Non-contact bruise detection in apples by thermal imaging


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Received 14 April 2002; accepted 5 January 2003

Abstract

Thermal imaging is a non-destructive and non-contact infrared sensing technique. Such imaging creates a bit-map called a thermogram by detecting infrared radiation emitted from an object. Up to 100% of apple bruises were detected using thermal imaging during warming of the fruits by discriminating surface temperature between bruised and sound tissues. Apples were bruised by dropping them from 0.46 m onto a smooth concrete floor and then were held at 26 ± 8°C and 50% RH for 48 h. They were then thermally imaged using a ThermaCam™ PM390 (FLIR Systems, Inc., Portland, OR) during heating and cooling treatments. Thermal images of bruised tissue showed at least 1–2 °C difference from sound tissue within 30–180 s. The temperature differences between bruised and sound tissues were possibly due to the differences in thermal diffusivity. Under steady-state temperature, thermal imaging did not detect bruises, indicating that the temperature differences were not due to emissivity differences. The technique could provide a basis for automatic bruise sorting, and possibly a better understanding of bruised tissue.

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Keywords: Infrared; Thermal imaging; Apple; Non-destructive; Bruise detection

Industrial relevance: Mechanically damaged fruits and vegetables account for tremendous economic losses in developed and especially in less developed regions of the world. In addition to attempt to avoid mechanical damage in the first place it is essential to identify such damages since increased microbial contamination and accelerated ripening of plant products can result from such damages. This paper describes the possible application of non-contact infrared sensing technique for bruise detection, which could possibly also be used to identify pre-treatment related changes in thermal diffusivity of food systems.

1. Introduction

Apples (Malus sylvestris, Mill.) are an important fruit worldwide. In 2000 the United States had an estimated total apple production value of $1,326 million while the fresh market portion was $795 million or 60% of total production value (USDA, 2002). However, millions of dollars are lost by the apple industry every year for two major reasons; mechanical damage and downgrading due to lack of an effective measure of apple quality (Wu, 1997). Apple sorting by size and color is well automated but a need for sorting by firmness and to eliminate defects still exists.

2. A case study of better apple sorting

Economically, the elasticity of demand for fresh apples (ε_Q) is −0.37 (Roosen, 1999). The ε_Q is defined as the ratio of percent change in quantity (%ΔQ) to percent change in price (%ΔP):

ε_Q = \frac{\%ΔQ}{\%ΔP} \hspace{1cm} (1)

Inversely, the flexibility of the demand (F_Q) is a reciprocal of the elasticity of demand:
$F^B_0 = \frac{1}{\epsilon^B_0}$

(2)

When $\epsilon^B_0 = -0.37$, $F^B_0 = 3$; meaning that for every 1% decrease in quantity, the price will increase by 3%.

If we assume that the automatic grading system can sort out 5% more defective apples than by manual grading, the fresh apple price will increase by $3 \times 5% = 15\%$ of the total value where the total value can be determined from multiplication of averaged quantity ($\bar{Q}$) and averaged price ($\bar{P}$). Consequently, based on 1996–98 data of the US fresh market (USDA, 2002):

Total value by human sorting = $\bar{P}\times\bar{Q} = 6127.33$ million lbs $\times$ $0.2$/lbs

Total value by automatic sorting = $(1+0.15)\bar{P}(1-0.05)\bar{Q}$

= $1.15(0.2/lbs) \times 0.95(6127.33$ million lbs)

= $1338.82$ million

Total value difference = $1338.82 - 1225.47$ million = $113.35$ million annually.

Thus, with better grading, the total market value of fresh apples should increase by $113$ million a year, based on the above assumptions. However, this estimate measures the relationship between price and quantity, assuming that the quality of the incoming crop remains constant. The economic impact of the quality shift cannot be evaluated. To evaluate the quality shift, statistical data must be collected for at least 3–4 years after the automatic sorter has been applied (Schotzko, 2000).

3. Review of current defect sorting techniques

Normally, apple bruises take place beneath the peel and are difficult to detect by either visual or automatic color sorting, especially for the dark-colored apples such as red ‘Delicious’. Dark-colored apple skin can easily obscure human vision or mislead CCD color sorting systems. X-Ray imaging (Diener, Mitchell & Rhoten, 1970; Schatzki et al., 1997; Thomas, Kannan, Degwekar & Ramamurthy, 1995) and magnetic resonance imaging (MRI) (Chen, McCarthy & Kauten, 1989; Zion, Chen & McCarthy, 1993) are among the successful imaging techniques used for defect grading. Both methods acquire two-dimensional cross-sectional images of the fruit to detect internal defects. Theories of X-ray imaging and MRI are described elsewhere (Tollner, Brech & Upchurch, 1993). Although both techniques exhibit great potential for bruise detection in apples, the associated high equipment costs make both techniques less practical for on-line fruit grading application.

Near-infrared (NIR) reflectance is another promising method to detect bruises in apples (Pen, Bilanski & Fuzzen, 1985; Upchurch, Affeldt, Hruschka, Norris & Troop, 1990; Upchurch, Throop & Aneshansley, 1994; Wen and Tao, 2000). The NIR technique acquires infrared reflectance scattered from a thin, near-surface layer of fruit (Greensill & Newman, 2001). The wavelengths range from 700 to 2200 nm are useful to detect bruises because reflectance is less for bruised areas than for sound tissue areas (Brown, Segerlind & Summitt, 1974). Wen and Tao (2000) acquired NIR reflectance images with a CCD camera attached with a selective optical filter. Incorporating mid-infrared (MIR) images, they were able to extract the stem-end/ calyx from the true defects of the apples. With this technique, the recognition rate was 96.67% for defective red Delicious apples.

Hyperspectral imaging, the NIR-based technique, was also applied to detect bruises in apples (Lu, Chen & Park, 1999). Hyperspectral imaging combines spatial and spectral information of an object. The system acquired image data between 430 and 900 nm at a spectral resolution of 3.74 nm. Bruised tissue was found to have lower relative reflectance than normal tissue in the near-infrared region between 700 and 900 nm (Lu et al., 1999), which was comparable to results from works by Brown et al. (1974).

Thermal imaging offers a potential alternative technique for bruise detection in apples (Danno, Miyazato & Ishiguro, 1978). Thermal imaging is a non-destructive infrared sensing technique that measures infrared energy emitted from the object surface. The detected energy is converted by the camera into a thermal map called a thermogram. Unlike NIR, thermal imaging does not require an illumination source for spectral reflectance, which can be affected by the varied skin color of apples or by the illumination setup. Danno et al. (1978) monitored bruised apples under changes in temperature by means of natural convection. The temperature difference between bruised and sound skin was found to be usually in the range from 0.2 to 1.0 °C, with measuring times of at least 10 min. Thermal imaging may be used not only for defect sorting but possibly for other quality attribute sensing because of its non-destructive character. However, no work has been reported on such measurement using this technique. Our work presents an improved technique from that of Danno et al. (1978), by applying forced convection to detect bruises in apples. This technique results in faster heat transfer to the apples so that temperature differences greater than 1 °C can be created.

4. How does thermal imaging detect bruises?

To detect apple bruises, a thermal imaging device must detect the differences in temperature between

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1 Average of equivalent packing house door returns for CA, NY, OR and WA, and price at first sale for other States.
bruised and sound tissues as a result of their thermal property differences. Four major thermal properties in heat transfer are associated with thermal bruise detection: thermal diffusivity \(\alpha\), thermal conductivity \(k\), specific heat \(C_p\), and thermal emissivity \(e\). The first three, together with density \(\rho\), have a relationship given by

\[
\alpha = k/(\rho \cdot C_p).
\]  

(3)

This work was based on the hypothesis that there is a difference in \(\alpha\) between bruised and sound apple tissues. In newly bruised tissue, impact bruising compresses tissue making it denser (less porous), thus increasing \(\rho\) and leaving total mass, water content, and \(C_p\) unchanged. The damaged cells release water into tissue air spaces, which may increase \(k\) (Stroshine, 1998). Over time, the moisture in old bruises migrates out of damaged tissue, leaving a brown, corky bruise behind (Mohsenin, 1996), reducing bruise mass, \(\rho\), \(C_p\) and possibly \(k\). The experiments described below explore temperature differences between bruised and sound tissues, possibly caused by differences in \(\alpha\), for 48-h-old bruises in three apple varieties. Thermal emissivity of apples could also affect thermal-imaged bruise detection. Preliminary experiments with apples at thermal equilibrium showed no thermal image differences between bruised and sound tissue, indicating no differences in thermal emissivity between bruised and sound tissues.

5. Objectives

The objective of this work was to determine the potential of using thermal imaging to detect bruises in apples during forced convective heat transfer.

6. Materials and methods

Forty-five apples, red ‘Delicious’, ‘Fuji’ (purchased from local grocery store) and ‘McIntosh’ (freshly harvested from WSU’s Tukey research orchard) with average densities of 857.2, 871.5 and 797.2 kg/m\(^3\), respectively, were acquired. The apples were bruised by dropping them from 0.46 m onto a smooth concrete floor and then were held at 26 °C and 50% RH for 48 h to allow bruise development. Note that bruises created in this experiment were more severe than the typical bruises in commercial apples. Our purpose was to assure a sufficient size of bruise for our experimental concept validation. Each apple was then thermally imaged using a ThermaCam™ PM390 with 3.4–5 μm spectral band (FLIR Systems, Inc., Portland, OR) during heating and cooling treatments. Prior to the testing, the apples were refrigerated (\(\approx\)3 °C) for at least 3 h. Then each apple was imaged for 3 min (see Fig. 1) while being subjected to one of the following randomly-assigned treatments.
Fig. 2. Thermograms of apples by treatment A. The colors of thermograms are coded on the top right corner scale. The numbers in the boxes indicate the temperatures of the marked point in Celsius. The square pieces on the apples were paper sample labels.

A. Heating with forced convection in ambient air at 50% RH, 26 °C.
B. Heating with forced convection in the same air heated to 37 °C.
C. Cooling with forced convection in ambient air at 50% RH, 26 °C after heating in 40 °C water for 2–3 min.

Fig. 3. Thermograms of apples by treatment B. The colors of thermograms are coded on the top right corner scale. The numbers in the boxes indicate the temperatures of the marked point in Celsius. The square pieces on the apples were paper sample labels.

7. Results and discussion

In this work, we believe that the temperature difference between bruised and sound tissue was due to the changes in α. On the other hand, there may be an effect of changes in thermal emissivity due to bruising as well. However, the bruises did not show in thermal images...
Fig. 4. Thermograms of apples by treatment C. The colors of thermograms are coded on the top right corner scale. The numbers in the boxes indicate the temperatures of the marked point in Celsius. The square pieces on the apples were paper sample labels.

when the apples were at thermal equilibrium, indicating no significant differences in thermal emissivity between sound and bruised tissues.

The thermal images showed distinct temperature differences between bruised and sound tissues during heating or cooling. The heating treatments (A and B) were
more successful than the cooling treatment (C), with consistent results for Fuji and McIntosh apples. The bruises in treatments A and B warmed up more slowly and were up to 1–2 °C cooler than the sound tissue (see Fig. 2 and Fig. 3).

For the cooling treatment (treatment C), the temperatures of bruises in most apples were 1–2 °C cooler than those of sound tissues, which contradicted the results in heating treatments (A and B). Results were mixed for red Delicious apples in treatment C, where bruise detection was more successful with deep than with shallow bruises (see Fig. 4 and Fig. 5). It also appeared that some red Delicious apple bruises were 2–3 °C warmer than the sound tissue under treatment C (see Fig. 6). The reason behind this variation is not known, but treatment C involved briefly heating and then cooling the outside of apples whose centers remained cold; the result was a combined transient heating and cooling that was too complex to draw a conclusive pattern of temperature differences.

Heating treatments A and B gave consistent results and imply a difference in α between bruised and sound tissues. With heating treatments, bruises warmed more slowly than did sound tissue, implying that α was higher in bruised than in sound tissues. With the higher α, bruise can transfer heat from the apple exterior into the sound interior tissue faster than can the surrounding sound tissue, resulting in lower surface temperature in bruised than in sound tissues. Individual investigations of each variable (k, ρ and C_p) to explain the changes in α were conducted later (Varith, 2001) and found that the differences in α between bruised and sound tissues agreed with above statement.

### Table 1

<table>
<thead>
<tr>
<th>Variety</th>
<th>Treatment</th>
<th>Successful bruise detection (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuji</td>
<td>A</td>
<td>100.0</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>86.7</td>
</tr>
<tr>
<td></td>
<td>C</td>
<td>86.7</td>
</tr>
<tr>
<td>Macintosh</td>
<td>A</td>
<td>100.0</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>100.0</td>
</tr>
<tr>
<td></td>
<td>C</td>
<td>86.7</td>
</tr>
<tr>
<td>Red Delicious</td>
<td>A</td>
<td>66.6</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>40.0</td>
</tr>
<tr>
<td></td>
<td>C</td>
<td>60.0</td>
</tr>
</tbody>
</table>

Compared to the NIR imaging where the reflectance in the NIR ranged between 700 and 2000 nm is less from the bruised areas than sound areas (Brown et al., 1974), thermal imaging of heating treatments exhibit results in a similar manner. For heating treatments, the bruised areas showed less surface temperature than that of sound areas. Thus, the thermal imaging camera detected less infrared emission in bruised tissue than in sound tissue according to the Stephan–Boltzmann’s law (Eq. (4) below) where temperature is directly proportional to the radiant heat flux emitted from apple per unit area (Kaplan, 1999):

$$W = \delta \varepsilon T^4 \quad (4)$$

where:

W = Radiant heat flux emitted per unit area (watts/m²);
Table 2
Guidelines for detecting bruises in three apple varieties using thermal imaging. The superscript notations on the treatments are explained below the table

<table>
<thead>
<tr>
<th>Variety</th>
<th>Treatment</th>
<th>Thermal imaging temperature span (°C)</th>
<th>Best time to detect bruise after treatment (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuji</td>
<td>A</td>
<td>0–16</td>
<td>180</td>
</tr>
<tr>
<td></td>
<td>C</td>
<td>0–35</td>
<td>90</td>
</tr>
<tr>
<td>McIntosh</td>
<td>A</td>
<td>0–17</td>
<td>180</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>0–24</td>
<td>90</td>
</tr>
<tr>
<td>Red Delicious</td>
<td>A</td>
<td>0–18</td>
<td>90</td>
</tr>
<tr>
<td></td>
<td>C</td>
<td>0–35</td>
<td>90</td>
</tr>
</tbody>
</table>

a After 90 s in treatment C, the cold temperature inside the apple cooled the tissue near the skin which may cause reading difficulty.

b There was an infrared specular reflection from the heater detected by the thermal imaging camera (see the bright-white spot on the right-side of each apple in Fig. 3). This specular reflection may cause misinterpretation of the bruise image.

c The conical-irregular shape of the Red Delicious apple caused a less uniformed heat transfer than in more spherical apples such as Fuji and McIntosh and resulted in difficulty in differentiating the bruise from the sound tissue.

\[ \delta = \text{Stephan–Boltzmann constant} = 5.673 \times 10^{-8} \text{ watts/ m}^2/\text{K}^4; \]
\[ \varepsilon = \text{Emissivity (unity for a blackbody target)} \]

During heating treatments (A and B), bruise images became distinct within 30–180 s, depending on apple variety. Bruises in Fuji and McIntosh apples were evident in 30–60 s whereas most bruises in red Delicious apples required 150–180 s or were not detectable. Table 1 shows the percentage of bruises detected in apples by treatment and variety. It is observed that different apple varieties may require different detection protocols.

Table 2 summarizes guidelines to detect the apple bruises using thermal imaging from this experiment. Note that for treatment C (cooling after 40 °C water heating), although some bruises showed immediately (at 0 min of cooling), the surface temperature of the apples was not uniform, which caused difficulty in differentiating the bruised and sound tissues. It is also noted that at the edge of the apple, which was of less importance for bruise detection, the thermogram is slightly distorted due to the temperature compensation between the apple and the environmental background; hence, the apparent temperature at the edge of the object may not be accurately measured.

8. Conclusions and implications

Bruises were successfully detected using thermal imaging. Success was most consistent using treatments that warmed cold apples during the thermal imaging. Fuji and McIntosh apples at 3 °C warmed by air at 26 °C gave 100% bruise detection within 180 s or less, yielding better detection performance than previous work by Danno et al. (1978). Air at 37 °C gave slightly less accurate results but in 90 s. Red Delicious apples gave the least consistent results with bruises successfully detected up to 66% whereas deep bruises were more easily detected than shallow ones. Even though treatment C, which involved briefly heating and then briefly cooling the cold fruits, was too complex to give conclusive results, a potential of using cooling treatment to detect bruises in apples still exists. The bruise detection was due to thermal diffusivity differences (\( \alpha \)) between bruised and sound tissues, not due to thermal emissivity differences, because they showed no temperature differences between bruised and sound tissue at steady state.

Thermal imaging may provide rapid, non-contact bruise detection in apples at points in packing operations, such as at the wax drying tunnel, where apple temperature is changing due to external heating or cooling and thermal diffusivity differences.

Acknowledgments

This work was funded under USDA NRICGP grant # 9901675.

References


