Int. Agrophysics, 2009, 23, 9-17

INTERNATIONAL
Agrophysics
www.international-agrophysics.org

Detection of physiological disorders and mechanical defects in apples using thermography**

P. Baranowski and W. Mazurek*

Institute of Agrophysics, Polish Academy of Sciences, Doświadczalna 4, 20-290 Lublin, Poland

Received November 10, 2008; accepted December 16, 2008

A b s t r a c t. This paper presents the results of the studies on detection of fruit bruises and watercore in their tissues. Both passive and active pulse phase thermography was applied to early detect tissue defect. Watercore occurrence in 'Gloster' apples was evaluated from heating curves. It was found that the derivative of apple temperature in time per apple mass is a good parameter to identify apples with and without watercore. For apples with watercore the rates of temperature increase per mass in particular initial stages of heating were considerably lower than for apples without watercore affected tissue irrespective of the part of the fruit surface from which the measurements were made. Pulsed-phase thermography (PPT) method was used to detect early apple bruises in 'Idared' and 'Gloster'. In PPT method the studied object is heated with an individual thermal pulse (most frequently a rectangular pulse) and the temperature decay on the surface is analysed on a pixel by pixel basis as a mixture of harmonic waves, thus enabling the computation of phase and amplitude images. The analysis of phasegrams made it possible to determine the relation between the frequency response, phase delay and defect depth. PPT method used for early bruise detection enables identify defects which are invisible in passive thermography.

K e y w o r d s: apple watercore, apple bruise, thermography

INTRODUCTION

Recent years have brought new ideas of application of thermography in agrophysical studies (Baranowski *et al*., 2005b; Fito *et al*., 2004; Jones, 1999; Mazurek *et al*., 2006). It is connected with new possibilities given by active thermography which enables not only to study the surface changes of object thermodynamical processes but also to have an insight into deeper layers of specimens to give information about the sizes, properties and the depth of the defects (Ibarra-Castanedo and Maldaque, 2004; Więcek and Zwolenik, 1999). It occurred that thermography is especially useful in agrophysical studies. Many processes of mass and energy exchange in agrophysical systems are have their reflection in the change of the surface temperature of the studied bodies (Walczak *et al*., 2003). This concerns the soil-plant-atmosphere system where the transport of water and gas from the soil through the plant membranes into the atmosphere and the turbulent transport of air in the atmosphere create specific actual distribution of temperature on the surface of plant and soil. Measuring this parameter considerably improves evaluation the rate of evaporation from soil and transpiration from plants (Baranowski *et al*., 2005a). Similarly, in various stages of fruit production the dynamics of the fruit surface temperature distribution gives important information about the quality of the product. During growth, harvesting, storage and distribution fruits are the subject of constant changes of their temperature as a result of interaction with external factors such as solar radiation, frost, shading by leaves, cooling in storage houses what has an impact on their quality (Bowen and Watkins, 1997; Ferguson *et al*., 1999; Harker *et al*., 1999; Woolf and Ferguson, 2000). An important problem in postharvest technology of fruit is nondestructive detection of defects coming from diseases, mechanical damages and physiological disorders. These defects manifest themselves with changes of thermodynamical properties of the infected tissue.

The requirement of precise control and monitoring of fruit quality at harvest and during storage stimulates interest in non-destructive technologies such as optical density analysis (Throop *et al*., 1994), colorimetry (Kuczyński, 2006), spectrometry or spectrophotometry (Schmilovitch *et al*., 2000; Voltz *et al*., 1996), X-ray imaging (Kim and Schatzki,

*Corresponding author's e-mail: pbaranow@ipan.lublin.pl
**This work was financed from Polish national budget for science in years 2008-2009 as the research project No. N N310 3062 34.

2000; Schatzki *et al*., 1997), magnetic resonance imaging (MRI) (Clark *et al*., 1998; Wang *et al*., 1988), acoustic resonance (Zude *et al*., 2006), near infrared (NIR) or middle infrared (MIR) imaging (Cheng *et al*., 2003; Upchurch *et al*., 1994; Veraverbeke *et al*., 2006). By combining several wavelengths within multispectral or hyperspectral systems, supported by computerized image processing techniques, an automate detection and classification of many internal and external defects are possible (Abbott, 1999; Kleynen *et al*., 2003; Xing *et al*., 2006). However, regardless of the electromagnetic spectrum applied and the complexity of the information which can be derived from imaging, it is critical that the underlying relationship between the sensed signal and the physical or chemical property of the studied object is valid .

Detection of watercore in fruit

Watercore is a physiological internal disorder in which the intercellular air spaces around the core line become filled with fluid and a characteristic translucent tissue is created (Baranowski *et al*., 2008). It is widespread in some cultivars such as ‘Delicious’, ‘Gloster’, ‘Paulared’, ‘Freedom’, ‘Elisa’, ‘Champion’. A characteristic feature of this disorder is that it develops when the fruit is reaching maturity on the tree and sometimes dissipates during storage (Hung *et al*., 1994). The main reasons of watercore development in apples are high or low air temperatures in preharvest period, poor calcium nutrition, maturity status at harvest and cropping level (Ferguson *et al*., 1999; Yamada and Kobayashi, 1999). Some authors have suggested that watercore is caused by changes in membrane integrity during maturation and ripening (Bowen and Watkins, 1997; Kumpoun *et al*., 2003; Wang and Faust, 1992). It has been revealed that flesh tissue of apples with watercore has higher sorbitol and sucrose concentrations and lower glucose concentration than tissue without watercore (Yamada and Kobayashi, 1999). Fruit with watercore are susceptible to develop brown watercore or flesh browning (Argenta *et al*., 2002). In the previous research on watercore detection the authors focused on finding a non-destructive methods compatible with existing storage and packing house operations.

The optical density concept uses the differences in light transmission through the apples as an indicator of watercore occurrence. The results of the studies by Throop *et al*. (1994), who used the broad spectral range throughout the visible and near infrared to 1.1 μm, revealed 99% separation accuracy between affected and unaffected fruit. The optical density method also proved to be useful for detection of internal browning in apples with a 91% accuracy rate. The main limitation of this method is a rigid requirement regarding the fruit calyx orientation during the imaging, what makes it difficult to transfer the technique into packing line conditions.

Another technique that has been used for watercore detection is X-ray imaging. The studies of Schatzki *et al*. (1997) revealed greater than 50% accuracy in detecting affected fruit. However, in some cultivars watercore was not observed despite severe internal fruit tissue changes. It was due to the lack of significant density difference between the severe watercore regions and the clear regions. Furthermore, X-ray recognition strongly depends on the acuity and training of individual operators and in case of fruit moving during the imaging process the accuracy of the method decreases. Kim and Schatzki (2000) elaborated the algorithms of apple watercore sorting system using X-ray imagery improving applicability of the method but some unsolved problems of profitability of the method still exist.

The feasibility of using magnetic resonance imaging and magnetic resonance spectroscopy was evaluated by Clark *et al*. (1998) and Wang *et al*. (1988). They found that these methods could be applied for evaluation of the severity with which apples are affected by watercore and for describing the internal distribution of affected tissues. The changes of intensity of watercore in apples were monitored throughout the storage period. The magnetic resonance imaging is very promising method of watercore detection, however it needs additional research before commercial use.

The mass density sorting method relies on the fact that apples with different intensities of watercore have different mass densities. When passing through the low density fluid, the heavier fruit sink and the lighter stay on the surface. This method was tested for various cultivars and occurred to be very effective (90-100% accuracy). Cavalieri (1997), who tested this method for separating slightly affected and unaffected apples from those with greater amounts of watercore, noticed that in the future it might be possible to combine the weight seizing with digital imaging equipment to electronically calculate the density of apples.

Thermography can be a promising alternative to these methods. It proved to be useful not only for the measurement of temperature changes on the surface of the investigated objects but also for detection of internal heat intrusions and heterogeneity of the thermal properties within bodies. Water gathered in intercellular spaces of watercored tissue is responsible not only for the increase of a fruit mass density but also for the increase of its thermal capacity and decrease of thermal. Therefore it could be expected that fruit with watercore would be heated more slowly than fruit without watercore-affected tissue.

In the process of apple sorting an important problem is how to effectively detect early bruises. In spite of the fact that bruise is the cause of rejecting the highest number of fruit in the sorting lines, the manual sorting method is still commonly used for detecting this defect. Bruise is defined as a damage of fruit tissue as a result of external forces, which cause physical changes of texture and/or chemical changes of colour, smell and taste. Two basic effects of apple bruise can be distinguished *ie* browning and softening of fruit tissue. Existing sorting systems are not capable to effectively distinguish fruit with bruise which occur in short time before inspection. Because of some shortages of existing methods of early apple bruise a grooving interest in alternative non-destructive sorting methods is observed.

The majority of apple bruise detection methods, elaborated to date, show deficiencies in the case of dark skin colour or small surfaces of the bruise. Although it has been confirmed that X-ray imaging and magnetic resonance offer great potential possibilities for apple bruise detection (Chen *et al*., 1989; Schatzki *et al*., 1997; Zion *et al*., 1993), these methods have not been implemented to existing sorting systems in spite of some ready-made prototype solutions due to cost and methodological problems. The application of the near infrared spectroscopy method (NIR 700-2200 nm) has shown low effectiveness for bruise detection in case of multicolour apples eg 'Jonagold' or 'Braeburn', and for early bruise (Kleynen *et al*., 2003; Upchurch *et al*., 1994; Xing and Baerdemaeker, 2007; Xing *et al*., 2005; Wen and Tao, 2000).

Preliminary investigations with the use of thermography for apple bruise detection indicate that this method can bring quite new possibilities, provided that the process of heat conduction in the fruit will be precisely identified and the mechanism of heat contrast creation between the bruised part and sound areas on the fruit surface will be understood (Hellebrand *et al*., 2000; Lurie, 1998; Roos, 2003; Veraverbeke *et al*., 2006, Walczak *et al*., 2003).

According to Varith *et al*. (2003), the temperature of the bruised apple surface is different than that in sound tissue areas of thermograms. It can be explained by differences in thermal properties (thermal diffusivity), caused by the loss of water in bruised areas which have lower density than sound tissue. These authors made observations of apple temperature after apples sustained severe bruises (they were dropped from a height of 0.46 m) and they were stored at a temperature of 25°C and air humidity of 50%.

In this study chosen aspects of thermographic studies on detection of watercore and mechanical defects in apples are presented. The study is based on a hypothesis that internal defects and physiological disorders of fruit lead to changes of tissue thermal properties. During thermal stimulation, heterogeneities of thermal properties lead to the occurrence of thermal contrasts on the surface of these materials which can be successfully registered with the use of thermographic device.

Water gathered in intercellular spaces of watercored tissue is responsible not only for the increase of a fruit mass density but also for the increase of its thermal capacity and decrease of thermal conductivity. Therefore, it was expected that heating curves of fruit with watercore-affected tissue would have different courses than for unaffected fruit.

The aim of the study in reference to bruise detection was to check whether the phase analysis of fruit response to the stimulating heating pulse performed by PPT is capable of providing information about the bruise size and depth.

MATERIAL AND METHODS

'Gloster' apples (*Malus domestica* Borkh) with and without watercore were selected to provide 35 fruit in each category. The watercore occurrence in apples was stated by cutting the fruit after other measurements had been completed. After the experiment ten of the studied apples were rejected from the analysis because apart from the watercore symptoms they contained some other disorders or the volume of watercored tissue was small. The apples were transported to the laboratory directly after harvest. They were preserved in temperature of 1.5°C a few days before the experiment.

Thermal images of the apple surface were taken with AGEMA 880 LWB system which is sensitive in the spectral range of 8-13 µm. The detector in the scanner unit is mercury cadmium telluride (MCT), cooled with liquid nitrogen. The system's sensitivity (NEDT) is 0.007 at 30°C of object temperature. It works with field frequency of 25 Hz, line frequency of 2500 Hz and each frame of the image consists of 280 lines. The lens with an angular field of view of 7° was used. Additionally a change coupled device (CCD) camera registered the visible images of the studied object (Fig. 1). The system interface and software made it possible to register and analyse simultaneously the sequences of thermal and visible range images – eight images in each sequence registered with a time interval of ten minutes. Both cameras were mounted at a height of 1.4 m above the surface of fruit pointing downwards. The linear field of view of the thermal scanner at the scanned object's level was 0.14 m. The emissivity of the fruit was set to 0.96.

Before the measurement the fruit was moved from the cooling room (1.5°C) into the thermostatted measurement site where the ambient temperature was maintained at 20°C

Fig. 1. Setup for watercore detection in apples.

and air humidity at 60%. Then, the fruit was left for about 3 minutes to obtain stable conditions of measurement which was started when the fruit surface temperature increased to about 7.5°C. After completing the sequences of thermal images the apple was weighed with an electronic digital balance operating at capacity up to 1000 g with readability of 0.001 g. To determine the density of fruit, its volume was evaluated on the base of the visible range image analysis. The spatial scale of the image was defined using the straight-line selection tool to make a line selection that corresponds to the known distance. Then, the measurements of fruit image diameter in horizontal and vertical planes were done and the mean value of these two readings was assumed to be the diameter of the sphere representing the fruit surface. The density of the fruit was calculated as the ratio of the mass of fruit to the volume of this sphere.

'Jonagold', 'Champion' and 'Gloster' of apples (*Malus domestica* Borkh) were brought from the orchard directly after harvest and then, before thermographic measurements, they were stored for 15 h in temperature 21°C. Special measuring system for active thermography was designed, consisting of thermographic camera VIGOcam v50, two halogen lamps (500 W each) fixed on tripod, system controlling the time of the pulse time and parameters of registration and external conditions in the thermostated laboratory. The camera used in the experiment was sensitive in spectral range of 8-14 µm. The camera is constructed with the use of a 384 x 288 microbolometric detector array. The system's thermal sensitivity (NETD is 0.08 at 30°C of object temperature. Spatial resolution of the camera is 1 mrad. It works with a frame rate of 60 Hz.

The VIGOcam v50 camera is equipped with 3.5" LCD display, video camera, laser pointer, radio link that enables remote control, SD memory card reader, microphone and loudspeaker. Connection with a PC computer is possible via USB or Ethernet port. The lens with an angular field of view of 22° was used (Fig. 2). Thermal images were registered and preliminary processed with the use of firmware software THERM v50. This software along with numerous functions for processing of thermographic data enables to export individual images and whole sequences in text format to other programs. To analyse pulsed phase thermography (PPT) sequences in this study we used IR_View v.1.7 free software created at Laval University, Computer Vision and System Laboratory.

The measurement of radiation temperature of apples was done in controlled external conditions. All the measurement series were performed at air temperature of 21°C and relative humidity of 60% in daily light. The distance between camera lens and studied apple surface was 0.5 m. The halogen lamps were situated in a distance of 0.3 m from the apple surface and the distance between the centres of both lamps was 0.38 m. The sequences of the thermograms were registered with frequency of 15 images s^{-1}. Each sequence contained about 600 images. To analyse the respon- se of the object to the heat pulse, separately images obtained during the heating process (during heat pulse duration) and images of cooling.

The pulsed phase thermography method was used to study the thermal contrasts on the apple surface between bruised and sound tissue after the heat pulse occurrence. In the PPT method, an individual rectangular heat pulse is used and the characteristic thermal response of the object to this pulse is analysed (Fig. 3).

According to the superposition rule, the heat response signal can be presented as a superposition of the number of waves, each having different frequency, amplitude and phase delay. It is done by the use of the Fourier transformation algorithm. The continuous Fourier transformation is expressed by the infinite integral of exponential functions:

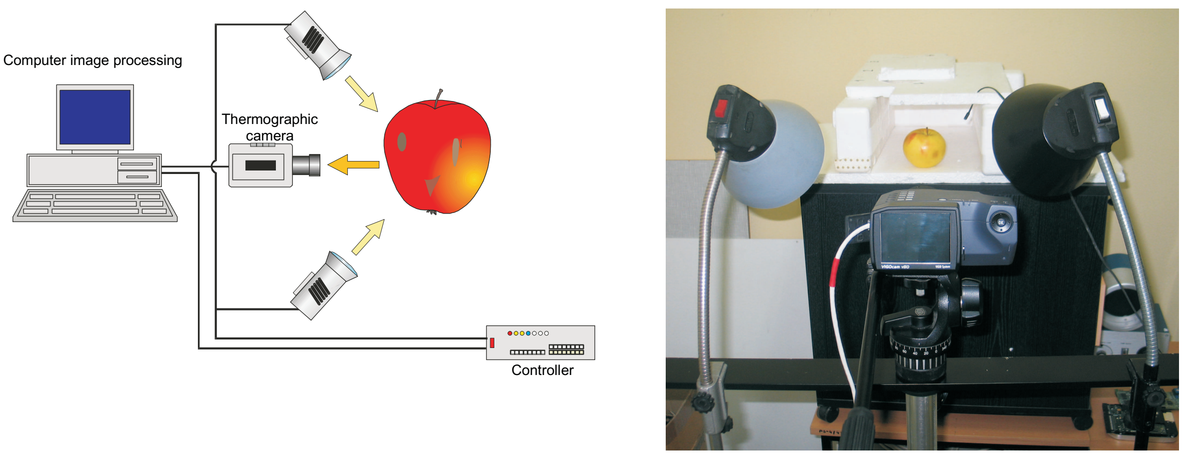

Fig. 2. Setup for early apple bruise detection study: scheme (left) and photo (right).

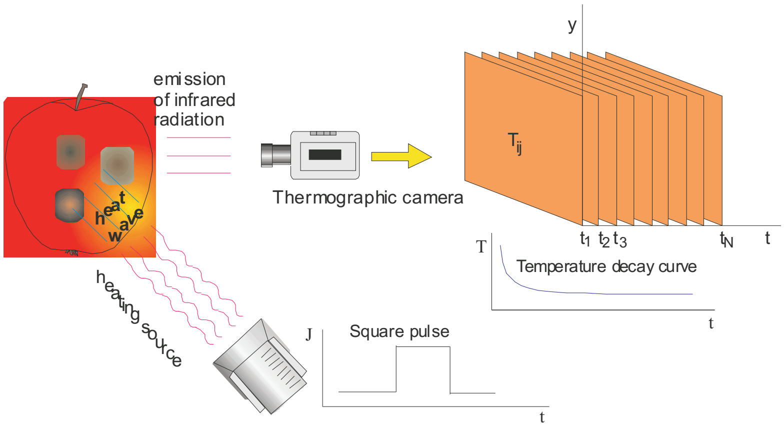

Fig. 3. Principle of pulsed-phase thermography (PPT).

$$F(t) = \int_{-\infty}^{\infty} f(t) e^{(-j2\pi ft)} dt, \qquad (1)$$

where: j^2=-1. In the case of sampled (discrete) signals, a faster and more effective discrete Fourier transformation is used. When a finite series of signal samples (T_0, T_1, T_2, ..., T_{N-1}, T – temperature of fruit surface) is analysed, it can be transformed into a harmonic series (F_0, F_1, F_2, ..., F_{N-1}) by using the following formula:

$$F_n = \sum_{k=0}^{N-1} T_k e^{\left(\frac{-j2\pi nk}{N}\right)} = \mathrm{Re}_n + \mathrm{Im}_n, \qquad (2)$$

where: Re, Im are the real and imaginary parts of the transform, j is an imaginary unit, n is the number of harmonic components (n = 0, 1,..N), k is the value of the signal sample. In PPT, the so called algorithms of fast Fourier transform can be used *eg* the Cooley-Tukey algorithm.

The real and imaginary parts of Fourier transform are used to calculate the phase ϕ_n:

$$\phi_n = \tan^{-1}\left(\frac{\mathrm{Im}_n}{\mathrm{Re}_n}\right). \qquad (3)$$

In the sequence of N thermograms of the studied surface, there are $N/2$ useful frequency components. The other half contains interference information which can be safely rejected. The phase analysis of thermograms enables important information to be obtained about the process of heat penetration within the studied objects.

RESULTS

The base for analysis was the change of apple surface temperature of watercored apples and apples without watercore symptoms particular stages of warming up under temperature gradient between apple surface and surrounding air. Thermograms of an apple with watercore in particular stages of this process are presented in Fig. 4. The exemplary thermograms presented in this figure were obtained 12 (B), 36 (C), 58 (D) and 76 (E) minutes after the beginning of heating process. The model of regression was used, described with the following equation:

$$T(t) = A_0 + \frac{A_1 t}{A_2 + t}, \qquad (4)$$

where: T – radiation temperature of the fruit surface (°C), t – time (min), A_0, A_1, and A_2 – regression coefficients. For all the studied fruit, the applied model gave a very good correlation between estimated and measured values. An example of a fitted lines and measured values of apple surface temperature in proceeding stages of heating for the fruit are presented in Fig. 4F.

The derivative of apple temperature in time per apple mass was found to be a good parameter to evaluate the differences in thermal properties between apples with sound and watercore affected tissues. For apples with watercore the rates of temperature increase per mass in particular initial stages of heating were considerably smaller than for apples with sound tissue irrespective of the part of the fruit surface considered (Fig. 5). It results from this figure, that apples with watercore indicate higher density range (920-950 kg m^{-3}) and soluble solid content range (14 and 16%) as compared to apples without watercore (density 840-890 kg m^{-3} and soluble solid content 8-15%). It is also seen from Fig. 5 that the smaller are fruit density and soluble solid content, the higher is the temperature increase rate during the heating process per mass unit.

The obtained courses of temperature changes on fruit surface during the heating process showed for all the studied varieties the occurrence of temperature differences between bruised and sound parts in the range 0.5-1.5°C. The highest differences of radiation temperature were noticed for 'Jonagold' variety and the lowest for 'Gloster' variety, what is determined by highest differences of firmness between these two varieties.

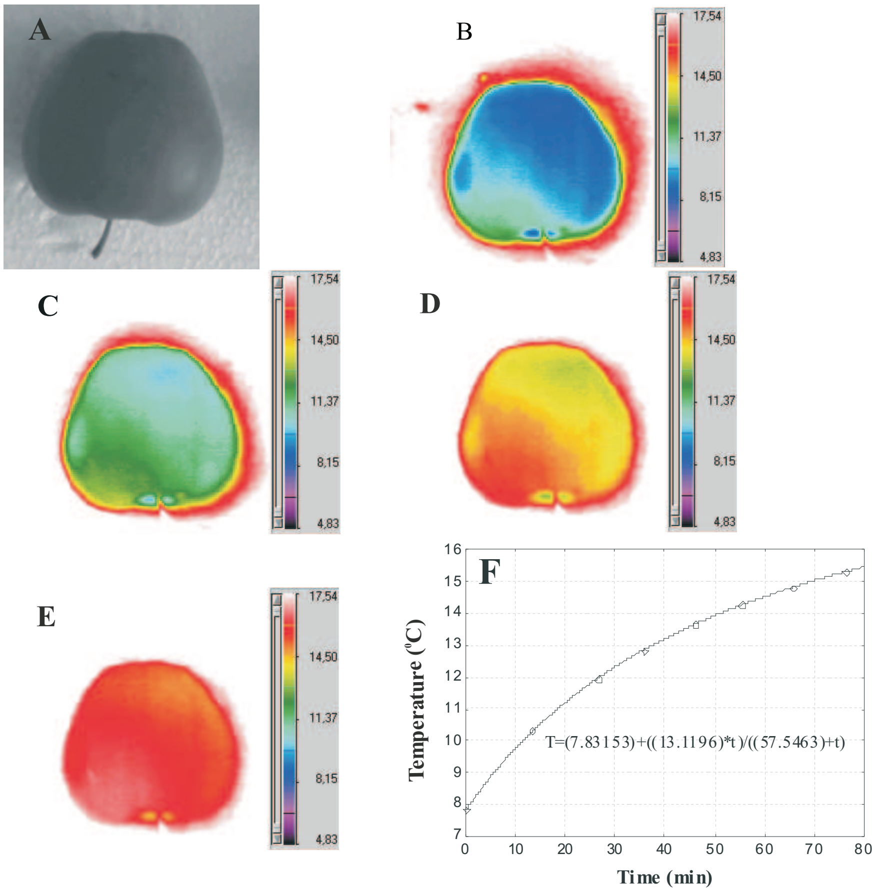

Fig. 4. Visible light image of a studied 'Gloster' apple (A), a sequence of thermograms during heating process (B-E), measured temperature increase and fitted curve (F).

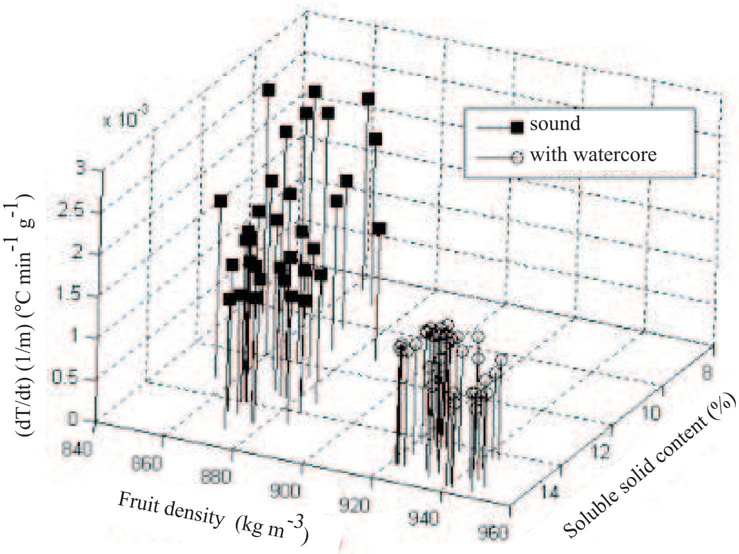

Fig. 5. Relation between fruit density, soluble solid content and derivative of apple temperature in time per apple mass.

For the three investigated varieties the analysis of radiation temperature distribution after pulse occurrence was performed. In this study the pulsed-phase thermography (PPT) method was used. The number of images in a sequence was chosen that way that the value of fruit surface temperature during cooling approached the value close to the cold image temperature of the apple surface. Each sequence contained about 500 images registered with the frequency rate of 15 images per second. The analysis of the sequences was done with the use of IR View software.

An example of a cold image (A) and a thermogram obtained directly after the pulse heating are presented in Fig. 6. On the surface of the fruit two bruises were created which differed with the depth of tissue deformation. The upper bruise was shallower (up to 2 mm) and the lower bruise deeper (up to 5 mm).

The results of phase analysis for exemplary shallower bruises (A) and deeper bruises (B) for apples of three investigated varieties are presented in Fig. 7. It results from this figure that for each variety there exists the most suitable frequency for which discrimination between shallower and deeper bruises is the most effective. This frequency corresponds to a characteristic decrease of phase (a minimum phase peak). The deeper is the bruise the smaller is the frequency value of the minimum phase peak. It is apparent from Fig. 7 that clear depth discrimination can be performed in the range from '0' to a limiting frequency, which in the case of the phase profiles presented in Fig. 7 is equal to about 2 Hz. From this limiting frequency to the maximum frequency fmax (7 Hz) phase values of the points belonging to apples of various depths are all mixed together and not depth distinction can be made.

Some differences of phase values in minimum peak points occur between fruit varieties. Both for deeper and shallower bruises the lowest values of phase in minimum peak points were noticed for 'Gloster'.

The analysis of the bruise depth impact on the minimum phase peaks and optimum frequency for detecting bruises is presented in Fig. 8. With the increase of the bruise depth the absolute value of phase delay corresponding to the minimum peaks decreases while the frequencies at which these deeper bruises are detectable decrease. This tendency refers to all three studied varieties although, in case of 'Jonagold' smaller bruise depths were observed.

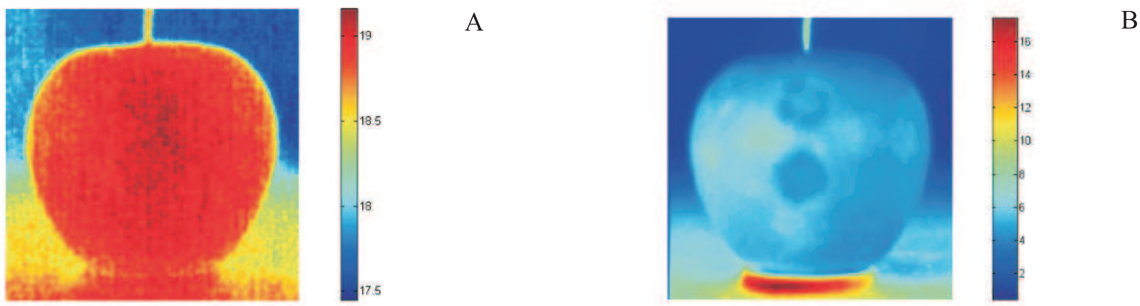

Fig. 6. Thermograms of 'Champion' apple before (A) and after (B) pulse heating.

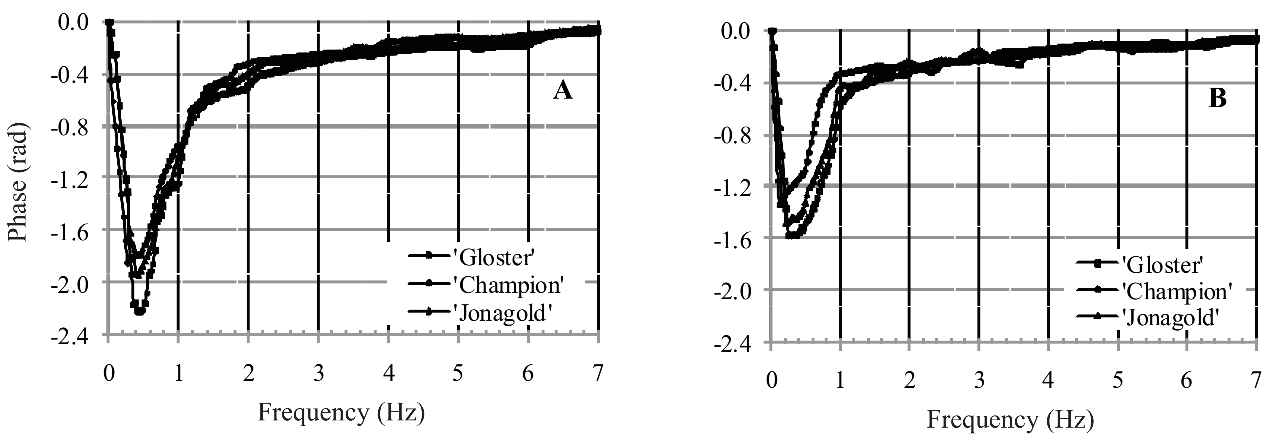

Fig. 7. Change of phase for various frequencies of thermal response in shallower (A) and deeper (B) bruised areas in apples of the three studied varieties.

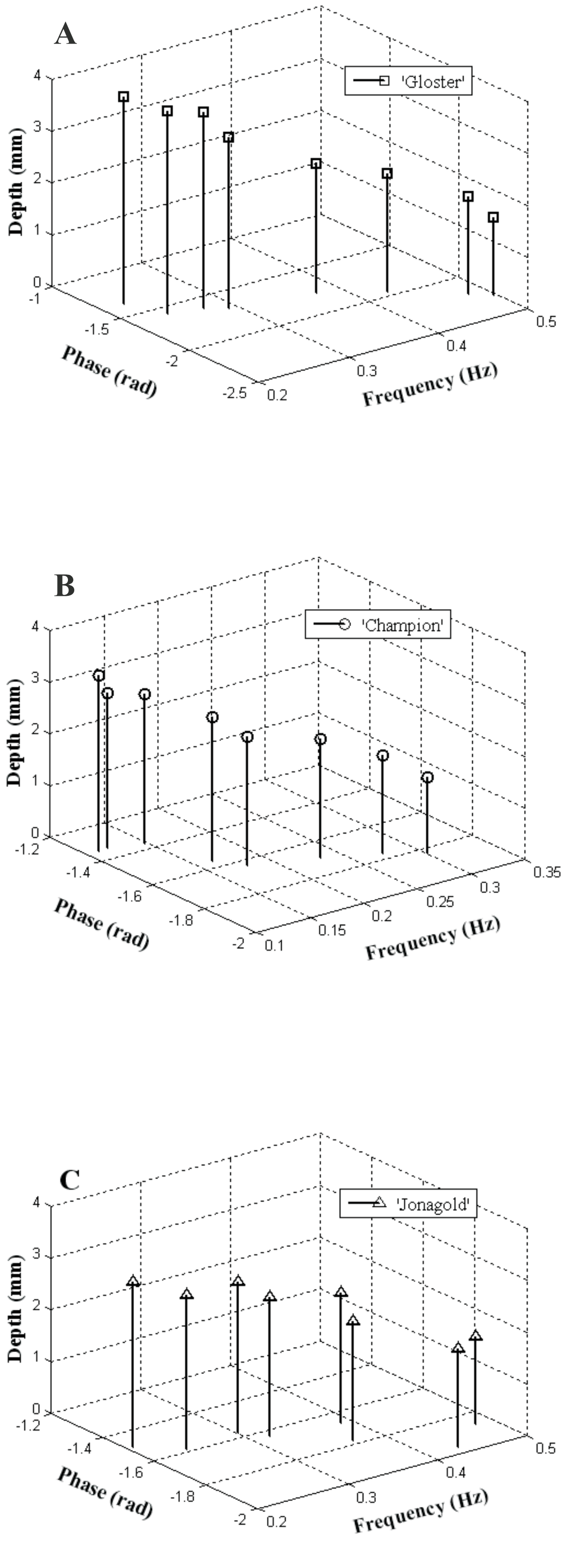

Fig. 8. Relation between bruise depth, minimum peak phase and frequency of thermal response for the studied varieties of apples.

CONCLUSIONS

1. Usefulness of pulsed phase thermography (PPT) method for early apple bruises detection was stated.

2. Thermographical measurement of the radiation temperature changes on the surface of fruit during the heating process can be used to distinguish apples with watercore disorder.

3. Characteristics of temperature decrease after pulse extinction depend on the intensity of bruise and its depth.

4. The derivative of apple temperature in time per apple mass is a good parameter to evaluate the differences in thermal properties between apples with and without watercore affected tissues.

REFERENCES

Abbott J.A., 1999. Quality measurement of fruits and vegetables. Postharvest Biol. Technol., 15, 207-225.

Argenta L., Fan X., and Mattheis J., 2002. Impact of watercore on gas permeance and incidence of internal disorders in 'Fuji' apples. Postharvest Biol. Technol., 24, 113-122.

Baranowski P., Usowicz B., Walczak R.T., and Mazurek W., 2005a. Evaporation into the boundary layer of the atmosphere. (Eds P. Baranowski, B. Usowicz), EU 5th Framework Program QLAM-2001-00428, Centre of Excellence for Applied Physics in Sustainable Agriculture AGROPHYSICS, IA PAS Press, Lublin, Poland.

Baranowski P., Lipecki J., Mazurek W., and Walczak R.T., 2005b. Detection of apple bruises with the use of thermography (in Polish). Acta Agrophysica, 125, 19-29.

Baranowski P., Lipecki J., Mazurek W., and Walczak R.T., 2008. Detection of watercore in 'Gloster' apples using thermography. Postharvest Biol. Technol., 47(3), 358-366.

Bowen J.H. and Watkins C.B., 1997. Fruit maturity, carbohydrate and mineral content relationships with watercore in 'Fuji' apples. Postharvest Biol. Technol., 11, 31-38.

Cavallieri R., 1997. Detection of watercore in apples. Tree Fruit Postharvest J., 8, 3-8.

Chen P., McCarthy M.J., and Kauten R., 1989. NMR for internal quality evaluation of fruits and vegetables. Am. Soc. Agric. Eng., 32(5), 1747-1753.

Cheng X., Tao Y., Chen Y.R., and Luo Y., 2003. NIR/MIR dual sensor machine vision system for online apple stem-end/calyx recognition. Transaction of the ASAE, 46(2), 551-558.

Clark C.J., MacFall J.S., and Bieleski R.L., 1998. Loss of watercore from 'Fuji' apple observed by magnetic resonance imaging. Sci. Hort., 73, 213-227.

Ferguson I., Volz R., and Woolf A., 1999. Preharvest factors affecting physiological disorders of fruit. Postharvest Biol. Technol., 15, 255-262.

Fito P.J., Ortolá M.D., De los Reyes R., Fito P., and De los Reyes E., 2004. Control of citrus surface drying by image analysis of infrared thermography. J. Food Eng., 61, 287-290.

Harker F.R., Watkins C.B., Brookfield P.L., Miller M.J., Reid S., Jackson P.J., Bieleski R.L., and Bartley T., 1999. Maturity and regional influences on watercore development and its postharvest disappearance in 'Fuji' apples. J. Am. Soc. Hort. Sci., 124, 166-172.

Hellebrand H., Linke M., Beuche H., Herold B., and Geyer M., 2000. Horticultural products evaluated by thermography. AgEng. Press, Warwick, UK.

Hung Y.C., Hao Y.Y., Tollner E.W., and Upchurch B.L., 1994. Physical properties and storage stability of apples affected with watercore disorder. Trans. ASAE, 37, 1249-1253.

Ibarra-Castanedo C., and Maldague X.P., 2004. Pulsed Phase Thermography reviewed. QIRT J., 1(1), 47-70.

Jones H.G., 1999. Use of thermography for quantitative studies of spatial and temporal variation of stomatal conductance over leaf surfaces. Plant Cell Environ., 22, 1043-1055.

Kim S. and Schatzki T.F., 2000. Apple watercore sorting system using X-ray imagery – I: algorithm development. Trans. ASAE, 43, 1695-1702.

Kleynen O., Leemans V., and Destain M.F., 2003. Selection of the most efficient wavelength bands for 'Jonagold' apple sorting. Postharvest Biol.Technol., 30, 221-232.

Kuczyński A.P., 2006. Studies on the dynamics of browning and its application in the estimation of apple flesh freshness (in Polish). Acta Agrophysica, 138, 1-158.

Kumpoun W., Motomura Y., and Harada Y., 2003. Inhibition of *Aspergillus* rot by sorbitol in apple fruit with watercore symptoms. Postharvest Biol. Technol., 29, 121-127.

Lurie S., 1998. Postharvest heat treatments. Postharvest Biol. Technol. ,14, 257-269.

Mazurek W., Baranowski P., and Lipecki J., 2006 Implement of thermography of the fruit quality studies (in Polish). Proc. VII Conf. Thermography and Thermometry in Infrared, November 16-18, Ustroń, Poland.

Roos Y.H., 2003. Thermal analysis, state transitions and food quality. J. Thermal Analysis and Calorimetry, 71, 197-203.

Schatzki T.F., Haff R.P., Young R., Can I., Le L.C., and Toyofuku N., 1997. Defect detection in apples by means of X-ray imaging. Trans. ASAE, 40, 1407-1415.

Schmilovitch Z., Mizrach A., Hoffman A., Egozi H., and Fuchs Y., 2000. Determination of mango physiological indices by near-infrared spectrometry. Postharvest Biol. Technol., 19, 245-252.

Throop J.A., Aneshansley D.J., and Upchurch B.L., 1994. Camera system effects on detecting watercore in 'Red Delicious' apples. Trans. ASAE, 37, 873-877.

Upchurch B.L., Throop J.A., and Aneshansley D.J., 1994. Influence of time, bruise-type, and severity on near-infared reflectance from apple surfaces for automatic bruise detection. Trans. ASAE, 37(5), 1571-1575.

Varith J., Hyde G.M., Baritelle A.L., Fellman J.K., and Sattabongkot T., 2003. Noncontact bruise detection in apple by thermal imaging. Innov. Food Sci. Emerg. Technol., 13, 211-218.

Veraverbeke E.A., Verboven P., Lammertyn J., Cronje P., De Baerdemaeker J., and Nicolaý B.M., 2006. Thermographic surface quality evaluation of apple. J. Food Eng., 77, 162-168.

Voltz R.K., Tustin D.S., and Ferguson I.B., 1996. Mineral accumulation in apple fruit as affected by spur leaves. Sci. Hort., 65, 151-161.

Walczak R.T., Baranowski P., and Mazurek W., 2003. Application of thermography in agrophysics. Proc. Course for Young Research Workers 'Physicochemical and Physical Methods of Studies of Soil and Plant Materials. Theory and Practice', November 27 - December 2, Lublin, Poland.

Wang C.Y., Wang P.C., and Faust M., 1988. Non-destructive detection of watercore in apple with nuclear magnetic resonanse imaging. Hort. Sci., 24, 106-109.

Wang S.Y. and Faust M., 1992. Variation in lipid composition of apples in relation to watercore. J. Am. Soc. Hort. Sci., 117, 829-833.

Wen Z. and Tao Y., 2000. Dual-camera NIR/MIR imaging for stem-end/ calyx identification in apple defect sorting. Trans. ASAE, 43(2), 449-452.

Więcek B. and Zwolenik S., 1998. Multichannel thermography systems for real-time and transient thermal process application. Quantitative Infrared Thermography QIRT'98, 322-325.

Woolf A.B. and Ferguson I.B., 2000. Postharvest responses to high fruit temperatures in the field. Postharvest Biol. Technol., 21, 7-20.

Xing J. and Baerdemaeker D.J., 2007. Fresh bruise detection by predicting softening index of apple tissue using VIS/NIR spectroscopy. Postharvest Biol. Technol., 45 176-183.

Xing J., Bravo C., Moshou D., Ramon H., and Baerdemaeker D.J., 2006. Bruise detection on 'Golden delicious' apples by VIS/NIR spectroscopy. Comp. Electron. Agric., 52, 11-20.

Xing J., Bravo C., Jancso P.T., Ramon H., and De Baerdemaeker J., 2005. Detecting bruises on 'Golden Delicious' apples using hyperspectral imaging with multiple wavebands. Biosys. Eng., 90, 27-36.

Yamada H. and Kobayashi S., 1999. Relationship between watercore and maturity or sorbitol in apples affected by preharvest fruit temperature. Sci. Hort., 80, 189-202.

Zion B., Chen P., and McCarthy M.J., 1993. Imaging analysis technique for detection of bruises in magnetic resonance images of apples. Proc. ASAE Annual Int. Summer Meeting, June 20-23, Spokane, WA, USA.

Zude M., Herold B., Roger J.M., Bellon-Maurel V., and Landahl S., 2006. Non-destructive tests on the prediction of apple fruit flesh firmness and soluble solids content on tree and in shelf life. J. Food Eng., 77, 254-260.