

Quality Evaluation of Agricultural Products by Infrared Imaging Method

I. Grading of Fruits for Bruise and Other Surface Defects

Akibumi DANNŌ, Mitsuru MIYAZATO, and Etsuzi ISHIGURO
(*Laboratory of Agricultural Physics*)

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Introduction

Evaluation of bruise, defect and damage in the agricultural products, such as fruits, vegetables and others, has always been one of the most elusive problems associated with the harvesting, handling, transportation, and marketing of the agricultural products. The visual inspection method has been widely used, but this method is a very time-consuming one, and human fatigue influences the results¹⁾. A simple, rapid, and automatic method for quality evaluation of the agricultural products has not yet been developed.

Infrared imaging method can provide practical solution to these problems. Most of the successful applications capitalize on the ability of infrared imaging devices, to measure temperature without contact. Since not a few surface defects of fruits and other agricultural products influence temperature changes, an equipment that may be capable of sensing these changes is considered to be useful in the inspection of qualities.

Although thermal imaging devices are currently in use for medical investigation of breast cancer^{2,3)}, little work is being carried out on the evaluation of qualities for the agricultural products. Thermal imaging devices have been applied to this task and appear to have established as one of the more reliable method available. Preliminary results on quality evaluation of fruits were discussed in a present paper.

Experimental Procedure

2.1. Fruits tested

Apple (Roll's Janet), Satsuma mandarin, and Natsudaidai were chosen. Satsuma mandarins were picked from Toso Orchard, University Farm, Faculty of Agriculture, Kagoshima University, the other fruits being purchased at the market. Natsudaidai is of medium to medium-large size (similar to grapefruit) and is extensively grown in the Japanese coastal regions⁴⁾. Dimensions and weight of fruits and test dates are listed in Table 1.

The objective of this study is to examine the effect of surface defects on temperature-distribution on the surface of fruits. The mechanical and biological damages, in general, occur on a continuous scale, but it is very difficult to obtain a desired damage-level fitting for the experimental purpose. Hence, artificially damaged fruits were used

Table 1. Dimensions of fruits and their test dates

Kind of fruits	Dimensions				Test date	Picked date
	Number of samples	Average diameter [cm]	Average height [cm]	Average weight [g]		
Apple (Roll's Janet)	21	7.09	6.15	143.9	May 25, 1976	
Satsuma mandarin	24	6.88	4.90	128.3	Dec. 16, 1975	Nov. 27, 1975
Satsuma mandarin	27	7.29	5.34	147.8	Dec. 16, 1975	Dec. 4, 1975
Natsudaikai	21	9.44	7.52	302.7	May 25, 1976	

for the present experiment. They were prepared by the following methods.

- 1). Pressed bruise: A uniform bruise, outside diameter 30 mm and inside diameter 20 mm, was made on each fruit by compressing a steel coaxial cylinder with 10–15 kg pressures on it.
- 2). Scratched bruise: A uniform bruise, outside diameter 30 mm, was made by covering the surface of each fruit with a guard ring, the inside of which was scratched with sand paper of #60.

2.2. Storage conditions

Temperature changes caused by surface defects, such as bruise, damage and rot, in fruits, are usually very small, temperature difference between the bruised and the unbruised skin being less than $1.0^{\circ}\text{C}^{5)}$. Therefore, it is of great importance to determine suitable conditions for the infrared measurement. One of the suitable conditions is the one in which fruits were kept at a constant temperature for more than 24 hrs before measurement, and the constant temperature was selected to be slightly higher, or slightly lower, than room temperature.

The artificially damaged fruits were usually stored at room temperature for several days. While, in order to control a desired damage-level, samples were stored at a higher temperature accelerating the damage, or at a lower temperature suppressing it.

Before measurement, the samples were kept at constant temperature more than 24 hrs. Thermo-regulated rooms were used for storage of fruits. For higher temperature storage, temperature of the room was regulated at 30°C , and for lower temperature storage it was regulated at 10°C .

2.3. Apparatus

A Fujitsu Infra-Eye 102A, a medical thermography, was used for all the measurements. A mercury-cadmium-telluride (Cd Hg Te) detector was employed for infrared measurement. The main features of this instrument are as follows:

Useful wavelength range: 8–14 microns

Measuring temperature range: 1, 2, 3, 5, 10, 20, 30, and 50°C

Field of view: Azimuth 20 deg., Elevation 15 deg.

Instantaneous field of view: $2\text{ mrad} \times 2\text{ mrad}$

Frame time: 1, 2, 4 sec.

Number of scanning lines: 157/sec, 314/2 sec, and 628/4 sec.

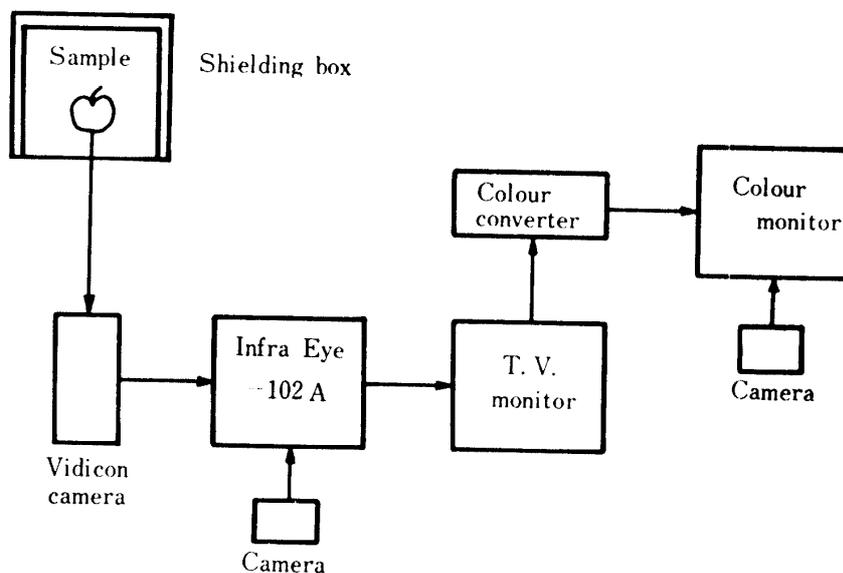


Fig. 1. Block diagram of experimental arrangement.

Fig. 1 shows a block diagram of the experimental arrangement. Samples were placed in a shielding box, and any unwanted radiations from background were suppressed. The shielding box was surrounded by foamed polystyrene sheets on all sides barring the front one. Infrared radiations emitted from the samples were collected by an infrared vidicon camera. The signal received by the vidicon camera was transmitted to the Infra-Eye 102A. Thermal images were produced by a black and white T.V. monitor and a colour T.V. monitor, respectively. While, a temperature-curve was represented by temperatures on a scanning line passing through the sample at a given elevation.

A base temperature can be determined, to indicate the mean-value of temperature on the surface of sample. While, a measuring-temperature-range can be selected, to cover the temperature difference between the maximum and the minimum temperatures of the sample, and can be adjusted in discrete ranges of 1, 2, 3, . . . , and 50°C . A frame time to search a target field can be chosen to depending on the variations of temperature from one second per scan in a rapid variation to four seconds per scan in a normal variation.

2.4. Measurement of surface temperature

Surface temperature of fruits was generated by a thermal image taken by the infrared camera in much the same way as in a television picture in black and white T.V. monitor. The measuring-temperature-range was indicated by a glance-scale divided into 5 parts between white and black, and the 5 divisions of the glance-scale were shown at the lower part of the picture. The same thermal image can also be observed in the colour T.V. monitor, and the measuring-temperature-range was expressed by ten colour changes from white, red, orange, . . . , blue, and black. Before looking at the thermal image in the monitors, a base temperature and the measuring-temperature-range should be adjusted in order to make uniform distribution in colour density of the picture. The thermal image was then taken by a 35 mm camera attached to the monitor.

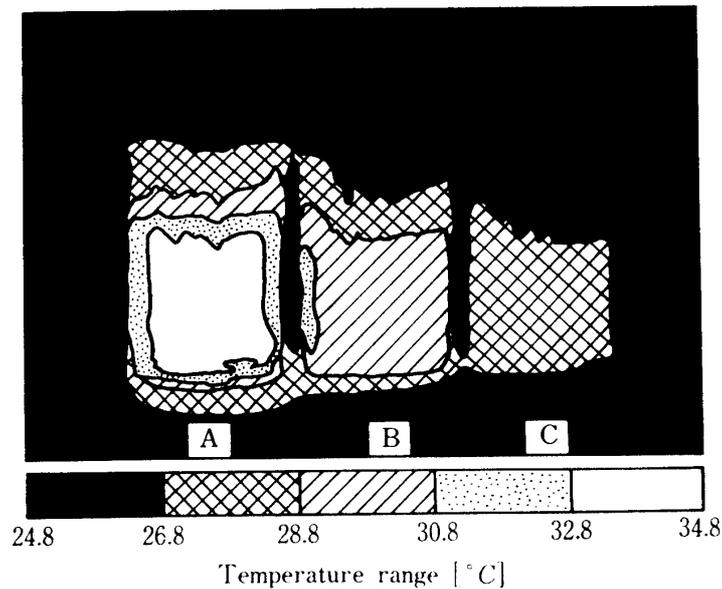


Fig. 2. Thermal images for the beakers filled with water.
 Temperature of water: A 34°C, B 30°C, C 29°C.
 Measuring temperature range: 10°C.
 Base temperature: 29.8°C.

2.5. Temperature-curve

In the Infra-Eye 102A, temperatures on the single scanning line at a given elevation can be measured continuously, and a temperature-curve was shown in the T.V. monitor. In adjusting the elevation of scanning line, the temperature-curve was measured on the line just passing through the center of the bruise on the surface of fruits. The upper limit and lower limit of the curve should be selected to cover the maximum and minimum temperatures of the sample, and they are corresponding to the measuring-temperature-range. The range is divided into five equal parts. The temperature-curves can be taken by a 35 mm camera attached to the T.V. monitor, under the same conditions of the photograph of the thermal image.

Results and Discussion

3.1. Surface temperature of model substances

A preliminary result of this investigation was accomplished by filing the data for temperature-distribution of the model substances. Beaker made of glass, as model of cylindrical substances, and flask made of glass and tennis ball made of soft rubber, as model of spherical substances, were prepared. Those were filled with water.

3.1.1. Surface temperature of cylindrical substance

Beakers having a capacity of 500 ml were used. Temperature of water filled in the beaker was higher than room temperature. After being filled with water for several minutes, temperature of the beaker itself turned up to be homogeneously distributed. Then, temperatures on the surface of beaker were measured by the Infra-Eye 102A.

Fig. 2 shows the thermal images for the beakers of higher, medium, and lower temperatures, respectively. As seen from Fig. 2, temperature-distribution along axial direction is quite homogeneous. While, the temperature-distribution on the upper part of

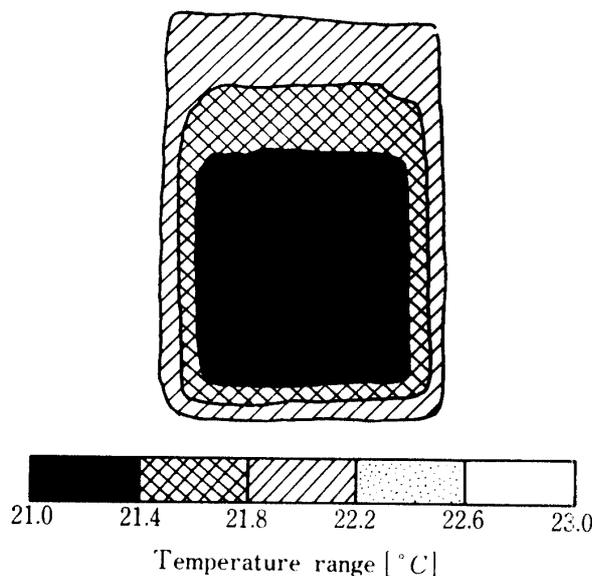


Fig. 3. Thermal image for the beaker filled with water and covered with black paper.

Temperature of water: $21.0^{\circ}C$.

Measuring temperature range: $2.0^{\circ}C$.

Base temperature: $22.0^{\circ}C$.

beaker decreases gradually. This happened because temperature on the wall located above the water level in the beaker gradually approached to room temperature. On the other hand, the temperature-distribution along radial direction is almost homogeneous over the wide range around the center, but decreases with a steep gradient at the both sides of beaker.

The emissivity (that is ratio of radiant emittance of a source and that of a black body at the same temperature) of glass is $0.94-0.91$ at temperature range from $20^{\circ}C$ to $100^{\circ}C$ ⁶⁾. In order to estimate reflection of infrared radiations at the surface of beaker, the surface of beaker was covered with black paper (the emissivity of black paper is $0.96-0.98$ at temperatures of $40-100^{\circ}C$ ⁶⁾). The temperature-distribution on the surface covered with black paper was almost the same as that of uncovered one. From this result, it was ascertained that the influence of reflection on the glass surface for the temperature-distribution was negligible.

Fig. 3 shows the thermal image for the beaker filled with water which was slightly lower than room temperature, and the beaker covered with black paper. The temperature-distribution along axial direction is quite homogeneous. While, the distribution on the upper part of beaker increases gradually and approaches to room temperature. On the other hand, the temperature-distribution along radial direction is almost homogeneous over the wide range around the center, but it increases with a steep gradient at the both sides.

Temperatures at the homogeneous region observed in the thermal image are higher than that at the background in Fig. 2, while just the opposite relationship is observed in Fig. 3.

3.1.2. Surface temperature of spherical substance

A rubber ball for softball tennis was used. The dimensions of the ball are 61 mm in

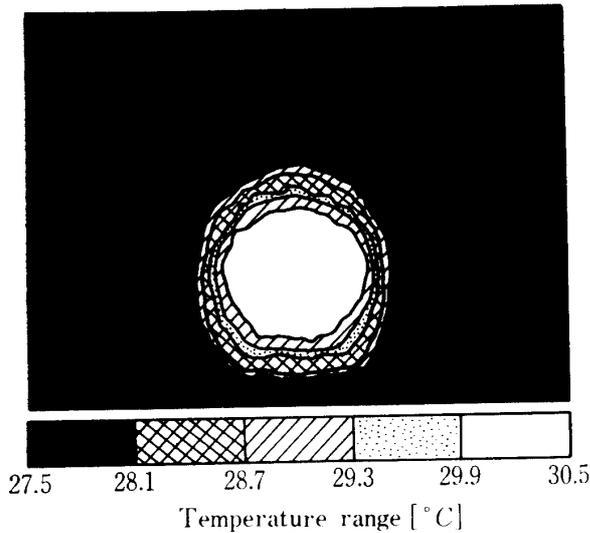


Fig. 4. Thermal image for the ball filled with water
 Temperature of water: 30.0°C .
 Measuring temperature range: 3.0°C .
 Base temperature: 29.0°C .

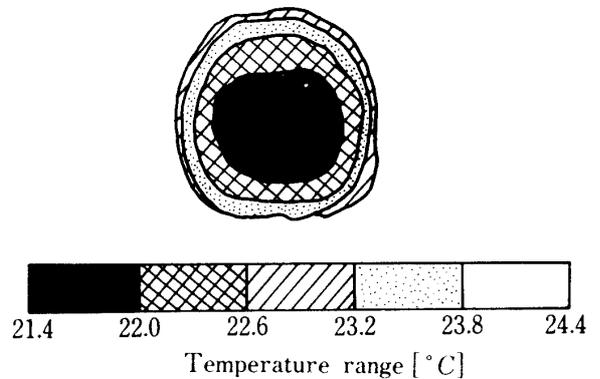


Fig. 5. Thermal image for the ball filled with water
 Temperature of water: 22.0°C .
 Measuring temperature range: 3.0°C .
 Base temperature: 22.9°C .

diameter and 1.1 mm in thickness. Air in the ball was evacuated and water was filled in its place. The emissivity of soft rubber is 0.86 at 20°C ⁶.

Temperatures of the ball filled with water can be looked upon as having a homogeneous distribution of spherical substance. Surface temperatures of the ball measured at room temperature are shown in Fig. 4 and Fig. 5.

In Fig. 4, temperature of the ball tested was slightly higher than room temperature. The temperature-distribution on the spherical surface is quite homogeneous over the wide area around the center. The maximum temperature at homogeneous region is slightly higher than room temperature. On the other hand, the distribution at the circumference decreases with a steep gradient.

In Fig. 5, temperature of the ball tested was slightly lower than room temperature. The temperature-distribution is also quite homogeneous over the wide area. The minimum temperature at homogeneous region is slightly lower than room temperature. While, the distribution at the circumferences increases with a steep gradient.

From these results obtained in model substances, it is concluded that the temperature-distribution observed in the thermal image expresses exactly the same temperature-distribution of the target, excepting the one at the boundary between the target and the background.

3.2. Surface temperature of unbruised fruits

Unbruised fruits which were fresh and were not artificially damaged were used as controls. Since the emissivities of fruits tested are not clear in literature, these values are estimated to be about 0.9 – 0.8 at room temperature with reference to the data of the plant⁶. Before the infrared measurement, fruits were stored in the thermo-regulated rooms more than 24 hrs, in order to give the storage conditions described in § 2.2.

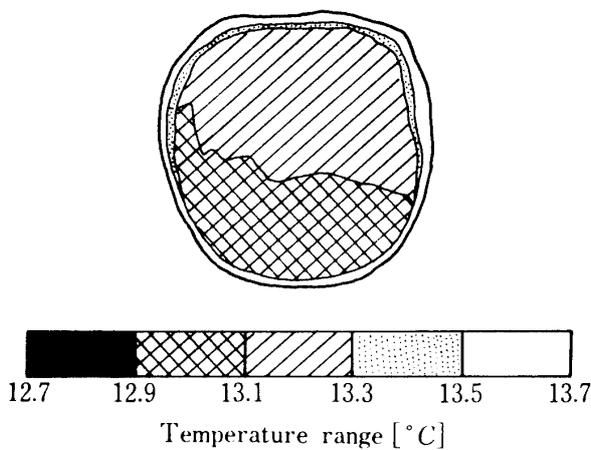


Fig. 6. Thermal image for the unbruised apple (Roll's Janet).
 Stored at room temperature for several days and then stored at 10°C for 24 hrs before measurement.
 Measuring temperature range: 1.0°C .
 Base temperature: 13.2°C .
 The time measured: 4 min. 27 sec.

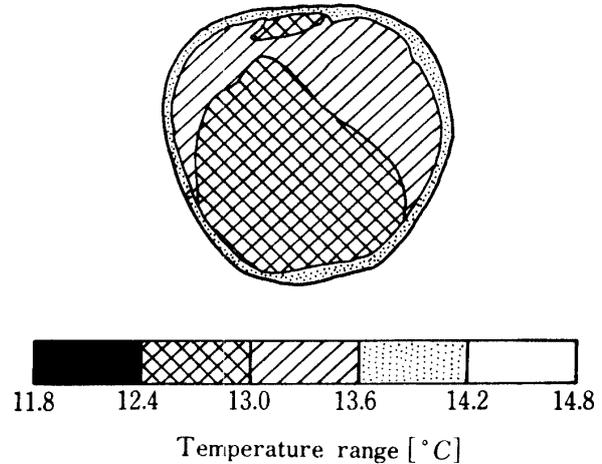


Fig. 7. Thermal image for the unbruised apple (Roll's Janet).
 Stored at lower temperature for several days and then stored at 10°C for 24 hrs before measurement,
 Measuring temperature range: 3.0°C .
 Base temperature: 13.3°C .
 The time measured: 6 min. 47 sec.

3.2.1. Surface temperature of unbruised apple

Fig. 6 shows the thermal image for the unbruised apple (Roll's Janet) stored at temperature slightly higher than room temperature. Since temperature difference between the apple and the background was small, the measuring-temperature-range was selected to be 1.0°C . The temperature-distribution on the surface of the unbruised apple was quite homogeneous over the wide area around the center, as observed in the case of the ball filled with water.

Fig. 7 shows the thermal image for the unbruised apple stored at 10°C for 24 hrs before measurement, and measured at room temperature. The measuring-temperature-range was selected to be 3.0°C . The temperature-distribution observed in Fig. 7 is very similar to that observed in Fig. 6, but temperature changes at circumference indicated in Fig. 7 are more remarkable than that observed in Fig. 6. Although, the division of isothermal curves in Fig. 7 is 0.6°C , and that in Fig. 6 is 0.2°C , isothermal curves in the thermal images of Fig. 6 and Fig. 7 indicate the same tendency.

Since the shape of apple is not of a perfect sphere, there is some heterogeneity in the temperature-distribution between the upper part and the lower part. As the calyx in apple gives a hollow, temperature corresponding to this part is slightly lower than the surrounding, as seen in Fig. 7. While, temperature at the lower part of the apple has some influence from the floor, and some heterogeneity in the temperature-distribution was observed.

3.2.2. Surface temperature of unbruised Satsuma mandarin

Fig. 8 and Fig. 9 show the thermal image and the temperature-curve for the unbruised Satsuma mandarin stored at lower temperature. As seen in Fig. 8, in general, the temperature-distribution of the surface of mandarin is nearly homogeneous over the wide area around the center. However, in details, some heterogeneity in the tem-

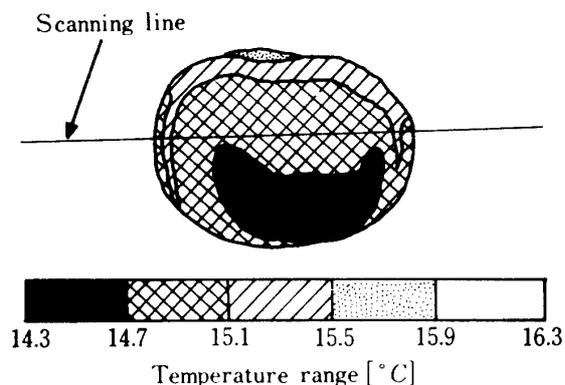


Fig. 8. Thermal image for the unbruised Satsuma mandarin.

Stored at lower temperature for several days and then stored at lower temperature for 24 hrs before measurement.

Measuring temperature range: 2.0°C .

Base temperature: 15.3°C .

The time measured: 34 min. 44 sec.

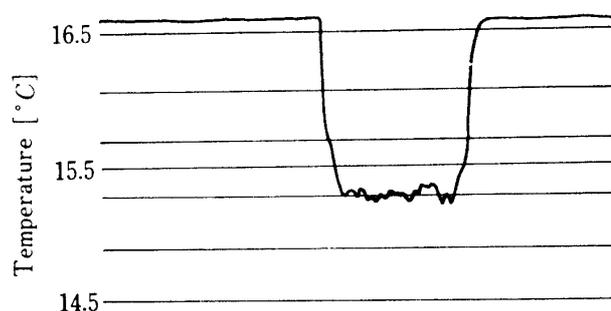


Fig. 9. Temperature-curve for the unbruised Satsuma mandarin.

Measuring conditions are the same as described in Fig. 8.

perature-distribution was observed. Since the shape of Satsuma mandarin is rather flat sphere, temperature at the lower part of the mandarin is slightly lower than that at the upper part. On the other hand, the temperature-curve passing through the center of mandarin indicates rather loose variation. Therefore, it is assumed that the temperature-curve is not influenced by the effect of shape, as shown in Fig. 9.

3.3. Temperature-distribution of bruised apple

3.3.1. Temperature-distribution of bruised apple

The thermal image of the artificially damaged apple (Roll's Janet) was measured under the same conditions as described in § 3.2.

The temperature-distribution and the temperature-curve for the apple bruised by compressing are shown in Fig. 10. Samples were stored at lower temperature for several days, and then stored at lower temperature for 24 hrs before measurement.

As seen in Fig. 10, a concentric circular pattern in the temperature-distribution is observed, and the pattern is corresponding to the shape of the pressed bruise. While, a crescent-shaped pattern observed in the down hemisphere corresponds to the gradual temperature changes between the bottom of apple and the floor.

On the other hand, in the lower part of Fig. 10, the temperature-curve passing through the center of the pressed bruise indicates two minimums which are just corresponding to the parts of the concentric circular bruise. The temperature at the minimum is about 0.3°C lower than that of the surrounding.

The view of the pressed bruise on the surface of apple was dark brown colour, showing concentric circular shape. The thermal image corresponding to the bruise expresses no change in colour on the surface, while expresses temperature changes caused by the bruise on the surface. From these observations, it is concluded that temperature at the pressed bruise is slightly lower, compared with the temperature at the unbruised

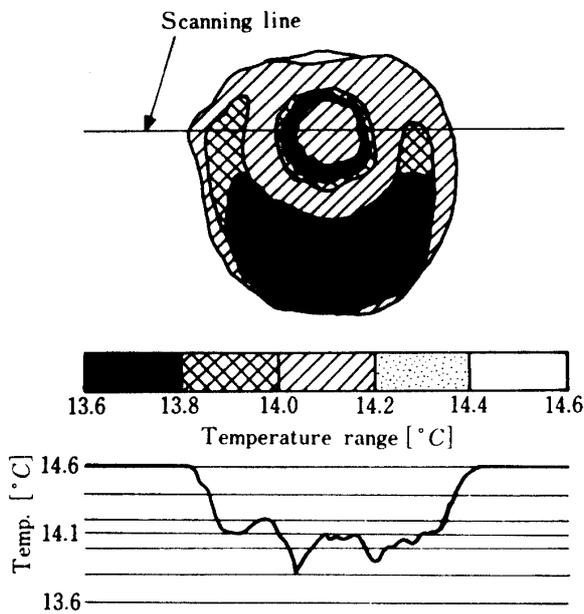


Fig. 10. Thermal image and temperature curve for the apple (Roll's Janet) bruised by compressing.

Stored at lower temperature for several days and then stored at lower temperature for 24 hrs before measurement.

Measuring temperature range: 1.0°C .

Base temperature: 14.1°C .

The time measured: 9 min. 36 sec.

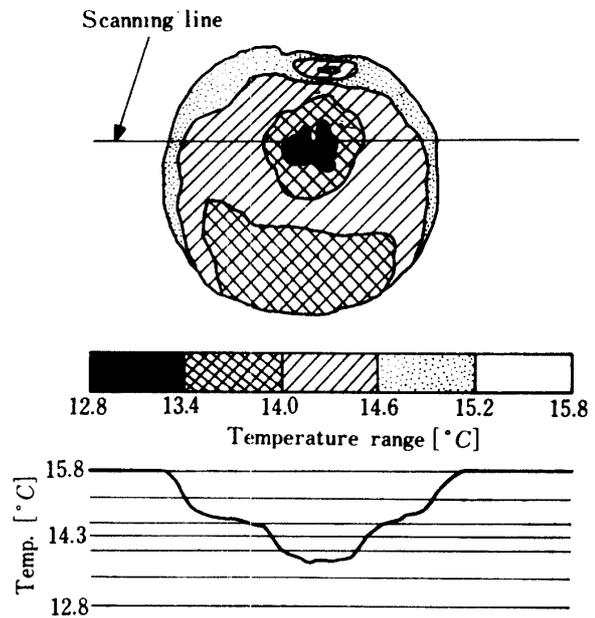


Fig. 11. Thermal image and temperature curve for the apple (Roll's Janet) bruised by scratching.

Stored at room temperature for several days and then stored at lower temperature for 24 hrs before measurement.

Measuring temperature range: 3.0°C .

Base temperature: 14.3°C .

The time measured: 26 min. 36 sec.

skin, and the pattern corresponding to the bruise is almost similar to the shape of the bruise.

On the other hand, temperature at the center of the concentric circular pattern is usually slightly higher than the surrounding, and is equal to the temperature at the unbruised skin. This happens because the center of the bruise by compressing is the normal skin.

Fig. 11 shows the thermal image and the temperature-curve for the apple bruised by scratching. Samples were stored at room temperature for several days, and then stored at lower temperature for 24 hrs before measurement. As seen in Fig. 11, a circular pattern in the temperature-distribution is observed, and the pattern is just corresponding to the shape of the scratched bruise. While, the temperature-curve, in the lower part of Fig. 11, passing through the center of the bruise indicates only one minimum just corresponding to the part of the circular bruise. Temperature at the minimum is about 1.0°C lower than that at the unbruised skin.

From these results, in spite of the bruise caused by the compress or by the scratch, temperatures at the bruise are usually slightly lower than that at the unbruised skin, and these slight temperature changes can be detected in the thermal image.

3.3.2. Temperature-distribution of bruised Satsuma mandarin

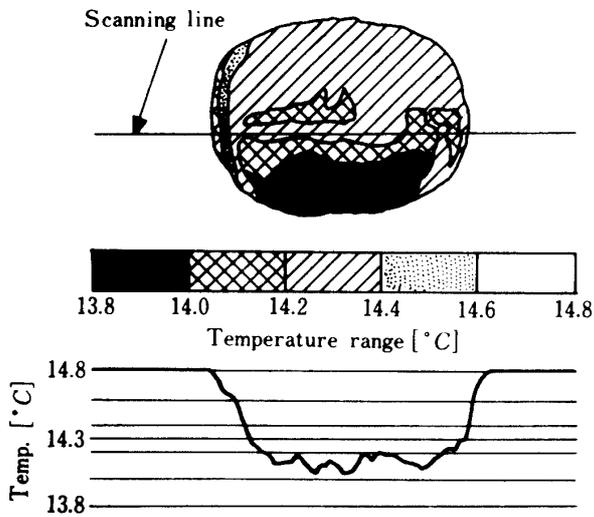


Fig. 12. Thermal image and temperature curve for the Satsuma mandarin (picked on Nov. 27) bruised by compressing.

Stored at higher temperature for several days and then stored at lower temperature for 24 hrs before measurement.

Measuring temperature range:
1.0°C.
Base temperature: 14.3°C.
The time measured: 10 min. 7 sec.

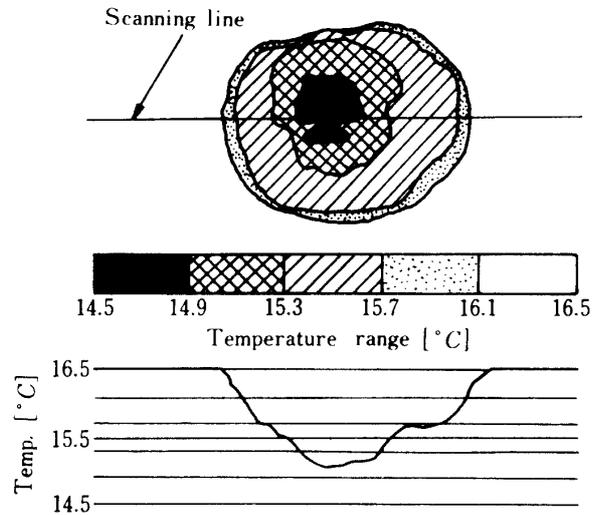


Fig. 13. Thermal image and temperature curve for the Satsuma mandarin (picked on Nov. 27) bruised by scratching.

Stored at higher temperature for several days and then stored at lower temperature for 24 hrs before measurement.

Measuring temperature range:
2.0°C.
Base temperature: 15.5°C.
The time measured: 29 min. 47 sec.

The thermal image of the artificially damaged Satsuma mandarin was measured under the same conditions as described in § 3.2. The temperature-distribution and the temperature-curve for the Satsuma mandarin bruised by compressing are shown in Fig. 12. Samples were stored at higher temperature for several days, and then stored at lower temperature for 24 hrs before measurement.

A concentric circular pattern in the temperature-distribution was observed as seen in Fig. 12. The pattern is corresponding to the shape of the pressed bruise, but the pattern is not so clear as observed in the case of the bruised apple. While, the temperature-curve passing through the center of the pressed bruise indicates two minimums corresponding to the parts of concentric circular bruise, as observed in the case of bruised apple. The temperatures at the minimum are about 0.2°C lower than that at the unbruised skin.

The temperature-distribution and the temperature-curve for the Satsuma mandarin bruised by scratching are also shown in Fig. 13. These samples were stored at higher temperature for several days, and then stored at lower temperature for 24 hrs before measurement. Compared with the results obtained in the apple bruised by scratching, almost the same results were obtained. While, since the artificial damage caused by scratching is rather more effective compared with that by compressing, the temperature at the scratched bruise is about 0.8°C lower than that at the unbruised skin.

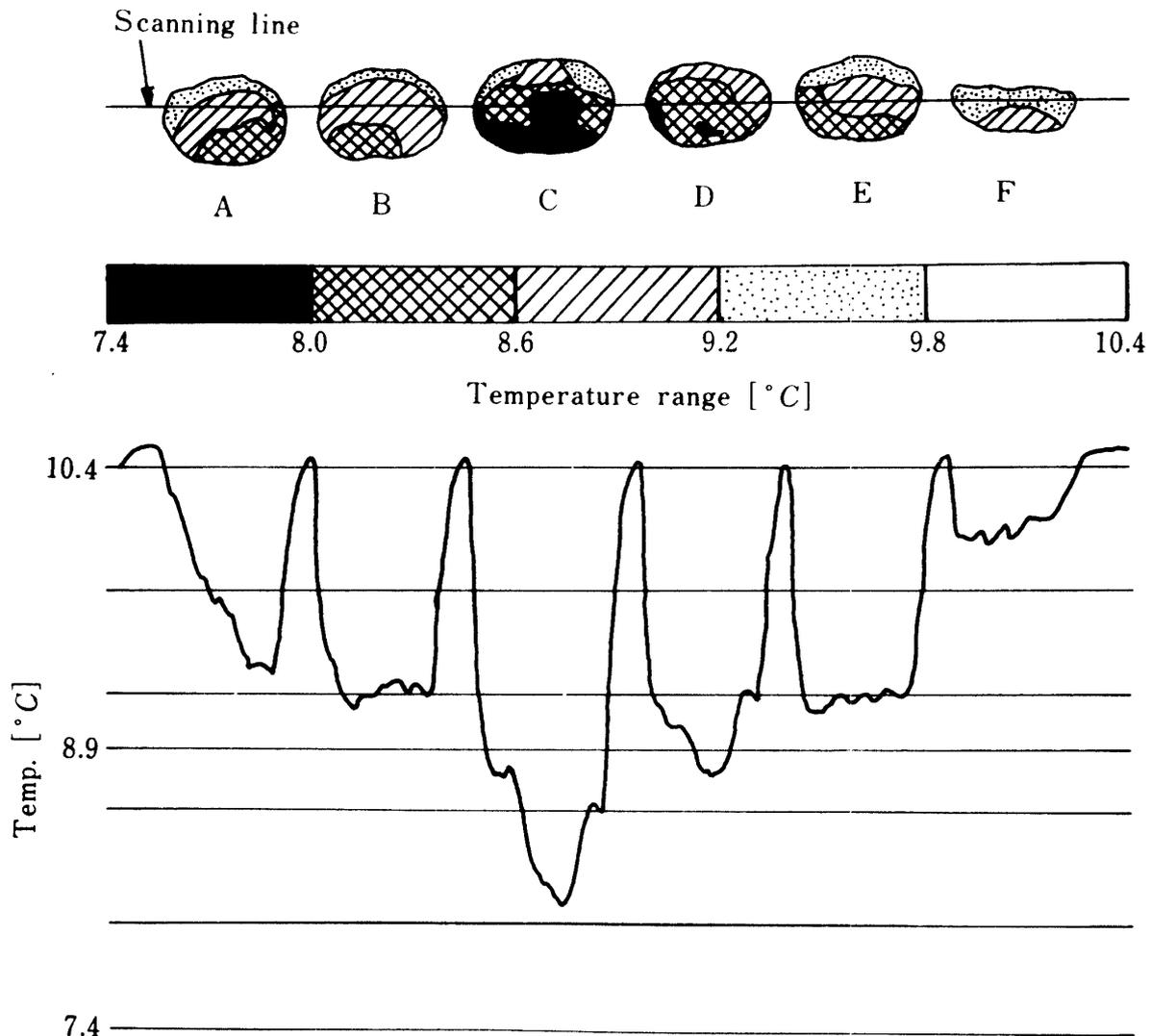


Fig. 14. Thermal image and temperature-curve for the bruised and unbruised Satsuma mandarins.

Stored at higher temperature for several days and then stored at lower temperature for 24 hrs before measurement, Pressed bruise: A (picked on Dec. 4), B (picked on Nov. 27), Scratched bruise: C (picked on Dec. 4), D (picked on Nov. 27), Unbruised: E (picked on Dec. 4), F (picked on Nov. 27).

Measuring temperature range: 3.0°C .

Base temperature: 8.9°C .

The time measured: 4 min. 40 sec.

Fig. 14 shows the thermal image and the temperature-curves for two mandarins bruised by compressing (picked on Dec. 4 and Nov. 27), and two mandarins bruised by scratching (picked on Dec. 4 and Nov. 27), and two unbruised mandarins (picked on Dec. 4 and Nov. 27), which are arranged in a line from the left to the right. These mandarins were stored at higher temperature for several days, and then stored at lower temperature for 24 hrs before measurement. It is clear from the data of Fig. 14 that the temperature-distribution patterns between the damaged mandarin and the normal one are remarkably different, and temperatures at the bruise are lower than that at the unbruised mandarin.

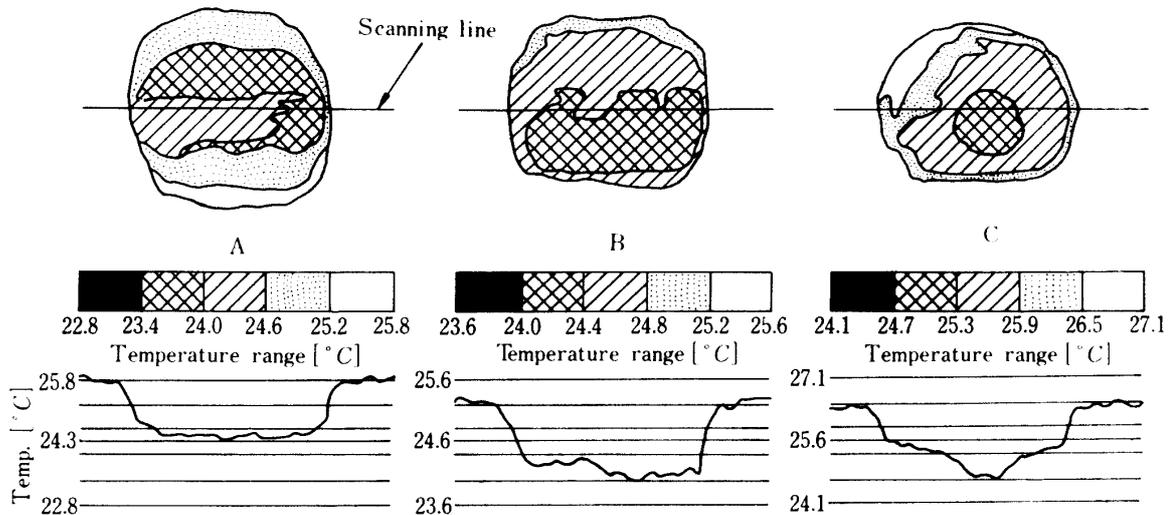


Fig. 15. Thermal image and temperature curve for the unbruised and bruised Natsudaidai.

Unbruised: A, Pressed bruise: B, Scratched bruise: C.
 Measuring temperature range: A, 3.0; B, 2.0; C, 3.0 [$^{\circ}\text{C}$].
 Base temperature: A, 24.3; B, 24.6; C, 25.6 [$^{\circ}\text{C}$].

3.3.3. Temperature-distribution of bruised Natsudaidai

Natsudaidai is a kind of citrus, and is larger in dimensions than Satsuma mandarin. The skin of the former is thicker and stronger than in the latter. Therefore, artificial damages on Natsudaidai can easily produce heavy damage in comparison with the case of Satsuma mandarin, when the same amount of pressure is applied.

The temperature-curves for the unbruised, compressing bruised, and scratching bruised Natsudaidai are shown in Fig. 15. The temperature-curves for the unbruised Natsudaidai are almost flat, while that for the bruised samples indicate minimums. These results are quite similar to that obtained in the case of Satsuma mandarin (§3.3.2). The temperatures at the pressed and scratched bruises are lower from 0.3 to 0.8 $^{\circ}\text{C}$ compared with that at the unbruised skin.

Time Dependency of Temperature-Distribution of Fruits

The infrared measurements of bruised fruits were made at room temperature immediately after having brought out the fruits from the thermo-regulated rooms. Since there were some temperature differences between temperature of fruits and room temperature, temperatures of fruits varied from time to time. A series of measurements were made to elucidate the relationship between temperature-distribution of fruits and the time measured.

4.1. Time dependency of temperature-distribution of apple

A series of measurements of the temperature-curves for the number of bruised apples (Roll's Janet) is shown in Fig. 16. Apples were arranged in a line from the left to the right in the following order: A, B were pressed bruise, C, D scratched bruise, and E, F unbruised apples. These apples were stored at lower temperature for several days, and then also stored at lower temperature for 24 hrs before measurement.

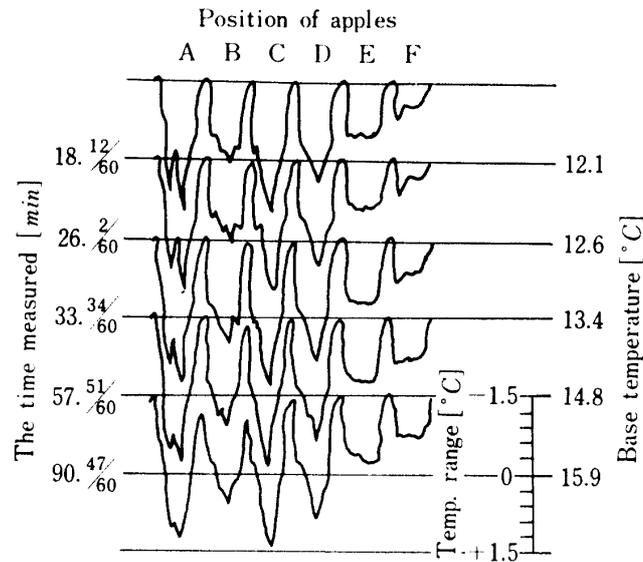


Fig. 16. A series of temperature-curves for the bruised apples (Roll's Janet) as a function of the time measured.

Stored at lower temperature for several days and then stored at lower temperature for 24 hrs before measurement.

Pressed bruise: A, B; Scratched bruise: C, D; Unbruised: E, F.

Measuring temperature range: 3.0°C .

As seen in Fig. 16, the temperature-curves corresponding to the pressed bruise have two minimums, and that of the scratched bruise have one minimum, and that of the unbruised show flat variation. The pattern of temperature-curves shows similar variation during the series of measurements, but the surface temperatures of these apples change continuously in accordance with the time elapsed.

Fig. 17 shows the temperature changes at the bruise as a function of the time measured. Since these apples were stored at lower temperature for several days, the damage-levels caused by artificial treatments were not so much developed. Therefore, temperatures at the bruised and at the unbruised apples increase continuously in accordance with the time measured, and temperature differences between the bruised and the unbruised are nearly constant over the wide range of time. On the other hand, temperature differences between the pressed bruise and the scratched bruise are very small.

Fig. 18 also shows the temperature changes for the bruised apples as a function of the time measured. These apples were stored at higher temperature for several days, and then stored at lower temperature for 24 hrs before measurement. Therefore, the damage-levels caused by artificial treatments were developed. As observed in Fig. 17, temperatures at the bruised and at the unbruised apples increase continuously in accordance with the time measured, and temperature differences between the bruised and the unbruised are also nearly constant over the wide range of time. On the other hand, a little temperature difference between the pressed bruise and the scratched bruise is observed. The damage-levels for the scratched bruise are more developed compared with that for the pressed bruise, during the storage at higher temperature.

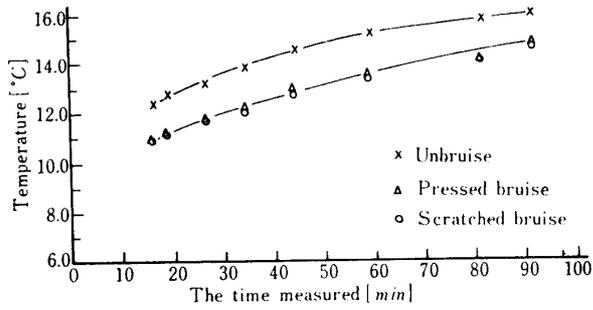


Fig. 17. Relationship between temperature changes at the bruised apples (Roll's Janet) and the time measured.

Stored at lower temperature for several days and then stored at lower temperature for 24 hrs before measurement. Measuring conditions are the same as described in Fig. 16.

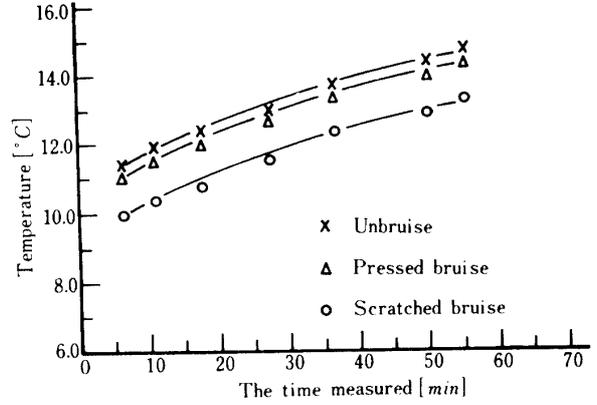


Fig. 18. Relationship between temperature changes at the bruised apples (Roll's Janet) and the time measured.

Stored at higher temperature for several days and then stored at lower temperature for 24 hrs before measurement.

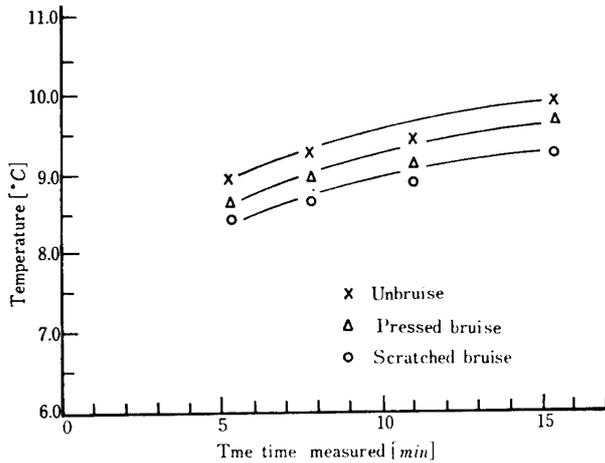


Fig. 19. Relationship between temperature changes at the bruised Satsuma mandarin and the time measured.

Stored at lower temperature for several days and then stored at lower temperature for 24 hrs before measurement.

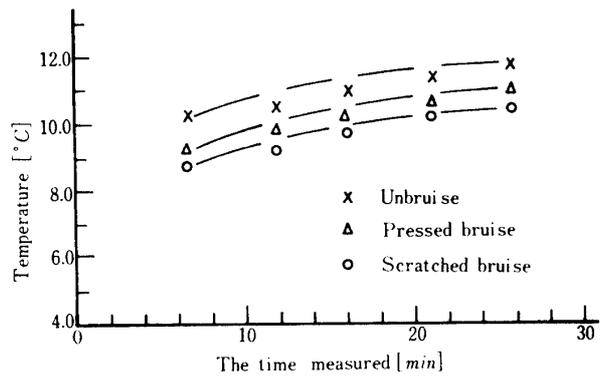


Fig. 20. Relationship between temperature changes at the bruised Satsuma mandarin and the time measured.

Stored at higher temperature for several days and then stored at lower temperature for 24 hrs before measurement.

4.2. Time dependency of temperature-distribution of Satsuma mandarin

The temperature changes for the bruised mandarin as a function of the time measured, are shown in Fig. 19. These mandarins were stored at lower temperature for several days, and then also stored at lower temperature for 24 hrs before measurement. As observed in the case of apples in Fig. 17, the same tendency in temperature changes at the bruised, and temperature differences between the bruised and the unbruised are observed in Fig. 19. On the other hand, a little temperature difference between the pressed bruise and the scratched bruise is observed. This happens because the damage-levels for the pressed bruise on Satsuma mandarin are not so remarkable as compared with that for the scratched bruise.

Fig. 20 also shows the temperature changes for the bruised Satsuma mandarin as a function of the time measured. These mandarins were stored at higher temperature for several days, and then stored at lower temperature for 24 hrs before measurement. As observed in the case of apples in Fig. 18, the same tendency in temperature changes at the bruise, and temperature differences between the bruised and the unbruised are observed. On the other hand, a little temperature difference between the pressed bruise and the scratched bruise is observed. This is because the damage-levels for the pressed bruise on Satsuma mandarin are developed during the storage at higher temperature.

Conclusion

The infrared imaging method was investigated to examine the possibility of quality evaluation of fruits. Temperature on the surface of fruits can be measured without contact by infrared imaging method. Temperature-distributions on the surface of fruits were estimated from the thermal image. Temperature at the surface defect is usually slightly lower than that at the normal surface. In order to measure small temperature changes on the surface of fruits, suitable conditions for the infrared measurement were established by varying the storage temperature of the fruits before measurement. Under these conditions, any surface defect of fruits can be detected by the thermal image within temperature changes of 0.2°C .

The quality evaluation of artificially damaged fruits by the infrared imaging method shows the following conclusions:

1. Temperature-distribution on the surface of model substances is quite homogeneous over the wide range around the center, excepting the one at the boundary between the target and the background.
2. Temperature-distributions on the surface of unbruised fruits are almost homogeneous, while some heterogeneity in temperature-distribution is observed, corresponding to the shape of fruits.
3. Especially, temperature pattern which is just corresponding to the shape of the bruise is observed in the temperature-distribution for all the bruised fruits tested.
4. Temperatures at the bruised are usually slightly lower compared with temperature at the unbruised skin. The temperature difference between the bruised and unbruised is usually within the range from 0.2 to 1.0°C .

Summary

An infrared imaging method was investigated to examine the possibility of quality evaluation of fruits. Temperature on the surface of fruits can be measured without contact by this method. Surface temperatures of fruits were estimated from the thermal image obtained.

A preliminary workings of this investigation were carried out, using model substances. Surface temperatures of the model substances were considered to be of homogeneous distribution. The temperature-distribution observed from the thermal image indicates exactly the same temperature-distribution of the model substances. Fruits tested in the present experiments were apple, Satsuma mandarin, and Natsudaidai. Unbruised fruits were used as controls. The temperature-distribution of the unbruised fruits is almost homogeneous over the wide range at the center, while some heterogeneity in the distribution is observed, corresponding to the shape of fruits.

Artificially damaged fruits were prepared. Pressed and scratched bruises were given artificially on the surface of fruits. Especially, the temperature pattern just corresponding to the shape of bruise is observed in the temperature-distribution for all the bruised fruits tested. Temperature at the bruise is usually slightly lower compared with temperature at the unbruised skin. Temperature difference between the bruised and the unbruised skin is usually in the range from 0.2 to 1.0°C. Based on these results, it is concluded that the thermal imaging method is very effective for the grading of fruits.

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