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Adapted thermal imaging for the development of postharvest precision steam-disinfection technology for carrots

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ABSTRACT

Postharvest carrots are brushed, hydro-cooled to 4–6 °C and treated with chemical fungicide before storage to prevent soft rot caused by *Sclerotinia sclerotiorum* (Lib.) de Bary during storage. Replacement of the fungicide with high-temperature surface heat treatment poses a dilemma: excessive heating will cause damage whereas insufficient heating will result in incomplete disinfection. This problem is further compounded by the difficulty in providing uniform surface heating. To alleviate this problem, a system for the uniform application of high-temperature short-duration steam disinfection was developed using accurate real-time temperature monitoring of individual produce segments by thermal imaging. Uniform short-duration high-temperature heat was delivered from above by steam jets combined with electric steam-drying elements and reflectors. Produce was subjected to rotational and linear motions to expose each surface segment to the same amount of heat. The novel use of thermal imaging to monitor surface temperature in steam systems was essential for determining transferred heat and heating uniformity in a treated object. The resultant, uniform application of short-duration high-temperature steam provided surface heat-disinfection with minimal internal heating and damage. Application of the steam treatment immediately after carrot hydro-cooling reduced post-storage phytotoxic color change by 60–80% and resulted in significantly reduced sensitivity to post-storage soft rots caused by *S. sclerotiorum*. Carrot sprouting was not increased by the steam treatment, suggesting retention of the hydro-cooling's physiological effect. These results suggest that precise heat treatment can be optimally applied after hydro-cooling to improve postharvest quality of carrots in a procedure that is harmless to man and the environment.

1. Introduction

The use of chemicals for pest control in agricultural products is becoming increasingly restricted by various authorities, and by consumers who prefer technologies which are safe to humans and the environment. For certain organic products, such as organic carrots in Israel, there is no available technology to replace fungicide application and prevent losses caused by postharvest diseases. One of the primary causes for rejection are molds, and spoilage caused by the fungus *Sclerotinia sclerotiorum* (Lib.) de Bary (Afek et al., 1999; Boland and Hall, 1994; Reeleder et al., 1989).

In the last few years, carrot growers have been brushing carrots to remove the peel epidermis before storage in order to improve the product's appeal: this practice increases the appearance of some postharvest diseases and probably increases tissue susceptibility to chemical and physical damage (Eshel et al., 2009). Carrots are hydro-cooled before packing, and the cooling water may be infected with pathogens; therefore, it is preferable to perform the surface-disinfection step after hydro-cooling to prevent pathogen colonization in the carrot tissue (Eshel et al., 2009; Punja et al., 1992). Moreover, minimal heat should be transferred to the tissue, so that the high investment in hydro-cooling is not compromised and the influence of the total cooling rate is maintained.

The use of heat treatments has been found to be effective in controlling postharvest disease, but can damage the treated plant tissue if not applied carefully (Afek et al., 1999; Hansen et al., 2004; Porat et al., 2000). Previous studies (Grinstein et al., 1997; Pereira et al., 2009; Tang et al., 2007) have shown that pest control by heat treatment improves with increases in temperature and amount of heat transferred. However, excessive heating duration, temperature or affected tissue volume may damage the treated

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item, while insufficient heating may leave non-sterilized surface segments (Eshel et al., 2009; Lurie, 2006). Thus, uniform application of heat to all surface segments of the produce is an essential requirement for effective pest control. Kozempel et al. (2000a,b) also studied the disinfection of agricultural products using steam, again with a focus on disinfection of a single item per test, using a laboratory setup. The process was generally conducted in a sealed chamber, and the technology was never converted for use in on-line (continuous) processing, simulating commercial conditions. An efficient setup for postharvest pest control using hot water and brushes was tested in the laboratory and later applied at the processing plant for disinfection of pepper, melon, tomato and other produce (Prusky et al., 1996). This technology was generally more efficient for smooth surfaces, and particularly for products having natural wax coatings. Temperature measurements in whole fruits have shown that shorter heat duration causes heat penetration to smaller depths in the plant tissue, resulting in less damage to the produce (Lurie, 1998, 2006).

Several studies have tested the use of steam to disinfect from insects and other diseases in the field and postharvest (Howard and Le Griffin, 1994; John et al., 1992; Kolberg and Wiles, 2002; Lee et al., 2006; Nishijima et al., 1992; Pelletier et al., 1998). Preliminary tests in carrots by Afek et al. (1999) showed certain advantages of the steam heat treatment over those using hot water. Laboratory disinfection by steam jets was shown to reduce carrot and sweet potato rots that develop in storage (Afek and Orenstein, 2002; Afek et al., 1999). Steam treatment developed by the same group for large quantities of carrots in packinghouses showed reduced heating uniformity of the product segments and less successful rot reduction as compared to the laboratory setup (Afek, personal communication).

The main hypothesis of the present work was that surface temperatures higher than 55 °C, reported by Lurie (1998, 2006) as the upper limit for hot water treatment, can substantially improve disinfection. Steam treatment durations should be substantially reduced to avoid a large increase in the absorbed heat and damage to internal tissues. It was also hypothesized that cooling prior to the heat treatment would further reduce heating of the inner layers and the consequent damage. Furthermore, as noted above, it is stipulated in the present study that short-duration high-temperature heat disinfection can provide good control and still transfer only negligible amounts of heat to the inner tissues, thereby avoiding tissue damage, if the application is uniform over all of the surface segments, and particularly if the whole product is pre-cooled.

Accurate real-time monitoring, in the heat-treatment chamber, of each surface segment of the product is required. Such monitoring may be provided by thermal-imaging devices that have recently been adapted for the assessment of water stress in crops and for postharvest applications (Bulanon et al., 2008; Cohen et al., 2005; Fito et al., 2004; Moller et al., 2007; Vadivambal and Jayas, 2009). Thermal-imaging has been used in volume disinfection of persimmon and apple fruits to monitor the volume temperature uniformity after heating (ca. 48 °C) with radio frequency waves and water (Tiwari et al., 2008; Wang et al., 2006). Wang et al. (2007a,b) tested a similar volume heat treatment with hot air for disinfesting walnuts based on the surface temperatures measured by thermal imaging.

The objective of the present study was to develop a technology and method for the disinfection of carrots on the processing line using high-temperature uniform steam treatment by (a) using precise steam application that prevents major changes in the subsurface temperature of the treated (pre-cooled in the case of carrots) product, and (b) modifying thermal-imaging technology to be able to monitor multi-spot surface-temperature uniformity in real time. We thus suggest a novel method for precise steam application using thermal imaging, to disinfect the surface of agricultural products.

2. Materials and methods

2.1. The steam system

To achieve optimal short-term, high-temperature and uniform-exposure heat treatment of all of the surface segments of cylindrical products, in this case carrots, a dedicated steam-treatment system was developed. The system was designed to handle up to several hundred kilograms of agricultural produce per experiment. Accordingly, and relying on preliminary tests, a 15-kW electric steam boiler was adapted to deliver the steam to the system. The pressure inside the steam line was stable at 0.4 MPa for up to 10 min of continuous work. Longer stable operation times were possible at lower pressures. Three parallel 50-cm long and 20-mm outer-diameter tubes, with two rows of nozzles in each, were assembled above a roller conveyor. Uniform heating of all surface segments of the product on the conveyor was facilitated by imposing linear and rotational motions of 0.06–0.19 $\mathrm{m\,s^{-1}}$ and 0.35–1.1 $\mathrm{s^{-1}}$ rotation/s, respectively. The system featured the potential for mounting on-line in a processing plant and providing continuous operation (Fig. 1).

Electric heaters were attached to the steam nozzles to heat and dry the steam and to minimize droplet generation when the steam was ejected through the nozzles from the high pressure tube into the ambient air (Fig. 1C). In all experiments, the electric heaters were operated at 3 kW power. To suit carrot diameters, the nozzles were all placed at a height of 14 cm above the conveyer. The distance between the nozzles and the target surface was minimized to provide minimal energy losses during passage of the jets of steam through the ambient air. The developed steam-treatment system was tested to determine the optimal conditions for maximum carrot disinfection with minimal damage.

2.2. Real-time temperature measurements

Multi-spot carrot surface temperatures were monitored and measured in real time by a thermal-imaging system to enhance heat uniformity (Fig. 1). The measurements were performed with a FLIR PM545 (FLIR Systems, Danderyd, Sweden) thermal-imaging unit which was adapted for mounting in front of the exit of the treatment chamber to monitor most of the product segments, and in particular the upper segments, throughout the treatment (Fig. 2). The thermal unit measurements were analyzed using commercial software (ThermCAM Research Pro 2.8 SR-1 by FLIR Systems Inc.). The accuracy of the thermal-imaging system was ±1 °C, with calibration of the device at least once a year at the FLIR factory station in Sweden. The emissivity of the carrots was taken as 0.95 to fit the measured temperature range and the acceptable value for vegetation (Hellebrand et al., 2006). Sharp and accurate thermal images were obtained by activating the electric steam-drying elements, which eliminated dense fog and airborne droplets (Fig. 1B and C). Image clarity was also due to the unobstructed view between the thermal-imaging system and the produce being monitored. Thermal images of carrot cross sections were taken and the temperature along the sections' vertical and horizontal axes was measured by the above hardware and software, to evaluate the amount of heat transferred to the product's inner layers and the total amount of transferred heat. To reduce errors, the post-heat-treatment cross-sectional image was taken as follows: immediately after the heat treatment the carrots were cut in half, stuck on a nail in front of a hot background and the image was taken. This procedure typically lasted 10 s. Detachable heat-radiating reflectors, made of polished aluminum, were mounted above the nozzles and the electric heating elements. These reflectors enabled focusing additional heat radiation on the upward-facing segments with lower than maxi-