Analyses of regression

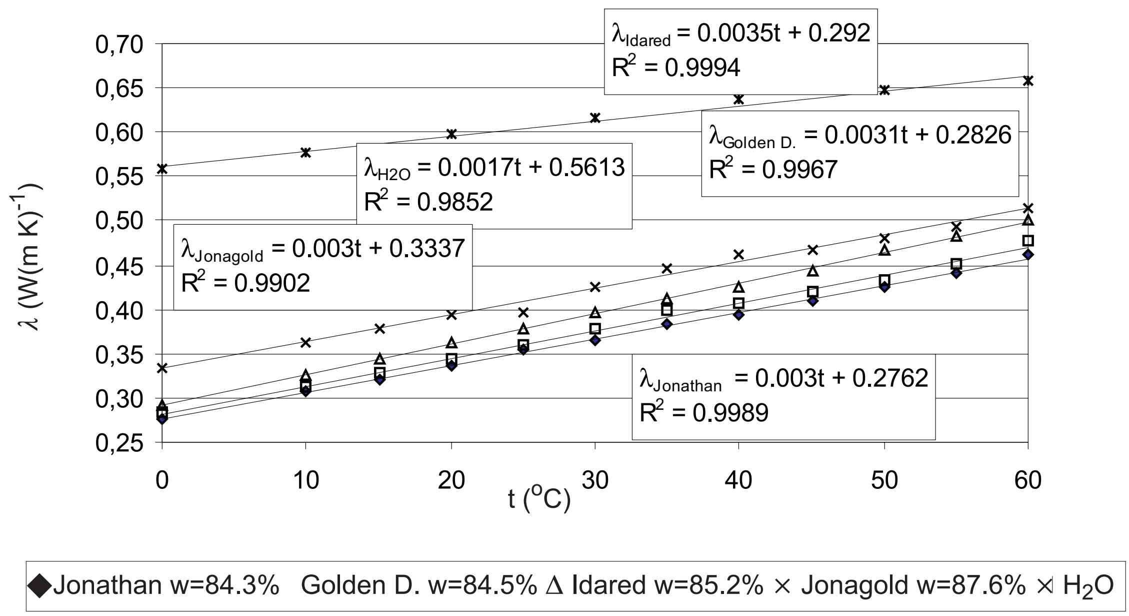

Fig. 1. Influence of temperature on the coefficient of thermal conductivity of apples and water.

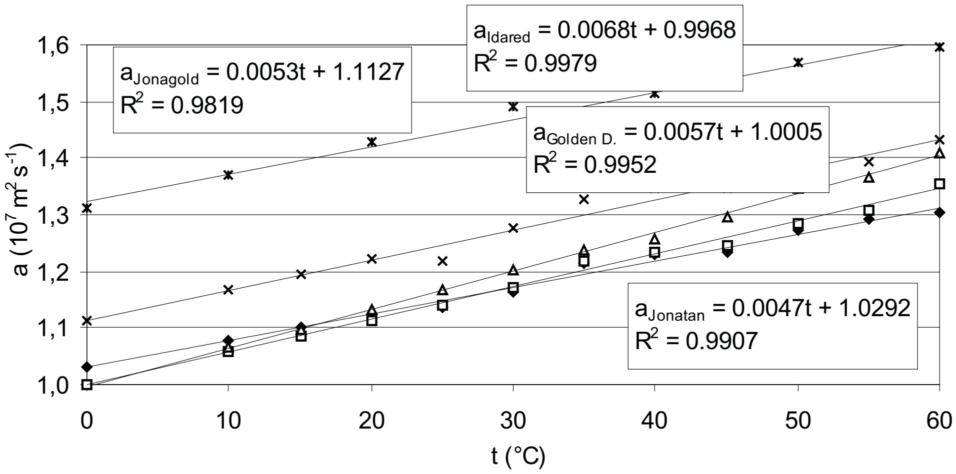

Fig. 2. Influence of temperature on the coefficient of thermal diffusion of apples and water. Legend as in Fig. 1.

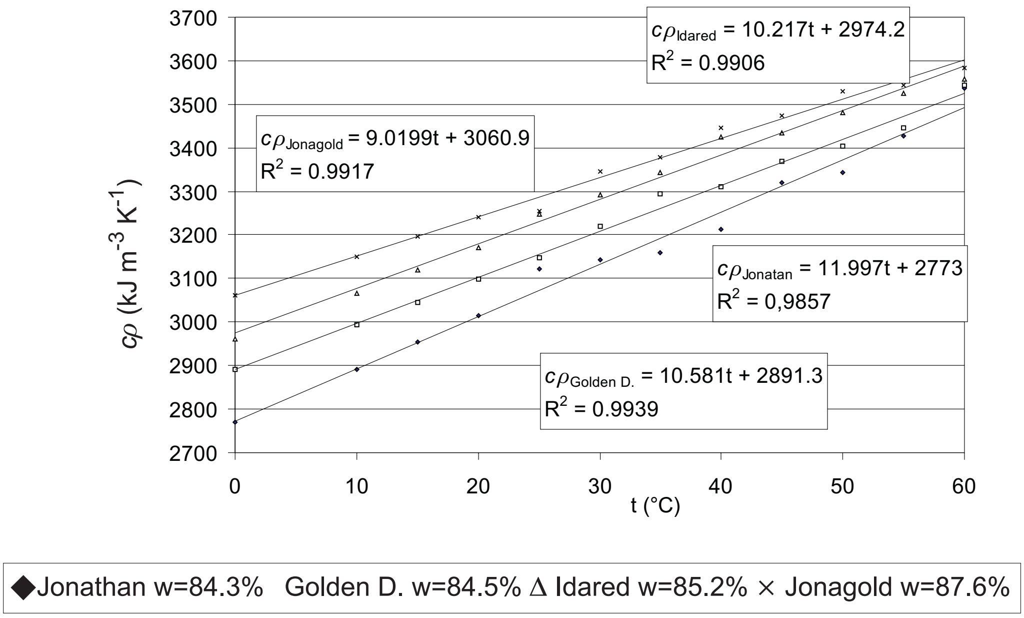

Fig. 3. Influence of temperature on the volumetric heat capacity of apples.

carried out for individual varieties were obtained in the form of functional relations that describe influence of temperature on the individual thermal properties of apples (Table 4). For all the equations, coefficients of regression equations are significant at the leve l of α=0.01.

Influence of temperature on the thermal properties of four apple varieties at constant moisture levels

At the same moisture and temperature levels, varieties Golden Delicious, Jonagold, Idared, and Jonathan differed significantly in respect to all the studied thermal properties,

Table 3. Relative moisture of apples and values of thermal coefficients at the temperature of 313 K (40°C)

Parameter	Variety			
	Idared	Jonathan	Golden Delicious	Jonagold
w (kg H_2Okg^{-1}100,%)	85.2	84.3	84.5	87.6
u (kg H_2O kg$_{d.b.}^{-1}$)	5.7567	5.3694	5.4516	7.0645
$\bar{\lambda}$ (Wm^{-1}K^{-1})	0.4262	0.3946	0.4081	0.4630
λ_r (Wm^{-1}K^{-1})	0.4299	0.3972	0.4079	0.4539
$\bar{a}$ (10^{7}m^{2}s^{-1})	1.2570	1.2287	1.2339	1.3459
a_r (10^{7}m^{2}s^{-1})	1.2673	1.2191	1.2307	1.3284
$(\overline{c\rho})$ (kJ m^{-3}K^{-1})	3425.4	3212.9	3311.3	3445.4
$(c\rho)_r$ (kJ m^{-3}K^{-1})	3380.1	3253.0	3310.8	3422.9

Table 4. Regression equations describing relations between thermal properties of fresh apples and temperature in the range from 273 to 333 K

Variety	n	Regression equation	R^2	$F_{calculated}$	$F_{0.05}$	$F_{0.01}$	
Idared	88	λ = 0.0035(T-273.15)+0.292 (W m^{-1} K^{-1})	0.9994	604.976	3.95	6.98	**
Idared	88	a = 0.0068(T-273.15)+0.9968 (10^{7}m^2 s^{-1})	0.9979	473.168	3.95	6.98	**
Idared	88	($c\rho$) = 10.217(T-273.15)+2974.2 (kJ m^{-3} K^{-1})	0.9906	52.328	3.95	6.98	**
Jonathan	91	λ = 0.003(T-273.15)+0.2762 (W m^{-1} K^{-1})	0.9989	281.152	3.95	6.98	**
Jonathan	91	a = 0.0047(T-273.15)+1.0292 (10^{7}m^2 s^{-1})	0.9907	373.215	3.95	6.98	**
Jonathan	91	($c\rho$) =11.997(T-273.15)+2773 (kJ m^{-3} K^{-1})	0.9857	63.681	3.95	6.98	**
Golden D.	104	λ = 0.0031(T-273.15)+0.2826 (W m^{-1} K^{-1})	0.9967	507.339	3.94	6.90	**
Golden D.	104	a = 0.0057(T-273.15)+1.0005 (10^{7}m^2 s^{-1})	0.9952	398.245	3.94	6.90	**
Golden D.	104	($c\rho$) =10.581(T-273.15)+2891.3 (kJ m^{-3} K^{-1})	0.9939	115.279	3.94	6.90	**
Jonagold	88	λ = 0.003(T-273.15)+0.3337 (W m^{-1} K^{-1})	0.9902	316.848	3.95	6.98	**
Jonagold	88	a = 0.0053(T-273.15)+1.1127 (10^{7}m^2 s^{-1})	0.9819	230.457	3.95	6.98	**
Jonagold	88	($c\rho$) = 9.0199(T-273.15)+3060.9 (kJ m^{-3} K^{-1})	0.9917	94.155	3.95	6.98	**

**significance at the level of α=0.01, n – number of measurements.

e.g., thermal conductivity (w=50%, T=313 K, t=40°C) is, respectively, 0.3256, 0.3133, 0.3038, and 0.2505 Wm^{-1}K^{-1}. If we assumed that the above coefficient for cv. Golden Delicious is 100%, then the relative volume for individual varieties studied is as follows: Jonagold 60%, Idared 93%, and Jonathan 77%. The maximum estimated error of neglecting the individual properties of varieties would be 23%.

In the same conditions (T=313 K, w=50%), volumetric heat capacity for individual apple varieties is different, i.e., for Golden Delicious it is 3088, for Idared 2921, for Jonagold 2704, and for Jonathan 2319. If we assumed that for var. Jonagold the coefficient value is 100%, the difference for individual varieties would be as follows: Idared 79%, Jonagold 73%, and Jonathan 63%. The difference between var. Golden Delicious and Jonathan is 37%. If we neglect differences between individual varieties in this case, it would lead to considerable error.

In the same conditions (T=313 K, w=50%), the coefficient of thermal diffusion (10^{7}m^{2}s^{-1}) is as follows: for var. Jonagold 1.1583, for Jonathan 1.0806, for Golden Delicious 1.0551 and for Idared 1.0374. If the value of the thermal diffusion coefficient for var. Jonagold was assumed as 100%, then for Jonathan the value of this coefficient is 93%, for Golden Delicious it is 91%, and for Idared it is 89%. The above shows that the thermal properties of individual apple varieties are different.

Since the volume water fraction in apples is (e.g., for Jonagold) about 83%, and the mass fraction about 88%, thermal properties of apples and water were assumed equal, since water can be used as a standard. Both in the case of apples and for water, with a temperature increase, the coefficient of thermal conductivity and diffusion increase, and the increase is of a similar character (Figs 1-2). At the increase in the range T=298-333 K (25-60°C) coefficient of thermal conductivity for var. Jonagold changed in the range from 0.3972 to 0.5144 W $m^{-1}K^{-1}$ (from 0.606 to 0.658 for water), and the coefficient of thermal diffusion for apples from 1.2192 to 1.4342 $10^7 m^2 s^{-1}$ (from 1.46 to 1.597 for water); specific volumetric heat for apples increases from 3455 to 3805 J kg^{-1} K^{-1} and for water it decreases in the temperature range from 298 to 313 K (40-60°C). We did not find any temperature influence on apple density, and in the range from 293 to 333 K (25-60°C) water density decreases only slightly (from 0.9965 to 0.983 g cm^{-3}). Probably due to the above, the specific volumetric heat of apples has a rising tendency with a rising temperature, and decreases slightly in the case of water.

Results of our own studies confirmed a rectilinear relation between the coefficient of the thermal conductivity of fresh apples and temperature that has also been discovered by numerous other researchers [2,7,9]. According to the equations quoted by these authors, raw material at a temperature of 313 K has thermal conductivity [2] of 0.537 $Wm^{-1}K^{-1}$ generally for apples, and for var. Golden Delicious [7] it is 0.479 (in the present studies for the same variety it is 0.408), for var. Jonathan - 0.395, for var. Idared - 0.426, and for var. Jonagold - 0.463. The var. Jonathan studied by the present authors at the same temperature was characterised by a regressive value of thermal conductivity coefficient of 0.397, the same values for var. Idared was 0.430 and for var. Jonagold - 0.454. According to Lozano *et al*. [5] the same coefficient for var. Granny Smith was 0.467 $Wm^{-1}K^{-1}$.

The experimentally determined value of the thermal diffusion coefficient for apples according to Iljasov *et al*. [2] at a temperature of 40°C was 1.784 $10^{-7}m^2s^{-1}$ and for var. Golden Delicious it was 1.532 [7]. According to our studies, the values of thermal diffusion coefficient were as follows: var. Jonathan - 1.229, var. Golden Delicious - 1.234, var. Idared - 1.257, and var. Jonagold - 1.346 $10^{-7}m^2s^{-1}$.

CONCLUSIONS

On the basis of the present studies and analyses of the results obtained, conclusions were drawn on the influence of temperature on thermal conductivity, heat diffusivity and specific heat volumetric capacity of apples from the following varieties: Idared, Jonathan, Golden Delicious, and Jonagold at the temperature range from 273 to 333 K (0-60°C) and the moisture level characteristic of fresh fruit of a given variety and the moisture levels chosen.

1. Temperature exerts a significant influence on the coefficients of thermal conductivity, thermal diffusion and volumetric heat capacity in the apple varieties studied. In the case of each of these influences, the significance is at the level of α=0.01. For the coefficient of thermal conductivity and thermal diffusion, significant differences between all of the properties studied were observed at the significance level α=0.01. In the case of specific volumetric heat, no statistically significant differences were found except for the varieties Jonagold and Idared.

2. Both in the case of apples and water, with an increase of temperature, the coefficient of thermal conductivity and diffusion increases as well.

3. Relations between the heat properties studied and temperature are expressed as rising linear functions, and their graphs are straight lines with positive directional coefficients. Mathematical elaboration of the present results on the influence of temperature on the thermo-physical properties of apples enables their application for working out the theory and technology of the drying process.

4. At the same temperature and moisture level, varieties Golden Delicious, Jonagold, Idared, and Jonathan differed significantly in all the thermal features studied (α=0.01), e.g., thermal conductivity (w=50%, T=313 K, t=50°C) is, respectively, 0.326, 0.313, 0.304 and 0.251 $Wm^{-1}K^{-1}$.

5. In the same conditions (T=313 K, w=50%) coefficient of thermal diffusion is 1.1583 for var. Jonagold, 1.0806 for var. Jonathan, 1.0551 for var. Golden Delicious, and 1.0374 m^2s^{-1} for var. Idared. If the values of the thermal diffusion coefficient for var. Jonagold were assumed as 100%, then for var. Jonathan the value of this coefficient is 93%, for Golden Delicious - 91%, and for var. Idared - 89%.

6. In the same conditions (T=313 K, w=50%), volumetric heat capacity was 3088 for var. Golden Delicious, 2921 for var. Idared, 2704 for var. Jonagold, and 2319 kJ $m^{-3}K^{-1}$ for var. Jonathan. The difference between the varieties Golden Delicious and Jonathan is 37%. If varietal properties are neglected, it will result in considerable error.

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