

Characterization of Apple Surface Wax Layer by Active Thermography

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Abstract— The present paper reports the preliminary results of a study carried out to characterize the thermal response of apple surface wax layer. The experimentation has been performed on three different cultivars of apple (Golden delicious, Fuji and Red delicious). The present study is part of a research project which final aim is to reproduce artificially bio-wax films in order to cover and protect fruits during their life cycle from the tree to the table. Wax is a natural substance which covers the surface of some species of fruits such as the apples. This wax layer protects the fruit against parasites, atmospheric agents, thermal excursions, moisture loss, mechanical damage and microbiological infections. These singular features are object of studies and research activities. Consequently, an interesting challenge of researchers and agronomists is to develop new synthetic substances obtained by natural extracts or essences.

In the proposed application case, the active thermography has been used in order to study the thermal response of the three apple varieties after a cooling process inside a climatic chamber. The thermographic images have been recorded during the heating process from 5 °C to 27 °C for 132 minutes. Consequently, the three heating rates have been compared. In this experimentation, the Fuji and Red apples have showed a slower heating rate due to the thicker wax layer. The emissivity has been measured for each apple and the whole experimentation has been carried under controlled environmental conditions to assure the repeatability and reproducibility of the experiment.

The results have allowed to define the main thermal features and characteristics of the wax layer for future investigation.

Index Terms — biological agriculture, apple wax, active thermography, emissivity, thermal response analysis, infrared thermal imaging.

I. INTRODUCTION

Biological farms and biological agriculture are new concepts which are spreading more and more in the world. The biological farming intends to encourage a new approach to food and agriculture. The aim is to promote the natural processes in the farm so to produce natural products with high quality. This new environmental sustainable approach is based on the use of ecological agriculture methods free from toxic substances. So, the only permitted substances are those which come from the soil and nature. No pesticides, chemical substances, artificial products are allowed, [1].

The diffusion of diseases, such as cancer and mental disorders, and the soil/water contamination have induced the

governmental organizations and institutions to pay more care to the preservation of the natural ecosystem balance. The past agriculture practices and the conventional chemical farming become unsustainable and unprofitable. Researchers and agronomists are working on modern technologies and methods which do not interfere with ecosystem: biological fertilisers, biological antiparasitics products, natural nutrients, etc... [2]. This new approach is becoming increasingly accepted by farmers worldwide. Studies show that biological farms have good productivity, food is more nutrient and healthy, and no side-effects are present for fauna and flora.

Fungi, bacteria, parasites, atmospheric agents, thermal excursions, mechanical damage and microbiological infections represent some problems to be faced. Biological farming aims to address the cause of these problems, rather than the symptoms. The solution is offered by nature. For example, the apples are naturally covered with a wax layer, which protects the fruit from external agents [3], [4]. This layer in addition contributes to preserve the organoleptic properties and quality of the apple. The production of artificial and biological waxes is today an interesting challenge, [5]. Preliminarily, it is fundamental to characterize the features of the natural wax. Several properties have to be investigated: thermal, chemical, mechanical and organoleptic. Today several techniques are used to this aim, [6]. Nevertheless, most of them are invasive and destructive. In this view, the authors aim to characterize the thermal response of apple surface wax layer in order to define its thermal properties. This paper intends to describe the potentialities of the active thermography for characterizing the dynamic thermal response of any object. Thermography is today widely used for several applications [7]-[10], due to its non-invasive properties. It is an image-based technique which transforms the thermal IR energy emitted by an object into temperature values. A thermal camera is able to capture a scene and to reproduce it into a thermographic or thermometric image. Pixel by pixel, the image shows the temperature distribution of the object surface.

If the thickness of the wax layer changes, even its thermal response to external stimuli or thermal excitation changes. The thermography is a non-invasive tool, which can be used as an effective tool for detecting irregularities without any risk for the investigated object. By using an infrared thermal camera, it is possible to measure the electromagnetic radiation emitted by

the object in the infrared spectrum. The emitted infrared energy is correlated with the superficial temperature. Modern thermal cameras have high accuracy and resolution. As a consequence, changes and temperature differences can be detected with a sensitivity less than 15 mK.

The paper is organized as follows. In Section II, the theory of active thermography is described. Section III reports the description of the used measurement procedure and setup. Experimental results are showed in Section IV. Finally, future works and conclusions are outlined in Section V.

II. ACTIVE THERMOGRAPHY THEORY

Any object with temperature over the absolute zero is able to exchange thermal energy or heat with the surrounding environment. Depending on the object and the environment temperature, the object can absorb or emit energy in the IR range within the interval 0.78 μm – 1 mm of the electromagnetic spectrum. In detail, we can evaluate the radiance W by means of the Planck's Radiation Law:

$$W(\lambda, T) = \frac{2\pi hc^2}{\lambda^5} \left[\exp\left(\frac{hc}{\lambda kT}\right) - 1 \right]^{-1} \quad (1)$$

where T is the thermodynamic temperature of the object, λ the wavelength of radiation, h is the Planck constant, c is the velocity of light in vacuum and k is the Boltzmann constant.

The mechanism that allows infrared energy to be emitted or absorbed depends on the atoms and molecules movements. Molecules can move according to specific directions and, depending on the number of atoms, can even vibrate, rotate or twist along an axis. Higher temperature values are cause of greater interactions, consequently the object exchanges a greater amount of thermal energy. Equation (1) describes this relation existing between the radiance and the object temperature. The object emissivity is an important parameter to be known in order to evaluate accurately the amount of radiated energy with respect to the incident radiation energy. The Kirchoff's Law allows us to estimate the emissivity value ε_λ as:

$$\varepsilon_\lambda = 1 - \tau_\lambda - \rho_\lambda \quad (2)$$

where τ_λ is the transmittance and ρ_λ is the reflectance of the object. Since the emissivity of the object and the reflected temperature have a high influence on temperature measurement, these parameters must be measured very accurately and fixed by the thermal camera settings utility. Consequently the thermal camera detects the object radiance and, by means of appropriate algorithms, the scene is converted in an infrared image.

Depending on the specific application, different thermographic techniques have been defined. Passive and active thermography are the two basic techniques. In the first case, the radiance of the object is measured by means of a thermal camera without any external excitation. This technique is used to study the surface temperature distribution of an object so to characterize zones with higher temperature values. In the second case, an external thermal excitation is

applied in order to increase or decrease the temperature of the object. Consequently, the dynamical thermal response is observed over time. In this way, it is possible to characterize the presence of irregularities in the object structure or different thickness in superficial layers. In fact, objects with different materials or different compositions have a different thermal response.

Lastly, lock-in IR thermography and spectral thermography are two advanced techniques which allow to extract detailed information about the object properties by means of external excitation systems and spectral filters, respectively [11]. Today, thermography is used in several application fields: building diagnostics, medical imaging, surveillance and security, non-destructive testing etc...

By considering the specific application case, the active thermography technique has been used in order to characterize the dynamical thermal response of the apple wax layer.

III. THE MEASUREMENT PROCEDURE

In this Section, the measurement procedure is described. The used measurement instrumentation includes a climatic chamber as external thermal excitation system and a thermal IR camera for recording the thermal response over time, see Figure 1. The whole experimentation has been carried out under controlled environmental conditions in order to assure the repeatability and reproducibility of the experiment. In detail, the used sensing system is the thermal infrared camera FLIR x8400sc. It is a high performances thermal camera with an Indium Antimonide (InSb) detector, a resolution of 1280x1024 pixels, a frame rate up to 106 Hz, a temperature range [-20 3000] $^\circ\text{C}$, a spectral range of [1.5 5.1] μm , and a sensitivity smaller than 18 mK.

The used thermal conditioning system is the climatic chamber Angelantoni Discovery DY-250. It has a temperature range of [-75 180] $^\circ\text{C}$, a relative humidity range of [10% 98%], a dew point range of [2 94] $^\circ\text{C}$, and a temperature fluctuation up to ± 0.3 $^\circ\text{C}$.



Fig. 1. Measurement instrumentation.

The measurement procedure can be divided in three steps:

- *Step A:* each apple has been weighed, its diameter has been measured, and its thermal emissivity has been evaluated;

- *Step B*: the apples have been cooled at a temperature of 278.15 K (5 °C) by means of the climatic chamber (cooling process);
- *Step C*: the apple thermal response has been recorded during a time interval of 132 minutes (heating process).

During the entire measurement process the environmental temperature was continuously monitored and kept constant at 304.65 K (31.5 °C) in order to facilitate the *Step C*.

A. Apple Cultivars and Spectral Emissivity

The experimentation has been performed on three different cultivars of apple (Golden delicious, Fuji and Red delicious), see Figure 2 [12], [13]. They are three varieties of apple widely produced and consumed with different organoleptic characteristics. The main visual differences are attributable to the colour and to the superficial wax layer. The red varieties are typically characterized by a thicker wax layer, which gives major resistance to changing weather conditions, thermal excursions and external agents.



Fig. 2. Apples under test.

For each apple, the thermal emissivity has been estimated for assuring an accurate temperature evaluation from the measured radiation, [14]. In fact, this parameter influences measurements obtained by infrared thermography regulating the effective radiation emitted by an object. To this aim a standardized procedure has been used. In detail, a little piece of Scotch™ Brand 88 black vinyl electrical tape with known emissivity of 0.96 has been glued on a portion of each apple skin waiting for thermal equilibrium. By setting the emissivity parameter of the thermal camera to that of the known material, the absolute temperatures of both materials (Scotch tape and apple skin) have been put in comparison. The surface emissivity value of each apple is estimated by making equal the acquired temperature values of the tape and of the apple surface near it. Table I reports the main features of the three examined apples.

B. Climatic Chamber setup and Thermal Conditioning

The thermal conditioning of the three apples to standardized conditions has been performed by using the climatic chamber. In detail, the chamber parameters has been set to 278.15 K (5 °C) and 40 % of relative humidity. The three apples have been placed inside the chamber and have been cooled from a temperature of 304.65 K (31.5 °C) to 278.15 K

(5 °C). The cooling process has taken about 6 hours to complete. Before performing the thermographic measurements, the three apples have been put at rest to environmental temperature for few minutes in order to avoid the formation of dew which could alter the thermographic measurements.

TABLE I. APPLE FEATURES

Apple Cultivars	Apple Features			
	Mass [g]	Diameter [cm]	Colour	Emissivity
Golden Delicious	220	24.2	yellow	0.965
Fuji	230	24.5	red/yellow	0.972
Red Delicious	230	24.1	red	0.977

C. Thermographic Measurements and ROI selection

The three apples, after the cooling process, have been placed on a table with an antireflection surface at a distance of 0.5 m from the IR camera. The reflected temperature has been estimated by using a crumpled and re-flattened piece of aluminium foil. By assuming an emissivity equal to 1 and a distance of 0 m, the thermal infrared camera have measured the temperature of the aluminium piece, [12]. The measurement is repeated by using this temperature value as the reflected temperature. The resulting temperature value is the final and real reflected temperature.

After setting the thermal camera parameters (emissivity and reflected temperature), the heating process has been recorded over an interval of 132 minutes with a sampling rate of 0.008 Hz (one thermographic frame every 125 s). For each apple, 63 thermographic frames have been acquired. Figure 3 shows four images concerning different steps of the measurement process.

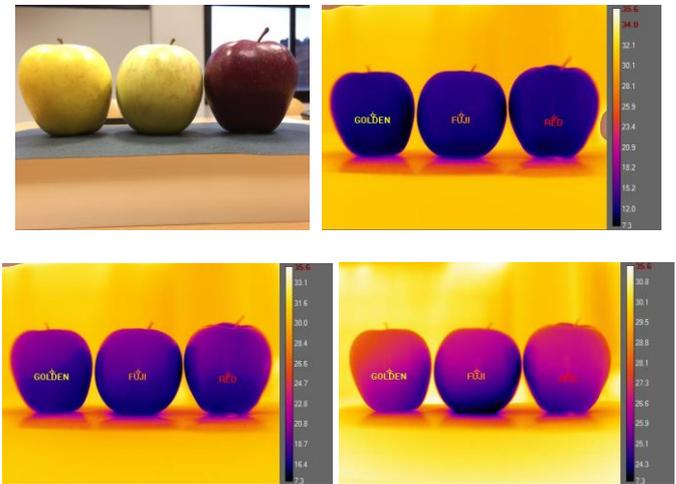


Fig. 3. Thermal response over time.

In the upper left image, the three apples and the setup are shown. The image in the upper right side shows the initial thermographic image of the captured scene. In this image, it is possible to see the three chosen ring-shaped ROIs (Region Of Interest). The image in the lower left side shows an

intermediate thermographic frame. In the lower right image, the last thermographic frame is depicted. By a quick overview, it is possible to observe the slow heating rate of the three apples. In detail, at the end of the measurement process, the Golden apple has shown a temperature higher than the other ones by considering the graduated colour scale.

To compensate possible irregularities of the superficial temperature distribution and possible reflection effects due to the external lightning or external heat sources, three further oval-shaped ROIs have been considered for the following thermal analysis, see Figure 4 for reference.



Fig. 4. The additional oval-shaped ROIs.

These further ROIs allow to get additional information on the mean temperature of each apple.

IV. EXPERIMENTAL RESULTS

The FLIR ResearchIR software has been used to process the thermographic IR records in order to estimate the temperature trend of each ROIs over time.

Figure 5 reports the temporal plot of the ring-shaped ROIs of the three apples. In the ordinate axis, the temperature values are reported in °C measurement unit. The abscissa axis reports the frame number with a sampling period of 125 s.

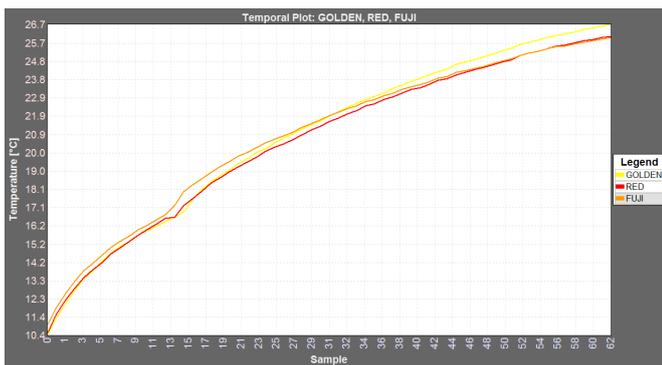


Fig. 5. The apples thermal response over time (ring-shaped ROIs).

It is clearly visible that the Golden apple has a faster heating process, it can be imputed to the less thickness of the wax layer. Differently, the Fuji and Red cultivars show a comparable thermal response. Tables II and III report the

statistic values for each ring-shaped ROIs for the first and the last frames, respectively. In detail, the Tables report the mean temperature value of the ROI area, the temperature standard deviation of the selected pixels, the temperature value of the central pixel, the maximum and minimum temperature values in the ROI area, and finally the number of pixels of the ROI.

TABLE II. STATISTICS OF THE RING-SHAPED ROIs (FRAME #1).

ROI Statistics	Apple Cultivars		
	Golden	Fuji	Red
Mean [°C]	10.4	11	10.5
Standard Deviation [°C]	0.2	0	0
Center Value [°C]	10.4	10.9	10.6
Maximum [°C]	10.9	11	10.6
Minimum [°C]	10.1	10.9	10.5
Number of Pixels	9	9	9

TABLE III. STATISTICS OF THE RING-SHAPED ROIs (FRAME #63).

ROI Statistics	Apple Cultivars		
	Golden	Fuji	Red
Mean [°C]	26.7	26	26.1
Standard Deviation [°C]	0	0	0
Center Value [°C]	26.7	26	26.1
Maximum [°C]	26.7	26	26.1
Minimum [°C]	26.7	25.9	26
Number of Pixels	9	9	9

These statics provide a more clear overview about the initial and the final stages of the heating process for each apple.

Figure 6 reports the temporal plot of the oval-shaped ROIs of the three apples (see Figure 4 for reference).

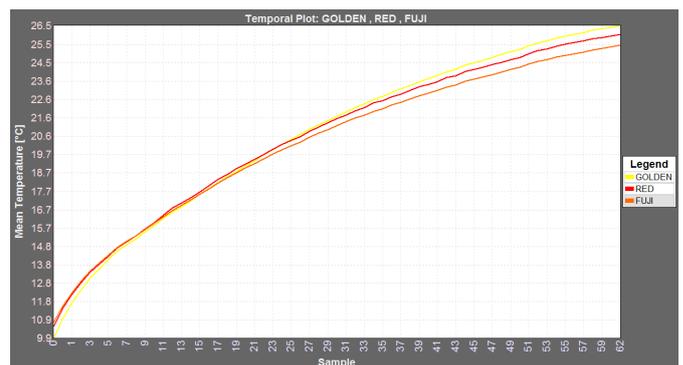


Fig. 6. The apples thermal response over time (oval-shaped ROIs).

In this plot, the three apples have a more different behaviour in terms of thermal response during the heating process. The greater extension of the considered ROIs allows to compensate specific error contributions due mainly to a non-

uniform superficial heating of the single apple caused by an irregular shape, and due to a possible thermal energy reflection by the apple skin.

In the previous Figure, the Golden apple shows a faster heating rate than the Red apple, whereas the latter one shows a faster heating rate than the Fuji apple. Such a behaviour can be explained by a thinner wax superficial layer of the apples, respectively. As a consequence, the results have demonstrated that the Fuji cultivar has the thickest wax layer. In detail, Tables IV and V report the statistic values for each oval-shaped ROIs for the first and the last frames, respectively.

TABLE IV. STATISTICS OF THE OVAL-SHAPED ROIS (FRAME #1).

ROI Statistics	Apple Cultivars		
	<i>Golden</i>	<i>Fuji</i>	<i>Red</i>
Mean [°C]	9.9	10.7	10.5
Standard Deviation [°C]	0.8	0.7	0.6
Center Value [°C]	9.9	10.9	10.7
Maximum [°C]	11.9	12.4	14.2
Minimum [°C]	7.8	8.7	8.7
Number of Pixels	70372	62094	71830

TABLE V. STATISTICS OF THE OVAL-SHAPED ROIS (FRAME #63).

ROI Statistics	Apple Cultivars		
	<i>Golden</i>	<i>Fuji</i>	<i>Red</i>
Mean [°C]	26.5	25.5	26
Standard Deviation [°C]	0.7	0.7	0.6
Center Value [°C]	26.6	25.9	26.3
Maximum [°C]	28	26.7	27
Minimum [°C]	24.9	23.8	24.5
Number of Pixels	70372	62094	71830

By analysing the temperature report in Figure 6 and comparing data included in the previous Tables, the mean thermal excursion rate for the Fuji cultivar is equal to 0.1121 °C per minute. At the end of the heating process, its recorded temperature deviation is of 1 °C (about 3.77%) with respect to the Golden apple temperature. The latter one has got the maximum thermal excursion rate (0.1257 °C/minute).

V. FUTURE WORKS AND CONCLUSIONS

The carried out experimentation has allowed us to characterize the dynamical thermal response of the natural wax layer of three apple cultivars (Golden delicious, Fuji and Red delicious). Wax is a natural substance which covers the apple surface and protects it against thermal excursions. The final aim of the present research activity is to define the main thermal features of the wax and its response to thermal stress.

The future work aims to recreate artificial and biological waxes with the same thermal features in order to cover different kinds of fruit and protect them from parasites, atmospheric agents, thermal excursions, moisture loss, mechanical damage and microbiological infections.

At the present stage, the preliminary studies performed on the comparison between the thermal responses of the three apple varieties has shown that the Fuji apple has a better response to thermal excursions. Therefore, this apple cultivar has a greater resistance to thermal stress due to a thicker wax layer. The possibility to recreate artificially the same features even for other varieties of fruits (such as pear, peach, cherry etc...) will permit in the next future to avoid the use of pesticides and chemical substances, and to preserve crops from weather and climatic changes.

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