Determination of Thermal Emissivity and Surface Temperature Distribution of Horticultural Products

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Abstract
A temperature decrease of the surface is observed, when heat is transmitted from the product for the transpiration of biological products like fruits and vegetables. By thermal imaging, this change in temperature can be measured and used for the quality evaluation of horticultural products. In the experimental studies performed here, a commercial infrared thermal imaging camera has been applied having a temperature resolution of better than 0.1 K. Since the intensity of thermal radiation is related to the temperature to the power of four and is directly proportional to the emission factor of the sample, this emission factor (emissivity) must be known. Different experiments were performed by using markers with known emissivity and by contact measurements in order to determine the emissivity of different horticultural products. The results indicate that the emissivity is in the range of 0.94 ± 0.04 for all those horticultural products studied here.

Introduction
Thermal imaging has become an important tool in research and production in many branches in connection with dropping costs over the last decades. At present, new applications in agriculture and horticulture are visible like designing and control of storage houses and vegetable displays, quality evaluation and control of sensitive biological products (Linke et al 2000). The imaging camera is utilised normally as a "two-dimensional" thermometer. In reality, the thermal radiant flux (or radiation flux) at a limited wavelength band (3 - 5 μm or 7 -14 μm, dependent on type of sensor) is measured. This two-dimensional distribution of the radiant flux of a three-dimensional object is then converted into a temperature distribution. At least two main error sources limit the accuracy of the temperature determination:
- The radiant flux $\Phi$ depends on the emissivity $\varepsilon$ and on the temperature $T$ (Stefan-Boltzmann law)
$$\Phi = \varepsilon \ T^4 \ \sigma \ A$$
with $A$ the surface area of the radiating body and $\sigma$ a proportionality constant (dimension factor). Therefore, the emissivity of the object in the interesting waveband must be known to convert radiation data into temperature. Usually a
"global" emissivity is taken (e g \( \varepsilon = 1 \) assuming blackbody radiation or \( \varepsilon = 0.95 \) for outdoor images). The results are called apparent temperatures. For accurate measurements, the emissivity of the object must be known.

- The thermal radiation of a body is a superposition of direct (specular) radiation with an intensity distribution according Lambert's (cosine) law of illumination and of diffuse radiation. Diffuse radiation is typical for high temperature (\( > 1000 \) K). The share of direct radiation of water, the main component of fruits and vegetables, depends on the thickness of the water layer (Haußeker 1996). Only those areas of fruits will be measured correctly, which are parallel oriented to the sensor plane of the camera. This effect is visible in thermal images of spherical shaped fruits e.g. apples or tomatoes. The temperature at the outer circumference seems to be lower than from the centre of the fruit.

In this paper, the aim is to report and to discuss measurements of the emissivity of fruits. Until now, only few data on the emissivity of fruits and vegetables are given in the literature. In standard handbooks, the emissivity of water, wood, paper and some other organic materials is listed. The emissivities of these materials are in the range between 0.80 and 0.95 (e.g. King 1987, Ebert 1962).

**Materials and methods**

An IR imaging camera "Varioscan 3021-ST" serves for the measurement of the radiant flux. The software "IRBIS Plus V2.0" enables inputs of emissivity as "global" for the whole image, and as "local" for a definite area or a free definable pixel range. The measuring principle is to use a calibrated marker at the surface of the fruit to get the true surface temperature (Fig. 1). Marker of different materials are measured at the surface of a temperature controlled aluminium ingot containing a blackbody radiator (black hole C01 in Fig. 2).

![Fig. 1 Scheme of the measuring principle.](image-url)
Fig. 2 Thermal image and apparent temperatures ($\varepsilon = 1$) of calibration measurements (C01: blackbody radiator; C02: white paper; C03: adhesive paper; C04: adhesive aluminium foil; C05: aluminium ingot).

The temperature of the aluminium ingot is regulated by an internal water bath. The emissivity of the blackbody radiator is measured by dynamic temperature measurements (heating curves and cooling curves), as it is necessary to have temperature contrasts. In thermal equilibrium at room temperature, no image will be gotten. The measurement error increases at low contrast (near room temperature) because of a small signal to noise ratio. The ingot temperature is measured with thermocouples and the radiant flux with the imaging camera. The emissivity of the blackbody radiator is found such a way as 0.99. With this value, the emissivity of the markers is gotten (Fig. 3).

Fig. 3 Emissivity of different materials (ambient temperature 22.5 °C).

As marker for the fruit experiments, small pieces of adhesive paper are taken, since they show nearly no variation in emissivity ($\varepsilon = 0.924$), and this type of marker can...
easily be handled. Since a marker seals locally the surface and stops such a way the transpiration with local changes in the temperature, the solution is a protecting foil (10 µm polyethylene), which covers other parts of the fruit too and guarantees similar ambient conditions during the time of measurement. Therefore, the transmission properties of foils had to be measured. Measurements of the calibration device without foil and with two different foils (10 µm and 30 µm) do not change the calibration, hence it is possible to use transparent foils as cover in emissivity measurements of fruits.

**Results and discussion**

To determine the emissivity, it is necessary to know the radiant flux (radiation intensity) and the true temperature of the radiating surface. Assuming a similar temperature near the marker C01, the known temperature of the calibrated marker is set as the temperature of the measuring circles C02 and C03 at the fruit (Fig. 4).

Then the emissivity at the circles C02 and C03 is found by changing the inputs for the software until the measuring circles C02 or C03 show the same temperature as the marker. The measurement of fruit emissivity has to be performed as dynamic temperature measurements in order to have sufficient contrast. Therefore, the fruits
are warmed up for few hours (sealed in plastic foils) at 32 °C, then placed at a support and thermal images are taken every 30 s. After 120 s, the fruit with marker is pressed against the protecting foil and imaging is continued up to 270 s (Fig. 5). The decline of the apparent emissivity of C02 and C03 till 120 s results mainly from transpiration caused temperature differences between marker and measuring circles. After stopping transpiration by the protecting foil, the temperature increases and the true emissivity is measurable. There are several error sources. Changing air conditions give deviations in the radiation flux measurements. Temperature gradients between marker and measuring circles result in incorrect emissivity calculations. Thus the placing of the measuring circles is important. From Fig. 4 it can be seen that there is a local variability of temperature in the surrounding of the marker.

One explanation is, this might be an insufficient tightening between foil and fruit surface resulting in thin insulating air layers or water vapour layers. Further careful experiments must be performed to analyse this situation. The first measured emissivities are in the range 0.90 to 0.97 (apple: 0.94 - 0.97; pear: 0.95 - 0.96; nectarine: 0.93 - 0.95; tomato: 0.90 - 0.95). Since these numbers are get from one to three fruits each, more measurements must be performed for statistical verification of these preliminary results.
The temperature distribution of an apple will be get by using the measured emissivity and temperature profiles (Fig. 6). A circle C01 is set with $\varepsilon = 0.924$, the emissivity of the marker. The effect of direct radiation is visible, the "true temperature" is valid for the centre of the image only. The share of "Lambert's cosine law radiation" causes this apparent temperature decrease from the centre to the circumference. Additionally, at the circumference we have a superposition with the laminar boundary layer, which results from transpiration and heat exchange with ambient air.

**Conclusions**

The measuring place developed here gives the possibility to study the influence of type, maturity, and other factors of fruits, which could influence the emissivity. Since emissivity measurements must be performed by dynamic temperature measurements, the change of thermal properties with temperature is to be proofed carefully. The first results indicate that emissivity of a definite part of the surface (pixels in measuring circle) can be determined accurately. Due to the principle applied (calibrated marker and 10 $\mu$m protecting foil), a higher variability occurs in the surface temperature of fruits near the marker. Further studies are necessary to find the sources of this variability (thin air layers or water vapour) and to find rules for correct setting of the measuring circles. The first measured emissivities are in the range 0.90 to 0.97 (apple: 0.94 - 0.97; pear: 0.95 - 0.96; nectarine: 0.93 - 0.95; tomato: 0.90 - 0.95).

**References**


