Int. Agrophys., 2011, 25, 131-139

INTERNATIONAL
Agrophysics
www.international-agrophysics.org

Radiation temperature of tomatoes and mechanical properties of their skin

B. Gładyszewska[1], P. Baranowski[2]*, W. Mazurek[2], A. Ciupak[1], and J. Woźniak[2]

[1]Department of Physics, University of Life Sciences, Akademicka 13, 20-950 Lublin, Poland
[2]Institute of Agrophysics, Polish Academy of Sciences, Doświadczalna 4, 20-290 Lublin, Poland

Received October 24, 2010; accepted January 24, 2010

A b s t r a c t. This paper compares radiation temperature distributions on the skin surface and in the pedicle part of tomato fruit during storage at two ambient temperatures with the results of mechanical tests. Variations in Young's modulus, Poisson's ratio and critical surface tension were studied. An increase in Young's modulus and critical surface tension was reported, while Poisson's ratio stabilized at the level of 0.45-0.46. Thermographic studies were performed using passive and active methods, and fruit skin was subjected to mechanical tests where the prepared samples were uniaxially stretched to determine Young's modulus and Poisson's ratio of the skin. The results of passive thermography tests reveal that the differences between skin temperature and pedicel temperature decreased over time (fruit ripening), but a higher drop was noted in respect of the fruit stored at the temperature of 21 than 13°C. Regardless of ambient temperature, the highest water loss rate was observed in the first period of fruit storage. The heat response of tomato skin and pedicels showed significant differences in the thermal properties of the studied plant parts. The respective characteristics of the skin thermal response changed significantly over time, in particular at higher storage temperature (21°C). A corresponding, statistically significant decrease in Young's modulus noted under the above storage conditions suggests a possible correlation between the thermal and mechanical characteristics of tomato skin.

K e y w o r d s: tomato, skin, mechanical properties, thermal image analysis

INTRODUCTION

Tomato fruit comprises cell material which is characterized by a high water content and high sensitivity to mechanical stress as well as variations in harvest, transport and storage conditions. In tomatoes, the skin has a protective function, and its mechanical properties determine the fruit quality and processing suitability. The skin of tomato fruit protects the soft internal tissue, and it affects the product integrity. Stress relaxation in vegetable tissue was extensively studied and relevant models has been proposed (Blahovec, 2001). However, there is lack of models concerning 2D objects as fruit skins. The skin also controls the growth process (Andrews *et al*., 2002; Bargel and Neinhuis, 2005). The skin is an important source of nutrients. A high content of vitamins A and C, potassium, flavonoids, lycopene and antioxidants in the skin increases the health benefits of the entire fruit. The mechanical properties of coat layers in fruit, including tomato skin, are an important consideration that affects the quality and safety of the end product, product storage, processing and the structural design of machines and devices used in food processing systems (Thiagu *et al*., 1993). Textural attributes of tomato fruit skin are among the most important external features examined during ripening, they determine further storage, and they are one of the key visual stimuli for consumers in the purchasing process (Batu, 2004; Gładyszewska and Ciupak, 2009; Lopez Camelo and Gomez, 2004).

Brummell (2006) defines the ripening process as a series of geneticaly programmed biochemical processes that give the unripened, usually acidic and hard fruit its soft and sweet texture. The noted drop in turgor pressure results from the accummulation of dissolved substances in the cells and water loss, leading to changes in the fruit textural properties, leading to the decay of cells walls and a temporary increase in the pressure of the chambers surrounding the seeds (Almeida and Huber, 2001). Such transformations are also accompanied by an increase in respiration levels and the release of heat energy (Saltveit, 2005).

Nondestructive methods are increasingly often applied in studies of fruit and vegetable quality (Cybulska *et al*., 2010; Khojastehnazhand *et al*., 2009). They support the

*Corresponding author's e-mail: pbaranow@ipan.lublin.pl

remote determination of physical quantities describing the studied objects (Abbott, 1999; Brown and Sarig, 1994; Xing *et al*., 2006). Thermography is one of such methods, and it supports non-contact, real time measurements of temperature distributions on the surface of the investigated objects (Baranowski and Mazurek, 2009). This method relies on measurements of the radiated thermal energy flux whose density is defined by the Stefan-Boltzmann law. The term “radiation temperature” is used to account for the radiation characteristics of this form of energy transfer in non-contact temperature measurements. Radiation temperature is equal to thermodynamic temperature multiplied by the object emissivity coefficient to the power of ¼. The thermographic device visualizes the density flux of infrared radiation, producing a thermal map of the investigated object. Colours represent temperature ranges which are displayed in digital form when a given point is selected in the camera or the monitor during data processing.

Recent years have witnessed the growing popularity of thermographic applications for investigating the quality of agricultural products. The aim of such studies is to determine mechanical damage to fruit and vegetables (Baranowski and Mazurek, 2009; Baranowski *et al*., 2009; Van Linden *et al*., 2003; Varith, 2001; Varith *et al*., 2003), physiological changes in fruit flesh such as the watercore (Baranowski and Mazurek, 2009; Baranowski *et al*., 2008; Jones, 1999) and changes on the fruit surface, such as discolourations or spots, which are undetectable in the visible range of the spectrum (Veraverbeke *et al*., 2006), and to determine the transpiration rate during fruit storage (Leonardi *et al*., 2000). Several attempts were also made to apply thermographic methods in analyses of grain infestations with insects and microorganisms (Neethirajan *et al*., 2007; Oerke *et al*., 2006; Rajendran, 1999), and the results of those studies were put to practical use for testing grain stored in silos (Manickavasagan *et al*., 2006). Thermal imaging methods have been deployed to determine the germination capacity of seeds based on their surface temperature in the early stage of swelling, to evaluate the plants response to water stress (Jones, 1999; Walczak *et al*., 2004), salt stress (Matuszak *et al*., 2004), oxidative stress (Mazurek *et al*., 2000), temperature stress (Fuller and Wiśniewski, 1998) and biotic stress (Chaerle and Van der Straeten, 2001). The results of thermographic studies investigating temperature distributions in plant stands were used together with agrometeorological data to determine the actual evapotranspiration rate (Walczak *et al*., 2004) and to evaluate the quantity and the diameter of orchard fruit in pomological research (Stajanko *et al*., 2004).

The impact of various storage conditions on the mechanical and thermal properties of fruit is also studied to investigate the extent to which the physiological status of agricultural products affects other qualitative parameters in the production process (Hellebrand *et al*., 2000).

The aim of this study was to determine changes in radiation temperature distributions on the skin surface and in the pedicle part of tomato fruit cv. Admiro during storage at two ambient temperatures, and to investigate the correlation between the said changes and variations in the mechanical properties of fruit skin.

MATERIALS AND METHODS

Skin tensile tests and thermographic evaluations were carried out on tomato fruit (*Lycopersicon esculentum* Mill) cv. Admiro supplied by the Leonów Greenhouse Gardening Company in Niemce near Lublin. The investigated fruit material was delivered directly after harvesting. Tomato fruits were in the initial ripening stage with green-orange colored skin.The harvested fruits were similar in size, but they were additionally sorted prior to placement in a controlled environment chamber. Fruits with visible defects and skin damages were rejected, and the remaining material was sorted to select fruits with similar skin pigmentation. The fruits were placed side by side in plastic containers with no contact between separate items. Tomato fruits were divided into two equal groups of 50 items each, and they were placed in a controlled environment chamber – one group at the temperature of 13°C and the other group at 21°C. The first temperature (13°C) was optimal for tomato storage, whereas the second regime (21°C) approximated the conditions of retail turnover. Several fruits were selected from each group for mechanical tests as well as passive and active thermographic measurements. The first tests investigating the mechanical properties of the skin and the thermographic measurements of the fruit stored at the temperature of 21°C were carried out several hours after the harvest, whereas the fruit stored at temperature 13°C was analyzed after one day of storage in a controlled environment chamber. Subsequent measurements were performed every two or three days until full ripening.

Rheological investigations involved the determination of Young’s modulus, Poisson’s ratio and critical surface tension of the skin based on uniaxial tensile tests. The method of random markers was applied to determine Young’s modulus, Poisson’s ratio and critical surface tension of the skin (Gładyszewska, 2006). This method relies on the analysis of the image of and the distance between points on the surface of the sample subjected to uniaxial stretching tests. The images of the stretched specimen with graphite markers randomly sprayed on its surface and the value of the tensile force corresponding to each image were downloaded to the computer. The signal from the tensometer was transmitted to the computer with the use of an analogue-to-digital converter, and the registered image of a stretched specimen was downloaded to the video input. Figure 1 shows schematically the set-up used for uniaxial stretching tests.

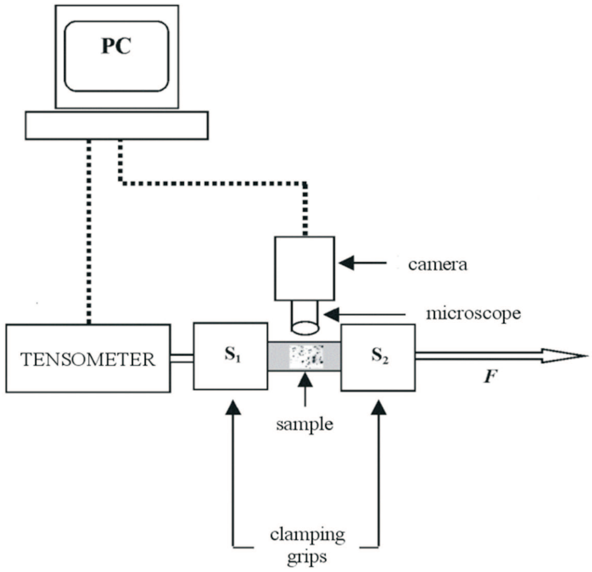

Fig. 1. Scheme of the setup used for uniaxial stretching tests. S1 and S2 – clamping grips, F - force.

Using a CCD camera equipped with a microscope lens for viewing the specimen at 240x320 pixel resolution under 5 x magnification, the stretched specimen was observed until the moment of tensile failure. The specimen was placed in clamping grips. The fixed clamping grip was connected to the Megaton Electronic (AG and Co) KT-1400 tensometer with a force measurement range of 0-100 N, and the moving grip was flexibly connected to a transmission device for stretching the specimen.

The main advantage of the method of random markers is that the obtained results are independent of the effects observed along the specimen edges. The studied material can also be examined at different points, even if damaged. Unlike most tensile testing devices, this method supports observations of the force and not the total increase in strain. The observed specimen area is exposed to a uniformly variable force, whereas the damage occurs in a parallel or perpendicular direction to the tensile force, subject to the structure of the plant material (Gładyszewska, 2007).

Tomatoes were removed from the controlled environment chamber and kept in a laboratory until fruit temperature became equal to ambient temperature (around 2 h). The ambient temperature in the laboratory was stabilized at 21±1°C. After washing and drying the surface of the fruit, skin specimens were procured for tensile tests. Due to the absence of an unambiguous boundary separating the flesh and the skin, longitudinal strips were sliced off from each fruit with a profiled, single-blade knife with a limiter. The incision was made from the base of the tomato to the stalk. The samples had the shape of a strip with the length of 30 ± 0.1 mm and the width of 10 ± 0.1 mm. The above values were measured with the use of a caliper. The thickness of each sample was measured under an optical microscope at 5 points in the central part of the stripe on both sides. The sample was placed on a slide in the slit of a measuring table for observing its longitudinal section under an ocular microscope. Thickness was expressed as the average of 10 individual measurements with the accuracy of ± 0.05 mm. The applied instrument produced a constant, measurable increase in the tensile force which equaled 4.2 N min^{-1}. Powdered graphite markers were applied to the surface of the fixed sample with a special brush. Each measurement was performed in 30 replications. Young's modulus E is defined as the ratio of stress over strain in the direction of the x-axis (Eq. (1)). Young's modulus for each sample was determined based on the value of the slope of a straight line approximating individual dependence $\varepsilon_x = f(\sigma)$, where ε_x is the relative elongation in the direction of the x-axis, and σ is the value of stress.

The critical surface tension of a stretched specimen was determined using Eq. (2), and Poisson's ratio ν was computed based on dependence (3):

$$E = \frac{\sigma}{\varepsilon_x}, \tag{1}$$

$$\sigma_k = \frac{F_z}{S}, \tag{2}$$

$$\nu = -\frac{\varepsilon_y}{\varepsilon_x}, \tag{3}$$

where: F_z – maximum value of the force at which the specimen is damaged (N), S – cross-sectional area of the specimen (mm^2), ε_x – relative elongation in the direction of the applied tensile force (-), ε_y – relative elongation in a perpendicular direction to the applied force (-).

Figures 2 and 3 present the microscopic images obtained with the use of a scanning electron microscope. The images illustrate the damage to skin cells layers in tomato fruit.

Samples of peeled skin from ripe and fully pigmented as well as green tomato fruits cv. Admiro were fixed and dehydrated in acetone at various concentrations. The samples were dried at critical point in the EMITECH K850 device and mounted on cylindrical aluminum object stages. A layer of gold was sprayed on the samples in the EMITECH K550X Sputter Coater. Microscopic images of the specimens were produced by the BS300 TESLA scanning electron microscope at accelerating voltage of 15 kV.

Microscopic analyses supported observations of the effects of the applied tensile force. Figs 2a and 3a present the cross-sections of skin stripes incised with a sharp scalpel, while Figs 2b and 3b show cell deformations. Green and red tomato fruits were sliced in mid-length to observe different cell layers. A microstructural analysis of the skin incised from green and fully mature fruits (Figs 2a, 3a) shows differences in cell geometry, most likely as the result of biochemical changes taking place during the ripening process.

An analysis of surface disruptions in the skin of green tomato fruits (Fig. 2b) reveals distinctive stretching or even significant damage to the cell wall. The obtained images show the highest degree of damage along the outer layer of the smallest cells. The cross-section of a skin sample from a mature tomato fruit (Fig. 3b) indicates that the applied tensile force suppresses cells in the outermost layer, leading to the explicit destruction of the walls of the largest cell directly beneath the smallest cells.

The distribution of radiation temperature on the surface of tomato fruit cv. Admiro was investigated with a noninvasive method (passive method) as well as a pulsed-phase method (active method). In passive (static) thermography, temperature distribution and the specimen emissivity coefficient are measured under stationary or semi-stationary conditions *ie* when the quantity of produced heat is equal to the amount of energy dispersed into the environment. Active thermography methods (Ibarra-Castanedo, 2005; Maldague *et al*., 2002) involve the excitation of the specimen surface with a short-term heat pulse (lasting from several milliseconds to a few seconds) and observations of temperature changes over time at specific points in a sequence of thermal images. Any heterogeneities in the thermal properties of the specimen parts (in this case, the skin and an abscission joint in the pedicel part of the fruit) are represented in the thermograms as pixels with varied temperatures, and they are expressed by thermal contrast. Consecutive measurements with the use of passive thermography were carried out every 2-3 days. Active thermography tests were performed on selected fruits directly after passive measurements. Before each measurement, tomato fruits were removed from the controlled environment chamber and stored in the laboratory until they reached ambient temperature.

Thermographic analyses of tomato fruit cv. Admiro were performed with the involvement of the VIGOcam v50 camera (VIGO Systems S.A., Poland) with an operating range of 8-13 μm. The camera is equipped with a microbolometric detector, it has spatial resolution of 384 × 288 pixels and radiometric resolution of 60 mK. The measurements were performed under controlled temperature and relative humidity of ambient air. Changes in the above parameters were monitored every 1 min with the use of the LB705 device.

During thermographic measurements, each fruit was placed in a position revealing the abscission joint in the fruit pedicel part and a considerable part of the fruit skin to the camera (Fig. 4). The thermal camera was positioned 1.2 m from the surface of the fruit. The emissivity coefficient of the entire fruit surface was adopted at 0.98.

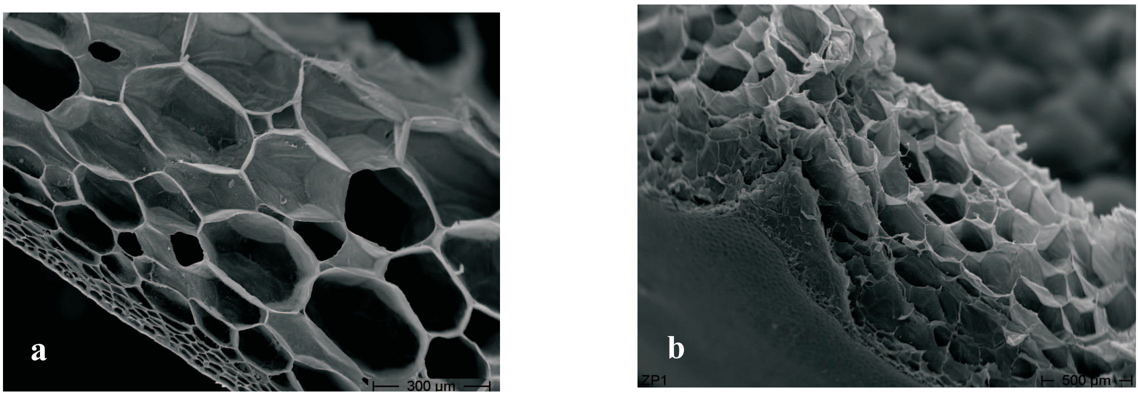

Fig. 2. Cross-sections of the skin of green tomato fruits: a – before, b – after the break.

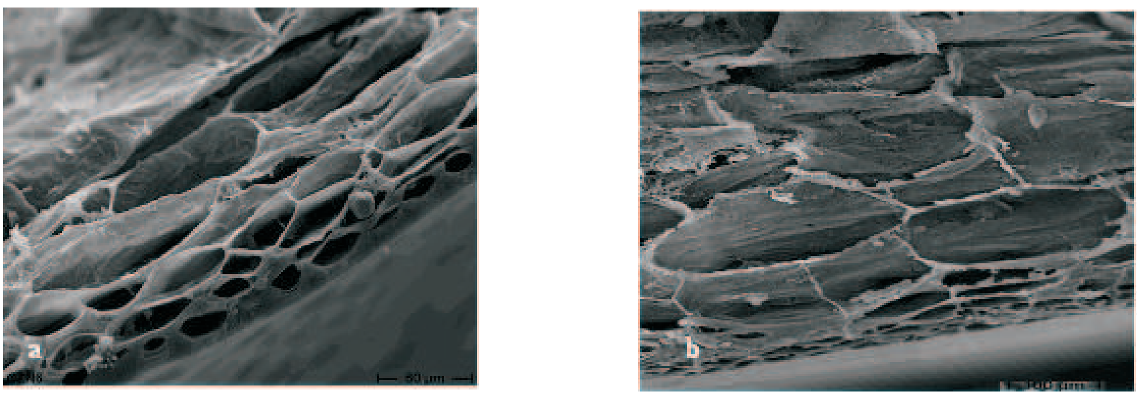

Fig. 3. Cross-sections of the skin of ripe tomato fruits: a – before, b – after the break.

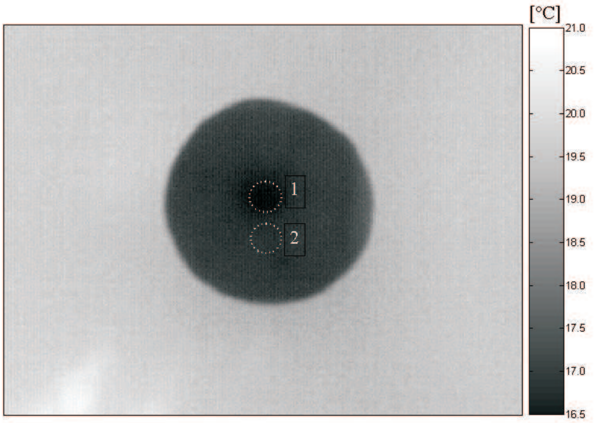

Fig . 4. Thermogram of tomato fruits cv. Admiro with two selected areas representing the pedicel (1) and the skin (2) of the fruit.

In passive measurements, an individual thermogram was produced for each fruit, whereas in active measurements, two-minute thermogram sequences were recorded with the frequency of one image per second. The heat pulse was produced by four PHILIPS PAR 38 175W infrared (IR Red) lamps. Heat pulse duration was 3 s.

The thermograms were analyzed by calculating the mean temperature of the pedicel part of the fruit (area 1 in Fig. 4) and a selected skin area (area 2 in Fig. 4). The difference between pedicel and skin temperatures was calculated for each measurement. The differences between the temperature of the studied fruit parts and ambient temperature were also calculated for all images. Air temperature and air humidity were measured for every thermographic image.

RESULTS AND DISCUSSION

The examinations involving tomato fruit cv. Admiro stored at 21°C were completed after 12 days due to fruit softening and progressive difficulty with preparing analytical specimens. The fruits stored at 13°C remained firm until the end of the four-week experiment.

Figure 5 presents changes in the mean values of Young's modulus of the skin of tomato fruits cv. Admiro stored at 13 and 21°C. In the group of fruits stored at 13°C, the value of Young's modulus reached 4.15 MPa on harvesting day, 3.79 MPa after 14 days and 3.04 MPa after 21 days of the experiment. On the last day of the experiment, Young's modulus decreased by approximately 40% in comparison with day 1 to reach 2.48 MPa. Changes in Young's modulus characterizing the skin of tomato fruits cv. Admiro stored at 21°C are presented in Fig. 5b. After 24 h of storage (the first day of the experiment), the mean value of Young's modulus was 6.4 MPa. A 30% drop in the above parameter was noted two days later. On the last day of the experiment (day 12 of fruit storage at 21°C), the value of the longitudinal elasticity modulus reached 2.25 MPa, showing a 65% decrease from the first day of the experiment.

Changes in the values of Poisson's ratio characterizing the skin of tomato fruits cv. Admiro are presented in Fig. 6. In the group of fruits stored at the temperature of 13°C, Poisson's ratio decreased from 0.73 on harvesting day to 0.56 after 26 days of storage (Fig. 6a), implying a 22% drop. As regards the fruits stored at 21°C, the mean values of Poisson's ratio did not change significantly and were determined in the range 0.46-0.47 (Fig. 6b).

Changes in critical surface tension values of the skin of the studied tomato cultivar are presented in Fig. 7. In the group of fruits stored at 13°C, critical surface tension values reached 0.29 MPa on harvesting day and were maintained until the fourteenth day of storage. On the last day of measurement, the value of critical surface tension decreased by more than 30% in comparison with the first day of the experiment, reaching 0.19 MPa (Fig. 7a). In the group of fruits stored at the temperature of 21°C (Fig. 7b), the value of critical surface tension on the first day of the experiment was 0.49 MPa. After the successive seven days, the studied parameter decreased by more than 50% to reach 0.24 MPa. On the last day of experiment, the value of critical surface tension was only 0.19 MPa.

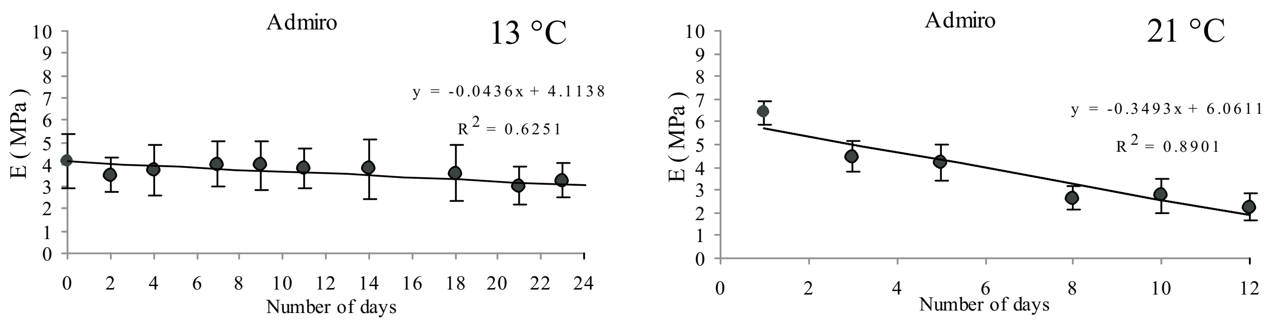

Fig. 5. Average values of Young's modulus *E* determined for tomato fruit skin samples on every day of the storage period with standard deviation.

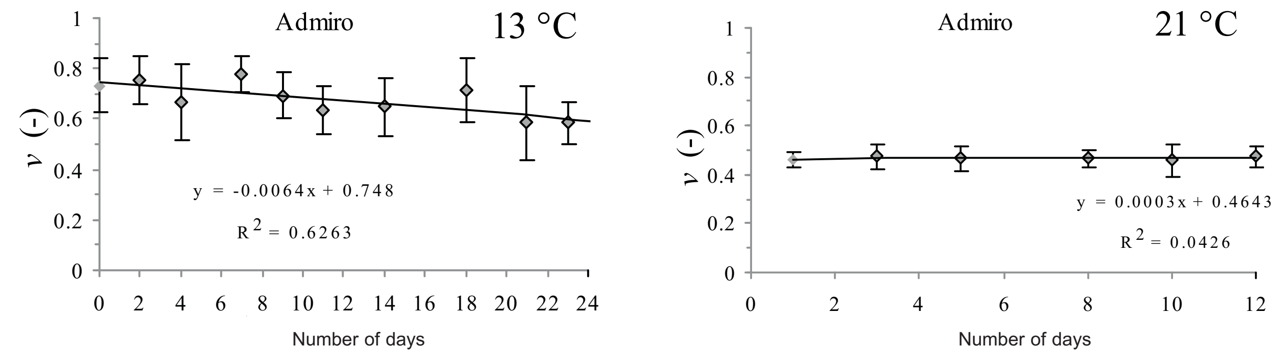

Fig. 6. Average values of Poisson's ratio v determined for tomato fruit skin samples on every day of the storage period with standard deviation.

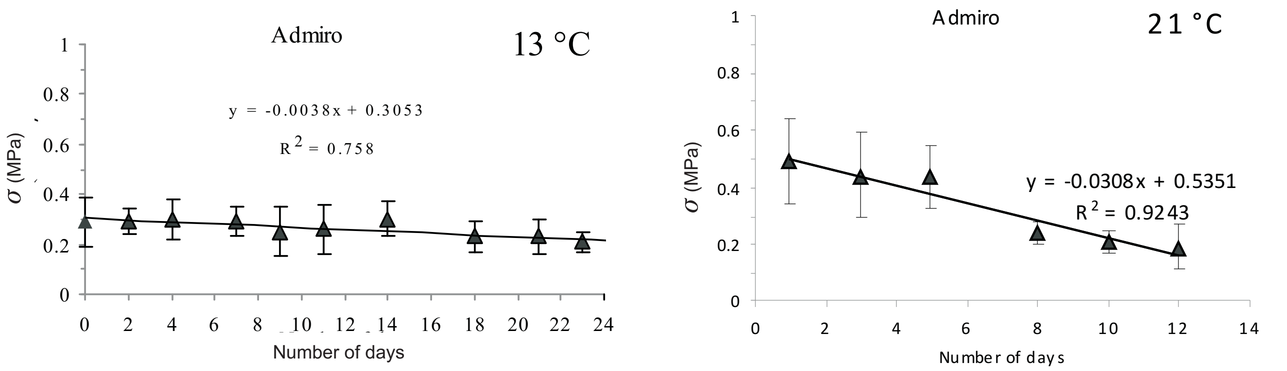

Fig. 7. Average values of stress determined for tomato fruit skin samples on every day of the storage period with standard deviation.

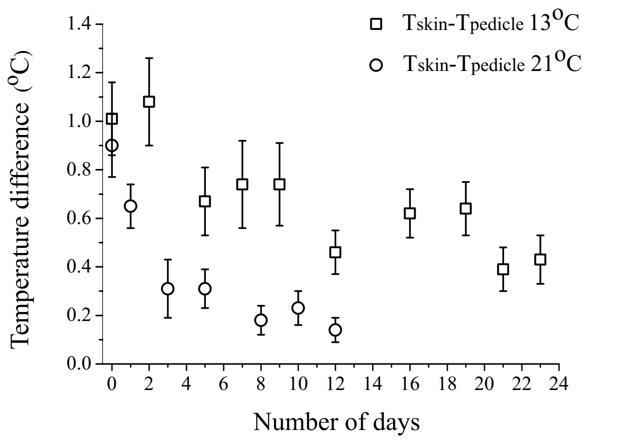

Fig. 8. Changes in temperature differences between the skin and the pedicel parts of tomato fruits stored at different ambient temperatures (mean values for 25 tomato fruits in each group).

The analysis of thermograms produced with the involvement of the passive method revealed significant differences between the temperature of the fruit pedicel part and selected skin areas at various stages of fruit storage as well as differences between fruits stored at various temperatures. On every day of the experiment, greater differences were noted in respect of the fruits stored at a lower temperature (13°C), suggesting more distinctive variations between the thermal properties of the skin and the pedicel with a higher temperature gradient between ambient air and the fruit (although the fruits removed from the controlled environment chamber were set aside for two hours to reach ambient temperature, their flesh temperature remained below that reported in the fruits stored at 21°C). In the testing period of 12 days for fruits stored at 21°C and 23 days for fruit stored at 13°C, the differences in the temperature of the pedicel and the skin were significantly minimized. In the course of 12 days, the noted differences were less profound in the group of fruits stored at 21°C (0.76°C) than the fruits stored at 13°C (0.55°C). After that period, the differences in temperature between the pedicel part and the skin reached less than (0.1°C) for the fruits stored at 13°C. The leveling of temperature differences between the pedicel part and the skin during storage (fruit maturation) could result from changes in the properties of ripening fruit tissue that influence the fruit thermal and, possibly, mechanical properties.

The changes in temperature differences between the skin and the pedicel parts of the stored fruit, as shown in Fig. 8, illustrate the variations in the intensity of physiological processes during the fruit maturation process. The changes in the mean fruit mass values and mass loss rates during storage were investigated. As demonstrated in Fig. 9, a more rapid decrease in mass over time was observed in the fruits stored at a higher temperature. Figure 9a and 9b show changes in mass loss rates at the final stage of the experiment (for fruits stored at 21°C – between day 10 and 12, and for fruits stored at 13°C – between day 19 and 23). A clear drop in mass loss rates was observed in the above period. The above was probably related to the process of cell ageing in fruit skin, pedicel and flesh which influenced the rate of transpiration and respiration in fruit. In this context, it may be worth investigating whether the described changes in fruit characteristics had any impact on the skin and the pedicel thermal response to excitation with a heat pulse. The characteristics of thermal response to a heat pulse noted in the studied parts of tomato fruits are presented in Fig. 10

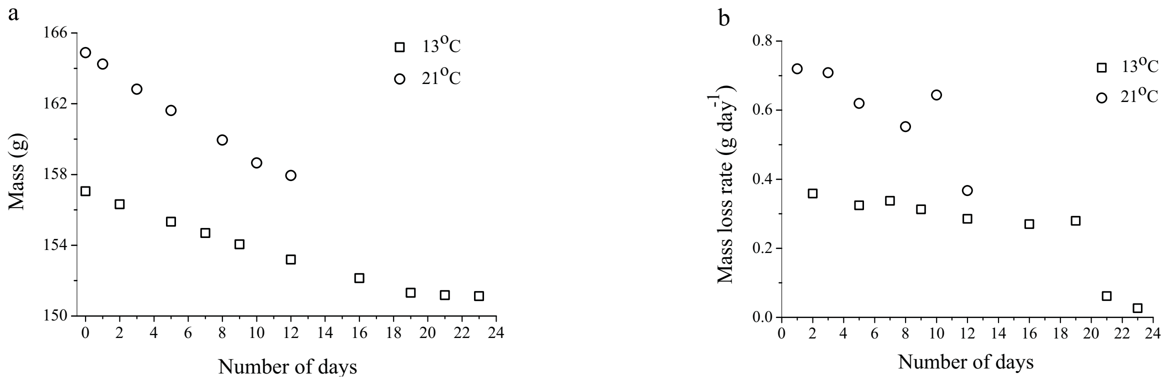

Fig. 9. Changes in the mean mass (a) of fruits stored at two different ambient temperatures and changes in the mass loss rate (b).

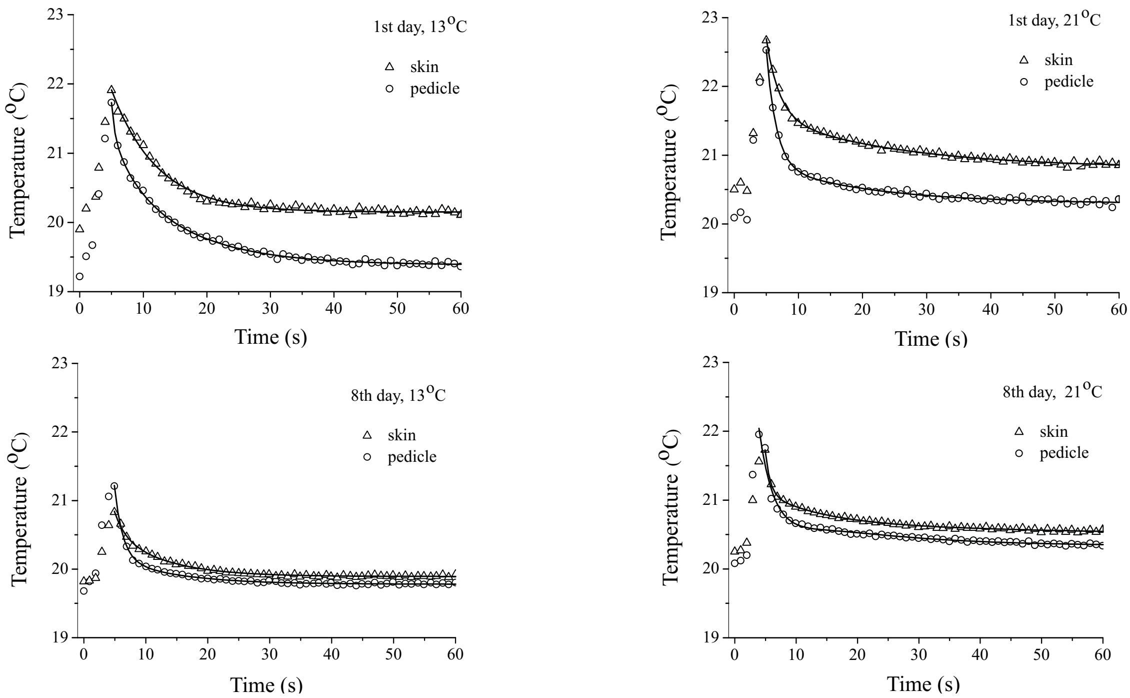

Fig. 10. Exemplary characteristics of the thermal response of tomato fruit pedicle and skin to thermal excitation induced by the pulsed-phase method at various stages of fruit storage at two ambient temperatures with fitted exponential curves.

after 1 and 8 days of the experiment. Considerable changes in the thermal response to a heat pulse were reported both for the skin and the pedicel part of tomato fruits. After the first day of the experiment, the increase in temperature during heat pulse excitation was higher in both fruit parts than after eight days of the experiment (the first part of the charts in Fig. 10), and greater variations were reported in the pedicle and the skin thermal response during post-pulse cooling (a part of the chart with a fitted exponential curve). The noted results point to changes in the thermal properties of the investigated fruit parts as well as the whole fruit during storage. The differences observed between the studied fruit parts were gradually leveled out over time.

CONCLUSIONS

1. The storage of tomato fruits cv. Admiro at the temperature of 13 and 21°C led to a drop in the values of Young's modulus and critical surface tension. The above decrease resulted from biochemical changes in the skin during tomato ripening and the ensuing changes in tissue structure. Poisson's ratio for tomato skin decreased over time in fruits stored at 13°C, whereas it remained stable with minor variations between 0.45 and 0.46 in the group of fruits stored at 21°C.

2. The distribution of radiation temperature on fruit surface changed over time, and it differed considerably between tomato fruits stored at various temperatures throughout the experiment.

3. The differences in temperature between the pedicel and the skin of the fruit were minimized over time for the fruits stored at both 13 and 21°C. The mass loss rates in fruits stored at various temperatures differed significantly, and an evident decrease in this parameter was observed during the final stage of fruit ripening.

4. The characteristics of thermal response to the heat pulse applied in the active thermography method also revealed differences at various stages of fruit ripening. The obtained results suggest considerable changes in the structure, the water content and the mechanical properties of fruit during the ripening process.

5. Storage temperature had a significant impact on the rate of fruit pigmentation. Fruit stored at the temperature of 21ºC reached full maturity after 12-14 days, while the fruit stored at 13 ºC entered the maturation stage after around four weeks.

6. The results of this study are the product of preliminary investigations, and they should be supplemented with additional data. Further research analyzing the mechanical and thermal properties of the skin of tomato fruit stored under different temperatures is required to predict maturation times based on changes in the above parameters over time.

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