Infrared Thermography to Monitor Natural Ventilation during Storage of Potatoes

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ABSTRACT

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 and relative air humidity values, only for local spots. A thermographic infrared imaging camera system however is able to record a general view over a comparably wide area of the store 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 (FCV) box store for potatoes to reduce high temperature differences, which is a typical problem in such types of stores.

It was proved that the FCV principle is working even for huge stores. For stores of that type no cooling or ventilation devices are applied to save energy and finally to protect the environment. Thus, these types of stores are only dependent on ‘natural’ ventilation with ambient (environment) air.

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. The visibility of the air movements i.e. directions of flow can be seen by temperature changes. This allows controlling of separate grouped numbers of dampers. Airflow direction and velocity of the outside air can therefore better be involved into control strategies. Anyway, the assumed efficiency of the ‘air-throw ventilation strategy’ (‘cellar-effect’) to cool the whole store by simply opening the top dampers only, could not be verified.

Keywords: Thermography, free convective ventilation, potato store, Germany

1. INTRODUCTION

One of the most important objectives during storage of potatoes is the maintenance of the potato quality. It is obvious to reduce stock costs, which imply energy, and other costs. For achieving this objective the conditions for a favourable store climate must be maintained during the storage period.

Stores with a storage capacity up to 16,000 tons of potatoes have storage box piles with heights up to 8.5 m placed on a ground area of approximately 5000 m^2. Keeping a well-adapted climatic control may arise to a great problem for stores of that size. The desired temperature should be maintained everywhere in the store within the range of 4 to 5 °C for a long storage time up to 5 to 8 months.

Generally, free convective ventilated stores are working without additional electrical cooling or ventilation. Ventilation is caused only by buoyancy forces as a result from both air density and temperature differences within the stack of boxes of respiring potatoes.

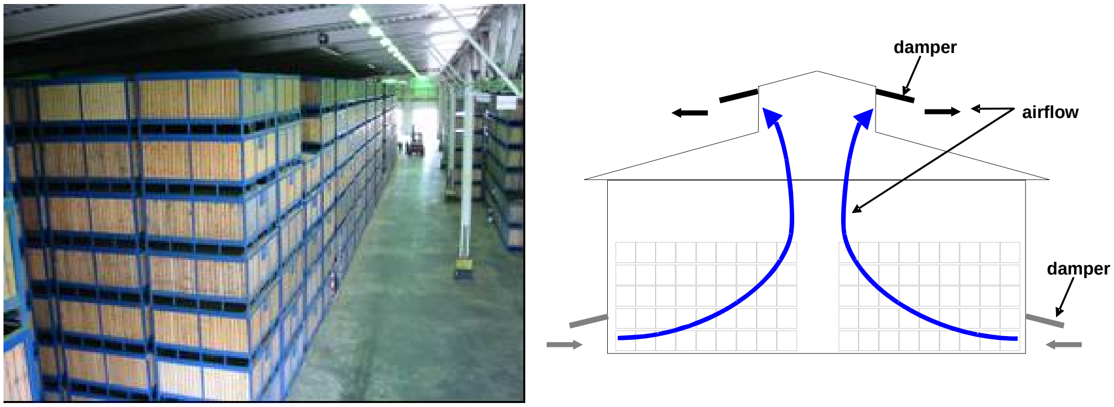

Figure 1. Storehouse for potato bin boxes with free convective airflow

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

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

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

Traditional temperature sensors distributed in the boxes give only local information about the state of the environment of the product, i.e. temperatures. A thermographic imaging system can be applied as a climate control component in a big potato box store (Gottschalk et. al. 2004). An infrared imaging camera system is on the other hand able to record a wide-ranging view over a comparably wide area to detect local differences of surface temperatures in the storage (Figure 1). Application of thermography in a free convective ventilated box store for potatoes is able to detect high temperature differences, which is a typical problem in such types of stores.

2. OBJECTIVES AND HYPOTHESIS

Infrared (IR) cameras are offered as a solution for assuring that temperature tolerances are maintained throughout manifold operations. The application of thermography as a temperature data recording system (Figure 2) or as a climate control element in storehouses for agricultural products is a new approach in control of storerooms.

The range of possible application of thermography may grow in the future because costs for imaging systems are expected to decrease the next following years. Operability, accuracy, reliability etc. will also be improved. It will become therefore interesting to install IR-cameras (1) to inspect temperature of the stored commodities, (2) investigate temperature proceed of the commodities dependent on environment climate, and (3) detect abnormal temperature progress due to microbial caused development of diseases or similar effects.

The objective of this project was to investigate the applicability of thermographic infrared-cameras (IR) inside storerooms, especially of a potato box store with free convective ventilation. It should be worked out that such a system has sufficient reliability, necessary accuracy, capability to represent temperature distribution and its changes of the stored potatoes, and possibility to embed it into a climate control system. With this system air flow movement indicated by temperature changes can be controlled.

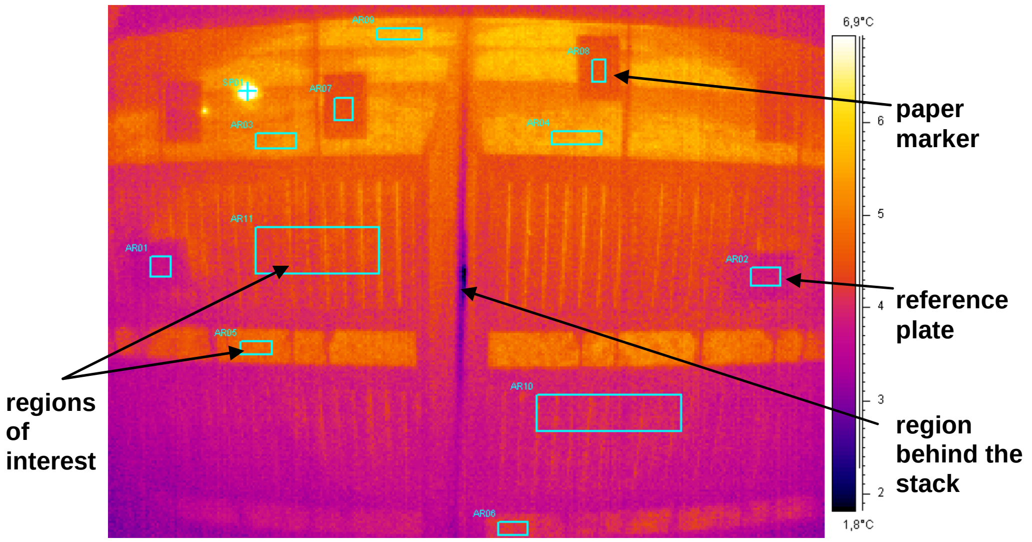

Figure 2. Infrared image of a potato box stack with selected areas of interest

3. LITERATURE REVIEW

Thermography has been developed during the last two decades to an important tool in engineering, human and animal medical research and other fields. A number of studies have shown the possibility to examine plants using thermography (Hellebrand et al., 2001; Hellebrand et al., 2002). For example, infrared image analysis has been applied to determine physiological disruptions in harvested plants (Inoue, 1990), to investigate the transpiration behaviour of intact plants at the pre-harvest phase (Inoue et al., 1990) and to determine the produce quality during the post-harvest phase (Linke et al., 2000). Temperature differences caused by diseases and wind influences on the leaves of standing cereal plants has been able to be observed with a thermal imaging system (Nielsson, 1995; Hellebrand et al., 2000; Daley, 1995). Thermography has recently found an application in observing temperature distribution in potato storage boxes to examine the potato temperatures dependent on different filling conditions during ventilation of the boxes (Hoffmann et al, 2007). In all these fields, thermography is mostly used for basic research.

A further application field of thermography is its practical use as a control element to detect temperature changes or low differences. Beside to the well-known application for military purposes (e.g. detection of living objects in the dark) thermography is used for early detection and prediction of infections of animals and humans. The ability to measure temperature differences on the surface of the skin down to 0.08 K resolution opens one of obvious applications for infrared thermography to detect within about 1 second whether a person has an elevated body temperature from fever. If the temperature difference exceeds a critical value (1 K higher than the average temperature of a healthy person) the checked person can be sent for further examination.

In the same way thermography is applied as a control element for the detection of fire in waste bunkers of residue combustors. In this case complete technical control solutions are offered by specialized companies.

4. THERMAL BEHAVIOR OF STORED POTATOES AND RESULTING CLIMATE CONTROL

Potatoes are living objects, their quality can be best maintained during storage if temperature, humidity and ambient air flow is in an appropriate condition during the different storage periods. During the tuber dormancy period the optimal storage temperature e.g. for table potatoes is at 3 to 5 °C and ca. 95 % relative humidity of the ambient air (Gottschalk and Ezekiel, 2006). The temperature and relative humidity set point for optimal storage is dependent on variety, and widely dependent on the condition, i.e. the ‘quality’ of the tubers when stored (Grähs, 1987).

In the potato tubers a continuous heat production is generated due to metabolic activities. Elemental heat and mass transfer processes occur between the bulk of potato and the air passing the tuber surfaces. Temperature differences between the potato bulk and the ambient air cause buoyancy forces, stimulating efficient ventilation through the stack, which forms free convective ventilation, i.e. a ‘natural’ ventilation (Maltry, 1998). The airflow is controlled only by ventilation dampers arranged in the roof and floor areas of the storehouse (Figure 1). Air streams can reach the stack from the top as well as from the bottom.

There are a few alternative methods to ventilate a potato storehouse. The so-called “cellar-effect” follows intuitively the traditional way to ventilate a store and is supposed to be a specific but adequate ventilation method for FCV storage (Pötke et.al., 1999). In this mode, only the roof dampers are opened. It is assumed that the cold outside air is ‘falling’ in through the roof dampers and due to the buoyancy forces ‘sinking’ through the stack down to the floor and transported simultaneously the heat of the potatoes. The sinking, cool air is crossing the rising warm air, which is enriched with humidity and therefore becomes lighter than dry air. More effectiveness is reported in the case of simultaneous opening of roof and floor dampers (Pötke et.al., 1999), but generally there is less knowledge about the real airflow distributions for the different ventilation types. By means of thermography it is now possible to monitor the temperature changes on the potato and box surfaces on the stack due to airflow fluctuations.

5. EVALUATION OF THE TEMPERATURES FROM THERMOGRAPHY DATA

For investigation purposes in a potato box store an infrared camera was used as a thermographic measuring system, working at a wavelength range of 7.5 to 13 µm and having sensitivity (resolution) of 0.07 K at 30 °C. Temperature accuracy without explicit calibration of the absolute temperature is approx. ±2.0 K (Kelvin). The maximum frame rate of the camera is 50 images per second. An image acquisition rate up to that high rate is not adequate for control of the store but may used to record fast temperature fluctuations due to airflow movements. In practical, for on-line acquisition and/or control a time interval of 1 to 15 minutes was used. The camera is equipped with a 45° wide-angle optical system.

The physical principle of infrared thermography follows the effect that all bodies are emitting thermal radiation. The spectrum and the intensity of this radiation depend on the temperature of the radiating body. The wavelengths of the radiation are within the infrared range, which is $\lambda = 8.5$ to 12 µm. The thermography is a technology, on which the thermal radiation is acquired, the according temperature calculated from it and visualized. Thus, temperature distributions on the surfaces of arbitrary bodies can be seized. The interesting temperature for stores ranges between –10 °C to +30 °C.

With the thermographic measuring procedure used here the radiant heat of a body is seized in the infrared wavelength range. The radiating power density $\Phi_{.}$ depends on the surface temperature T and the emissivity ε and is proportional to the emitting surface A, according to the Stefan-Boltzmann radiation law:

$$\Phi = \sigma \varepsilon T^4 A \qquad \text{(Stefan-Boltzmann radiation law)}$$

The proportional coefficient σ is a natural constant also named after Stefan-Boltzmann:

$$\sigma = 5{,}67032 \cdot 10^{-8} \cdot W \cdot m^{-2} \cdot K^{-4} .$$

The emissivity ε expresses the relationship between the specific radiant emittance of a perfect black body (with $\varepsilon = 1$) and the radiation of a body of a real material at the same temperature. The emissivity $\varepsilon(\lambda,T)$ is a material characteristic normally smaller than 1, thus:

$$\varepsilon(\lambda,T) < 1 .$$

The emissivity ε itself 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 region of interest of the recorded infrared image (Figure 2), a corresponding area has to be assigned with a defined emissivity (Table 1).

6. CALIBRATION OF THE INFRARED MEASURING SYSTEM

A special attention must be dedicated to the calibration of the infrared measuring procedure. As mentioned above, the temperature of the surveyed areas is calculated from the radiating power density, which is determined by the camera. The direct computation of the temperature from the radiating power density according to the radiation law leads to incorrect measurements with deviations of up to ±2 K. The measurements can however be corrected using a reference temperature and applying a compensation calculation. The deviations can be reduced to below 0.1 K by these calculations if an ideal precise reference is used.

The temperatures of reference plates (Figure 2) are measured continuously with conventional platinum sensors as references for IR image calibration. These sensors were separately calibrated before and after each experiment by using a laboratory calibrator with accuracy of ±0.05 K. The used sensors are found of high reliability for these applications. It can therefore be assumed that the calibrated reference sensors have an inaccuracy of max. ±0.05 K.

The temperature deviations are dependent on the temperature itself. The whole range of temperature of interest has to be measured and compared to the reference temperature for determining the regression line to compensate the error (Figure 3). The corrected temperature values are then read from the obtained regression line.

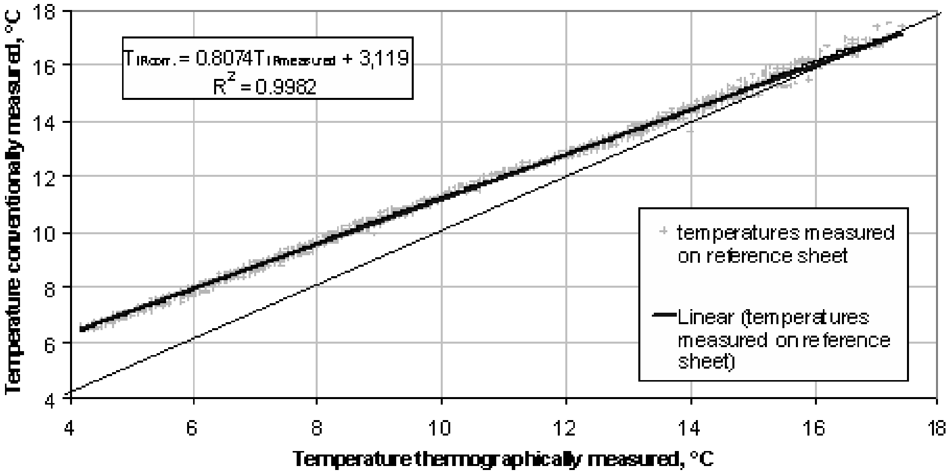

Figure 3. Correlation between conventional and thermal imaging measuring technique measured on a reference plate and corrected with linear regression

Surface temperatures of different materials (i.e. potatoes, wooden boxes, etc.) located at different positions and distances are recorded on the infrared (IR) image. Every image is divided into different parts of interest. The average temperature is calculated from each of these defined areas of the supervised region (Figure 2). The emissivity of the surface has to be defined for each of these areas. The emissivity of some known materials is taken from literature or by means of own examinations (Ebert 1962; King 1987; Schuster and

Kolobrodov, 2000; LaRocca 1996; Lutz, et al. 1997), Table 1. Surface temperatures recorded on the infrared images correlate with real, i.e. the conventionally (with sensors) measured temperatures. Emissivity values of wood and potato surfaces are almost the same and can therefore be used simultaneously with the same calibration setting.

Table 1. Emissivity of several 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

7. RESULTS

For direct comparison of thermal imaging and conventional measuring technique, two dull lacquer blackened metal sheets with defined emissivity were used. These sheets served as reference sheets and were fixed at a distance of approx. 5 cm on the potato boxes to ensure undisturbed aeration. Temperature changes of each reference sheet were simultaneously recorded using a contact thermometer giving the temperature reference. Temperature differences between the references and the IR images occur systematically and can be compensated to obtain correct temperatures from the images. The results confirm the correlation to the conventionally measured temperature values very well after correcting (calibrating) the thermography temperature values (Figure 4).

Thermography recorded temperature values (bright line in Figure 4) 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 linearly with decreasing surface temperatures.

7.1 Interpretation of the Infrared Data

Recorded temperature values from an infrared (IR) thermographic camera are systematically lower than conventionally measured (‘real’) values. Additionally, there is a temperature dependence of the IR measured data. The difference between IR and conventionally measured values increases linearly to decreasing measured absolute temperatures.

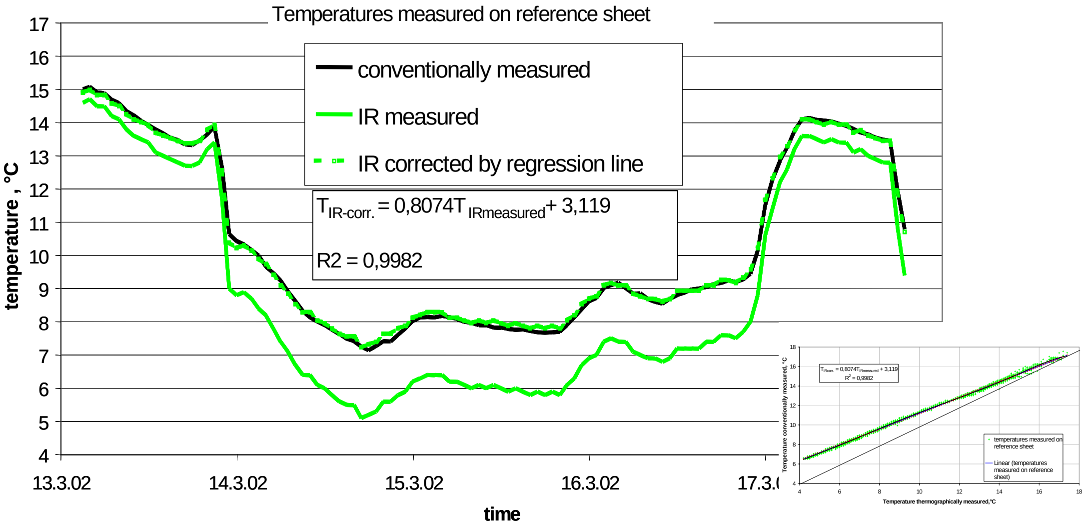

Figure 4. Temperature recording with conventional and thermal imaging measuring method on a reference sheet and correction

These results were obtained during lab-experiments in a climate chamber with forced air-cooling. These results were also verified in the free convective ventilated store. IR measured data in a big box potato store has shown more fluctuations compared to the lab experiments.

Because of the linear dependencies of the difference between real and measured IR temperature values, the method of linear regression is a straightforward method to compensate these dependencies. In order to be able to apply the linear regression calculation, measured data have been collected along an experiment time period covering the full range of the ambient temperature. From these data linear correlation calculation were carried out using Gauss' error mean square method (Figure 3). The derived linear regression straight line can now be used to compensate the average deviation of initially 1.37 K ± 0.58 K between thermographically and conventionally measured temperatures to finally 0 K ± 0.09 K. Taking into account that the calibrated references keep an accuracy of ±0.05 K, the overall accuracy of ±0.14 K can be achieved. This method is currently used to obtain high precision, which is necessary for climate control in the store.

7.2 Temperature Data Logging in the Store

For short-term temperature recording (with measuring rate of 1 image/minute or 1 image/15 minutes) temperature data of the 5th stack level of the 2nd row are pictured. The conventionally measured potato temperatures inside the box are compared to the thermographically measured temperatures of all, the surface of the potatoes, the wooden box fronts and sides, and the paper markers placed on top of the 7th stack level. Furthermore, the air temperatures in 9 m height, 1 m height and near the floor dampers are shown.

When roof and floor dampers were closed, all thermographically measured surface temperatures increased about 0.5 to 1 K, while the conventionally measured potato temperature inside the box remained constant at 4.7 °C. Even low inlet air temperatures of

-3 °C near the floor dampers increased the surface temperatures of potato layers to a higher value than the potato inside temperatures.

In the same way air temperature in 1 m height in the middle of the store and close to the floor dampers were increasing, too. A temperature-measuring rate of 1 image/15 minutes was chosen for these measurements.

It had to be proofed whether the so-called ‘cellar-effect’ will be effective as assumed. The effect of opening the roof dampers and closing the floor dampers simultaneously is shown in Figure 5. During night hours (22:00h to 6:00h) only the roof dampers were opened for test. The IR measured surface temperatures of the wooden boxes decreased slightly in that time. Conventionally measured air temperature in 9 m and 1 m height and the IR measured temperatures of the paper markers (Figure 2) in 9 m height decreased slowly (approx. 0.4 K). The temperature of the ambient air in 1 m height and close to the floor dampers was slightly higher than the IR measured temperature of the box front in the 5th stack level.

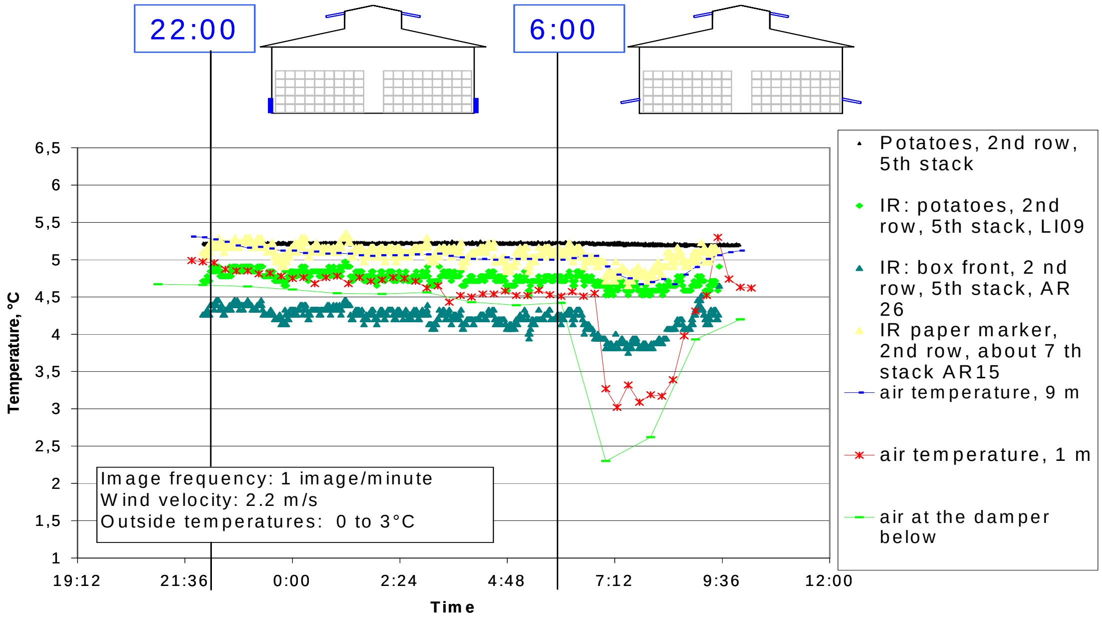

Figure 5. Proceed of temperature on the surface and inside the potato stack during ventilation in two modes

At 6:00h in the morning the floor dampers were opened (Figure 5). A significant drop of the temperature took place. Outside air with a temperature of 2.3 °C flew into the storehouse through the roof dampers. While the air temperature in 1 m height (in the middle of the store house) is still decreased by 1.5 K and the temperature in 9 m height is decreased by 0.3 K.

The influence of ventilation can only slightly be recognized on the potato surface. The potato surface temperatures are only 0.5 K lower than the temperatures inside the stack.

7.3 Air Flow Control

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 of a wide area.

The strategy for controlling the airflow and the storage climate is as follows (Gottschalk 2003, Geyer et.al, 2004). The wooden box surfaces are sufficient good indicators for the ambient temperature. Any changes of these temperatures due to airflow 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 (Gottschalk, 1994). After a validation period, the conventional sensors are dispensable. Airflow control is then based only on the IR images involving the model calculation results for the temperature distribution inside the boxes. Own investigations showed that opening the top dampers alone are mostly regulating the air temperature at the top region of the store.

The surface temperatures of wooden box walls are changing quickly upon airflow movement with fresh air. Potato tuber surfaces are reacting little slower. 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 (Figure 6).

The wooden surfaces can easily be taken as references for the air temperature. For practical application the paper markers used as a quick detecting instrument of airflow changes are furthermore dispensable. Warming up of the (tuber) surfaces is remarkable at the following conditions

- closed dampers and outdoor temperatures are equal or higher the inside temperatures
- instantly when closing the dampers: stop of air exchange
- 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 depended on

- outside air velocity
- temperature difference to outside air
- damper movement and activity

Further influences:

- 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 the upper region of the stack sufficiently are caused by solar heating of the roof during sunny days.

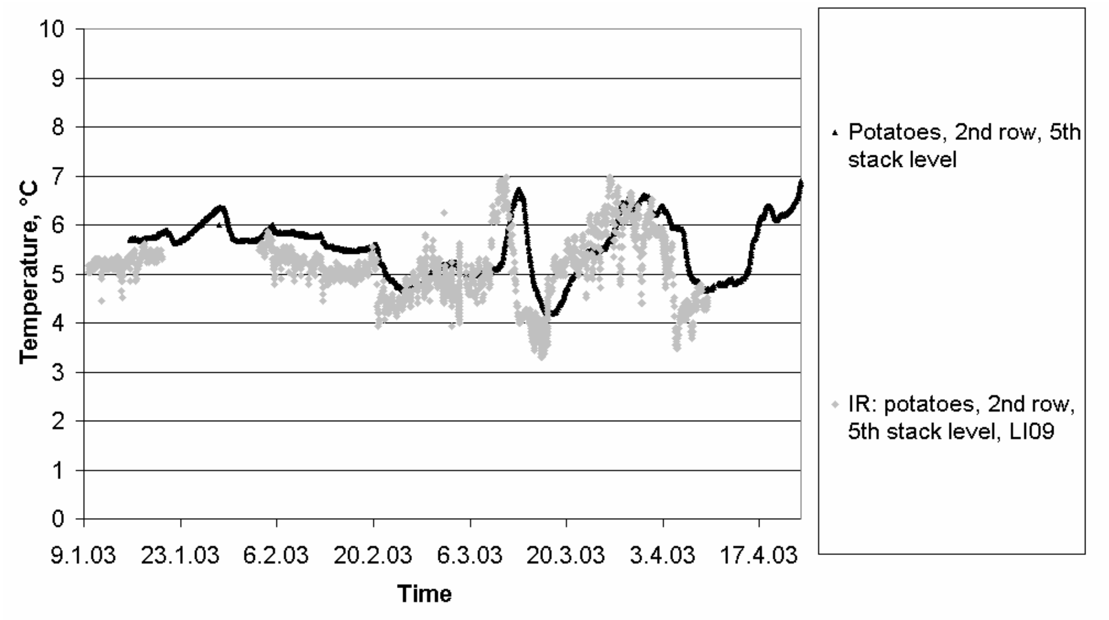

Figure 6. Temperature distribution on tuber surface (IR measured) and inside the 5th potato stack level (conventionally measured)

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 desired average storage temperatures can be achieved and maintained, but during increasing storage time the temperatures in 1 m and 8.5 m height of the box stack may diverge significantly. At the end of April it can be observed that the potatoes at the lowest level of the stack are somewhat too cold (below the desired storage temperature) and at the highest level too warm (above the desired storage temperature). Particularly in the upper levels the risk arises that the tubers germinate prematurely and mass loss increases remarkably due to increased transpiration.

Infrared thermography allows exceeding the dynamic range for control. For example, ventilation of the potato bin stack is normally avoided when fresh outside air temperature is significantly below zero degree (frost). This intent is to prevent the potatoes from freezing. But it was found that the surface temperatures of the tubers are changing slowly upon freezing air ventilation, which allows extending ventilation below the freezing point for a longer time. The thermography can quickly detect a critical tuber surface temperature. With exceeding the control range it is possible to benefit longer from cold outside air periods especially in late summer/early spring to achieve an equalized temperature distribution along the bin stack.

7.4 Economical and Ecological Effects

By the introduction of innovative climatic control technology in connection with free convective ventilation the energy expenditure is reduced in the store. An optimal climatic guidance reduces the losses in the store. This leads likewise to saving relevant environment within the pre-aged range, since the cultivation can be reduced accordingly.

Free convective ventilation in connection with innovative control is therefore characterized by the following aspects relevant to environment: It gives a contribution for the reduction of emission of climatic relevant gases due to lower power requirement and preserves resources due to reducing losses. Altogether for a store, e.g. with 15 kilotons of potatoes, approx. 1…2 kWh/t or approx. 15000 to 30000 kW/h, respectively of energy is needed. An amount of energy in this order of magnitude can be saved as operating cost when the store is working with the free convective ventilation principle. This saving corresponds to 150 to 300 GJ primary energy for each year. The emission reduction of climatic relevant gases amounts to approx. 10 to 20 t CO_2-aequivalent for this regarded 15 kiloton-potato store each year.

7.5 Discussion

Present results have shown that the thermal imaging technique is an up-and-coming technology for monitoring temperature/climate changes in potato stores. An infrared image supplies a lot of information about the temperature distributions in a store offering the chance to measure simultaneously temperatures of potatoes and the fluctuations of the ambient air.

However, the interpretation of infrared images requires special experiences. The originally displayed temperature values of an IR image are not complied with the real valid temperatures inside or behind the boxes. Selected parts of interest of the IR image must be set up in a defined session. The appended software takes into consideration the thermal radiation of the different materials (emissivity) and the object distance from the camera.

As we have seen, this pre-adjustment of the software is not sufficient for monitoring the real temperatures on the IR image. At potato store temperatures of 5 °C average, the IR camera normally measured temperatures approx. 2 to 4 K lower than the conventional sensors. A calibration procedure increases the accuracy significantly, which may make the system applicable for climate control.

The thermographic image gives the temperature distribution and its changes only for the regions which ‘can be seen’ by the camera. Additional cameras distributed inside the store room will observe more places to get a better overview of the temperature distribution in the room. Investment costs for IR-cameras have been decreased significantly the recent years. Expecting further application for such systems may lead to further decrease of costs and a distributed camera array in storerooms may become acceptable.

Even that a view into inside the boxes is not possible the temperature changes of the visible tuber surfaces give an acceptable indication of the temperature course of the tubers and the climate of the room. A control strategy can be developed for proper ventilation of the room.

It can be said that in opposition to the conventional measuring technique, the thermal imaging technique resolves existing temperature differences. Thus, lowest temperature differences can be visualized by the IR-camera.

8. CONCLUSION

Using purposively a thermographic camera allows controlling the tuber surface temperatures to attain the desired storage temperatures inside the box. The lowest limit of the potato tuber temperature is about 2 to 3 °C 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 (freezing point) because the air is warming up instantly when approaching the stack and the tubers are reacting inertly. This can instantly be controlled by thermography. 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.

The visibility of the air movements can be seen by temperature changes, i.e. directions of flow. This allows controlling separate grouped numbers of dampers. Airflow direction and velocity of the outside air can therefore better taken into consideration. The assumed efficiency of the ‘air-throw ventilation strategy’ (‘cellar-effect’) to cool the whole store by simply opening the top dampers only could not be verified.

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