THERMAL IMAGING SYSTEM FOR CLIMATE CONTROL OF POTATO STORES

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Abstract: Infra-red thermographic image processing is applied to determine temperature distribution in big box stores for potatoes. Low temperature differences can be measured and influences of airflow can instantly be visualised and controlled. It was verified that online thermographic data can be used in a temperature regulating system for climate control. The infrared images are considered within a model to predict temperature distribution inside the filled boxes. *Copyright © 2005 IFAC*

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1. PROBLEM OUTLINE

A thermographic imaging system is applied as a climate control component in a big potato box store. Traditional temperature sensors distributed in the boxes give product information, i.e. temperatures, only for local areas. An infrared imaging camera system however is able to record a general view over a comparably wide area to detect local differences of surface temperatures in the storage. The project objective is to improve climate control by application of thermography in a free convective ventilated box store for potatoes to avoid high temperature differences which is a typical problem in such types of stores.

To attain an adequate climate in a big box potato store is not easy to realise. The store floor sizes up to 5000 square metres and box stack levels up to 8.5 metres. The temperature set value for climate control is set to a temperature of nominally 5 °C to keep this optimal temperature all over the store for long term storage. Free convective ventilated stores are working without additional electrical cooling or ventilation. Ventilation is caused only by buoyancy forces as a result from both density and temperature differences within the stack of boxes of respiring potatoes.

It is found that potato temperatures diverge continuously above the normally existing temperature difference of approximately 1.5 °C along the height of 1 metre to 8.5 metres during the storage period (fig.1). At the end of the storage period in April it may happen that the potatoes are stored a little bit too cold in the lowest level and a little bit too warm in the topmost level of the stack.

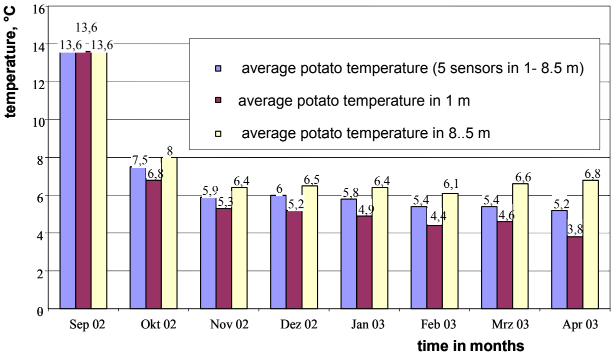

Fig. 1. Storage temperatures of potatoes in a free convective ventilated big box store house (controlled average temperatures and stack temperatures in 1 m and 8.5 m height).

Early sprouting may occur in the upper levels and bad ventilation strategies will lead to additional shrinkage and mass loss above the expected 2-3 % mass loss caused by natural physiological processes.

Present conventional climate control is not able to control temperatures in such a way that an adequate temperature distribution in the store can be reached, provided that no mechanical ventilation systems are installed to force air-flow. The climate control in such free convective type of stores respects only the average temperature of some few sensors distributed in potato boxes. Therefore, an uniform product quality is not yet secured for these types of systems.

2. METHODOLOGY

Basis for the climate control is the development of a 3-dimensionally working control algorithm. Some number of temperature data must be available for this purpose to describe a spatial 3-dimensional model which reproduces the effects of ventilation on the temperature distribution inside and on the front side of the box stack.

An infrared camera was used as a thermographic measuring system, working at a wavelength range of 7.5 to 13 µm and having a thermal sensitivity of 0.07 °C at 30 °C. Temperature accuracy without explicit calibration of the absolute temperature is ±2.0 K. The maximum frame rate of the camera is 50 images per second. An image acquisition rate up to that high rate is not suitable for control of the store, for on-line acquisition the highest rate of 3 to 5 minutes is used. The camera is equipped with a 45° wide-angle optical system.

The radiant flux Φ depends on the temperature T according to Stefan-Boltzmann law as well as on the emissivity ε of the surface area A:

$$\Phi = \sigma \, \varepsilon \, T^4 \, A$$

Stefan-Boltzmann constant
$\sigma = 5.6696 \cdot 10^{-8}\ \mathrm{W \cdot m^{-2} \cdot K^{-4}}$.

The emissivity is a material parameter and expresses the relation between the specific radiation of a black body ($\varepsilon = 1$) and the radiation of a real body at the same temperature ($\varepsilon < 1$). It is dependent on the wavelength, the temperature T, the surface properties of the material (e.g. potato, wood, steel, etc.), and the radiation angle of the examined object related to the camera. To every part of interest of the recorded infrared image (fig. 2), a corresponding area has to be assigned with a defined emissivity.

Extensive measurements were made to compare conventional and infrared imaging techniques. It was determined that the surface temperatures recorded on the infrared images correlate with real, i.e. the conventionally measured temperatures.

The infrared (IR) image records surface temperatures of different materials (i.e. potatoes, wooden boxes, etc.) located at different positions and distances. Every image is divided into different parts of interest, i.e. the regions of the supervised area from which the average temperature is calculated (fig. 3). The emissivity of the surface has to be defined for each of these regions. The emissivity of some known materials are taken from literature or by means of own examinations (Ebert 1962, King 1987, Schuster, et.al. 2000, LaRocca 1996, Lutz, et al. 1997),Table 1.

Table 1: Emissivity of the surface of some materials

Material	Emissivity ε
Potatoes	0,85 - 0,92
Wood	0,87 - 0,91
White writing paper (paper marker)	0,953
Polyimide resin film	0,94
Blackened reference sheet	0,92
Copper, polished	0,04

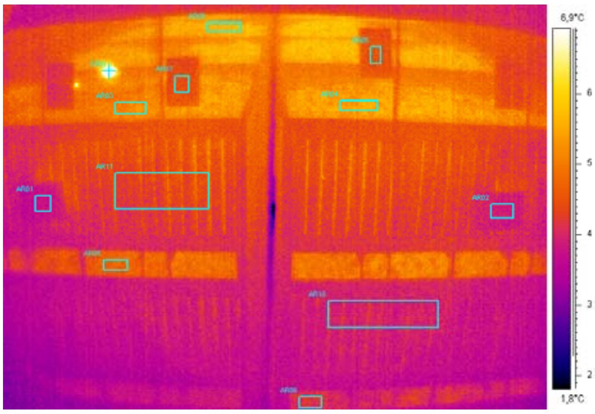

Fig. 2. Infrared image of a potato stack with selected parts of interest

For direct comparison of thermal imaging and conventional measuring technique, a by dull lacquer blackened metal sheet with defined emission degree (reference sheet) was fixed to the potato boxes at a distance of approx. 5 cm to ensure undisturbed aeration. On this reference sheet, temperature changes are recorded also conventionally by using a contact thermometer.

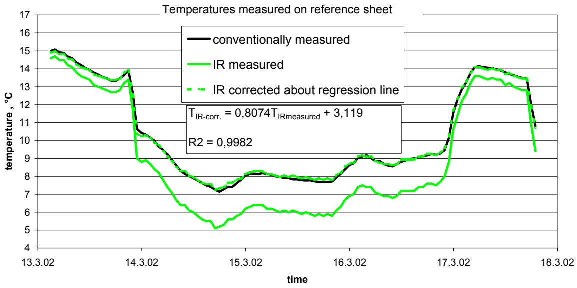

Fig. 3. Temperature recording with conventional and thermal imaging measuring technique on a reference sheet and correction

With thermography recorded temperature values (bright line in fig. 3) are obviously lower than conventionally measured values (black line). Additionally, there is a temperature dependent difference of up to 2 K. The differences between thermography and conventionally measured values are increasing with decreasing surface temperatures.

Two dull lacquer blackened metal sheets with defined emissivities were fixed on the potato boxes at a distance of approx. 5 cm. The temperatures of these plates are measured continually with conventional sensors as references for IR image calibration. Temperature differences between the references and the IR images occur systematically and can be compensated to obtain correct temperatures from the images. After correcting (calibrating) the thermography temperature values the results confirm the correlation to the conventionally measured temperature values very well (fig. 3).

TEMPERATURE DISTRIBUTION MODEL

The model for predicting temperature distribution inside a stack of boxes, dependent on the temperature profile outside the boxes, is based on numerical calculations of the heat transport inside the boxes. Real-time temperature measurements are input into the model for calculating the temperature profile for selected height levels of the stack (fig. 4).

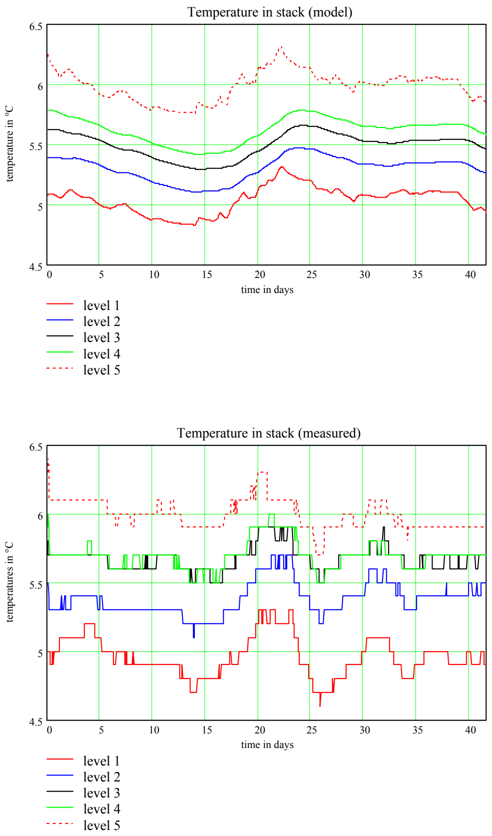

Fig. 4. Temperature distribution within a stack of 7 boxes calculated and measured

AIR FLOW CONTROL

The IR temperature data represent only the 'visible' part of the viewed area. Anyway, main advantages of using IR-data are (1) quick response on temperature changes, (2) high resolution of temperature differences, (3) visibility of air-flow movements when ventilating with fresh air from top and/or bottom dampers, (4) capability to measure without direct contact to the observed object at far distances, (5) possibility of on-line monitoring and control.

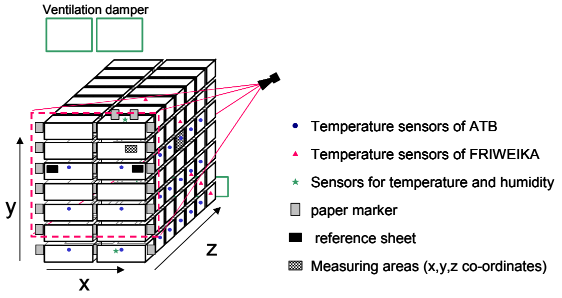

Fig. 5. Test station in the box store with sensors

The strategy for controlling the air-flow and the storage climate is as follows (Gottschalk 2002, Gottschalk, et.al. 2002, Geyer, et.al. 2004). The wooden box surfaces are sufficient good indicators for the ambient temperature. Any changes of these temperatures due to air-flow movements are visible on the IR images and temperature fluctuations can be determined with high accuracy. Adequate damper movements are controlled based on these temperature changes. The invisible parts of the box stack, mainly the potatoes inside the boxes, can only be derived by a certain number of sensors for temperature and air humidity. To keep these numbers of sensors to a minimum the temperature distribution inside the boxes are modelled to predict the temperature changes dependent on the changes of the surface ('visible') temperatures. After a validation period, the conventional sensors (fig 5) are dispensable. Air flow control is then based only on the IR images involving the model calculation results for the temperature distribution inside the boxes. Investigations showed that opening the top dampers alone are mostly regulating the air temperature at the top region of the store.

The surface temperatures (wooden box walls and potato tubers) are changing quickly upon air flow movement with fresh air. This can almost instantly be seen by IR-image movie-sequences. However, temperature changes inside the boxes are changing very slowly, depending on the temperature difference inside to outside (ambience) of the box stack. The wooden surfaces can easily be taken as references for the air temperature. Warming up of the (tuber) surfaces are remarkable at the following conditions

1. closed dampers and outdoor temperatures are equal or higher the inside temperatures
2. instantly when closing the dampers: stop of air exchange
3. closed dampers when outdoor temperature is lower (or frosty)

Warming of the potato tubers (approx. up to 0.8 K/day) is caused by metabolic heat production (respiration activity).

The temperature decreasing rate is depending on

1. outside air velocity
2. temperature difference to outside air
3. damper movement and activity, resp.
    - open dampers on roof top leads to a low decrease rate of temperature mostly on the top of the stack (mostly useful only in Jan/Feb)
    - open dampers on top and bottom leads to a faster temperature decrease rate
    - open dampers on bottom only leads to temperature decrease almost on bottom of the stack

Problems to cool down the upper region of the stack sufficiently are caused by solar heating of the roof during sunny days.

The control efficiency is strongly dependent on the outside condition, mainly on the outside air temperature, or said in other words, on the temperature difference inside to outside. In warmer periods it is difficult to keep inside temperature constant. Perhaps, only for a few hours at night it may be possible to use cooler air for re-cooling the stack.

The visibility of the air movements (by temperature changes), i.e. directions of flow, allow to control separately grouped parts of the dampers. Air flow direction and velocity of the outside air can therefore better taken into consideration. The assumed efficiency of the 'air-throw ventilation strategy' to cool the whole store by simply opening the top dampers only could not be verified. Efficient cooling effects for large parts of the store can be achieved only by controlling top and bottom dampers simultaneously (fig. 6).

CONCLUSION

Using a thermographic camera allows to control the tuber surface temperatures purposively to attain the desired storage temperatures inside the box. The lowest limit of the surface temperature is about 2…3 °C (or little higher) to avoid sweetening of the tubers. Sweetening occurs at low temperatures (approx. <3 °C, dependent on tuber variety) when (reducing) sugar is formed from starch (this process is starting below approx. 10 °C, but will heavily intensify when the temperature reaches near the freezing-point). Hence, best control set point is the desired inner box temperature. The store may be ventilated even when outside air is below 0 °C because the air is warming up instantly when approaching the stack and the tubers are reacting inertly. Temperature limit is the lowest allowed surface temperature for more than approx. 1 hour to avoid sweetening or freezing. Low temperature differences can be controlled by moving the top and bottom dampers, according to the temperature fluctuations, dependent on outside wind velocity, and can be determined by the thermography system.

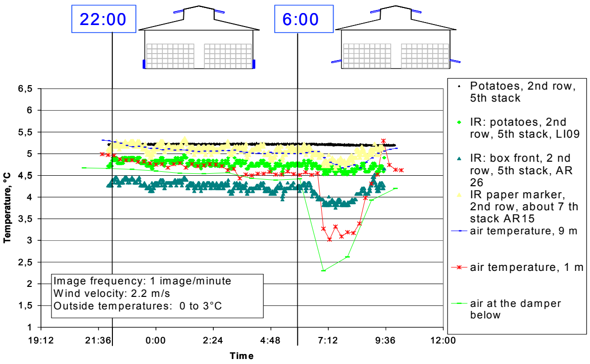

Fig. 6. Temperature distribution on the surface and inside the potato stack during a ventilation process

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