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Mechanistic understanding of temperature-driven water and bacterial infiltration during hydrocooling of fresh produce

Alexander Warning [a], Ashim K. Datta [a,*], Jerry A. Bartz [b]

[a] Department of Biological and Environmental Engineering, Cornell University, 175 Riley-Robb, Ithaca, NY 14853-5701, USA
[b] Plant Pathology Department, University of Florida, Gainesville, FL 32611-0690, USA

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ABSTRACT

Freshly harvested fruits and vegetables (produce) are chilled to extend their shelf life but the chilling process increases opportunities for contamination by pathogenic bacteria carried by water through openings such as stem scars. Using tomato as a representative system, a 3D porous medium transport model is developed. The model simulates the transport of water vapor, liquid water, bacteria, and energy in light of convection–diffusion processes driven by pressure gradients from condensation inside as well as by water concentration gradients between the cooling water and that in the tomato. Results show that increasing the rate of cooling (i.e., creating a higher temperature difference) increases the rate of infiltration due to higher-pressure gradients. A higher temperature differential drives bacteria further into the tomato. A less hydrated tomato will incur deeper and more extensive infiltration. Size, permeability, and diffusivity play a less significant role. The novel mechanistic understanding our study provides should aid in designing safer hydrocooling processes.

1. Introduction and objectives

Following harvest, fresh produce from the field is cooled in order to halt ripening (Burnett et al., 2000). One common method for achieving this is hydrocooling, which is the process of submerging produce in water colder than itself. Some hypothesize that cooling warm produce enhances water uptake due to the condensation of warm vapor, which creates a vacuum that pulls water into the produce through openings (Fig. 1) (Bartz and Showalter, 1981). In fresh produce, the major openings are the stem scar, stomata, and wounds (Burnett et al., 2000), while the rest of the produce is impermeable due to a waxy coat. If the wash water is contaminated, the increased water infiltration creates a food safety risk by possibly increasing the number of bacteria infiltrating into the opening. Tomatoes (Bartz and Showalter, 1981; Bartz, 1983; Zhuang et al., 1995; Bartz et al., 2015), oranges (Eblen et al., 2004; Singh, 2013), mangoes (Penteado et al., 2004; Bordini et al., 2007), cantaloupes (Richards and Beuchat, 2004), and apples (Buchanan et al., 1999; Burnett et al., 2000) have all been studied extensively for the correlation between hydrocooling temperature difference and water, dye, and/or bacterial infiltration.

1.1. Does temperature differential determine infiltration?

Several authors have conducted experimental work that supports (Bartz, 1983; Eblen et al., 2004) or contradicts (Burnett et al., 2000; Richards and Beuchat, 2004) the hypothesis that temperature differential alone determines infiltration. Several factors other than temperature differential affect water and bacteria uptake as well: chlorine concentration (Bartz, 1988), depth of immersion (Bartz, 1988, 1983; Bartz and Showalter, 1981; Bartz et al., 2015), immersion time (Bartz, 1988, 1983), wound freshness (Fatemi et al., 2006; Bartz and Showalter, 1981; Smith et al., 2006), type of opening (Burnett et al., 2000), opening size (Eblen et al., 2004), hydrophobicity of opening (Bartz, 1983), and cultivar (Bartz, 1991; Smith et al., 2006; Richards and Beuchat, 2004). Buchanan et al. (1999) found that in general cooling warm apples with cold water increased the chance of bacteria uptake. They also tested dye uptake and found that there was a 15.9% chance of some dye being absorbed into the apple when a warm apple was submerged in cold water while they found no dye uptake in the opposite temperature differential scenario. Bartz and Showalter (1981) and Bartz (1983) found that increasing the temperature differential and immersion depth increased water uptake and bacterial infiltration and of *Erwinia*

* Corresponding author at: Department of Biological and Environmental Engineering, Cornell University, Riley-Robb, Ithaca, NY 14853-5701, USA.
E-mail address: adw88@cornell.edu (A.K. Datta).

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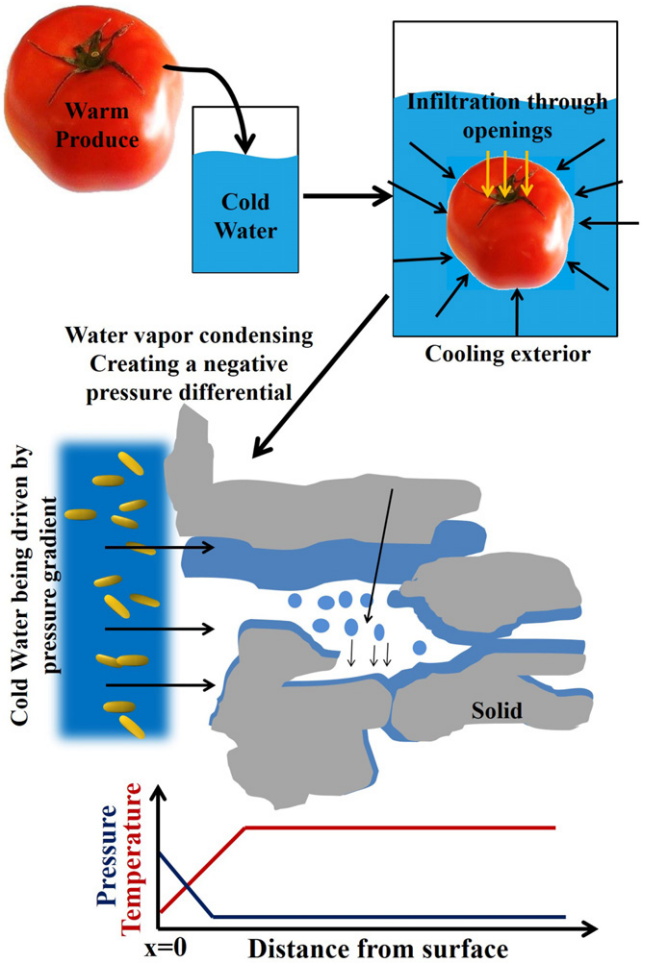

Fig. 1. A schematic of the physics of hydrocooling. Warm produce, a tomato, is put into cold water. The cold water cools the exterior while infiltrating the stem scar. The cooling of the tomato decreases its temperature and vapor condenses, creating a pressure differential that increases water infiltration. If the water is contaminated with bacteria, bacteria will be transported with the cooling water into the tomato.

carotovora in tomatoes. Zhuang et al. (1995) found an increase in infiltration of *Salmonella montevideo* with a higher temperature differential. Eblen et al. (2004) found that dye infiltrated oranges only at a negative temperature differential.

In contrast, Burnett et al. (2000) found that, regardless of temperature differential, bacteria infiltrated several openings in apples. Fatemi et al. (2006) did not study temperature differential or infiltration in apples but studied the infiltration of bacteria by capillary action. They found that fresh puncture wounds permitted penetration while old wounds did not. Penteado et al. (2004) and Bordini et al. (2007) found internalization of *Salmonella* in mangoes when there was a negative temperature differential. Richards and Beuchat (2004) found internalization and weight change were not dictated solely by temperature differential in cantaloupes.

The depth and location of infiltration has also been studied. In general, bacteria primarily penetrate near the surface of a highly porous fresh wound/opening (Samish and Etinger-Tulczynska, 1963; Burnett et al., 2000; Fatemi et al., 2006). A qualitative picture of how water and bacteria infiltrate fresh produce is painted from these studies: the transport properties of the produce in combination with the process parameters (immersion depth and temperature differential) affect the rate and amount of water absorbed. This study aims to produce a more quantitative understanding of how each property and parameter affects contamination.

This article begins by describing the objectives pursued, followed by a detailed presentation of a mechanistic porous medium-based transport model with a schematic, governing equations, boundary and initial conditions, and property data. The experimental methodology described, including with details of the geometry acquisition from magnetic resonance imaging (MRI) to make the computational model closer to reality. Imaging analysis of a stem scar via μCT and scanning electron microscope (SEM) is also conducted to determine whether the stem scar opening permits water and bacterial infiltration. The results are then discussed with validation from the literature and experiments. The validation uses total change in weight, core pressure, spatial temperature moisture change from MRI, and center (also referred to as the core, is the geometric center of a whole tomato) temperature. This is followed by sensitivity analysis.

1.2. Objectives

The objectives of this work are to: (1) develop a porous medium-based transport model (hereafter referred to as a hydrocooling model) using actual 3D tomato geometry obtained from MRI; (2) validate the hydrocooling model predictions against experimentally measured core temperature, pressure, and moisture content; (3) analyze the structure of the stem scar opening with various imaging techniques (μCT and SEM) by reference to pore size and bacterial size; (4) obtain important results such as the effect of temperature difference on water infiltration; (5) use this physics-based understanding of hydrocooling to further explain the experimental observations in the literature; and (6) provide quantitative recommendations for the washing of fresh produce.

2. Model formulation

2.1. Tomato structure

A tomato is divided primarily into six major structures, as shown in Fig. 2: the stem scar, the outer waxy impermeable cuticle, the vascular bundles, the core and placenta, the locule, and the pericarp (Musse et al., 2010). The stem scar and cuticle form the exterior of the tomato. The stem scar is the only opening in a tomato while the outer, waxy impermeable cuticle forms a liquid water and vapor barrier (Goodwin and Jenks, 2005). The vascular bundles form a water transportation network in the tomato that begins in the stem scar and runs to the locules through the placenta while also extending to the outer pericarp. There is diffusive transport and convective (flowing) transport in tomatoes. Thus, a network of highly permeable tissue is created in the tomato. The core and placenta form a porous region in the center of the tomato that connects the stem scar and locules. The core is slightly more porous than the placenta as it is a vertical region that extends down from the stem scar into the placenta (Musse et al., 2010) and the placenta then extends into the locular tissue. The locule is a gel-like region that contains seeds and is completely water saturated. Tomatoes are either bilocular or multilocular (Peralta et al., 2007). The final part of the tomato is the pericarp, which contains the radial and outer pericarp. The outer pericarp forms a ring on the outside of the tomato while the radial pericarp forms the fleshy regions between each locule (Musse et al., 2010).

2.2. Assumptions

The core opening is completely saturated with liquid water and so the vapor flux is assumed to be zero (no dissolved gases). Saturation was set to 0.999 for computational stability. The stem scar opening is assumed to be water congested enough that it is hydrophilic (Smith et al., 2006; Bartz et al., 2015) and will not repel