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Quantifying non-uniformity in hot air treatment using tomato as a test material for postharvest quality and disease control

By

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ABSTRACT

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The influence of uniformity of heat transfer with respect to the effect of heat treatment was investigated by correlating engineering parameters with the quantified heat treatment effects. Differences in treatment effect in terms of quality, anti-pathogen and chilling injury (CI) control properties among commodities was studied by exposing them to different target temperatures. Similar effects were also evaluated and quantified within an individual commodity by a custom-designed device. This device, whose design parameters were based on a heat transfer simulation, insured that one hemisphere of a tomato was exposed to air at 39°C and 0.24 m s^{-1}; while the other hemisphere was exposed to air at a lower temperature with a velocity of 0.24 m s^{-1} or 0.12 m s^{-1}.

Single-temperature heat treatment was most effective in limiting pathogen development and varied according to the parameter measured: 38°C for hypersensitive response (HR), 36°C for tissue breakdown, 36°C, 38°C or 39°C for mycelium abundance, and 38°C or 39°C for lesion size. Bilateral differences in temperature across the fruit significantly affected disease control: decreasing temperature differences significantly improved the uniformity of disease control.

Some of the effects of heat treatment on tomato quality, such as color development and resistance to CI, appear to be localized. A significant difference in redness was identified between heated parts and unheated parts of tomato fruits immediately after treatment; and the differences persisted during storage. Differences in lightness and chroma were noted on day 4. Delay in ripening caused by heat treatment was confirmed through the higher TA and TSS values of heated tomatoes or heated portion of partially heated tomatoes.

The heated parts of tomatoes showed a stronger resistance to chilling injury. The effective temperature control range for CI was wide, but temperatures higher than 39.5°C for 23 h hot air treatment could lead to adverse effects.

Differences in physiological effects between hemispheres in two chambers was reduced by directly decreasing the temperature difference between upper and lower chambers or relatively increasing the heating air flow rate, highlighting the importance of improving the uniformity of air flow around each individual treated fruit.

RÉSUMÉ

L'influence de l'uniformité du transfert de chaleur par rapport à l'effet du traitement thermique a été étudiée en corrélant les paramètres techniques du système développé avec les effets des traitements thermiques mesurés. Des différences dans l'effet des traitements thermiques sur la qualité des produits traités, des propriétés de ces produits à contrer l'effet des pathogènes ou leur sensibilité à la maladie du froid (MF) ont été étudiées en exposant des produits à différentes températures. Des effets semblables ont été également évalués et mesurés en utilisant des produits individuels et le système développé. Ce système, dont les paramètres de conception ont été basés sur une simulation de transfert de chaleur, garantissait qu'une moitié de chaque tomate était exposée à un courant d'air à 39°C et d'une vitesse de 0.24 m s^1; tandis que l'autre moitié était exposée à un courant d'air de plus basse température et de vitesse soit de 0.24 m s^1 ou de 0.12 m s^1.

Les traitements thermiques utilisant une température unique ont été les plus efficace pour limiter le développement de pathogène et les résultats ont varié selon le paramètre mesuré: 38°C pour la réponse à l'hypersensibilité (RH), 36°C pour la dégradation des tissus, 36°C, 38°C ou 39°C pour l'abondance de mycélium, et 38°C ou 39°C pour la taille des lésions. La présence de différences co-latérales de la température à l'intérieur d'un même fruit a significativement affecté le contrôle des maladies; une diminution de ces différences de température a significativement amélioré l'uniformité du contrôle des maladies.

Certains effets des traitements thermiques sur la qualité de la tomate, tels le développement de la couleur et la résistance à la MF, semblent être localisés. Une différence significative dans la rougeur de la tomate a été identifiée entre les parties chauffées et les parties non chauffées des tomates immédiatement après le traitement; et ces différences ont persisté pendant l'entreposage. Des différences dans la clareté et l'intensité de la couleur ont été observées dès le jour 4. Le retard dans la maturation provoqué par les traitements thermiques a été démontré par les valeurs plus élevées de l'acidité totale et des solides solubles totaux (SST) des tomates chauffées ou de la partie chauffée des tomates partiellement chauffées.

Les parties chauffées de tomates ont montré une résistance plus forte aux dommages de la réfrigération. La gamme efficace de contrôle de température pour MF était large, mais l'utilisation de températures plus hautes que 39.5°C pour le traitement de 23 h à l'air chaud pourrait générer des effets négatifs.

Des différences dans les effets physiologiques entre les parties des tomates exposées à chacune des deux chambres ont été directement réduites en diminuant la différence de la température entre ces chambres ou en augmentant le débit d'air de chauffage, accentuant l'importance d'améliorer l'uniformité de la circulation d'air autour de chaque fruit individuel traité.

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NOMENCLATURE

A	Area (m^2)
a	Width of tunnel (m)
b	Height of the tunnel (m)
C	Specific heat at temperature T ($J\ kg^{-1}\ °C^{-1}$)
C_p	Specific heat under constant pressure at temperature T ($J\ kg^{-1}\ °C^{-1}$)
$C(T)$	Specific heat at temperature T ($J\ kg^{-1}\ °C^{-1}$)
$C_i(T)$	Specific heat of i^{th} component at temperature T ($J\ kg^{-1}\ °C^{-1}$)
C_a	Specific heat of air ($J\ kg^{-1}\ °C^{-1}$)
$C_{pdryair}$	Specific heat of dry air ($J\ kg^{-1}\ °C^{-1}$)
$C_{pmoistair}$	Specific heat of moist air ($J\ kg^{-1}\ °C^{-1}$)
C_w	Specific heat of water ($J\ kg^{-1}\ °C^{-1}$)
C_{pr}	Specific heat of protein ($J\ kg^{-1}\ °C^{-1}$)
C_{fa}	Specific heat of fat ($J\ kg^{-1}\ °C^{-1}$)
C_c	Specific heat of carbohydrates ($J\ kg^{-1}\ °C^{-1}$)
C_{fi}	Specific heat of fibber ($J\ kg^{-1}\ °C^{-1}$)
C_{ash}	Specific heat of ash ($J\ kg^{-1}\ °C^{-1}$)
D_h	Hydraulic diameter (m)
E	Nash-Sutcliffe model efficiency coefficient
F	Volume force field (N)
h	Heat transfer coefficient ($W\ m^{-2}\ °C^{-1}$)
$\boldsymbol{I}$	Identity matrix
K	Thermal conductivity ($W\ m^{-1}\ °C^{-1}$)
$K_i(T)$	Thermal conductivity of i^{th} component at temperature T ($W\ m^{-1}\ °C^{-1}$)

K_a	Thermal conductivity of air ($W\,m^{-1}\,°C^{-1}$)
K_w	Thermal conductivity of water ($W\,m^{-1}\,°C^{-1}$)
K_p	Thermal conductivity of protein ($W\,m^{-1}\,°C^{-1}$)
K_{fa}	Thermal conductivity of fat ($W\,m^{-1}\,°C^{-1}$)
K_c	Thermal conductivity of carbohydrates ($W\,m^{-1}\,°C^{-1}$)
K_{fi}	Thermal conductivity of fiber ($W\,m^{-1}\,°C^{-1}$)
K_{ash}	Thermal conductivity of ash ($W\,m^{-1}\,°C^{-1}$)
k_{dv}	Deviation from Stokes' asumption
L	Characteristic dimension (m)
M	Mass (kg)
N	Number of measurement points
$\boldsymbol{n}$	Outward normal vector on the boundary
p	Pressure (kPa)
p_0	Initial pressure (kPa)
p_{per}	Perimeter of cross-section of the tunnel (m)
Q	Heat source ($W\,m^{-3}$)
q_{cond}	Conductive heat transfer rate ($J\,s^{-1}$)
r	Radial coordinate originate from the fruit center (m)
r_o	Fruit radius (m)
Re	Reynolds number
RH	Relative humidity, changing from 0 to 1
T	Temperature (K)
T_e	Heating medium temperature (K)
T_0	Inlet air temperature (K)

$T_{exp(i)}$	Measured temperature for time t_i (K)
$T_{mod(i)}$	Predicted temperature for time t_i (K)
t	Time (s)
U	Velocity field (m s^{-1})
u	Air velocity – x direction (m s^{-1})
v	Air velocity – y direction at in y axial (m s^{-1})
w	Air velocity – z direction at in z axial (m s^{-1})
V	Volume (m^3)
x, y, z	Spatial coordinates (m)
x_i	Mass fraction of i^{th} component
x_a	Mass fraction of air
x_w	Mass fraction of water
x_p	Mass fraction of protein
x_{fa}	Mass fraction of fat
x_c	Mass fraction of carbohydrates
x_{fi}	Mass fraction of fiber
x_{ash}	Mass fraction of ash
ρ	Density (kg m^{-3})
$\rho_{apparent}$	Apparent density (kg m^{-3})
ρ_{true}	True density (kg m^{-3})
ρ_I	Density of i^{th} constituent (kg m^{-3})
α	Thermal diffusivity (m^2 s^{-1})
ε_i	Volume fraction of i^{th} component
ε_a	Volume fraction of air

η	Dynamic viscosity (Pa s)
ω	Humidity ratio

FORMAT OF THE THESIS

This thesis is paper-based; however, the references for all chapters were placed at the end of the thesis to make the thesis less bulky.

CHAPTER I. GENERAL INTRODUCTION

1.1 Abstract

Heat treatment has been used for quarantine and decay control in an increasing variety of crops, and its use has been extended to the inhibition of the ripening processes or the induction of resistance to chilling injury. Through a brief overview of certain studies about the physiological, pathological and physical principles of heat treatment with emphasis on the physical or engineering aspects, an effort is made to determine the focus of further research.

The research effort on heat treatment in postharvest has been increasing steadily in recent years, with successful laboratory investigations and some scale-up development of the use of hot water, radio frequencies, microwaves and hot air in disinfestation, disinfection, chilling injury control and the slowing down of the ripening process in various fresh horticultural crops. Several aspects of the mechanisms of heat treatment in terms of decay control, induction of thermotolerance, and heat transfer under uniform heating media have been thoroughly evaluated. The threshold temperature and uniformity in space throughout the entire duration of the process are the two most important factors that should be taken into account during heat treatment process development on an industrial scale.

The challenge for heat treatment lies in the scale-up of some treatment methods by optimizing the temperature range and duration, improving the uniformity of heat treatment, and conducting research into a protocol for the adoption of different heat treatments as part of the postharvest chain.

1.2 Introduction

Heat treatment has been used for insects control and disinfection in an increasing variety of crops (Lurie 1998). Almost no country produces all the fresh fruits and vegetables that they require year-round, a situation that creates good opportunities for trade as well as the possibility of insects being introduced to the importing region. Phytosanitary restrictions have been continuously developed to protect regional agricultural industries from the introduction of damaging insect pests (Kader 2003). Many

importing countries require inspection certificates attesting to the absence of targeted live pests in a shipment after a pre-approved postharvest "sanitation" treatment (Ikediala et al. 2002). Because of consumer requirements, environmental concerns and regulatory issues (Mulas and Schirra 2007), a potential non-damaging physical treatment substitute for chemical prevention is needed. Although irradiation, hypobaric treatment and modified atmosphere packaging are non-pesticide technologies that have been investigated in an effort to extend the storage and shelf life of fresh produce, heat treatment appears to be one of the most promising means for postharvest quarantine and decay control (Fallik 2004). Heat treatments can also be used to inhibit ripening processes or to induce resistance to chilling injury (CI) and external skin damage during storage, thus extending the storability and marketing period of produce. Studies have examined many aspects of heat treatment in fruits and vegetables. The non-uniformity of heat transfer is one of the main obstacles on the way to the industrialization of heat treatment. This article will review studies disclosing the physiological and pathological impact of heat treatment on horticultural crops but focus will be on the physical or engineering aspects.

1.3 Heat treatment mechanism

Some physiological and pathological issues for various crops have been investigated. Research studies have been reviewed especially for quality aspects by Lurie (1998; 2006), Ferguson et al. (2000), Falik (2004) and Mulas and Schirra (2007a).

1.3.1 Decay control

The primary mode through which hot water treatments appear to limit decay development is through direct inhibition of pathogen growth and physical removal of inocula from the fruit surface. Moreover, plants defend themselves against pathogens by means of constitutive or induced mechanisms. Several studies have demonstrated the potential of heat treatment to interact with both constitutive and induced defence mechanisms (Schirra et al. 1999; Terry and Joyce 2004). Hot water brushing brings about a clear redistribution of the epicuticular wax layer, part of the constitutive defence system, and a significant reduction in cuticular cracks, thus improving physical barriers to pathogen penetration (Ben-Yehoshua 2003; Fallik 2004). It is well established that heat treatment favours wound healing by leading to the deposition of lignin-like material

(enhancement of a constitutive defence) at the wound sites, hindering pathogen invasion. Works by Lurie and Sabehat (1997) have demonstrated that heat treatment prevents the deterioration of constitutive enzymes such as anionic peroxidases, which play an important role in the defence of tomato fruit against *Botrytis cinerea* Pers.. Heat treatments inhibit biochemical pathways involved in ripening and other processes in many fruits and vegetables and therefore contribute to the maintenance of juvenility and resistance. Some physical and chemical treatments to control decay were proven to be more effective when applied in combination with heat treatment (Ben-Yehoshua 2003). Heat treatment, alone or in combination with other physical treatments such as UV hormesis, promotes the synthesis and accumulation of phytoalexins (induced antimicrobial compounds) and of chitinases and β-1,3-glucanases, enzymes associated with induced resistance through their ability to degrade fungal cell walls (Pavoncello et al. 2001; Ben-Yehoshua 2003).

1.3.2 Induction of thermotolerance

The mechanism by which heat treatment causes changes in fruit ripening such as inhibition of ethylene synthesis and cell wall–degrading enzymes may be linked to changes in gene expression and protein synthesis. Subsequent to high temperature treatment, the mRNA of fruit ripening genes disappears and those of heat shock proteins (HSP) accumulate. An immediate response to high temperature is dissociation of polyribosomes and then reassociation of some ribosomes into polyribosomes that preferentially translate the mRNA of HSP. Therefore, heat exposure severity will modulate the thermotolerance response. The exposure temperature must be high enough to initiate the synthesis of HSP yet should not be too high that transcription and translation of HSP are inhibited. Temperatures in the range of 35°C–40°C have been found to be effective, depending upon the commodity and process duration. After exposure to elevated, sublethal temperatures, the induced thermotolerance can protect many crops from exposure to a normally lethal temperature (Lurie 1998).

This thermotolerance could also apply for the low-temperature extreme CI threshold. Tomato fruits are sensitive to CI at low temperatures. When a heat treatment of 2–3 days in 38°C air was applied to tomato fruit, their sensitivity to low temperatures was

reduced, and they could be stored for up to a month at 2°C without developing CI (Lurie and Sabehat 1997). This resistance to low-temperature injury was found to be contingent to the presence of HSP (Lurie 1998). Furthermore, this beneficial effect of heat treatment has also been verified for pomegranate (Mirdehghan et al. 2007), peach (Murray et al. 2007), orange (Rodriguez et al. 2005) and avocado (Woolf et al. 2004).

1.3.3 Heat damage

Although heat treatment may be of benefit to treated horticultural crops, inappropriate heat (exposure of fruits to lethal temperatures or for excessive duration) might cause damage. Lurie and Sabehat (1997) found that for tomato, temperatures higher than 38°C were not generally as effective as 38°C. Treatment at 42°C or 46°C for 24 h caused both external and internal heat damage to tomato. External damage generally consists of peel browning, pitting, scalding or yellowing of green vegetables (Lurie 1998). One of the most common types of heat damage is surface scalding. 'Manila' mangoes showed severe skin scalding when forced-air heated at temperatures of 45°C or higher, slight skin scalding at 44°C and no damage at 43°C, indicating the presence of a threshold temperature for skin injury development (Ortega-Zaleta and Yahia 2000). Tissue damage caused by heat will also result in increased decay development. Evidence for internal damage can include poor colour development, abnormal softening, lack of starch breakdown and development of internal cavities (Lurie 1998). Antioxidant enhancement is an expected benefit of heat treatment; however, as long as the temperature is higher than the threshold temperature, negative effects could accompany heating injury (Yahia and Ortega-Zaleta 2000). Heat-damage tolerance to heat exposure is influenced by species, cultivar, harvest maturity, growing conditions and handling between harvest and treatment (Lurie 2006).

1.4 Classification by media

Traditionally, horticultural crop commodities are heated using hot water, vapour heat and hot air, all these methods have been revisited for more than a decade. However, with more understanding about radio frequencies (RF) and microwaves and various processing applications of microwaves for food and biological materials (Venkatesh and Raghavan 2004; Raghavan et al. 2005a), these two electromagnetic media have been

investigated in postharvest heat treatments in recent years (Tang et al. 2000; Orsat et al. 2001; Ikediala et al. 2002; Karabulut and Baykal 2002; Wang et al. 2003; Birla et al. 2004; Mitcham et al. 2004; Wang et al. 2005; Wang et al. 2006b; Zhang et al. 2006). Moreover, far infrared radiation (FIR) heating technology has also been studied recently as a rapid and contact less heating medium, and the results show that FIR heating achieved more uniform surface heating than air convection heating (Tanaka et al. 2007).

1.4.1 Hot water

Hot water was originally used for fungal decay control, but its use has been extended to insect control. The two main commercial hot water treatments are hot water dips (immersion) and hot water brushing (spray).

1.4.1.1 Hot water dips (immersion)

Hot water dips are effective for fungal pathogen control (Jacobi et al. 2000; Zhou et al. 2002; Karabulut et al. 2004; Spadaro et al. 2004; Malakou and Nanos 2005; Siomos et al. 2005; Wilson Wijeratnam et al. 2005; Spotts et al. 2006; Hong et al. 2007), because fungal spores and latent infections are either on the surface or in the first few cell layers under the peel of the fruit or vegetable. Postharvest dips to control decay are often applied for only a few minutes, at temperatures higher than heat treatments for disinfestations, since it is only the surface of the commodity that requires heating. Many fruits and vegetables tolerate exposure to water temperatures of 50°C–60°C (Barkai-Golan and Phillips 1991; Ranganna et al. 1998) for up to 10 min, and shorter exposure at these temperatures can control many postharvest plant pathogens.

Hot water dips have been used for disinfesting insects as well (Shellie and Mangan 2000; Diaz-Perez et al. 2001; Jacobi et al. 2001a; Tsouvaltzis et al. 2006). However, longer treatments than those for fungal control are necessary, because larvae usually bore into fruits or unshelled nuts to feed on the centre flesh, seeds or kernels. Thus, the centre of the commodity must be heated to the desired temperature during the treatment (Tang et al. 2000).

1.4.1.2 Hot water brushing (spray)

A recent extension of the hot water treatment has been the development of a hot water spray machine (Fallik 2004). This technique is designed to be part of a sorting line, in which the commodity is moved by means of brush rollers through a pressurized spray of hot water. This machine was used both for cleaning and for reducing the pathogen presence on several fruits and vegetables (Fallik 2004).

1.4.3 Vapour heat

Vapour heat is a method of heating commodities with air saturated with water vapour at temperatures of 40°C–50°C to kill insect eggs and larvae as a quarantine treatment before fresh market shipments. Heat transfer is by condensation of water vapour on the cooler fruit surface. This method is disputed because the vapour condensing heat-transfer coefficient is far higher than the coefficients of air and water, which are 5,000–100,000 W m^{-2} K^{-1}, 5–25/10–200 W m^{-2} K^{-1}, and 20–100/50–10,000 W m^{-2} K^{-1} for condensing vapour, free/forced air and water, respectively (Singh and Heldman 2001). It has been verified by Shellie and Mangan (2000), who state that the temperature of the fruit surface is even higher than the surrounding media. This explains why high humidity in vapour heating can sometimes damage the fruit undergoing treatment, whereas the slower heating and lower humidity of forced hot air may cause less damage.

1.4.4 Hot air

Hot air has been used for both fungus and insect control (Tang et al. 2000; Yahia and Ortega-Zaleta 2000; Jacobi et al. 2001a; Mitcham et al. 2004; Hoa et al. 2006) and studying the response of commodities to high temperatures.(Yahia and Ortega-Zaleta 2000; Soto-Zamora et al. 2005; Hoa et al. 2006). Forced hot air was preferred for the development of quarantine procedures. Lurie (1998) reviewed hot air heat treatment and concluded that exposure to high temperatures in forced or static air can also decrease fungal infections. However, the processing times are relatively long, running from 12 h to 96 h, at temperatures ranging from 38°C to 46°C. Lurie (1998) claimed that this method is unlikely to become a commercially attractive treatment. On the other hand, the

potential of hot air treatments to become a means of beneficially affecting crops physiology and, at the same time, preventing insect and fungal invasion justifies further development of these treatments (Lurie 1998). A common difficulty with hot air or water heating methods is the slow rate of heat transfer that results in several hours of treatment time, especially for large fruits (Wang et al. 2001).

1.4.5 RF and microwave

RF and microwave heating involves direct interactions between dielectric materials and electromagnetic waves to generate heat. This process avoids the heating limitations caused by airspaces or bulkiness of the produce that arise in conventional surface heating with air or water. Because of the dielectric properties of insects, RF may also heat those organisms faster than the surrounding plant tissue (Wang et al. 2003). Treatments using electromagnetic energies at RF and microwave frequencies leave no chemical residues on produce and have minimal impact on the environment (Tang et al. 2000). RF is classified as "non-ionizing" radiation and is therefore regarded as a safe treatment that will be acceptable to consumers. RF or microwave heating is suggested as an alternative with the goal of reducing the adverse thermal impact on treated commodities during the heating period (Tang et al. 2000).

1.4.5.1 Penetration depth

The penetration depth of RF and microwaves in a lossy material increases with decreasing frequency, which can explain why the penetration depth of RF is superior to that of microwaves. The penetration depth of microwaves in apples at room temperature increases from 12 mm to 43 mm when the frequency decreases from 2,450 MHz to 915 MHz (Tang et al. 2000). Limited penetration depth leads to non-uniform heating in large objects.

1.4.5.2 Dielectric properties

The dielectric and conductivity properties of agricultural and biological materials are influenced by frequency, temperature, salt content and moisture content (Ikediala et al. 2002). The dielectric properties of six commodities along with four associated insect pests were measured between 1 MHz and 1,800 MHz at temperatures between 20°C and

60°C (Wang et al. 2003). The dielectric loss factor of fresh fruits and insects decreased with increasing frequency at constant temperatures. The loss factor of fresh fruits and insects increased almost linearly with increasing temperature at 27 MHz RF but remained nearly constant at 915 MHz microwave frequency. The dielectric loss factor of codling moth larvae is greater than that of the tested host materials, particularly in the RF frequency range (Tang et al. 2000).

From the perspective of dielectric loss factors and penetration depth, RF is a better choice than microwaves for disinfestations in large fruits or vegetables. However, for pathogen control in small fruits, microwave is the high-temperature-short-time method of choice. Andreuccetti et al. (1994) demonstrated the possibility of using 2.45 GHz microwaves to destroy woodworms by heating the larvae to 52°C–53°C for less than 3 min. Karabulut and Baykal (2002) evaluated the possible use of microwave power to control postharvest pathogens of peach. In fruit inoculated with *Botrytis cinerea* and *Penicillium expansum* and treated with microwaves for 2 min, lesion diameters and the percentage of infected wounds were significantly lower than in the control fruit.

However, there are still challenges for the development of effective RF or microwave processes, namely providing uniform heating and developing a means to monitor and control the end produce temperature (Tang et al. 2000).

1.5 Heat transfer

Some heat application methods have resulted in non-uniform heating of fruit and caused a reduction in general quality attributes (firmness, fruit colour, pitting, bruising, etc.) (Wang et al. 2001). Heat transfer to the inner portions of foods during conventional heating is limited by the low thermal conductivity of food materials, thus necessitating prolonged heating in many cases (Ikediala et al. 2002). Since insects may stay in the centre of the fruit, the thermal energy should be delivered to that location. In conventional heating processes, by the time the treatment delivers sufficient thermal energy to the fruit centre to kill infesting insects, the fruit surfaces are exposed to high temperatures for an extended period, which might cause severe and visible thermal damage (Tang et al. 2000). Heating times to bring the fruit centre to the desired temperatures range from 23 min for cherry to 6 h for apple (Wang et al. 2001).

1.5.1 Heat transfer equations

Using a simulation model, Wang et al. (2001) studied some physical and thermal parameters affecting heat transfer in a single spherical fruit exposed to heating media such as forced hot air, hot water and RF.

In conventional heating, thermal energy is transferred from the heating medium to the fruit surface ($r = r_o$) by convection as described by the boundary heat flux equation (1).

$$-k\left.\frac{\partial T}{\partial r}\right|_{r=r_0} = h[T(r_0,t) - T_e] \qquad (1)$$

The thermal energy is then transferred from the fruit surface to the fruit interior by conduction governed by a general energy balance equation (2).

$$\rho C_p \frac{\partial T}{\partial t} = k\left(\frac{\partial^2 T}{\partial^2 r} + \frac{2}{r}\frac{\partial T}{\partial r}\right) + Q \qquad (2)$$

Heat of respiration is small over the period of quarantine heating. Thus, $Q = 0$. Dividing by ρCp and substituting α for $k/\rho Cp$ leads from Eq. (2) to Eq. (3).

$$\frac{\partial T}{\partial t} = \alpha\left(\frac{\partial^2 T}{\partial^2 r} + \frac{2}{r}\frac{\partial T}{\partial r}\right) \qquad (3)$$

Conductive heat transfer within fruit, as represented by the right hand side of Eq. (3), is slow owing to the relatively small value of thermal diffusivity for fruits. For RF or microwave heating, heat conduction is relatively small; Eq. (2) reduces to equation (4).

$$\partial T = \frac{Q}{\rho C_p}\partial t \qquad (4)$$

The results of the equations show that fruit size (r_o) is one of the most important parameters, which demonstrates the importance of sorting before heat treatment in order to achieve a uniform effect among treated fruits. The results also clearly point out the higher heating efficiency of water compared with air. More importantly, under RF or microwaves, heating increases linearly with treatment time and takes a very short time to reach the targeted temperature (Wang et al. 2001).

Although this modelling illustrates the basic heat transfer for a single commodity based on the assumption of spherical shape, the actual commodity is not absolute spherical in shape, to say nothing of its tissue composition. Wang et al. (2006) found that walnut orientation affects the heating uniformity under RF treatment. This effect also appeared in the study by Birla et al. (2004) on hot water immersion of orange.

1.6 Uniformity

In bulk processing, the heating field to which each individual commodity is exposed can hardly be the same, leading to treatment differences among commodities. Some researchers have studied these bulk heating issues for the scale-up of RF (Birla et al. 2004; Wang et al. 2006a) and hot water (Bollen and Dela Rue 1999; Birla et al. 2004; Fallik 2004; Wang et al. 2006b).

1.6.1 Heterogeneity in conventional media

For conventional media, low specific heat capacity and poor heat transferability can cause problems, making it difficult to obtain uniform heating within each individual fruit. It has been found that the part of apples within the cavity created by two adjacent abutted fruits and effectively sealed off from the heating medium was shown to delay the achievement of target temperatures (Bollen and Dela Rue 1999).

Heterogeneity exists not only within each single fruit but also among fruits exposed to air treatment. Vigneault and de Castro (2005) evaluated the applicability of using instrumented balls as an indirect measurement of air velocity, which was inferred as a function of the location of the simulators in relation to the air entrance. Their results demonstrated that the variance of temperature distribution increases as the container opening area is reduced below 25% (Vigneault and de Castro 2005) and that the airflow rate has a significant effect on the half-cooling time variance at the minimum opening configuration (Vigneault and de Castro 2005). With respect to the aerodynamic and thermal properties of batch processing, Alvarez and Flick conducted an experimental thermal study to characterize heat transfer intensity for spherical objects packed in stacked bins and cooled by forced air convection. Large differences (up to 40%) in heat transfer coefficient values were observed. This heterogeneity could be explained by the

fact that the airflow is not uniform. The turbulence generated behind the produce increased the intensity of turbulence by up to 60% (Alvarez and Flick 1999a; Alvarez and Flick 1999b).

1.6.2 Heterogeneity in electromagnetic media

Under ideal conditions, RF and microwaves allow rapid heating throughout a food material without temperature gradients, provided that the electric field is uniform and the sample is sufficiently homogeneous. Unfortunately, the tissues and composition of horticultural crops vary greatly with location. It is clear that the thermal properties are heterogeneous, with the result that neither the electric field nor the material is uniform or homogeneous. Mitcham et al. (2004) pointed out that the non-uniform heating of fresh fruits or vegetables caused by variations in RF fields is a major obstacle to the development of postharvest insect control treatments based on RF energy. The minimum temperature must be sufficient to kill insect pests, whereas the maximum temperature must remain below the limit of heat tolerance of the fruit or vegetable. When studying the influence of the number of RF units and intermittent stirrings on heating uniformity, Wang et al. (2005) verified that the rise in standard deviation of walnut temperatures at any time during RF heating increased linearly with the rise in mean temperature.

A fruit mover was developed to rotate and move fruit through water while the fruit is subjected to RF heating. Under those conditions, temperature uniformity in orange and apple improved significantly (Birla et al. 2004). Fresh fruit suffers thermal damage and shows evidence of burning at the points of contact with the container or with other fruit when heated with RF energy in air. The result of this overheating is caused by a concentration of electric fields around the contact areas, because the contact surfaces have the least resistance to RF energy. A medium that has similar dielectric properties to fruit was employed to avoid fruit-to-fruit contact during RF heating, resulting in more homogeneous RF fields (Wang et al. 2003). The loss factor of insects and fruits increased with increasing temperature. Ionic conductivity increased as a result of reduced viscosity at high temperatures. This effect serves as positive feedback, in that any difference in temperature tends to accelerate heating in warmer regions, resulting in even greater temperature differences. Thus the fruit to be heated must have a uniform initial

temperature and be exposed to a uniform electromagnetic field if uniform heating is desired (Wang et al. 2003). The results of the research conducted by Wang et al.(2003) show the importance of equipment material selection and the pre-conditioning before heat treatment, which should be considered when designing commercial equipment and enacting a protocol.

Freshly harvested commodities are non-uniform, and a homogeneous heating field is difficult to achieve. A better understanding of the effect of heat uniformity on the quality of a treated commodity prior to the scale-up of postharvest heat treatment is required. In addition, an understanding of the physiological processes occurring in the fruit and vegetable tissue during and after this non-uniform heat treatment should aid in developing successful treatments. Lu et al. (2006) reported that some heat treatment effects such as colouring and CI control are localized rather than systemic, which showed the importance of maintaining heat uniformity for each individual treated commodity.

1.7 Discussions and future research

The main problem for the scale-up of heat treatment techniques is that the temperature tolerances between an effective treatment and heat damage can be as little as 1°C–2°C. The duration of heat treatment at these temperatures also has an effect on produce quality (Bollen and Dela Rue 1999). Thus, further research is needed to optimize heating temperature and related duration for different treatment media and to find a way to maintain a fairly uniform micro-media environment for each treated crop.

The temperature difference between treated fruits could be decreased by mixing or increasing water circulation for water treatment and by combining RF or microwaves with water. Air would obviously result in the same problem, but no study gives the direct answer. The negative side of moving commodities in hot air is obvious, with mechanical injury occurring for the following reasons: first, commodities in water are easier to move with the help of buoyancy, and water can also reduce friction and ease collisions among the commodities, whereas air will not; and second, unlike walnut or other nuts, most fruits and vegetables are sensitive to mechanical bruising, and bruising can enhance the invasion of pathogens during storage. It is technically possible to achieve relatively uniform treatment by reducing the treatment load, such as by using a single-layer layout;

this method is rarely applicable from the economical point of view. If in-bin processing is necessary, some research results existing in the literature (Alvarez and Flick 1999a; Alvarez and Flick 1999b; Vigneault and de Castro 2005) for postharvest forced-air cooling might be shared for hot air treatment after validation.

The non-uniformity of heat transfer with respect to the effect of heat treatment on treated commodities should be investigated further to pave the way for the scale-up of heat treatment application by correlating the engineering parameters with the quantified heat treatment effects. Those differences in effect in terms of quality, anti-pathogen and anti-CI properties among commodities can be studied by exposing commodities to different targeted temperatures within the effective range. It is also important to evaluate how and to what extent the non-uniformity of heat transfer within an individual commodity influences the effects of heat treatment. Although it could be tedious, this type of research should be done before commercial application. In addition, research into a protocol for the adoption of different heat treatment methods in the postharvest chain is needed for the purposes of disinfestation, disinfection and quality control.

CHAPTER II. GENERAL HYPOTHESIS, OBJECTIVES, AND SCOPE

2.1 Hypothesis

The null hypothesis (H_0) of this study was that there are no significant effects of non-uniform heat treatment on response of tomato with respect to quality, chilling injury, and disease control.

2.2 Objectives

This study concentrates on investigating the extent of heating uniformity achieved with hot air, in order to obtain a uniform response in terms of spoilage, disease, and chilling injury control. Differences in effect in terms of quality, anti-pathogen activity and anti-CI properties among commodities was studied by exposing commodities to different targeted temperatures within the effective range.

The main objectives of this research program are to:

(1) develop experimental tools for investigation of non-uniform treatment on fruits.

(2) simulate the physical parameters' effect in the experimental design to optimize the design for other test materials in the future.

(3) study the effect of non-uniform treatment on quality attributes of tomatoes.

(4) study the effect of non-uniform treatment on chilling injury of tomato fruit.

(5) quantify the effects of non-uniformity of hot air treatment on pathogens.

(6) simulate the heat transfer of tomato under a non-uniform heat treatment.

2.3 Scope

The non-uniform effect of heat treatment could happen to any commodity exposed to heat treatment, and it could be found in any heating media and method. The test material used in this research is tomato, and the design and simulation of the heterogeneous treatment device is also based on tomato. The heating medium used in this research is hot air.

CONNECTING STATEMENT 1

Background information was provided with the main goal and specific objectives specified in Chapter I and Chapter II. In Chapter III, a comprehensive literature review in the field of postharvest heat treatment and the study of heat transfer uniformity will be presented.

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Jianbo Lu*, Clément Vigneault, Marie Thérèse Charles**, G. S. Vijaya Raghavan*. Heat treatment application to increase fruit and vegetable quality.**

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The first author, the PhD student, collected most of the information and prepared the manuscript; the second author provided part of the material; the rest of the authors are the multi-disciplinary team who guided, corrected, and reviewed the paper.

CHAPTER III. LITERATURE REVIEW

3.1 Abstract

Heat treatment has been used on fruits and vegetables for different purposes for a long time. The physiological mechanisms and pathological and microbiological responses involved in the process are not well understood. Furthermore, while heat transfer in stable conditions is a very simple phenomenon from an engineering point of view, heat transfer is very complex during transient processes like the heat shock treatments that have lately been used for generating heat stress responses in fruits and vegetables. Physiologists and pathologists have shown that uniformity and precision are very important for heat transfer processes. Engineers have also demonstrated that uniformity is a very complex problem to be solved when trying to scale up from individual produce treatment to the bulk processing required by the industry to make the system economically feasible. Microbiologists have demonstrated that some microorganisms are very sensitive to temperature variation and are easily controlled by heat treatment, while others may proliferate under the same temperature conditions. These aspects must be discussed in order to develop heat treatment methods, increase the efficacy of such methods, and eliminate the accidental propagation of human pathogens in the treated produce. The present chapter offers a multidisciplinary approach aimed at answering some of these concerns about this emerging technology, which uses short-time exposure to heat in order to control pathogens and/or generate a physiological stress response with the goal of enhancing and maintaining fruit and vegetable quality and safety.

3.2 Introduction

Heat has been used for drying, pasteurization, quarantine, and decay control in an increasing variety of foods. The use of heat treatment has been extended to the inhibition of ripening processes and the induction of resistance to chilling injury in some horticultural produce. An overview of many studies on the physiological, pathological, microbiological and engineering principles of heat treatment clearly demonstrates the importance of looking at these disciplines all together with a view to making significant progress in the use of heat to maintain or improve the quality and safety of horticultural

produce. Furthermore, fresh horticultural produce, including whole and fresh-cut fruits and vegetables, is increasingly associated with outbreaks of foodborne illnesses. The current pre-market sanitation treatments too often rely on the application during washing of chemical sanitizers, primarily chlorine, usually at temperatures < 10°C. Unfortunately, such measures are only marginally effective against human pathogens. Heat treatments between 45°C and 60°C have been successfully used as an alternative means of human pathogen control in whole or fresh-cut horticultural produce. However, the effect of a new range of short-time heat treatments involving temperatures between 10°C and 45°C to generate a physiological response to heat stress is not well understood.

The research effort on developing heat treatment in postharvest has been increasing steadily in recent decades, with successful laboratory investigations and some scale-up development of the use of hot water, radio frequency (RF), microwave and hot air in drying, disinfestation, disinfection, chilling injury control and retardation of the ripening process in various fresh crops (Lurie 1998). The mechanisms of heat treatment in terms of decay control, induction of thermotolerance, and heat transfer under uniform heating media are not all clear. From the point of view of generating a stress response, however, the temperature threshold and uniformity in time and space have been identified as the two most important factors that should be taken into account during heat treatment process development on an industrial scale. From the pathological and microbiological point of view, human and plant pathogens acquired during production, harvest or postharvest handling are mainly found on the surface of fruits or vegetables, although subsurface penetration or internalization within vascular tissues is also believed to occur. Effective heat penetration leading to the stress response resulting from this penetration must be studied in an interdisciplinary manner involving engineers, physiologists, microbiologists and pathologists. Such study will help establish the different mechanisms of plant and microorganism response.

The lethality of thermal treatments is restricted by the onset of heat-induced physiological defects in the produce. As a result, a treatment that reliably delivers lethal heat to the surface without raising the temperature in underlying tissues is needed to make these treatments practical. The inaccessibility of internalized microorganisms also limits

the efficacy of heat treatments. In addition, there is increasing evidence that pathogens that survive such treatments grow at a faster rate in stored and packaged produce.

The challenge for heat treatment lies in the scale-up of some treatment methods by optimizing the processing temperature and duration and improving the uniformity of heat treatment. The ecology of these pathogens in post-heat-processed fruits and vegetables must be examined in detail before these treatments can be recommended for commercial practice.

3.3 General aspects

Heat treatment has been used for disinfestation and disinfection in an increasing variety of crops (Lurie 1998). Almost no countries produce all the fresh fruits and vegetables that they require year-round, a situation that creates good opportunities for trade as well as the possibility of insects and human and plant pathogens being introduced to the importing region. Phytosanitary restrictions have been continuously developed to protect regional agricultural industries from the introduction of damaging pests (Kader 2003). Many importing countries require inspection certificates attesting to the absence of targeted live pests in a shipment after a pre-approved postharvest "sanitation" treatment (Ikediala et al. 2002). Because of consumer and environmental concerns and regulatory issues (Mulas and Schirra 2007), non-damaging physical treatment substitutes for preventive chemical treatments are needed. Although irradiation (Lurie 1998) and controlled or modified atmosphere storage and packaging (Raghavan et al. 2005b) are non-pesticide technologies that have been investigated in an effort to extend the storage and shelf life of fresh produce, heat treatment appears to be one of the most promising means for postharvest quarantine and decay control (Fallik 2004). Heat treatments can also be used to inhibit ripening processes or to induce resistance to chilling injury and external skin damage during storage, thus extending the storability and marketing period. However, the heterogeneity of heat transfer is one of the largest obstacles on the way to industrialization. An understanding of the physiological processes at play in fruit and vegetable tissue during and following a heterogeneous heat treatment should support any development of successful treatments. Heat treatment effects on chilling injury control and colour development were shown to be localized rather than systemic, a finding that

supports the importance of maintaining heat uniformity for each individual treated commodity (Lurie 1998).

Outbreaks of foodborne illness caused by the consumption of contaminated fresh fruits and vegetables are being reported with increasing frequency in the Western world (Rangel et al. 2005). A variety of commodities have been associated with these incidents. Leafy vegetables are the leading source of foodborne illnesses associated with fresh fruits and vegetables. Documented outbreaks associated with whole or fresh-cut leafy vegetables have involved a range of infectious agents, including *Escherichia coli* O157:H7, *Salmonella*, *Shigella*, *Listeria monocytogenes*, *Cyclospora*, *Giardia*, norovirus, and hepatitis A virus (Schlech et al. 1983; Sivapalasingam et al. 2004; Soderstrom et al. 2005). European outbreaks of salmonellosis caused by *Salmonella enterica* serovar Thompson and *S. enterica* serovar Newport were epidemiologically linked to packaged rocket salad (*Eruca vesicaria* ssp. sativa) and head lettuce (*Lactuca sativa*), respectively (Sivapalasingam et al. 2004). More recently, a major *E. coli* O157:H7 outbreak caused by contaminated packaged spinach in 2006 resulted in three deaths in the US (Anonymous 2006a, b, c; Charatan 2006). Most well-documented outbreaks have provided evidence that crops can be contaminated with foodborne pathogens in the field from irrigation with water of poor microbiological quality or by contact with livestock feces or improperly composted manure (Sivapalasingam et al. 2004). However, postharvest contamination may also occur if appropriate sanitary measures are not observed during storage or processing.

The source of human pathogens in horticultural production systems, the behaviour of such pathogens in stored produce, and the development of effective means for their control are the subject of an increasing amount of research activity. Microbiological analysis of freshly harvested plants reveals that small populations of endophytic microorganisms may be recovered from the internal tissues of some species (Samish and Etinger-Tulczynska 1963). The majority of microbial contaminants, including species responsible for common storage diseases, are associated with the plant surface, and it is widely assumed that human pathogens, including bacteria, viruses and protozoa, also occur at this locus. Current disinfection schemes are therefore designed to remove or

inactivate microbial contaminants on the plant surface. Sanitary washes in chlorine (sodium hypochlorite, calcium hypochlorite, chlorine dioxide) or alternatives such as peroxyacetic acid, hydrogen peroxide or acidified sodium chlorite remain the most common treatments to achieve this end. These sanitizers are applied as aqueous solutions that have low surface wetting ability and consequently limited disinfection potential (Beuchat 1996). For this reason, the development of alternative treatments that yield improved surface disinfection is highly desirable.

Traditionally, horticultural produce has been heated using hot water, vapour heat or hot air. However, a greater understanding of RF and microwaves and various processing applications of microwaves for food and biological materials (Venkatesh and Raghavan 2004; Raghavan et al. 2005a) have meant that these two electromagnetic media have been investigated in postharvest heat treatments in recent years (Tang et al. 2000; Orsat et al. 2001; Ikediala et al. 2002; Karabulut and Baykal 2002; Wang et al. 2003; Birla et al. 2004; Mitcham et al. 2004; Wang et al. 2005; Wang et al. 2006a, b; Zhang et al. 2006). Moreover, far infrared radiation heating technology has proven to be a rapid and contactless heating method and has exhibited more uniform surface heating than the air convection heating process (Tanaka et al. 2007).

Mild heat treatments appear to be attractive for effective control of storage diseases, delaying the onset of physiological disorders (chilling injury) and improving the quality of stored commodities (Mulas and Schirra 2007). The efficacy of these treatments for the control of human pathogens in fresh fruits or vegetables and their influence on the fate of such hazards have also been examined in several commodities.

3.4 Contamination with human pathogens

3.4.1 Whole produce

Consumption of cantaloupe has been responsible for at least 25 outbreaks in North America (Bowen et al. 2006). Other melon varieties including watermelon were identified as the source of pathogens in some of the documented incidents (Larson et al. 1979; Blostein 1993). Some outbreaks were caused by *E. coli* O157:H7, *Campylobacter jejuni* or noroviruses, but the majority were due to contamination with *S. enterica* serovar

Poona. A 2003 survey of cantaloupe produced in the US and Mexico revealed that 1.8% of samples were positive for *Salmonella* (Castillo et al. 2004). In contrast, much higher rates of isolation were reported in a study conducted in southern Texas (Materon et al. In press). These observations suggest that the incidence of contamination in commercial cantaloupe melons may be highly variable. While the magnitude of the risk associated with this occurrence is difficult to ascertain, it is clear that melons can become contaminated with human pathogens during production and that effective postharvest disinfection treatments are highly desirable.

The nature of the interaction between *Salmonella* and the cantaloupe melon surface has been examined in some detail. It is clear that *Salmonella* can adhere to or infiltrate the surface tissues (netting) and stem scar of cantaloupe (Richards and Beuchat 2004), where it has been shown to become attached and form biofilms (Annous et al. 2005). Cells embedded within biofilms resist removal or inactivation during sanitary washes, and more lethal treatments are required to ensure their destruction. Because *Salmonella* is not resistant to heat, thermal treatments applied to the surface could be of value for melon disinfection, and encouraging results have been reported. A 2 to 3 min treatment at 76°C was shown to reduce *S. enterica* serovar Poona populations by 5 log cfu cm^{-2} in a commercial-scale experimental process (Annous et al. 2004). Unfortunately, this treatment could not eradicate inoculum applied to the melon surface. Nevertheless, the treatment did not appear to have a deleterious effect on overall quality, and the results suggest that heat treatments could be of value where further processing is desirable, such as in fresh-cut processing. Furthermore, heat treatments have been shown to reduce fungal decay and improve overall quality attributes during prolonged storage.

Human pathogens such as *E. coli* O157:H7 (Del Rosario and Beuchat 1995) or *Salmonella* (Annous et al. 2004) have been shown to grow on the rind of cantaloupe melon stored at growth-permissive temperatures. Because fresh produce is frequently exposed to abusive storage conditions, it is essential to understand the consequences of alternative treatments on the behaviour of human pathogens during subsequent handling, particularly under temperature regimes characteristic of retail distribution systems or the home. The fate of several sight *Salmonella* serovars inoculated onto cantaloupe melon

prior to treatment for 2 min in water at 96°C was examined over several days in storage (Ukuku 2006). *Salmonella* grew at a faster rate on the rind of melons that received the heat treatment, a clear indication that the benefits derived from such treatments may be inappropriate for the disinfection of melons intended for storage prior to further use, either by the consumer or in the preparation of processed products.

Outbreaks of salmonellosis have also been linked to fresh tomato (Gupta et al. 2007). Two multi-state outbreaks caused by *S. enterica* serovar Javiana and *S. enterica* serovar Montevideo were associated with the consumption of uncooked tomatoes in the US in 1990 and 1993, respectively (Hedberg et al. 1999). In 2004, three major outbreaks of *Salmonella* infection totalling 561 cases were conclusively linked to the consumption of Roma tomatoes in the US and Canada (Anonymous 2005; Gupta et al. 2007). As it does on cantaloupe melons, *Salmonella* can survive for extended periods of time on tomato fruit, and contamination may occur during production. Experimental inoculation of either stems or flowers led to recovery of the bacterium from the surface, stem scar and pulp tissue of mature fruit (Guo et al. 2001). Postharvest bacterial infiltration into core tissues through the stem scar is known to occur upon immersion of warm horticultural produce into contaminated water at a lower temperature (Wei et al. 1995). Furthermore, tomato skin is prone to abrasion or puncture injuries that could provide additional points of entry into the fruit. Extensive growth of *Salmonella* in tomato flesh has been documented (Yuk et al. 2007).

Because tomato skin is comparatively thin and fragile, the fruit cannot withstand the temperatures that are applied in melon disinfection. Nevertheless, heat treatments at 50°C and up to 60°C for short periods of time have been applied to tomato (Fallik et al. 2002). Sapers and Jones (2006) immersed tomatoes inoculated with *E. coli* or *Salmonella* spp. for 2 min in water heated to 60°C. Overall reductions were limited to < 2.0 log cfu/g of homogenized tomato flesh. Since both species can grow readily in tomato pulp, this result clearly shows that heat treatments cannot provide satisfactory control of human pathogens in tomatoes intended for the fresh or fresh-cut market.

The sum of experimental evidence available from past research on the destruction of human pathogens associated with the surface of cantaloupe melon and tomato shows

that the efficacy of heat treatments is limited. Because the infectious dose for some human pathogens of immediate concern such as *E. coli* O157:H7 is very low (< 100 cells) (Ngarmsak et al. 2006), there is clearly a need to improve the performance of such treatments before they can be applied on a commercial scale.

3.4.2 Fresh-cut Produce

The benefits of pre-cutting heat treatments for microbiological quality enhancement have been demonstrated in many types of fresh-cut produce. For example, the shelf life of fresh-cut mango slices was enhanced by washing whole fruit in hot water (50°C) prior to slicing and packaging, because the treatment limited the transfer of microorganisms from the surface to the flesh during processing (Ngarmsak et al. 2006). Similar improvements in shelf life were obtained with fresh-cut cantaloupe cubes prepared from melons sanitized in hot water (Ukuku et al. 2004; Fan et al. 2006), although the treatments did not completely prevent transfer of *Salmonella* from the surface to cut flesh (Ukuku et al. 2004).

Interest in postharvest heat treatments is mainly focused on the improvement of quality or shelf life in stored commodities. A notable example is the control of edge browning in fresh-cut iceberg lettuce. Treatments applied at temperatures between 47 and 50°C were shown to successfully inhibit phenylpropanoid metabolism and delay the appearance of edge browning in packaged fresh-cut iceberg lettuce (Loaiza-Velarde et al. 1997; Fukumoto et al. 2002; Delaquis et al. 2004). Hot water treatments are also more lethal to microbial contaminants than conventional chlorinated water washes applied at a low (4°C) temperature (Delaquis et al. 1999). These findings appear to suggest that a hot water process would be very appropriate for fresh-cut iceberg lettuce. Unfortunately, bacterial pathogens that survive the treatment were shown to grow at faster rates in heat-treated fresh-cut lettuce than in conventionally processed fresh-cut lettuce (Li et al. 2001; Delaquis et al. 2002). Similar findings are reported for human pathogens inoculated onto broccoli florets and green beans immersed in water at 52°C for 90 s prior to packaging (Stringer et al. 2007). These observations suggest that the consequences of novel or alternative disinfection treatments for the behaviour of human pathogens in fresh-cut products must be carefully considered. The observations also point to gaps in current

knowledge about the nature of the interaction(s) between human pathogens and plant tissues. Effective heat treatments are expected to inactivate a larger proportion of the native microflora. Because competition between native microorganisms and colonizing human pathogens is believed to exert strong selective pressures in the plant phyllosphere, it is hypothesized that reduced competition from native species could account for more successful colonization of heat-treated plant tissues by human pathogens. In some cases, however, no correlation can be found between the size of the native microflora and the growth of specific pathogens. For example, growth of *Listeria monocytogenes* in cut iceberg lettuce subjected to heat treatments was unaffected by the size of the competing microflora (Delaquis et al. 2006). Interestingly, the intensity of wound-associated reactions assessed from measurements of phenolic compounds in the tissues was correlated with reduced growth of the species. This observation suggests that physiological reactions in plant tissues may play a significant role in the behaviour of human pathogens in fresh-cut produce. A more complete understanding of the nature of such interactions is clearly required.

3.5 Heat treatment mechanism

In recent times, several researchers have investigated some physiological and pathological issues for various crops in terms of quality (Lurie 1998; Lurie 2006). The overall quality of fresh produce treated at the optimal temperature and exposure duration is significantly better than the quality resulting from the control treatment (Fallik 2004). The primary mode by which heat treatments appear to limit decay development is through direct inhibition of pathogen growth. Physical removal of inoculants from the produce surface is also an important factor when hot water is used in combination with mechanical brushing or pressure spray water application methods. It is also well known that plants defend themselves against pathogens by means of constitutive or induced mechanisms. Several studies have demonstrated the potential of heat treatment to interact with both of these types of defence mechanisms (Schirra et al. 1999; Terry and Joyce 2004). Hot water brushing causes a clear redistribution of the epicuticular wax layer, which is part of the constitutive defence system, and a significant reduction in cuticular cracks, thus improving physical barriers to pathogen penetration (Ben-Yehoshua 2003; Fallik 2004). It

is well established that heat treatment favours wound healing at wound sites by leading to the deposition of lignin-like material, thus enhancing the constitutive defence and hindering pathogen invasion. It has been demonstrated that heat treatment prevents the deterioration of molecules such as anionic peroxidases, which play an important role in the constitutive defence of tomato fruit against grey mould rot (Lurie and Sabehat 1997). Heat treatments also inhibit the biochemical pathways involved in ripening and other processes in many types of fruits and vegetables and, therefore, contribute to the maintenance of juvenility and resistance. Heat treatment conditions of 62°C for 20 s induced resistance against green mould decay in grapefruit (Pavoncello et al. 2001). However, the induction of produce resistance was temporary, and inoculation 7 days after the heat treatment generated more decay than inoculation immediately after the treatment (Pavoncello et al. 2001). Some physical and chemical treatments to control decay were proven more effective when applied in combination with heat treatment (Farkas 1990; Rodov et al. 2000; Marquenie et al. 2002a; Ben-Yehoshua 2003; Leverentz et al. 2003; Marquenie et al. 2003; Wszelaki and Mitcham 2003; Ali et al. 2004; Conway et al. 2004; Conway et al. 2005; Malakou and Nanos 2005; Zhang et al. 2007). Heat treatment alone or in combination with other physical treatments promoted the synthesis and accumulation of phytoalexins, which are antimicrobial compounds, and chitinases and β-1,3-glucanases, which are enzymes associated with induced resistance through their ability to degrade fungal cell walls (Pavoncello et al. 2001; Ben-Yehoshua 2003).

3.5.1 Induction of thermotolerance

The mechanism by which a heat treatment brings changes in produce ripening, such as inhibition of C_2H_4 synthesis and cell wall degradation, may be linked to changes in gene expression and protein synthesis (Pavoncello et al. 2001). During high-temperature treatment, messenger ribonucleic acids (mRNA) associated with ripening genes disappear, and mRNA of heat shock proteins (HSP) accumulate. An immediate response to a high temperature is the disassociation of polyribosomes and the re-association of some specific ribosomes into polyribosomes that preferentially translate the mRNA of HSP. Therefore, heat exposure severity will modulate the thermotolerance response. The temperature must be high enough to initiate the synthesis of HSP but not so

high that the transcription and translation of HSP are inhibited. Temperatures of 35 to 40°C have been found to be generally effective, depending upon the commodity and process duration.

After many horticultural crops were exposed to sublethal temperatures, the induced thermotolerance protected them from exposure to a normally lethal temperature (Lurie 1998). This thermotolerance could also be applicable for the low-temperature extreme-chilling injury threshold. Most of the time, climacteric fruits are sensitive to chilling injury at low temperatures. When a hot air treatment for 2 to 3 days at 38°C was applied to tomato fruits, their sensitivity to low temperatures was reduced, and they could be stored for up to a month at 2°C without developing any chilling injury symptoms (Lurie and Sabehat 1997). This resistance to low-temperature injury was found to be contingent on the presence of HSP (Lurie 1998). Furthermore, this beneficial effect of heat treatment has also been verified for pomegranate (Mirdehghan et al. 2007), peach (Murray et al. 2007), orange (Rodriguez et al. 2005), and avocado (Woolf et al. 2004).

3.5.2 Heat damage

Although heat treatments are known to benefit treated horticultural crops, inappropriate heat treatments such as a lethal temperature or an excessive duration are harmful. For example, temperatures higher than 38°C were not generally as effective as 38°C treatments (Lurie and Sabehat 1997). Hot air treatments at 42 or 46°C for 24 h caused heat damage in tomato (Lurie and Sabehat 1997). Hot water treatments at 45 or 48°C caused severe damage in strawberry (Marquenie et al. 2002b), and the damaged fruits were susceptible to spoilage by pathogens (Porat et al. 2000a; Lu et al. 2007b). Damage can be both external and internal. External symptoms are generally peel browning, pitting, scalding, or yellowing of green vegetables (Lurie 1998). For instance, Manila mango fruits showed severe skin scalding when forced-air heating at temperatures of 45°C or higher was used, slight skin scalding from heating at 44°C, and no damage at 43°C; these findings indicate the presence of a threshold temperature for skin injury development (Ortega-Zaleta and Yahia 2000). Tissue damage caused by heat also encourages decay development. Evidence for internal damage includes poor color development, abnormal softening, lack of starch breakdown, and development of internal

cavities (Cheah et al. 1992; Lurie 1998). Heat treatment enhances antioxidant production, but temperatures higher than the threshold temperature lead to negative effects (Yahia et al. 2007). Furthermore, the heat damage tolerance of fruits and vegetables varies according to species, cultivar, harvest maturity, growing, handling and postharvest treatment conditions (Lurie 2006).

3.5.3 Hot water processing

Hot water was originally used to prevent fungal decay (Pavoncello et al. 2001), but its use has been extended to insect disinfestation. The two main commercial hot water treatments are hot water dips (immersion) and brushing (spray).

Since fungal spores and latent infections are generally present either on the surface or in the first few cellular layers under the peel of the fruit or vegetable, hot water dipping has been effective for controlling many pathogens (Cheah et al. 1992; Jacobi et al. 2000; Zhou et al. 2002; Karabulut et al. 2004; Spadaro et al. 2004; Malakou and Nanos 2005; Siomos et al. 2005; Wilson Wijeratnam et al. 2005; Spotts et al. 2006; Hong et al. 2007). Generally, decay control requires heating the commodity surface only; dipping heat treatment applied for decay control is generally very short (only a few minutes) at temperatures higher than those for disinfestation. Many fruit and vegetable types tolerate exposure to water temperatures of 50 to 60°C (Barkai-Golan and Phillips 1991; Ranganna et al. 1998) for up to 10 min. This short time exposure at these temperatures is enough to control many postharvest plant pathogens. Hot water dipping has been used for disinfesting insects as well (Shellie and Mangan 2000; Diaz-Perez et al. 2001; Jacobi et al. 2001a; Tsouvaltzis et al. 2006). For insects, a longer treatment time than for fungal control is necessary, as larvae usually bore into fruits or unshelled nuts to feed on the centre flesh, seeds or kernels. Even from a microbiological point of view, this depth of insect penetration requires much more aggressive heat treatment to disinfect the contaminated produce (Tang et al. 2000). From a physiological point of view, the longer durations required for such disinfection will not be acceptable for many types of horticultural produce, as the development of desirable quality attributes that characterize a fruit or vegetable may be impaired. Typical hot water treatments for insect disinfestation

range from 70 to 90 min (Ferguson et al. 2000), followed by a cooling treatment of 35 to 45 min to return the produce to its original temperature as quickly as possible.

Hot water spray is a recent extension of hot water treatments. This technique is designed to be part of a sorting line, where the commodity is moved by means of brush rollers through a pressurized spray application. This system is used on a number of fruits and vegetables to simultaneously clean the produce and reduce the presence of pathogens (Fallik 2004).

As long as the temperature and duration are appropriate, pressurized spray and immersion have no adverse effects on quality attributes, including pH, titratable acidity, soluble solids content, weight, firmness and peel colour (Fallik 2004; Schirra et al. 2005; Hong et al. 2007).

3.5.4 Hot air processing

Hot air has been used for both fungal and insect control (Tang et al. 2000; Yahia and Ortega-Zaleta 2000; Jacobi et al. 2001a; Lurie et al. 2004; Mitcham et al. 2004; Hoa et al. 2006) and for studies of the response of commodities to higher temperatures (Yahia et al.; Soto-Zamora et al. 2005; Hoa et al. 2006). Forced air is preferred for the development of quarantine procedures, but high temperatures generated by forced or static air can also decrease fungal infections (Lurie 1998). However, the process times are relatively long, lasting from 12 to 96 h at temperatures ranging from 38 to 46°C, compared to a few minutes to half an hour when water or water vapour medium is used. Processed produce weight loss generally increases as the treatment temperature and/or duration increases (Lurie et al. 2004). Hot air treatment is also the cause of reduced firmness, generally due to water loss (Jacobi et al. 2000). These negative effects give support to those claiming that this method is unlikely to become commercially and industrially attractive (Lurie 1998). On the other hand, hot air treatment has the potential to generate beneficial effects for some physiological aspects, including the enhancement of fruit pigmentation (Porat et al. 2000), and to prevent both insect and fungal invasion (Tang et al. 2000; Yahia and Ortega-Zaleta 2000; Jacobi et al. 2001a; Lurie et al. 2004; Mitcham et al. 2004; Hoa et al. 2006). Further research and development in that domain is therefore justified. Also, hot air has been used as an effective conditioning method to

reduce heat damage of mango compared to hot water disinfestation treatment (Jacobi et al. 2000; Jacobi et al. 2001a; Jacobi et al. 2001b).

3.5.5 Water vapour processing

A common difficulty with the hot air heating method is the slow rate of heat transfer, which leads to a longer processing time, especially for large produce (Wang et al. 2001). Water vapour disinfection is a method of heating horticultural produce using air saturated with water vapour to generate temperatures ranging from 40 to 70°C in order to kill insect eggs and larvae as a quarantine treatment before fresh market shipments (Jacobi et al. 1993; Moy 1993; Seaton and Joyce 1993; Heather et al. 1997; Jacobi and Giles 1997). Vapour heat treatment also successfully controlled grey mould rot on stored table grape (Lydakis and Aked 2003a, b) and anthracnose and stem end rot on mango (Jacobi and Wong 1992). In water vapour heating, forced air is circulated through the pallets to heat the commodity. For disinfection, the treatment consists of a warming period and a holding period (after the interior temperature of the produce reaches the desired temperature). As with hot water treatment, a cooling-down period is required after the holding period (Lurie 1998). The heating process is generated by water vapour condensation on the cooler produce surface, producing a very rapid heat transfer. As a comparison, the heat transfer coefficients of condensing vapour, free/forced air and water are, respectively, 5,000 to 100,000, 5 to 25/10 to 200 and, 20 to 100/50 to 10,000 Wm^{-2} K^{-1} (Singh and Heldman 2001). Since heat transfer is generated by the latent heat of condensation, the temperature of the produce surface is sometimes higher than the environmental media (Shellie and Mangan 2000). This phenomenon makes temperature control of the produce surface very difficult. The development of surface heat damage on produce is easy to understand when it is known that a temperature as little as 1°C above the optimal temperature could generate damage. This explains why water and air treatments are still more popular, although water vapour is theoretically more efficient with respect to heat transfer.

3.5.6 RF and Microwave processing

Radio frequency and microwave heating processes involve the interaction between electromagnetic waves and dielectric materials. These two methods have some

important advantages over conventional heat transfer methods (air, water and vapour). First of all, RF and microwaves are classified as non-ionizing radiation and are therefore regarded as safe treatments and are well-accepted by consumers. These heating methods avoid the limitations caused by air spaces or produce bulkiness that are considerations in conventional surface heating with air or water. Because of the dielectric properties of insects, the RF process generally heats them faster than the surrounding plant tissue (Wang et al. 2003), resulting in an insect and larval control method that is quite efficient. Furthermore, treatments using the electromagnetic energies of RF and microwave heating leave no chemical residues, eliminate cross-contamination and have a minimal impact on the environment (Tang et al. 2000). Radio frequency or microwave heating is suggested as an alternative with a view to reducing the adverse thermal impact on treated commodities during the heating period (Tang et al. 2000).

The penetration depth of electromagnetic waves in a lossy material increases as frequency decreases, a phenomenon that explains the deeper penetration of RF compared to microwaves. For example, the penetration of microwaves in apple at room temperature increases from 12 to 43 mm when the frequency decreases from 2450 to 915 MHz (Tang et al. 2000). A limited penetration depth leads to non-uniform heating in large objects. Under ideal conditions, RF and microwaves allow rapid heating throughout a food material without temperature gradients, provided that the electric field is uniform and the sample is sufficiently homogeneous. Unfortunately, the tissues and composition of horticultural produce vary greatly with location. It is clear that the thermal properties are heterogeneous, with the result that neither the electric field nor the treatment conditions experienced by the material are uniform or homogenous. The heterogeneous heating of fresh fruits or vegetables caused by variations in RF fields is a major obstacle to developing postharvest insect control treatments based on RF energy (Orsat and Raghavan 2005). The minimum temperature must be sufficient to kill any insect present, while the maximum temperature must remain below the limit of heat tolerance of the fruit or vegetable being treated (Mitcham et al. 2004). A study of the influence of the number of RF units and intermittent stirrings on heating uniformity showed that the standard deviation of walnut temperatures at any time during RF heating increased linearly with the rise in mean temperature (Wang et al. 2005). Temperature uniformity is therefore also

a problem when electromagnetic waves are used, but some solutions have been already tested. Temperature uniformity in orange and apple was significantly improved when the treated commodities were immersed in water to allow rotation during RF heating (Birla et al. 2004). The potential to heat with RF energy in air was also evaluated; fresh produce suffered thermal damage, however, as burnt sites were observed at the points of contact with the container or with other produce. This overheating was likely caused by a concentration of electric fields around the contact points. A material with dielectric properties similar to produce was used to avoid produce-to-produce contact during RF heating, resulting in more homogeneous RF fields (Wang et al. 2003). The loss factor of insects and produce increased with any temperature increase. Since ionic conductivity increases with the reduction of viscosity generated with any temperature increase, any temperature difference tends to accelerate heating in the warmer region and results in an even greater temperature difference. Processed produce must therefore have a uniform initial temperature and be exposed to a uniform electromagnetic field if uniform heating is to be guaranteed (Wang et al. 2003). Some of the research results have addressed the importance of equipment, pre-treatment and protocol selection considerations in the design of commercial equipment (Vigneault and de Castro 2005).

The use of electromagnetic wave heat treatment still has a long way to go before it can be commonly used as a disinfection and decontamination process for fruits and vegetables, since freshly harvested commodities are non-uniform, and a homogenous heating field is difficult to achieve. A better understanding of the effect of heat uniformity on the quality of the treated commodity is required before postharvest electromagnetic wave heat treatment can be scaled up.

The dielectric and conductivity properties of agricultural and biological materials are influenced by frequency, temperature, salt content and moisture content (Ikediala et al. 2002). The dielectric properties of six commodities along with four associated insect pests were measured between 1 and 1800 MHz at temperatures between 20 and 60°C (Wang et al. 2003). The loss factor of fresh produce and insects increased almost linearly with increasing temperature at 27 MHz RF, but remained nearly constant at 915 MHz microwave frequency. The dielectric loss factor of codling moth larvae is greater than the

loss factors of the tested host materials, particularly in the RF frequency range (Tang et al. 2000).

From the perspective of dielectric loss factors and penetration depth, RF treatment is a better choice than microwaves for disinfestation of large fruits or vegetables. However, for pathogen control in small produce, microwave treatment (high-temperature short-time) is preferable. The possibility of using 2.45 GHz microwaves to destroy woodworms by heating the larvae to 52 to 53°C for less than 3 min was demonstrated (Andreuccetti et al. 1994). The possibility of using microwave power to control postharvest pathogens of peach has been evaluated (Karabulut and Baykal 2002). In produce inoculated with grey mould rot and blue mould and treated with microwaves for 2 min, lesion diameters and the percentage of infected wounds were significantly smaller than in the control produce (Karabulut and Baykal 2002).

In summary, the development of effective RF or microwave processes to provide uniform heating and means of monitoring and controlling the end produce temperature still presents some challenges (Tang et al. 2000).

3.5.7 Heat transfer

Many heat application methods have resulted in a heterogeneous produce heating process and caused a reduction in general quality attributes (reduced firmness, poor produce color, pitting, bruising, etc.) (Wang et al. 2001). Heat transfer to the inner portions of food during conductive heating processes is limited by the thermal conductivity of the food (Ikediala et al. 2002). This limitation could extend the heating process duration considerably when a considerable inner temperature increase is required, mainly when the produce is sensitive to high temperatures, thus limiting the processing temperature. Since insects can lodge in the centre of produce, the thermal energy needs to be delivered to that location. In conventional heating processes, by the time the thermal energy required to kill infesting insects is delivered to the centre of the produce by the treatment, the produce surfaces are overexposed to high temperatures, which may cause severe damage (Tang et al. 2000). The heating duration required to increase the produce centre temperature to the desired level may range from 23 min for cherry to 6 h for apple (Wang et al. 2001) and even longer depending on the heating medium and process used.

With a mathematical model, it is possible to identify the most important physical and thermal parameters affecting heat transfer in a single spherical piece of produce exposed to heating media such as still or circulating hot air or water and RF (Wang et al. 2001). In conventional heating processes, thermal energy is transferred from the heating medium to the produce surface by convection. The thermal energy is then transferred from the produce surface to the interior by conduction. Even for energy from electromagnetic wave heating processes, heat is transferred from the heated part of the produce to the cold parts by conduction. Conductive heat transfer within fruits and vegetables is relatively slow because of their low thermal diffusivity. Therefore, the results of a heat transfer model for horticultural produce show that produce size is one of the most important parameters. This result highlights the importance of sorting the produce by size before heat treatment in order to achieve a uniform effect among treated produce. It is also important to note that water achieves a higher heating efficiency than air. More importantly, under electromagnetic waves, heating increases linearly with treatment duration (Wang et al. 2001), and produce takes a very short time to reach the treatment temperature at the heated point, although a relatively longer warm-up time is required for material with a lower loss factor.

Although this analysis (Wang et al. 2001) illustrates the basics of heat transfer in a single commodity based on the assumption of spherical shape, genuine commodities are generally far from being absolutely spherical and, furthermore, their tissue composition is not at all uniform. It is therefore not surprising that, even under perfectly controlled processing conditions, the results in real produce would not be uniform. For example, it has been shown that even the commodity orientation of walnut appear to affect its heating uniformity under RF treatment (Wang et al. 2006a). A similar effect also occurs in orange with the water immersion heating process (Birla et al. 2004).

The above discussion focuses on disinfestation for produce in which the core temperature should be high enough to kill insects lodging in the centre of the produce; for the purposes of disinfection, however, only the surface of the produce needs to be heated. For that specific application, the increase in the internal temperature of the produce should be as low as possible in order to limit quality loss. The use of a model-based

approach to designing periodic thermal treatments for surface decontamination revealed that a short-cycle heating process minimizes the overall produce temperature increase and therefore reduces the level of quality loss (Scheerlinck et al. 2004).

Studies have been conducted to examine the bulk heating issue in the scale-up of the RF (Birla et al. 2004; Wang et al. 2006a) or hot water (Bollen and Dela Rue 1999; Birla et al. 2004; Fallik 2004; Wang et al. 2006b) process. It was shown that, under bulk processing, the heating fields of individual commodities are hardly the same, leading to large treatment differences among commodities. Scaling up will be very difficult until this issue is resolved.

For conventional media, a low specific heat capacity and poor heat transferability cause problems in terms of obtaining uniform heating within each individual piece of produce. It has been found that the part of apples within the cavity created by two adjacent abutted fruits and effectively sealed off from the heating medium was shown to delay the achievement of target temperatures (Bollen and Dela Rue 1999).

Lack of homogeneity exists not only within each single piece of produce but also among bulk produce packed in the same container and exposed to the same air treatment. For air during analysis of the aerodynamic and thermal properties of batch processing, large differences (up to 40%) in heat transfer coefficient values were observed when the heat transfer intensity for spherical objects packed in stacked bins and cooled by forced air convection was characterized. This heterogeneity could be explained by the fact that the air is not uniformly distributed. The turbulence generated behind the produce increased in intensity by up to 60% (Alvarez and Flick 1999a; Alvarez and Flick 1999b). An investigation of air distribution in bulk packed produce demonstrated that the heterogeneity of temperature distribution increases as the container's opening area is reduced below 25% (Vigneault and de Castro 2005). The use of instrumented balls as an indirect measurement of air velocity (Vigneault and de Castro 2005) makes it possible to demonstrate that the airflow rate and opening configurations (including opening shape and position and total opening area) have a very important effect on cooling duration and uniformity (Vigneault and de Castro 2005). All these results obtained during the cooling

process in terms of air distribution around the produce and heterogeneity of temperature distribution within the produce are applicable to heating process applications as well.

3.6 Discussion

The main problem with respect to the scale-up of heat treatment techniques is that the temperature tolerances separating an effective treatment from heat damage can be as little as 1 to 2°C. The treatment duration at these temperatures also has an effect on produce quality (Bollen and Dela Rue 1999). Further research is therefore necessary to optimize the heating temperature and related treatment time for different media and to find a way of maintaining a fairly uniform micromedia environment for each treated crop.

The temperature difference between the treated produce and the medium could be decreased by mixing or increasing the amount of water circulated for water treatment, and by combining RF or microwaves with water. Air obviously has the same problems, and numerous studies have been conducted to find solutions (Alvarez and Flick 1999a; Alvarez and Flick 1999b; Vigneault and de Castro 2005). The effect of heat transfer heterogeneity on the quality of the treated commodities should be further investigated in order to scale up heat treatment application by correlating the engineering parameters with the quantified heat treatment effects. The effect of treatment leading to differences in terms of quality, pathogens and chilling injury among commodities should be studied by exposing commodities to different targeted temperatures within the effective range. It is also important to evaluate how and to what extent the non-uniformity of heat transfer within an individual commodity influences the heat treatment effects. Although potentially tedious and time-consuming, this type of research must be conducted before the application is commercialized. In addition, research into protocols for the adoption of different heat treatment methods in the postharvest chain is needed for disinfestation, disinfection and quality control purposes.

While contamination with human pathogens is widely believed to be a surface-associated phenomenon, penetration into plant tissues can evidently occur. The "internalization" of human pathogens and their dissemination through the vascular tissues of healthy plants has been demonstrated under laboratory conditions (Brandl 2006), although the extent of this occurrence in the field remains unknown. Subsurface

penetration of microorganisms during postharvest handling or processing is mainly due to physical forces (primarily hydrostatic pressure (Brandl 2006)) elicited by temperature differences between the plant organ and water. As a result, the proper management of temperature differences and appropriate water sanitation schemes will undoubtedly reduce the risk of infiltration during postharvest operations (Brandl 2006). On the other hand, the penetration of human pathogens into internal plant tissues during production remains an intractable problem that ultimately limits the efficacy of heat treatments. There is clearly a need to better understand this occurrence and to develop strategies that can mitigate the risk of internalization during production, distribution and handling.

Reports of enhanced microbial growth in fruits or vegetables that are subjected to mild heat treatments suggest that the impact of thermal processing on the response of human pathogens during subsequent storage needs to be examined in more detail. Little is presently understood about the factors responsible for this effect. The longer effective shelf life that can be achieved with heat treatments could simply provide more opportunity for growth over time in terms of its application. As discussed above, heat treatments are disruptive to the native microflora of plants and could alter the competitive balance between species. These relationships are poorly understood, and their influence on the fate of human pathogens in fresh horticultural produce needs clarification. Finally, the consequences of heat treatments on microenvironments must be considered in depth in terms of changes in water and nutrient availability or changes in the surface topography and chemical composition of fresh fruits and vegetables. Heat treatments may have a significant impact on the response of colonizing plant and human pathogens.

CONNECTING STATEMENT 2

A comprehensive literature review in the field of heat treatment and uniformity was provided in Chapter III. In Chapter IV, designing of a forced-air-twin-chamber for measuring the effect of heat treatment uniformity will be presented. Also simulation results of the equipment will be examined.

Manuscript has been prepared to be submitted to the Journal of *Food Engineering*: **Jianbo Lu*, G. S. Vijaya Raghavan*, Clement Vigneault**, Bernard Goyette**, S. R. S. Dev*. Design and Simulation of a Forced-air-twin-chamber for Measuring the Effect of Heat Treatment Uniformity.**

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Contributions made by different authors are as follows:

The first author, the PhD student, did the experimental work and prepared the manuscript; the second and third authors are the supervisors who guided the research work; the fourth author gave technical and professional support during the design and the construction of the experimental set up, the fifth author gave technical support during simulation.

CHAPTER IV. DESIGN AND SIMULATION OF A FORCED-AIR-TWIN-CHAMBER FOR MEASURING THE EFFECT OF HEAT TREATMENT UNIFORMITY

4.1 Abstract

To investigate the effect of heat treatment uniformity an insulated twin-chambered forced-air research apparatus was built. The design was based on simulation and analysis of design parameters. This apparatus ensured that the half portion of the horticultural produce located in one chamber was exposed to warm air at a desired temperature and velocity, while the other half, in the other chamber, was exposed to lower air velocity at a lower temperature. Temperature control for both chambers along with air flow rate was achieved using suitable instrumentation. The research tool and its performance in producing and maintaining the desired conditions through simulations and some experimental results are presented. A simulation model was developed to accurately predict resulting temperatures. The air humidity has significant effect on heat treatment, and specifically for the temperature gradient generated in our design. Tomato position, referring to the length of tunnel, is another factor to be considered when designing such experimental device. While air velocity is a factor affecting heat treatment uniformity, the tomato orientation did not show any significant effect with the present set up. This simulation method and experimental set up could also be used for other fruits.

4.2 Introduction

Efforts to develop heat treatments for postharvest applications have been increasing steadily in recent decades, with successful laboratory investigations and some scale-up development of the use of hot water, radio frequency (RF), microwave and hot air in disinfestation, disinfection, chilling injury control and retardation of the ripening process (Lurie 1998) in various fresh crops. Hot air has been used for both fungal and insect control (Tang et al. 2000; Yahia and Ortega-Zaleta 2000; Jacobi et al. 2001a; Mitcham et al. 2004; Hoa et al. 2006). Lurie reviewed hot air heat treatment and concluded that exposure to high temperatures in forced or static air can decrease fungal

infections. The potential to have in hot air treatment serve as a means of beneficially affecting commodity physiology while at the same time preventing both insect and fungal invasion, justifies further development of these treatments (Lurie 1998). A common difficulty with hot air or water heating methods is the slow rate of heat transfer, which results in hours of treatment time, especially for large fruit (Wang et al. 2001). The overall quality of fresh produce treated at optimal heat treatment temperatures and exposure durations is significantly better than that of untreated controls (Fallik 2004). Several studies have demonstrated the potential of heat treatment to interact with both constitutive and induced defence mechanisms (Schirra et al. 1999; Terry and Joyce 2004).

Although heat treatment may benefit many horticultural crops, inappropriate heat treatments can cause damage. Lurie and Sabehat (1997) found that temperatures higher than 38°C were not generally as effective as at 38°C and also 24 h at 42 or 46°C caused heat damage to tomato. 'Manila' mangoes showed severe skin scalding when forced-air heated at temperatures of 45°C or higher, but no damage at 43°C, indicating the presence of a threshold temperature for skin injury to develop (Ortega-Zaleta and Yahia 2000).Tissue damage caused by heat will also result in increased decay development (Lurie 2006).

Under bulk processing, the heating field to which each individual commodity is exposed can hardly be the same, leading to treatment differences among commodities. Some studies have investigated these bulk heating issues in scaling up RF (Birla et al. 2004; Wang et al. 2006a), and hot water (Bollen and Dela Rue 1999; Birla et al. 2004; Fallik 2004; Wang et al. 2006b) treatments. However, little similar research has been conducted for hot air treatment during mass processing.

For conventional media, low specific heat capacity and their poor heat transfer ability can cause problems making it difficult to obtain uniform heating within each individual fruit. Part of apples within cavities created by two fruit butted together and effectively sealed off from the heating medium were delayed in reaching their targeted temperature in hot water and air (Bollen and Dela Rue 1999).

Heterogeneity exists not only within each single fruit but also among fruit exposed to air treatment. The initial temperature and size of the produce and the position of

produce within the treatment chamber have a marked influence on the effectiveness of treatment (Narayannasamy 2006). Vigneault and de Castro (2005) demonstrated that the half-cooling temperature variance increases as the area of openings on the container walls was reduced. That variance at the minimum opening configuration was also significantly influenced by the airflow rate (Vigneault and de Castro 2005). When spherical objects were packed in stacked bins and cooled by forced air convection, large differences in heat transfer coefficient values were observed, given the lack of uniformity in airflow (Alvarez and Flick 1999a; Alvarez and Flick 1999b).

Horticultural crop tissues and composition vary spatially; hence their thermal properties are similarly heterogeneous. Mitcham et al. (2004) pointed out that non-uniform heating of fresh fruit or vegetables caused by variations in radio frequency (RF) fields was a major obstacle in developing postharvest treatments. The fruits to be heated should have uniform initial temperature and be exposed to uniform electromagnetic field if a uniform heating is desired (Wang et al. 2003).

Given fresh commodities' non-uniformity makes a homogenous heating field difficult to achieve, further studies are needed to optimize heating temperatures and durations of exposure to different treatment media as well as to maintain a fairly uniform micro-environment for each crop treated. Before the scaling up of a postharvest heat treatment is possible, a better understanding of the effect of heat uniformity on the quality of a treated commodity in necessary. In addition, an understanding of the physiological processes occurring in the fruit or vegetable tissue during and following this non-uniform heat treatment should aid in developing successful treatments.

Past research efforts on heat treatments were mostly empirical and commodity specific. These tests were very labour-intensive and costly, and the results are only useful for the specific commodity tested, under the specific conditions investigated. Investigations of the influence of physical parameters on heat transfer uniformity can be based on heat transfer theory via computer simulation models. A major advantage of the computer simulation model is its ability to assess the effect of various physical parameters on the heating profiles in fruits (Wang et al. 2001). Numerical modelling has been used to study physiological phenomena and design devices for hot air or hot water

postharvest heat treatment (Wang et al. 2001; Scheerlinck et al. 2004), far infrared radiation (Tanaka et al. 2007), and RF (Wang et al. 2005). It is also used in the study of fruit properties (Wu and Pitts 1999; Jancsók et al. 2001; Dintwa et al. 2008) and modified atmosphere packaging (Rennie and Tavoularis 2008). Among them, the Finite Element Method (FEM), based on solving a complex problem by splitting it into a large number of simple problems has seen increasing use in postharvest research. The advantages of the finite element method is that it can easily be applied to irregular-shaped objects, a medium composed of several different materials and allows mixed boundary conditions (Majumdar 2005). The efficient design of optimal heat treatment devices requires the use of sophisticated mathematical models, which would describe accurately all relevant heating media, treated material properties and mechanical design parameters, as well as the temporal and spatial variations of the important properties.

The objective of this study was to evaluate the influence of various factors on hot air heating methods and provide insights into the limitations of such methods. A further objective was to design a device to create a temperature gradient across sufficient individual items of produce in a 4×9 matrix positioning to allow a statistically valid investigation of their physiological and pathological responses.

4.3 Materials and methods

4.3.1 Simulation

A Finite Element Model was developed using the COMSOL Multiphysics version 3.4 (COMSOL Inc., USA) software package, which is capable of solving systems of partial differential equations by the finite element method. This allowed us to simulate the heterogeneous heating of the test material in a single twin-tunnel at 3 temperature levels (16°C, 3°C, and 1°C) and two air velocity levels (0.24 m s^{-1} for upper tunnel in combination with 0.24 m s^{-1} or 0.12 m s^{-1} for lower tunnel). The effect of tomato orientation, namely whether the tomato stem or blossom scar faced the air inlet was also investigated by simulation. Fig. 4.1 shows the simulation set up for one twin tunnel.

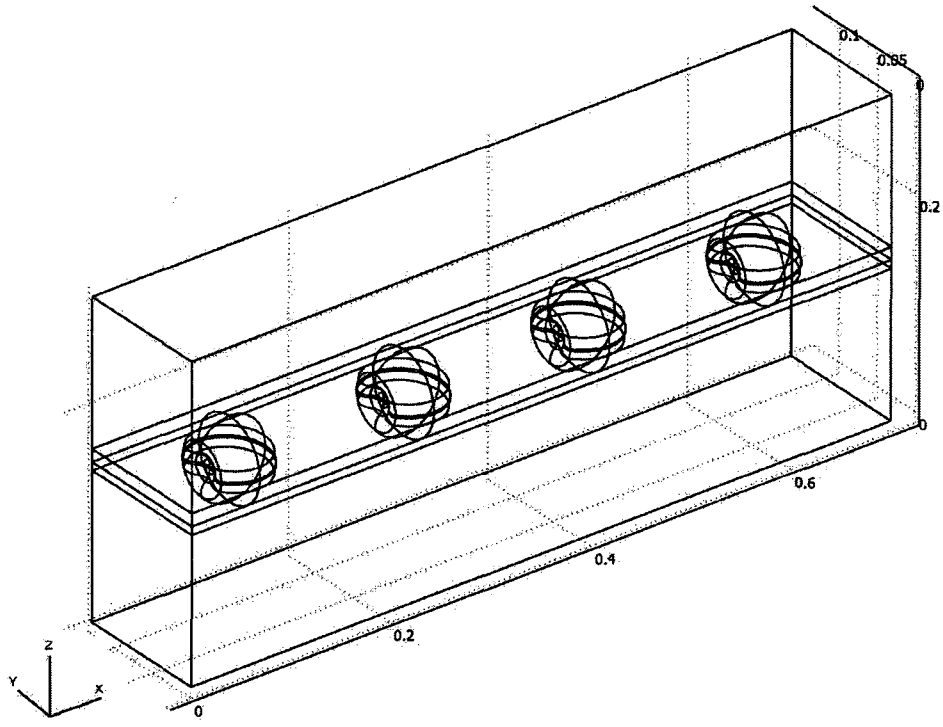


Figure 4.1: Schematic diagram of the computational domain of one forced-air-twin-tunnel.

4.3.1.1 Mathematical Model

4.3.1.1.1 Heat transfer

For an incompressible food material heated under constant pressure, the thermal energy equation is given as:

$$\rho C_p \frac{\partial T}{\partial t} + \nabla.(-K\nabla T + \rho C_p T\bar{U}) = Q \qquad (1)$$

where ρ is the density (kg m^{-3}), C_p is the heat capacity (J kg^{-1} $°C^{-1}$) and K is the thermal conductivity (W m^{-1} $°C^{-1}$). The temperature field is denoted by T *(K)*, and is a function of the spatial coordinates *x, y, z (m)* and time *t (s)*, i.e., $T=T$ *(t, x, y, z)*. Respiratory heat generated during hot-air heat treatment was considered to be negligible compared with heat transferred from the air, $Q=0$. U is the velocity field and is further described below.

4.3.1.1.1.1 Density of tomato

Apparent density was measured by a liquid displacement method (Abhayawick et al. 2002). Distilled water was used as the liquid, and the sampled tomato was pushed entirely under the water surface. The difference of volume before and after the tomato immersion was recorded as the volume of the sampled tomato. Three replicates measurements were taken for each tomato. Fifteen tomato fruits were measured, and the mean mass and volume were used to calculate density. Density was assumed to remain constant during the thermal treatment (Scheerlinck et al. 2004).

$$\rho_{apparent} = \frac{M}{V} \tag{2}$$

The thermal properties of tomatoes were estimated by means of empirical and model-based formulae, which account for the chemical components making up the fruit.

Since the thermal conductivity, K, and the heat capacity, C, are sensitive to the amount of air inside the porous structure of biological materials, the mass fraction of air for individual tomato was estimated as follows. From the true density of tomato (Miles et al. 1983):

$$\rho_{true} = \frac{1}{\sum \frac{x_i}{\rho_i}} \tag{3}$$

where x_i are the mass fractions of the different components. These were obtained from USDA (1996): x_w=0.93 (water), x_p=0.012 (protein), x_{fa}=0.012 (fat), x_c=0.051 (carbohydrates), x_{fi}=0.011 (fiber) and x_{ash}=0.005 (ash); and ρ_i, the density of each constituent. The apparent density of tomato is thus expressed as:

$$\rho_{apparent} = \left[\frac{1 - x_a}{\rho_{true}} + \frac{x_a}{\rho_a} \right]^{-1} \tag{4}$$

an expression for the mass fraction of air, x_a, can be formulated as:

$$x_a = \frac{\rho_a \left(\rho_{true} - \rho_{apparent} \right)}{\rho_{apparent} \left(\rho_{true} - \rho_a \right)} \tag{5}$$

4.3.1.1.1.2 Properties of moist air

The heating air was natural moist air, neither humidified nor dehumidified (ω=constant). The thermal conductivity of the moist air was given by Sahin and Sumnu (2006) as:

$$K_{air} = 0.0076 + 7.85 \times 10^{-4} T + 0.0156 RH \quad (6)$$

where RH is the relative humidity, ranging from 0 to 1, and the initial RH is 0.55±0.05. The temperature (T) is in degrees Celsius (°C).

The specific heat of moist air can be expressed (Sahin and Sumnu 2006) as:

$$C_{p_{moistair}} = C_{p_{dryair}} (1 + 0.837 RH) \quad (7)$$

where Cp_{dryair} is the specific heat of dry air and is given by:

$$C_{p_{dryair}} = 0.0769 T + 1076.9 \quad (8)$$

The density of moist air is thus:

$$\rho_{moistair} = \rho_{da} \frac{(1+\omega)}{(1+1.609\omega)} \quad (9)$$

where ω is a humidity ratio which can be obtained from a psychometrics chart with T and RH. ρ_{da} is the density of dry air:

$$\rho_{da} = \frac{0.0035 p}{T} \quad (10)$$

4.3.1.1.1.3 Thermal conductivity and specific heat of tomato

The thermal conductivity and heat capacity of tomato were calculated from the relationships (Miles et al. 1983):

$$C(T) = (1 - x_a) \sum x_i C_i(T) + x_a C_a \quad (11)$$

$$K(T) = (1 - x_a) \sum \varepsilon_i K_i(T) + \varepsilon_a K_a \quad (12)$$

where $K_i(T)$ and $C_i(T)$ are the thermal conductivity and specific heat of i^{th} component at a given temperature T (°C). The thermal conductivity and specific heat of

air (K_a and C_a, respectively) were assumed to be independent during thermal treatment, provided that the variance was negligible within the range of 20°C to 40°C. Their respective values were taken as 0.025 W m^{-1} $°K^{-1}$ and 1.005 kJ kg^{-1} $°K^{-1}$ (Scheerlinck et al. 2004). The volume fraction of a component (Miles et al. 1983) is given as:

$$\varepsilon_i = \frac{\rho}{\rho_i} x_i \tag{13}$$

Choi and Okos (1986) developed mathematical models for predicting the thermal properties of such food components as a function of temperatures in the range of -40°C to 150°C. Thermal conductivity (Eq. 14a-14f) and specific heat (Eq.15a-15f), of each component were as follows (ASHRAE 2002b):

Thermal conductivity:

$$K_p = 1.7881\times10^{-1} + 1.1958\times10^{-3}T - 2.7178\times10^{-6}T^2 \tag{14a}$$

$$K_{fa} = 1.8071\times10^{-1} - 2.7604\times10^{-3}T - 1.7749\times10^{-7}T^2 \tag{14b}$$

$$K_c = 2.0141\times10^{-1} + 1.3874\times10^{-3}T - 4.3312\times10^{-6}T^2 \tag{14c}$$

$$K_{fi} = 1.8331\times10^{-1} + 1.2497\times10^{-3}T - 3.1683\times10^{-6}T^2 \tag{14d}$$

$$K_{ash} = 3.2962\times10^{-1} + 1.4011\times10^{-3}T - 2.9069\times10^{-6}T^2 \tag{14e}$$

$$K_w = 5.7109\times10^{-1} + 1.7625\times10^{-3}T - 6.7036\times10^{-6}T^2 \tag{14f}$$

Specific heat:

$$C_p = 2.0082 + 1.2089\times10^{-3}T - 1.3129\times10^{-6}T^2 \tag{15a}$$

$$C_{fa} = 1.9842 + 1.4733\times10^{-3}T - 4.8008\times10^{-6}T^2 \tag{15b}$$

$$C_c = 1.5488 + 1.9625\times10^{-3}T - 5.9399\times10^{-6}T^2 \tag{15c}$$

$$C_{fi} = 1.8459 + 1.8306\times10^{-3}T - 4.6509\times10^{-6}T^2 \tag{15d}$$

$$C_{ash} = 1.0926 + 1.8896\times10^{-3}T - 3.6817\times10^{-6}T^2 \tag{15e}$$

$$C_w = 4.1762 - 9.0864 \times 10^{-5} T + 5.4731 \times 10^{-6} T^2 \quad (15f)$$

where temperature (T) is in degrees Celsius (°C).

4.3.1.1.1.4 Boundary conditions

The inlet air boundary condition is described in terms of temperature:

$$T = T_0 \quad (16)$$

where T_0=39°C for air to the upper tunnel, and T_0 = 23°C, 36°C, or 38°C for air to the lower tunnel.

The boundary condition of the outlet air is set as convective flux:

$$q_{cond} \cdot \vec{n} = -K \nabla T \cdot \vec{n} = 0 \quad (17)$$

All the walls, the Microcell, together with the plastic plate were assumed to be perfectly insulated. The thermal insulation condition means the thermal flux is zero:

$$\vec{q} \cdot \vec{n} = 0 \quad (18)$$

The boundary condition between air and tomatoes is heat flux:

$$-\vec{n} \cdot (-K \nabla T + \rho C_p \vec{u} T) = q_0 \quad (19)$$

4.3.1.1.2 Velocity field

The fluid motion and heat transfer are fully coupled when properties are temperature-dependent (Minkowycz et al. 2006). This pressure and velocity field can be calculated by a coupling to the velocity field by the momentum balance in terms of stresses. The generalized equations in terms of transport properties and velocity gradients are:

$$\rho \frac{\partial U}{\partial t} + \nabla \cdot (\rho U) = 0 \quad (20)$$

$$\rho_a \frac{\partial U}{\partial t} + \rho_a U \cdot \nabla U = -\nabla p + \nabla \cdot [\eta (\nabla U + (\nabla U)^T) - \left(\frac{2}{3} \eta - k_{dv} \right) (\nabla \cdot U) I] + F \quad (21)$$

Eq. 20 is a continuity equation and represents the conservation of mass, and Eq. 21, a weakly compressible Navier-Stokes application mode, is a vector equation and

represents the conservation of momentum. A weakly compressible model was used for numerical simulation of incompressible viscous flows. Given that its numerical discretization avoids any Poisson solver, it is very attractive for problems with complicated geometries (Bao and Jin 2001). Where η is the dynamic viscosity, ρ_a is the density of air which is equal to $\rho_{moist\ air}$, U is the velocity vector, T is absolute temperature, p is the pressure, and F is the volume force field. k_{dv} expresses the deviation from Stokes' assumption which states that the fluid particles are in thermodynamic equilibrium with their neighbours, it is therefore by default set to zero.

The laminar flow model for other than turbulent conditions was chosen based on calculation of the Reynolds number.

4.3.1.1.2.1 Reynolds number

$$\mathrm{Re} = \frac{\rho V L}{\eta} \tag{22}$$

where ρ is the density of air (1.127-1.20 kg m^{-3} at 40°C -20°C), V is the velocity of air, set at 0.24 m s^{-1}, η is the viscosity (18.51 – 19.30 μNsm^{-2} at 23°C -39°C), and L is the characteristic dimension. For internal convective flow it is expressed as the hydraulic diameter D_h (Bejan and Kraus 2003)

$$D_h = \frac{4A}{p} = \frac{4ab}{2a+2b} = \frac{2ab}{a+b} \tag{23}$$

where A is the area, and p is the perimeter of cross-section of the tunnel, a is the width of tunnel, equal to 0.13 m, and b is the height of the tunnel which is equal to 0.14 m. The maximum Reynolds number for the upper and lower tunnel were calculated as 1889 and 2097 respectively, and as they were both $\leq$ 2100 these conditions could be seen as laminar flow (Singh and Heldman 2001).

4.3.1.1.2.2 Boundary conditions

The boundary condition between air and the upper, side, bottom walls, Microcell™ (partition), or surface of tomatoes was that of a no slip wall. The condition prescribes that

$$U = 0 \tag{24}$$

Then, if the inlet air is streamlined, the boundary can be described by a velocity:

$$u = u_0 \tag{25}$$

where u_0 equal to 0.24 m s^{-1} for the upper tunnels, and 0.24 m s^{-1} or 0.12 m s^{-1} for the lower tunnels, according to the different runs. For both cases, the air velocity at y axial and z axial is zero, *i.e.* $v = 0$ and $w = 0$.

The outlet boundary condition is prescribed as:

$$(\eta(\nabla U + (\nabla U)^T) - \left(\frac{2}{3}\eta - k_{dv}\right)(\nabla U)N = 0 \tag{26}$$

$$p = p_0 \tag{27}$$

4.3.1.1.3 Meshing

A three-dimensional finite element model of tomato was developed based on the geometry of measured samples. Different mesh element sizes were used for different sub-domains based on the properties of the sub-domain and the precision required in the sub-domain of interest (Figure 4.2). Lagrange quadratic shape functions were used for the governing equations of air temperature and commodity temperature. The Navier–Stokes equations used second-order Lagrange elements when solving for the velocity, and linear elements when solving for the pressure.

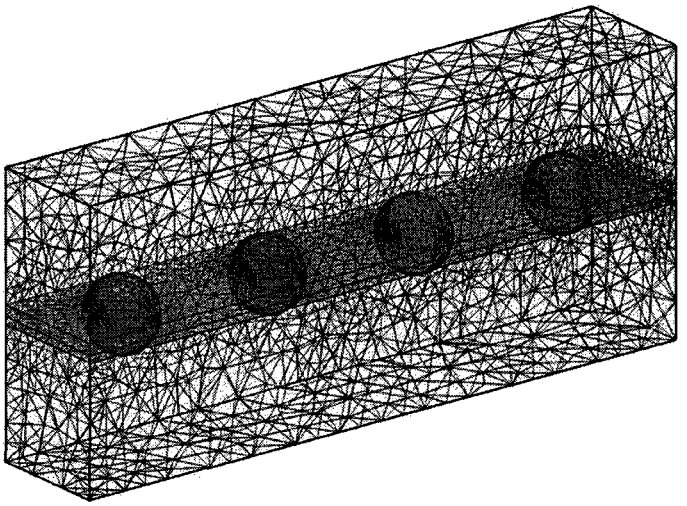


Figure 4.2: Meshed computational domain with 140912 elements.

4.3.2 Experimental set-up design

An experimental setup (Fig. 4.3) consisting of a forced-air-twin-chamber insulated device was built in order to expose the investigated produce to a heterogeneous heat treatment. The chamber allowed one to expose one hemisphere of each tomato in a chamber at a definite temperature, whilst the other was exposed in another chamber at a different temperature, thus creating a heterogeneous heat treatment. For this study, one hemisphere of tomatoes was submitted to warm air at a controlled temperature of 39°C and uniform circulation velocity of 0.24 m s^{-1}; whereas the other part was exposed to a lower temperature of 23°C, 36°C or 38°C. Temperature control for both chambers was achieved through electronic control. The two chambers were then divided into 9 parallel tunnels (Fig. 4.4) in order to expose tested tomato fruits to relatively uniform airflow. Steel was used to build the tunnel separation material because of its high heat conductivity increasing uniformity of the air temperature between adjacent tunnels.

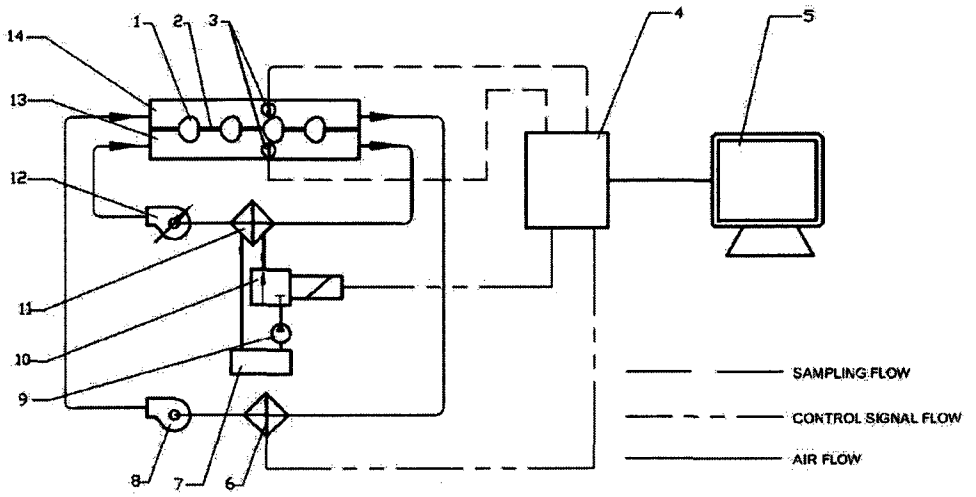


Figure 4.3: Schematic of experimental set-up consisting of a forced air twin-tunnel allowing a matrix of produce to be exposed to heterogeneous environmental conditions as follows: 1- Produce; 2-Microcell^{TM} and plastic supporting plate; 3-Thermocouples; 4-Data acquisition board; 5-Computer; 6-Heater; 7-Water bath; 8- Fan for upper chamber; 9-Pump; 10- Solenoid valve; 11- Heat exchanger; 12-Adjustable fan for lower chamber; 13- Lower chamber; 14- Upper chamber.

4.3.2.1 Structure

The experimental device (Fig. 4.4) was separated into two chambers by 12-mm-thick insulation material (Microcell^{TM}) supported by an 8-mm-thick plastic plate. Microcell^{TM} is quite flexible, allowing for adjustment to the size variability of the tomato fruits. These chambers consisted of an upper, heated chamber and a lower chamber heated to different temperatures. Each of the twin chambers was further divided into 9 parallel tunnels in order to expose the test tomatoes to relatively uniform airflow. The 0.700 m length of the tunnels kept the tomatoes from being subjected to too great an airflow gradient along the flow direction. Structural supports were constructed of a combination of steel and plastics to provide adequate strength with maximum thermal insulation.

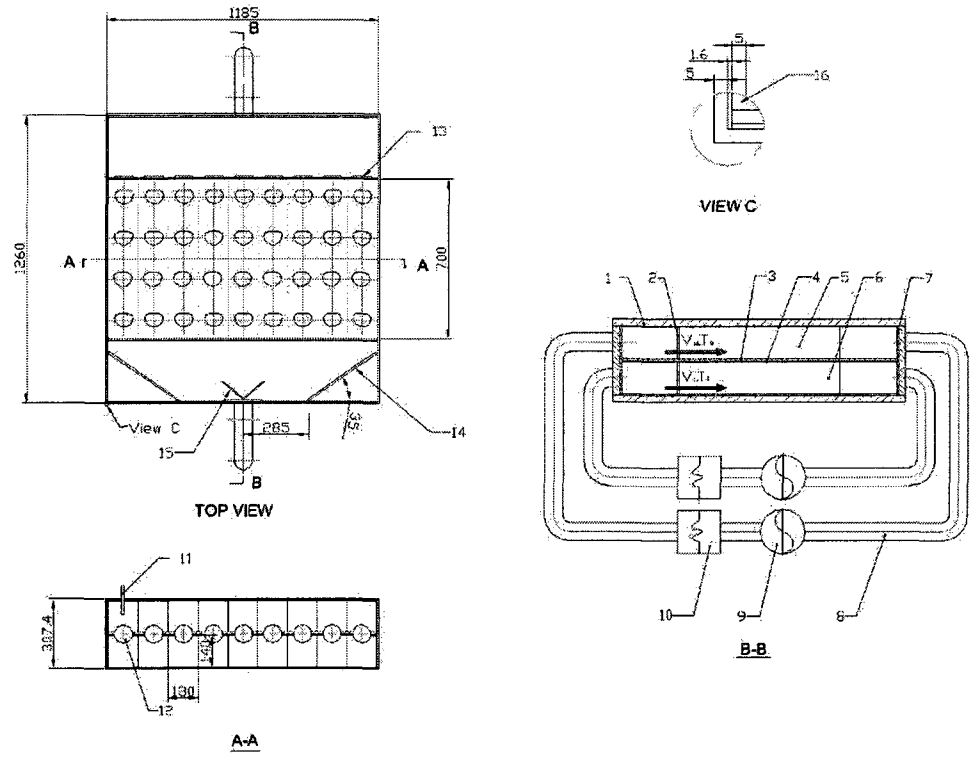


Figure 4.4: Experimental set-up consisting of a 1260 mm-wide × 1185 mm-long × 307 mm high forced-air twin-tunnel (1-9 from right to left in A-A) allowing a produce matrix to be exposed to non-uniform environmental conditions as follows: 1-Thermal insulation blanket; 2- Aluminum mesh plate coated with porous adhesive-bonded fabric; 3-Microcell^{TM}; 4-Plastic support; 5-Upper tunnel; 6-Lower tunnel; 7-Plastic outlet wall; 8- Air flow pipe; 9-Fans; 10-Heat exchangers; 11- Thermocouples; 12- Produce; 13-Adjustable tunnel outlet opening; 14- Baffler; 15- V-shape flow deflector; 16- Cellular polystyrene thermal insulation board.

The external shell of the chamber was a single fabricated steel structure (Fig. 4.3), supporting the inner components. Some parts such as the inlet and outlet side walls, and the supporting plate ware made of Acrylic Sheet (Professional Plastics, Inc, Fullerton, CA, USA), taking advantages of its electrical insulating ability, moisture and chemical

resistance, low thermal conductivity (0.186 $W \cdot m^{-1} \cdot K^{-1}$), ease of cleaning, pleasing appearance with or without an applied finish, transparency, ease of forming, and low cost.

4.3.2.2 Heat exchanger

As the air in upper chamber was to be controlled at temperatures higher than ambient, an electric heater, consisting of 8 incandescent bulbs, was used for heating. As the air temperature in the lower chamber was to be controlled across a wider range (23°C -39°C), temperature control was achieved by means of a heat exchanger which could function as either a heater or cooler. A radiator-like heater core and VWR Signature™ Heated/Refrigerated Circulators (VWR International, West Chester, PA, USA) were employed for this purpose. Hot or cold water controlled at the desired temperature passed from the circulator through a winding tube of the core, where heat exchange occurred between water and the air forced through. Fins attached to the core tubes serve to increase the surface for heat transfer to the air forced past them by a fan, thereby heating or cooling the produce.

Circulating water temperature was set 2°C higher or lower than the targeted air temperature in order to heat or cool air through the heater core. Temperature setpoints and actual temperatures were displayed simultaneously. Water could be circulated by a powerful variable-speed pressure/suction pump. A large capacity reservoir (28 L) helped compensate for unexpected heat load changes.

4.3.1.2.1 Solenoid valve

A two-way, normal open solenoid valve served to control water flow to the heat core. Solenoid valves are electro-mechanical devices that use a solenoid to control valve actuation. When an electrical current is supplied to the solenoid coil, the resulting magnetic field acts upon the plunger, whose resulting motion actuates the valve. Such valves are most commonly used to allow/block passage of air and other gases, liquids, hot water and steam, and hydraulic fluids. They generally function by allowing flow while in their open position, and restricting flow when closed.

4.3.2.3 Thermal insulation

Chambers were separated from each other by a 12 mm-thick insulation material (Microcell™, Foam N' More, Inc., Michigan) supported by an 8 mm-thick plastic plate. Microcell™, a "Skin-Soft" esthetically pleasing material that exhibits a smooth surface and extremely uniform cell structure, offers excellent flexibility and resilience and for thermal insulation applications. The Microcell™ is closed cell crosslinked polyethylene foam with excellent strength, flexible and is resistant to mildew mold, rot and bacteria. It also has a superior chemical resistance.

The chamber's external insulation was achieved by using blanket thermal insulation which is relatively flat and. The internal walls of the two side tunnels (leftmost and rightmost) were insulated with cellular polystyrene thermal insulation board to prevent heat transfer between the upper and lower chamber as conducted by the steel side wall.

An acrylic sheet, as a self-supporting thermal insulation was used to support the Microcell™, both separating the flows and serving as insulation as it provides a thermally insulated structure and possesses sufficient mechanical strength to serve as a constructional material itself.

Fibreglass blankets and mats, which offer high resistance to fire, high resistance to microbiological attack, high heat resistance, and low thermal conductivity were used as insulating material for pipes connecting fans and chambers.

4.3.2.4 Distributor

A uniform flow would be expected to generate the desired treatment conditions for each item of produce; however, many factors such as lack of effective duct length, fan outlet condition, discharge may lead to poor uniformity of flow. In order to address this issue, the selection of an appropriate length of transition is one of the most effective approaches to assuring uniform air flow into the designed space (ASHRAE 2002a). However, in our case, the set up was designed to be moveable between different lab rooms; therefore, its size was limited. Some of the alternative methods, such as flow deflector, bafflers, and flow straighteners were employed to address these issues:

4.3.2.4.1 V-shape flow deflector

A V-shape flow deflector located at the point where air entered each chamber was designed to assure that the air flow was uniform in each of the sub-divided tunnels. Two bafflers (guide plate) were also mounted at each rectangular corner to reduce or eliminate air turbulence at the corners.

4.3.2.4.2 Screen (flow straightener)

An aluminum mesh plate (68.3% open) coated with layers of porous adhesive-bonded fabric was placed over the entrance of the tunnel to ensure uniformity of airflows among tunnels.

4.3.2.4.3 Layer of coating

Results of preliminary tests indicated that the air flow rate close to the centerline of tunnels tends to be higher than on either aside of the center. Consequently, 3 layers of adhesive-bonded fabric were coated onto the screen mesh for the 3 tunnels closest to the centerline; 2 layers for the tunnels adjacent to previous ones; and 1 layer for tunnels near the side wall.

4.3.2.4.4 Opening of tunnel outlet

The adjustable opening or outlet of each tunnel was designed so as to allow the fine adjustment of air flow rate for each individual tunnel. The opening could be adjusted manually by one of three clutches assembled on a roll bar.

4.3.2.5 Fan

Centrifugal blowers (115 Volts Fasco CFM 135) were used to circulate air in both chambers. In order to investigate the effect of air velocity, the speed of the fan used for the lower chamber was adjusted by a rheostat (electrical resistance). One advantage of the resistance method was that the fan supply could be varied right up to full voltage without the loss of voltage which would occur with a semi-conductor. A good rule of thumb is to use a rheostat equal in value to the fan resistance, so the nearest was a 100-ohm unit.

4.3.2.6 Size of hole

Holes were cut on the Microcell™ and plate, their size and shape determined by the produce to be treated. In this specific study, medium-sized pink greenhouse tomato fruits were used as test material. Thirty medium size tomato fruits were randomly selected from the greenhouse for measurement. The shape and size were decided based on the mean dimensions of samples (80±0.45 mm; Fig 4.1), and this dimension was also used for simulation of temperature profiles. Holes of similar size to the longitudinal cross-section of tomato were cut in the Microcell™ to hold the fruit during treatment, and larger holes (82-mm-diameter) were cut in the plastic plate separating the twin chambers in order to position the tomato fruits along the center of the tunnel and to simultaneously expose half of each fruit to the conditions of one chamber and the other half to the conditions of the other chamber.

4.3.3 Instrumentation and control

Four channels of an 8-channel data acquisition system (Personal Daq/3001, IOtech Inc., Cleveland, Ohio, USA) were used for sampling and controlling the temperature of the upper and lower chambers, and the other four channels were used to record the temperature profile of one representative sample of non-uniformly treated tomato. The control program was written using DASYLab V 9.0 (National Instruments Corporation, Austin, TX, USA). Temperature was recorded at 4-min intervals.

An Agilent data acquisition system (34970 Data Acquisition/Switch Unit – Agilent Technology, HP, Palo Alto, CA, U.S.A.) simultaneously monitored the 18 air tunnels. The acquisition program used custom software written using Labview language (National Instruments Corporation, Austin, TX, U.S.A.). RH was recorded by a HOBO Pro RH and Temperature Data Logger (Onset Computer Corporation, Bourne, MA, USA).

4.3.4 Tomato fruit

Tomato fruits (*Lycopersicon esculentum* Mill. cv. DRW 453) of uniform size were manually harvested from a local commercial greenhouse. The fruit were at the breaker stage corresponding to stage 2 of the United Fresh Fruits and Vegetable Association and

USDA Agricultural Marketing Service Fruit and Vegetable Classification Chart. The harvested fruits were first surface-sterilized for 3 min using chlorine solution (1000 mg $kg^{-1}Cl_2$ as sodium hypochlorite), then thoroughly rinsed with tap water for another 3 min, and finally left on filter paper to drain and air dry as recommended by Polenta et al. (2006)

4.3.5 Heat transfer model validation and temperature measurements

The temperature of representative tomato sample second from the tunnel outlet and in the middle tunnel was recorded. After the temperature measurements, the tomato was cut in half to measure the penetration depth and location of the thermocouple. Three tomato fruits for each temperature gradient set up were used for model validation. The recorded data was then compared to simulated data for the same location.

The root mean square error (RMSE) was used as a criterion to test the proposed model's fit to experimental data (Scheerlinck et al. 2004):

$$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left[T_{\exp}(i) - T_{\mathrm{mod}}(i)\right]^2} \tag{28}$$

The Nash-Sutcliffe model efficiency coefficient was used to assess the predictive power of simulation models (Nash and Sutcliffe 1970). It is defined as:

$$E = 1 - \frac{\sum_{i=1}^{N}(T_{\exp}(i) - T_{\mathrm{mod}}(i))^2}{\sum_{i=1}^{N}(T_{\exp}(i) - \overline{T_{\exp}})^2} \tag{29}$$

where N is the number of measurement points, and $T_{exp}(i)$ and $T_{mod}(i)$ the measured and predicted temperature for time t_i, respectively.

Nash-Sutcliffe efficiencies can range from -∞ to 1. An efficiency of 1 (E=1) corresponds to a perfect match of modeled data to the observed data. An efficiency of 0 (E=0) indicates that the model predictions are as accurate as the mean of the observed data, whereas an efficiency less than zero (-∞<E<0) occurs when the observed mean is a better predictor than the model. Essentially, the closer the model efficiency is to 1, the more accurate the model is.

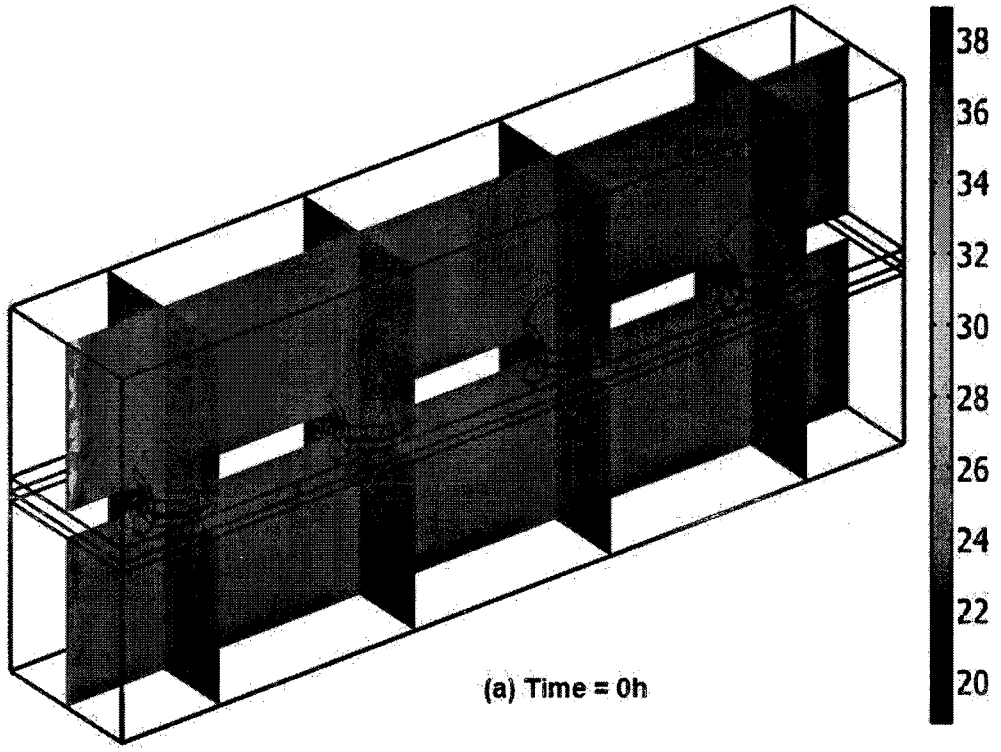
4.3.6 Statistical analysis

Experiments were performed according to a factorial design with time, tunnels, and repetition as factors. Statistical analysis was performed with the GLM procedure of SAS (SAS Institute Inc., 1991), and the treatment differences were separated using Duncan's Multiple Range Test.

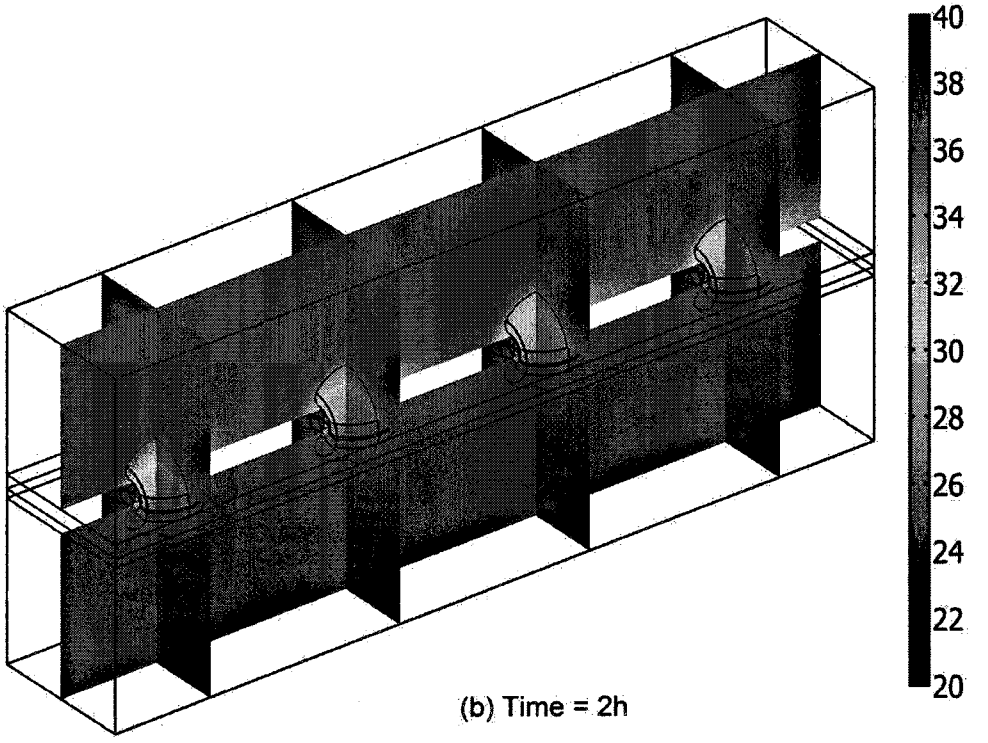
4.4 Results and discussion

4.4.1 Temperature gradient generating within tunnel

A temperature slice profile of air and tomatoes shows the temperature of the bulk of the air in the upper tunnel to be close to 39°C; however, the temperature of air in the immediate vicinity of the tomatoes was lower than that of the main stream of air, and the difference between them decreased as treatment proceeded (Fig. 4.5). In the mean time, in the lower tunnel where the flowing air temperature was set at 23°C, the temperature of air around tomatoes was higher than that of the main stream of air. Similarly, the temperature difference between air around tomatoes and the main stream of air decreased as the heating process went on.



(a) Time = 0h



(b) Time = 2h

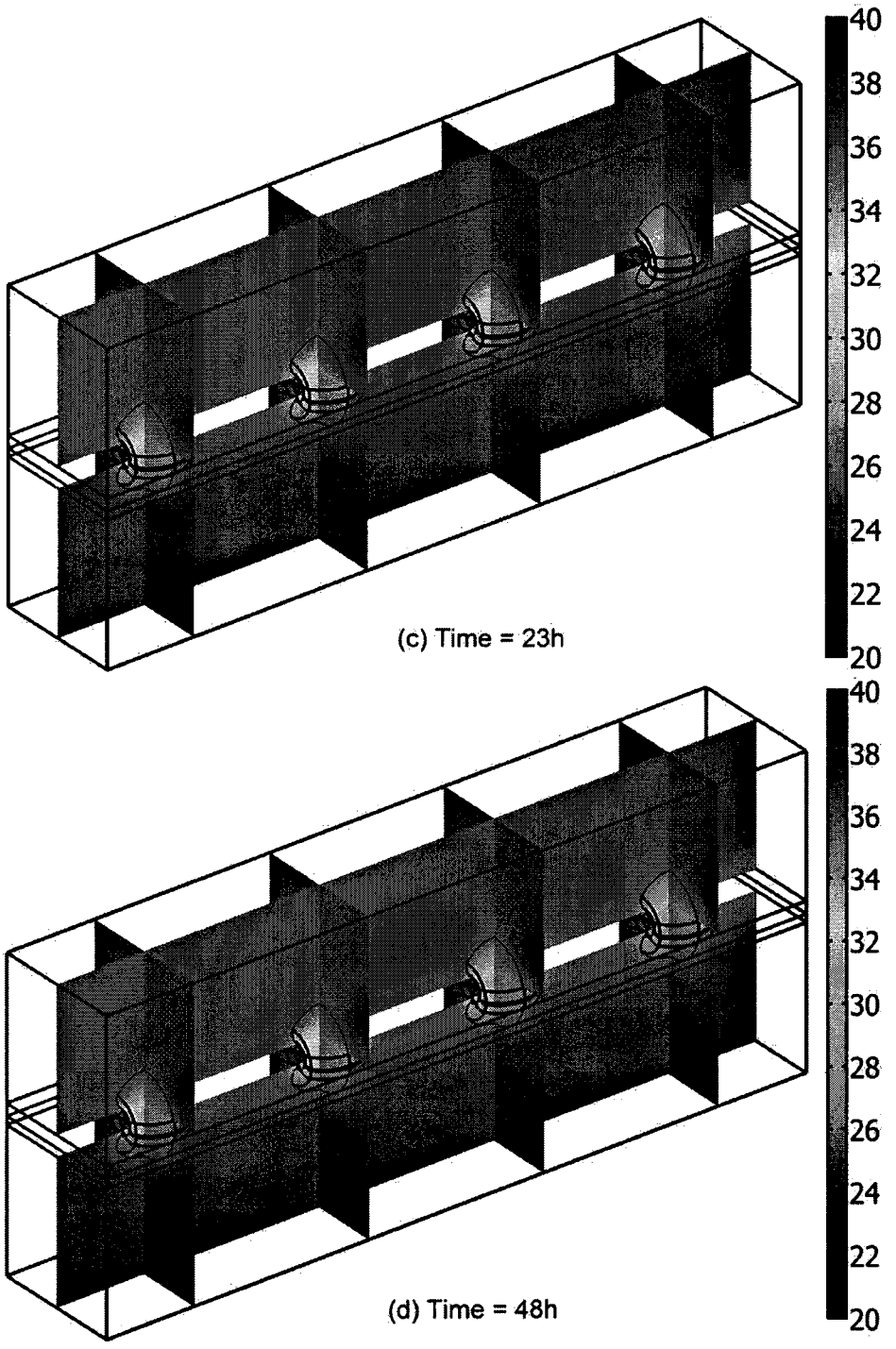


Figure 4.5: Simulation of heating tomatoes with inlet air at 39°C for upper channel and 23°C for lower channel, initial temperature of the apparatus and tomatoes was 21°C.

A temperature gradient was generated within each individual tomato, and this gradient gradually increased and then stabilized in the latter portion of the treatment period. Further, different temperature gradients could be indentified for tomatoes at different locations in the tunnel. For both the higher and lower temperature tunnels, the greatest temperature gradient occurred in the first tomato (nearest the inlet), as indicated by the difference between temperature profile of tomato closest the inlet and that of the tomato farthest from the inlet (Fig. 4.6).

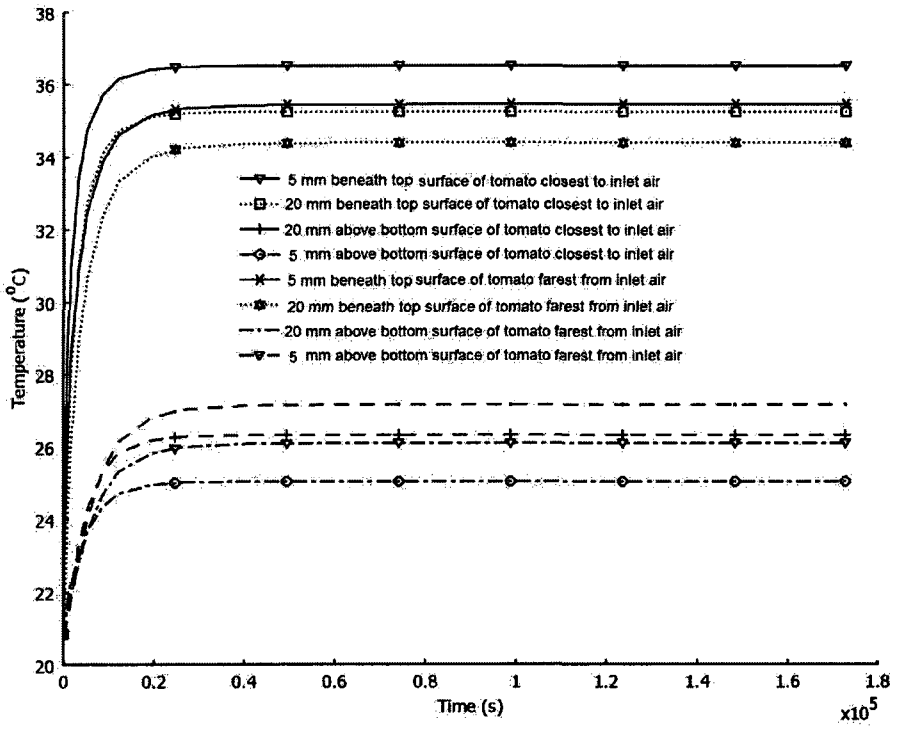


Figure 4.6: Comparison of temperature profile between the tomato closest to the air inlet and the fourth tomato farthest from inlet.

4.4.2 Effect of humidity

The temperature profile for a 48 h dry air heat treatment simulation (Fig. 4.7) can be compared to that obtained when heating by moist air (Fig. 4.6). It took almost 16 h longer time for temperatures to stabilize under dry air heating than moist air heating.

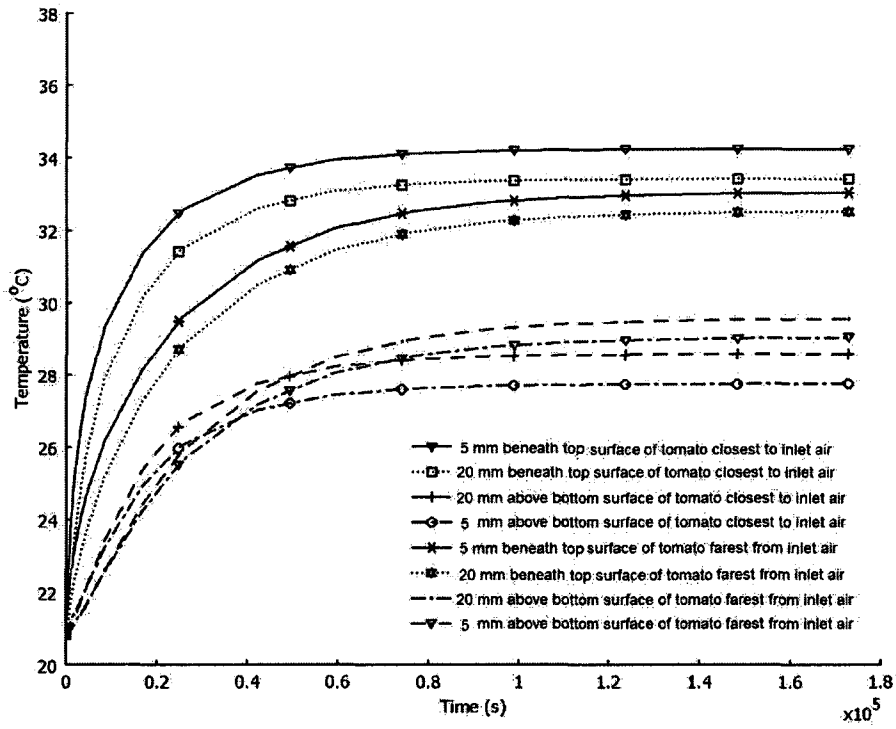
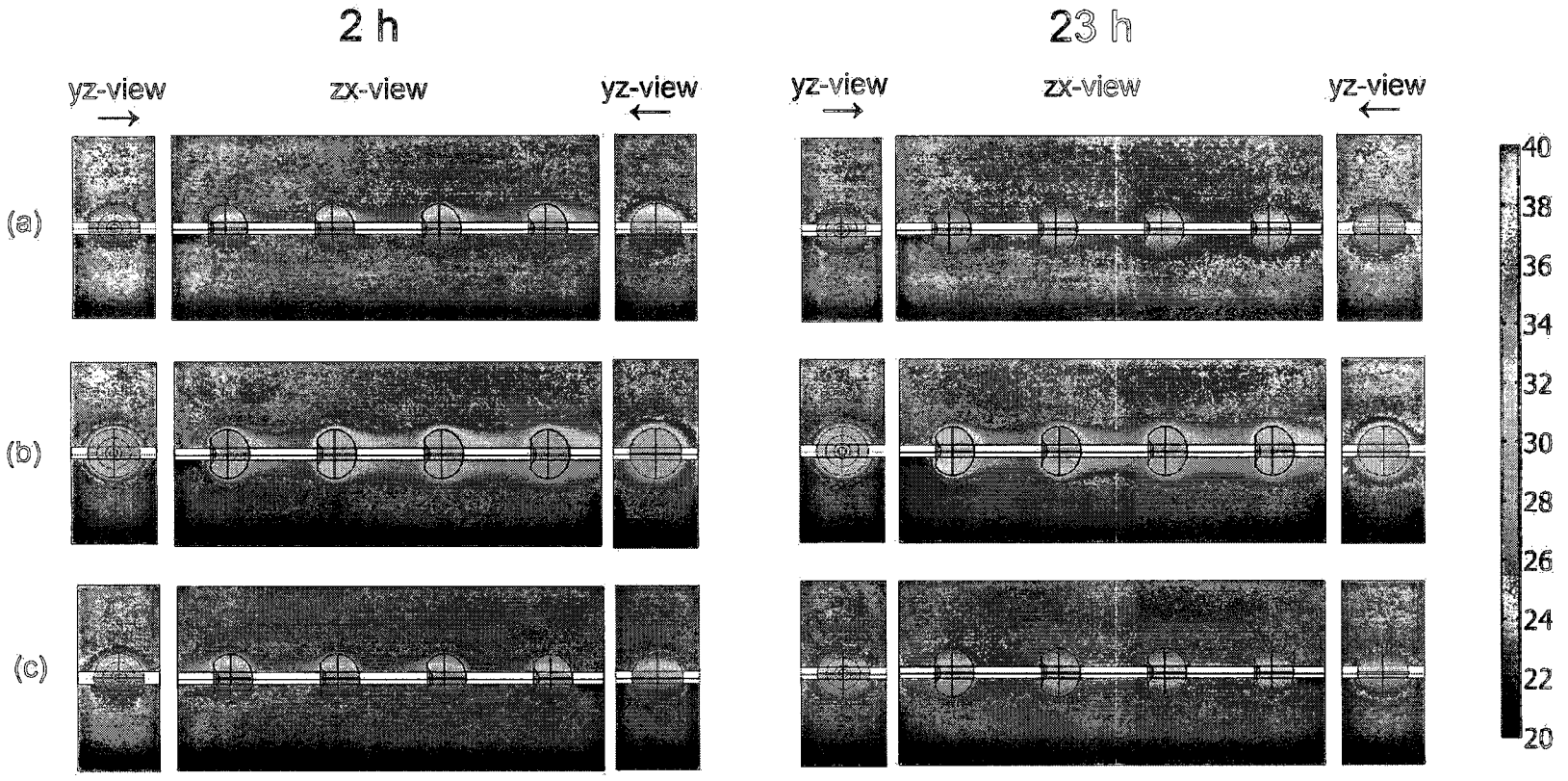


Figure 4.7: Comparison of temperature profile between the tomato closest to the air inlet and the fourth tomato (farthest from the inlet) using dry air.

The sampling point temperature of tomato in the upper chamber at 23 h was around 2°C lower when heated by dry air than that of their counterparts heated by moist air, while the sampling point temperature of tomato in lower chamber was more than 2.5°C higher than that of its counterpart heated by moist air. Thus, this temperature

difference leads to around 4.5°C drop of temperature gradient from that of the moist air treatment.

The long heating time and lesser temperature gradient shows the significant effect of humidity on heat treatment, and specifically of the temperature gradient generated for our design. This effect is the result of lower heat capacity (C_p) and thermal conductivity (K_{air}) of dry air compared to that of moist air which was indicated in Eq. 6 and Eq. 7 and is highly dependent on RH.


2 h
23 h
yz-view
zx-view
yz-view
yz-view
zx-view
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(a)
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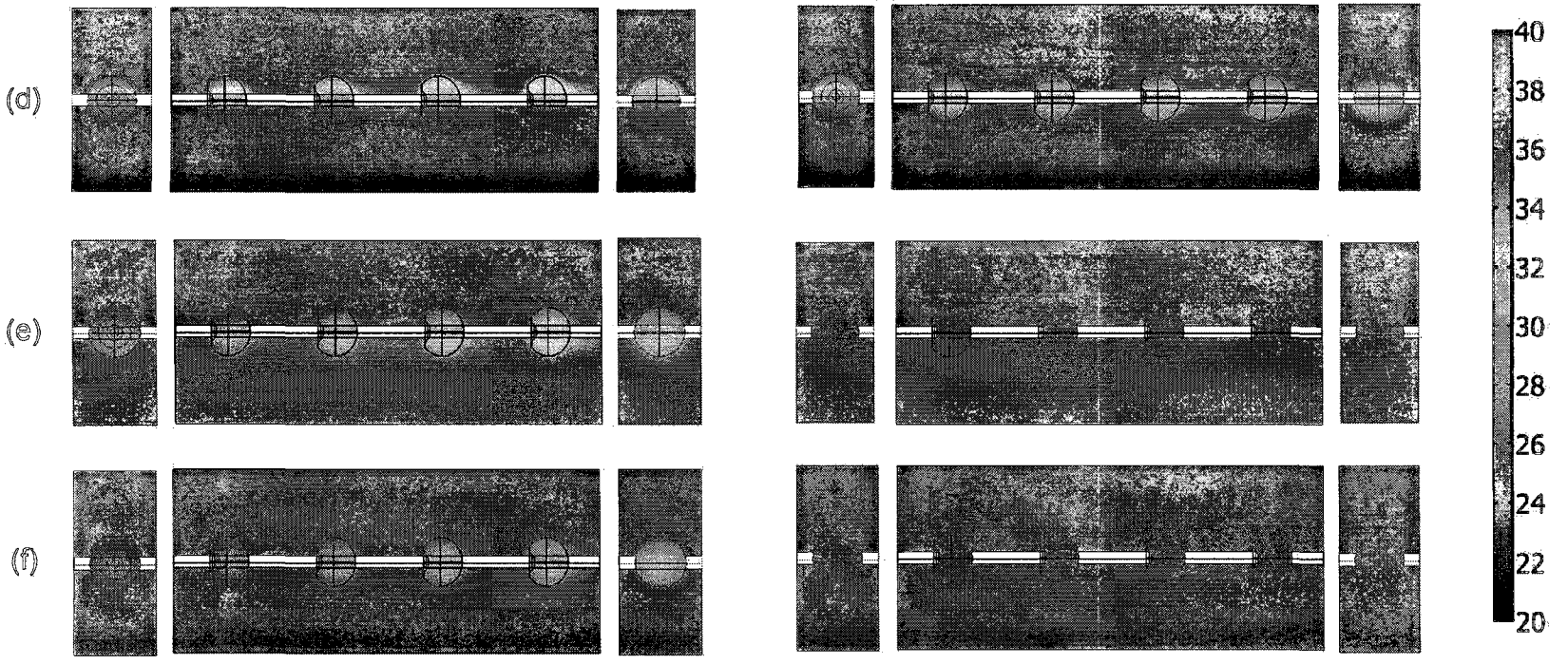


Figure 4.8: Comparisons of simulated results of tomatoes heated with (a) inlet air at 39°C for upper channel and at 23°C for lower channel, (b) tomato-shaped aluminium simulators heated with inlet air at 39°C for upper channel and 23°C for lower channel, (c) inlet air at 39°C for upper channel and at 23°C for lower channel but with blossom end facing air flow, (d) inlet air at 39°C and at 0.24m s^{-1} for upper channel and 23°C and 0.12 m s^{-1} for lower channel, (e) inlet air at 39°C for upper channel and at 36°C for lower channel, (f) inlet air at 39°C for upper channel and at 38°C for lower channel, respectively, at 2 h and 23 h.

4.4.3 Effect of thermal conductivity of the treated material

In comparison with metal, the thermal conductivity of fruits and vegetables is significantly smaller; hence one would hypothesize that the heat transferred from convective media would not be conducted through the solid fruits in as short time as it would be through a similar metal object. As long as a forced medium flow at a different temperature passes over the designated object, a temperature gradient will be generated. The heat transferred by convection from the media to the metal simulators was immediately conducted to all parts of the simulators due to its significantly higher thermal conductivity (Figures 4.8b and 4.9). Although parts of the simulator were exposed to flows at different temperatures, no temperature difference was identified among the four positions within each sample, as indicated by the uniformity of the temperature profile lines for both the simulators in Figure 4.9. Besides the uniform pattern of temperature, the temperature difference between two simulators at different positions also vanished at the later stages of the treatment period, implying that it is easy for materials such as metal to be uniformly heated or cooled, even if they were exposed to a non-uniform treatment. These results highlighted the effect of thermal conductivity, and emphasised the necessity to consider the effect of heat treatment uniformity on fruits and vegetables.

Further, the temperature discrepancy between the 1st and 4th sample was significantly less after both of their temperature stabilized (Fig. 4.9).

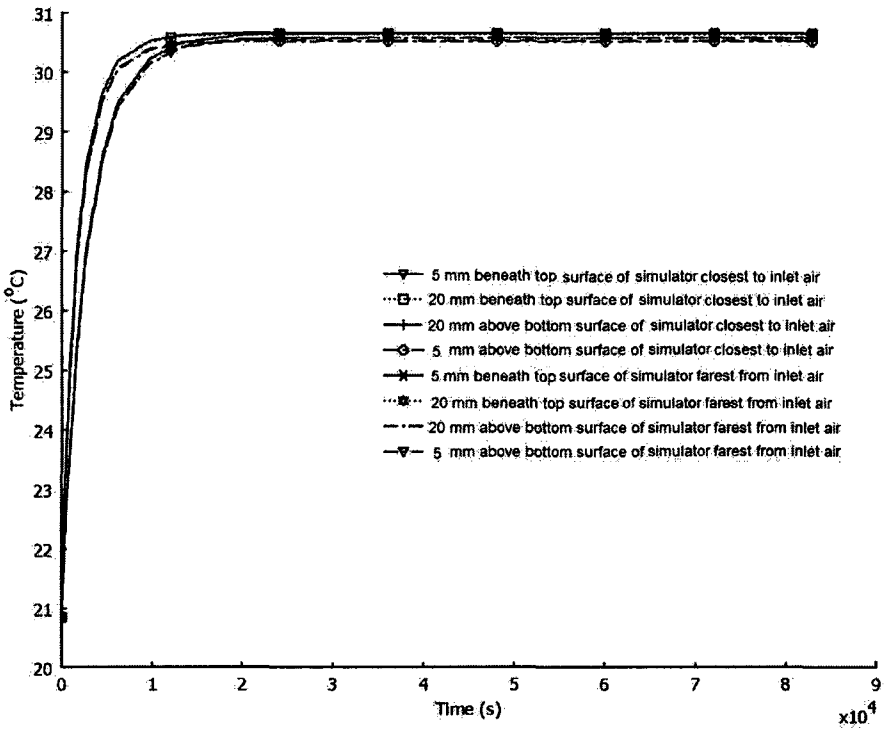


Figure 4.9: Comparison of temperature profile between the first aluminium simulator (closest to the air inlet) and the fourth simulator (farthest from the inlet).

4.4.4 Effect of fruits orientation and positioning on treatment uniformity

Compared to air flow facing the stem scar side of the tomato (Fig. 4.8a), the temperature profiles for each individual tomato were slightly more uniform and the maximum temperature gradient somewhat lesser when the air flow faced the blossom scar side of tomatoes (Fig. 4.8c).

A detailed comparison of the effect of tomato orientation and positioning on gradient generated uniformity (Fig, 4.10) shows that the position of heated tomato along the flow has a large impact on the temperature gradient generated. The closer to air inlet the tomato is, the earlier it is heated up and the higher the temperature is for the portion located in the upper tunnel. The temperature discrepancy between tomatoes became larger during the transient heating period, then gradually decreased and remained relatively stable. In contrast to the portion in upper heated tunnel, the temperature difference

between the 1st, 2nd and 4th tomato in the lower and cooler tunnel did not increase much during the transient heating period, but became larger when the temperature stabilized, with the lowest temperature occurring in the first tomato and the highest in the fourth one. Thus, at the stable temperature stage, the biggest temperature gradient occurred in the tomato closest to the air inlet, and the smallest in the one farthest from the inlet. At 23 h, the temperature gradient between the hot and cool hemispheres of tomato, measured at the equator, 5 mm beneath the top and bottom surfaces of stem or blossom scar flow facing fruit were 11.48°C and 11.38°C for the first tomato, 10.36°C and 10.35°C for the second tomato, and 9.36°C and 9.39°C for the fourth tomato from the inlet, respectively. A greater gradient drop, 1.12°C or 1.03°C , respectively, according to whether the fruit are stem or blossom facing, occurred between the 1st and 2nd tomato than between the 2nd and 3rd, or between the 3rd and 4th tomato (0.50°C or 0.48°C). The 2.12°C or 1.99°C (stem vs. blossom flow) gradient drop between the 1st and 4th tomato indicates the important effect of the position of the material being heated. This difference also implies that a limited number of tomatoes should be treated in a single tunnel to ensure that a relatively uniform temperature profile is generated.

The difference between the temperature gradient of stem facing and blossom facing tomato fruits is +0.10°C, +0.01°C, and -0.03°C for the 1st, 2nd, and 4th fruit from the air inlet, indicating that a higher temperature gradient occurs in the 1st and 2nd tomato if they are stem (*vs.* scar) facing, while for the 4th tomato the contrary is true. Furthermore, the temperature gradient in the 1st, 2nd, 3rd and 4th fruit was slightly more uniform when the blossom scar side of the tomato was exposed to the air flow. However, compared to the positioning effect, differences resulting from flow facing or sample orientation are negligible.

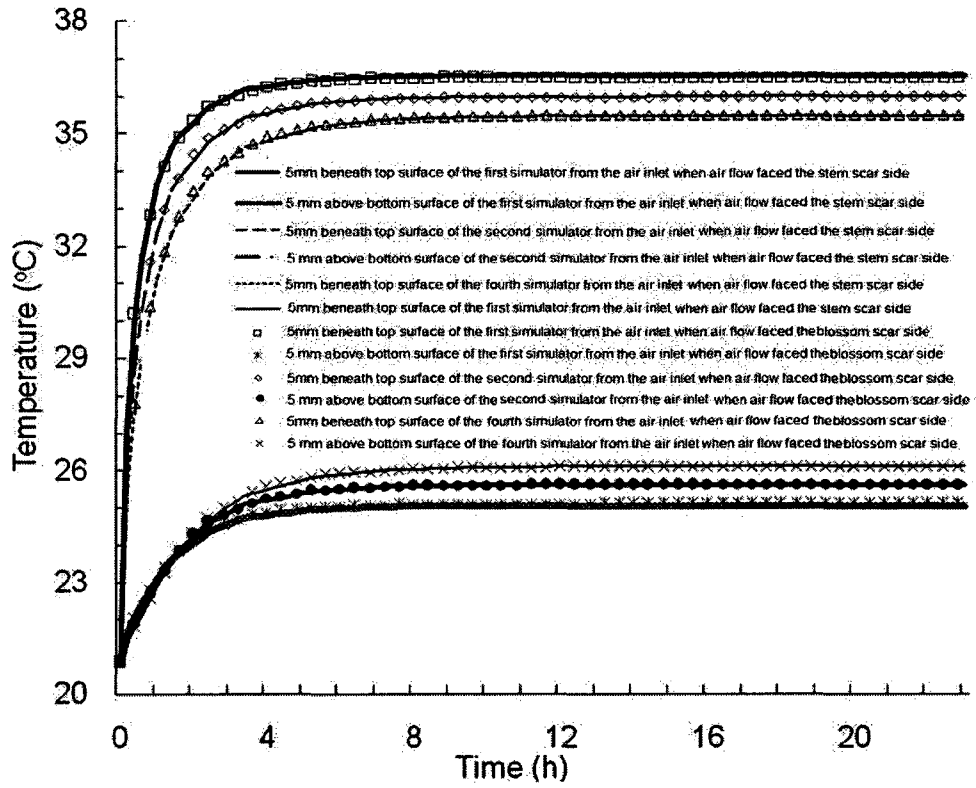


Figure 4.10: Comparison of temperature profile of tomatoes under different orientations and positions.

The temperature gradient generated in tomatoes was the result of the temperature profile of the air approaching and around them (Fig. 4.11). At 23 h, the temperature differences at the 1st tomato-air interface between the upper and lower tunnels were 12.62°C and 12.51°C, respectively for stem and blossom-facing fruit. These differences dropped to 11.40°C and 11.33°C for the 2nd fruit and to 10.31°C and 10.32°C for the 4th fruit. The largest tunnel-to-tunnel tomato-air interface temperature difference occurred with the fruit closest to the inlet, which explains the earlier heating and larger temperature gradient seen inside the first tomato. The pattern in air temperature drop, which is greatest between the first and second fruit (1.22°C and 1.18°C, stem/scar-facing), was less (0.55°C and 0.51°C) between the second and the third fruit, and lower still between the third and fourth fruit, which explains the drop in temperature gradient in tomatoes as they

are farther from the inlet. Similarly, the small difference in air temperature as the result of the orientation of tomatoes leads to the slightly more uniform treatment results for the blossom scar-facing fruit.

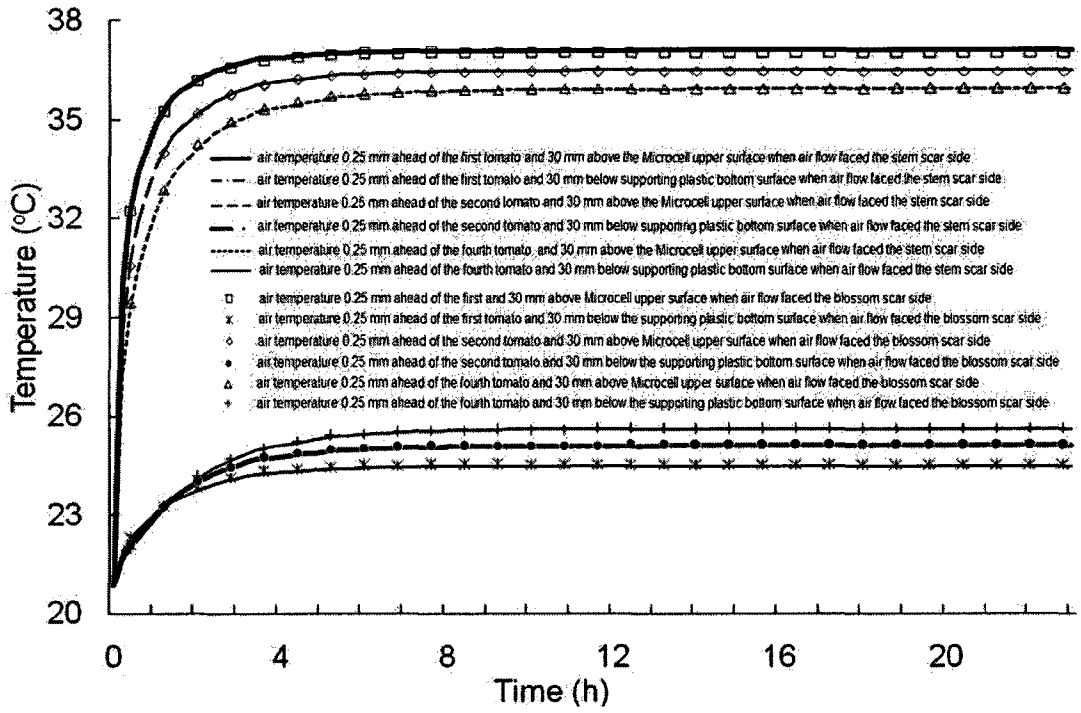


Figure 4.11: Comparison of the temperature profile of air close to tomatoes in different orientations and positions.

The temperature difference between air around each individual tomato, close to the Microcell, close to the supporting plastic plate, and main stream of air could be the result of different air flow patterns (Figures 4.12 and 4.13). The air flow far from tomatoes is much more streamlined, even as it approaches the first tomato; however, after passing the facing part of the first tomato, a significant recirculation pattern is apparent, and some air remained trapped between tomatoes and recirculated at a lower velocity. In the upper tunnel where air was supposed to transfer heat to tomatoes by convection, this recirculating air had lost some heat to the first tomato so that its temperature was lower than air at the inlet. Consequently, this recirculated air would bring less heat to the next

tomato. In contrast, in the lower tunnel where air is expected to remove heat from tomatoes, the warmer recirculated air could not remove heat as efficiently as it had from the first tomato given the lesser temperature difference between the next tomato surface and this air. Thus, the air to fruit temperature gradient for each of the last three tomatoes is less than that of the first tomato.

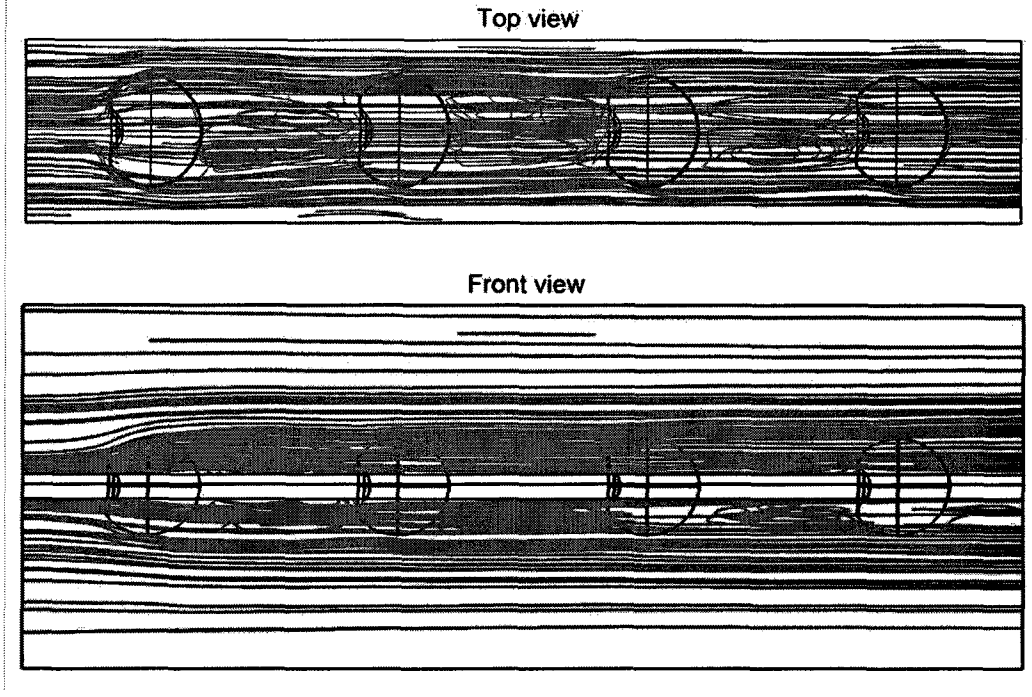


Figure 4.12: Air velocity streamline field.

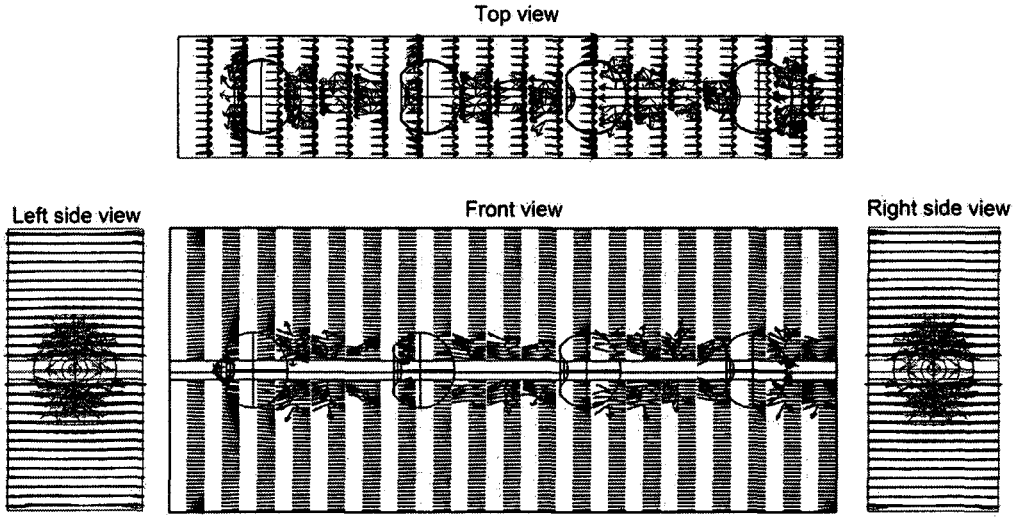


Figure 4.13: Normalized arrow view of air velocity field in simulated tunnel. The arrow indicates the air flow direction.

4.4.5 Effect of air velocity

As shown in Fig. 4.8d and 4.14, the general tendencies in the temperature profile for each heated tomato did not change significantly when the inlet air velocity in the lower tunnel was reduced from 0.24 m s^{-1} to 0.12 m s^{-1}; however, the temperature at sampled positions in both the upper and lower tunnels increased gradually over time. The temperature gradient within each tomato decreased by 0.39°C, 0.42°C, and 0.45°C, respectively, for the first, second, and fourth tomato when air velocity of the cooler tunnel was reduced. At 23 h, in the upper, warm tunnel, the temperature 5 mm beneath the fruit surface of the first, second, or fourth fruit from the air inlet increased by 0.09°C, 0.11°C, 0.16°C, respectively, when the lower tunnel air flow rate was decreased. Meanwhile, at the same time, the temperature 5 mm beneath the surface of the bottom of the first, second, or fourth fruit from the air inlet, in the lower tunnel, increased to an even greater degree (0.48°C, 0.53°C and 0.61°C, respectively) when the air flow rate was decreased. This result implied that heat treatment effects might be improved by a relative increase in air flow rate around heated portions of fruit.

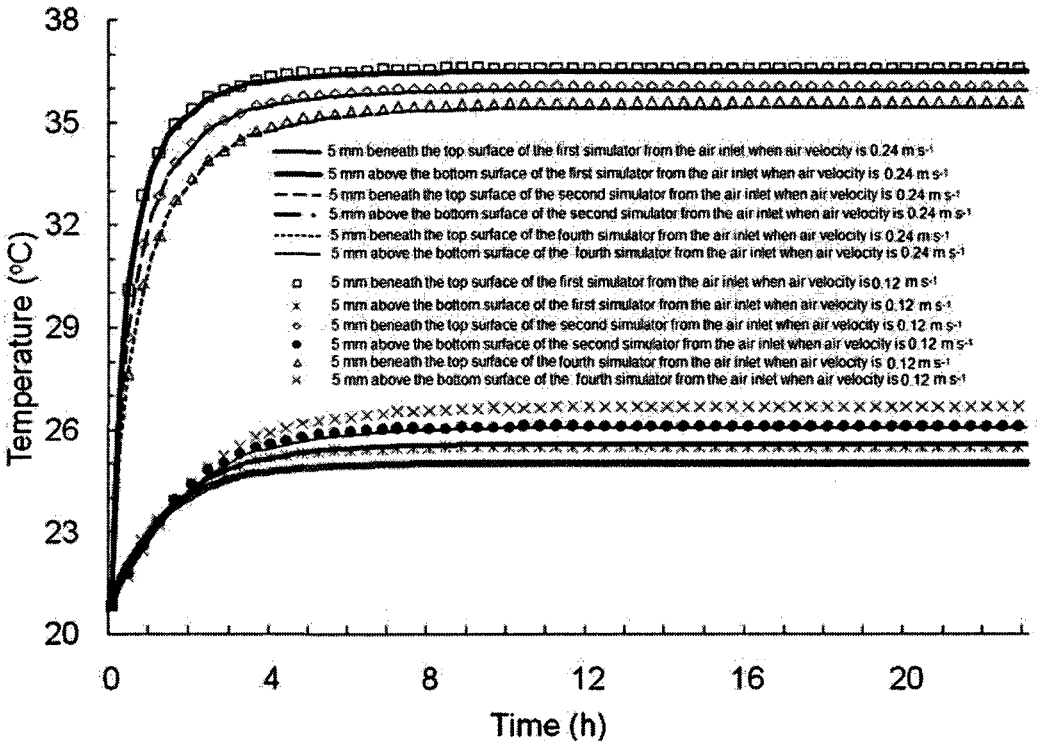


Figure 4.14: Comparison of temperature profile of tomatoes when inlet air velocity changed from 0.24 m s^{-1} to 0.12 m s^{-1}.

Temperature increases in tomato fruit were the result of the patterns of temperature change in the air immediately around the tomato fruits. The temperature of air around tomato fruits increased after the inlet air velocity for the lower tunnel was reduced (Fig. 4.15), thought this effect was much greater for the lower tunnel. Except for the beginning when the tomato fruits temperature was 2°C lower than inlet air in the lower tunnel, for the rest of heating process, air in lower tunnel functioned as a heat remover, withdrawing heat transferred from the hot portion of the tomato. This heat removal occurred by air convection. As air velocity decreased, the heat transfer coefficient and Biot number were reduced (Dincer 1994; Wang et al. 2001), resulting in less heat being removed by air from tomato parts in lower tunnel, and vice versa. The increase in temperature of portions of the tomato fruits and of the air around them in the

lower chamber was the direct result of the reduced Biot number and heat transfer coefficient. As a result of the reduction in heat conducted from parts of tomato in upper chamber, the temperature was also slightly increased.

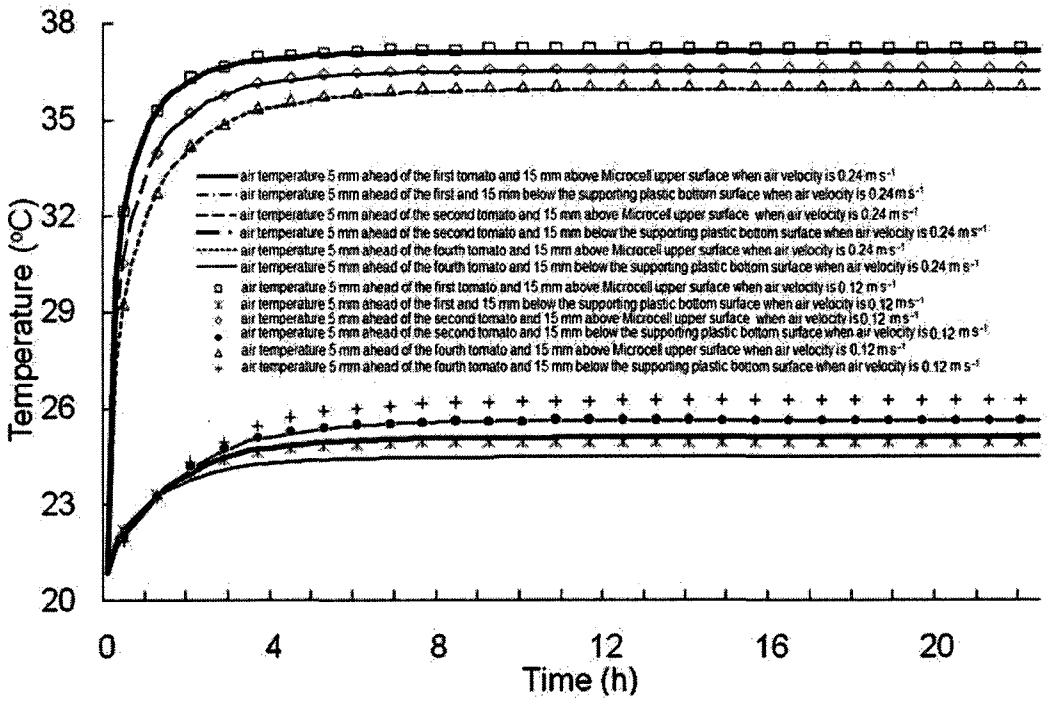


Figure 4.15: Comparison of temperature profile of air close to tomatoes when inlet air velocity changed from 0.24 m s^{-1} to 0.12 m s^{-1}.

4.4.6 Effect of air temperature differences

As long as the air temperature difference between the upper and lower tunnels was 3°C or 1°C (i.e., inlet air temperature of the lower tunnel was at 36°C or 38°C), the temperature gradient within the tomato was significantly reduced compared to the difference when it was 16°C (Fig. 4.8e-f and Fig. 4.16-4.17). Although the temperature of air approaching and immediately around tomatoes was still lower or higher than that of the main stream of air in the upper or lower chamber, respectively, this difference was much smaller than that when inlet air temperature difference was 16°C.

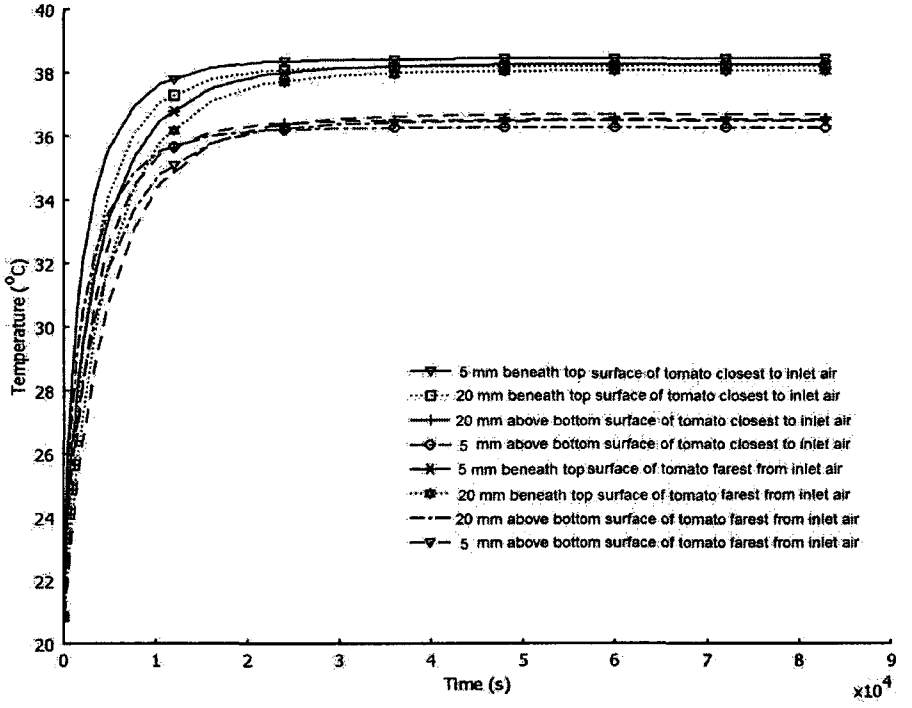


Figure 4.16: Temperature profile of tomato simulator when inlet air temperature of the lower tunnel was at 36°C.

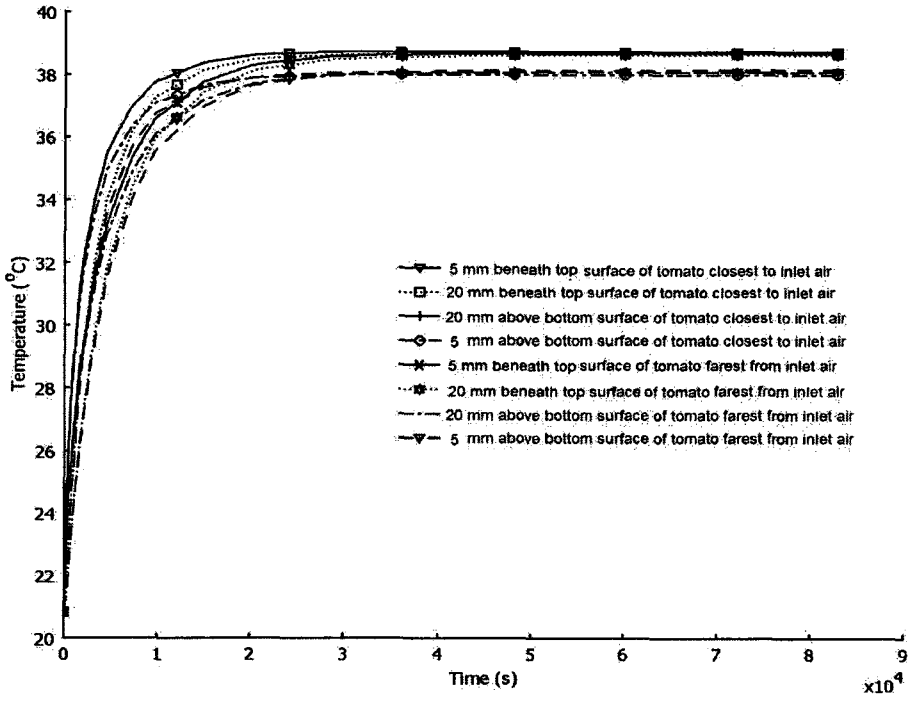


Figure 4.17: Temperature profile of tomato simulator when inlet air temperature of the lower tunnel was at 38°C.

4.4.7 Comparison of results of simulation and experiment

The temperature of representative tomato sample second from the tunnel outlet was monitored, and then compared to simulated data for the same location. Measured and simulated temperature profiles (Fig. 4.18) show that the simulation closely matched measured trends in temperature. The fitness of modeled data to the observed data was indicated by Nash-Sutcliffe efficiencies of 0.99 for 5 mm beneath top surface of tomato, 0.99 for 20 mm beneath the top surface of the tomato, 0.91 for 20 mm above bottom surface of the tomato, and 0.94 for 5 mm above bottom surface of the tomato. The RMSE between simulated and measured temperatures was 0.27°C for 5 mm beneath top surface of tomato; 0.24°C for 20 mm beneath the top surface of the tomato; 0.46°C for 20 mm above bottom surface of the tomato; and 0.29°C for 5mm above bottom surface of tomato. The results indicated that the model simulation was valid and the model was able to represent the heterogeneous heating process. In other words, the values predicted by

this model agreed well with the experimental data. The model is expected to allow a rough estimation of non-uniform treatment by air.

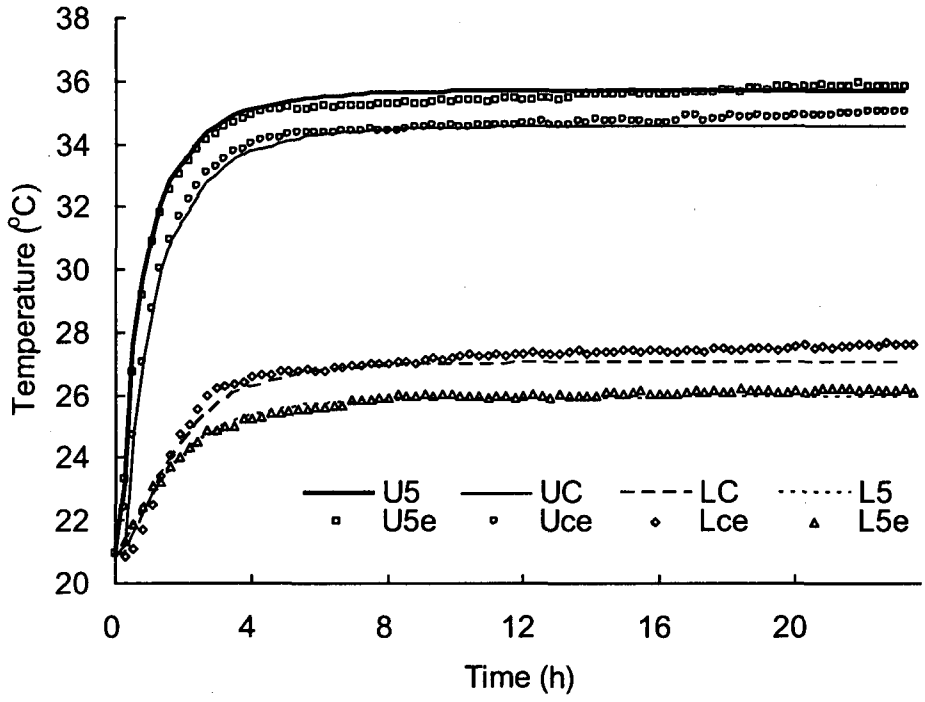


Figure 4.18: Comparison of results of simulation and experiment when inlet air temperature was set at 39°C and 23°C for upper and lower tunnels, respectively. All points are taken from the equatorial cross-section of the second tomato from outlet, *e* denotes experimental data: U5, U5e — 5 mm beneath the top surface; UC, Uce — 20 mm beneath the top surface; L5, L5e — 5 mm above the bottom surface; LC, Lce — 20 mm above the bottom surface.

For all tunnels, the temperature of air at the outlet was significantly lower (1.42°C) than that at the inlet (Fig. 4.19), implying the existence of a temperature gradient along the direction of air flow. However, this gradient could not be eliminated due to the heat transfer between air and produce. It may also be partly due to the result of imperfect insulation of the walls. This gradient can only be reduced by shortening the tunnel length. Hence, this result supported our short tunnel length designing idea discussed earlier.

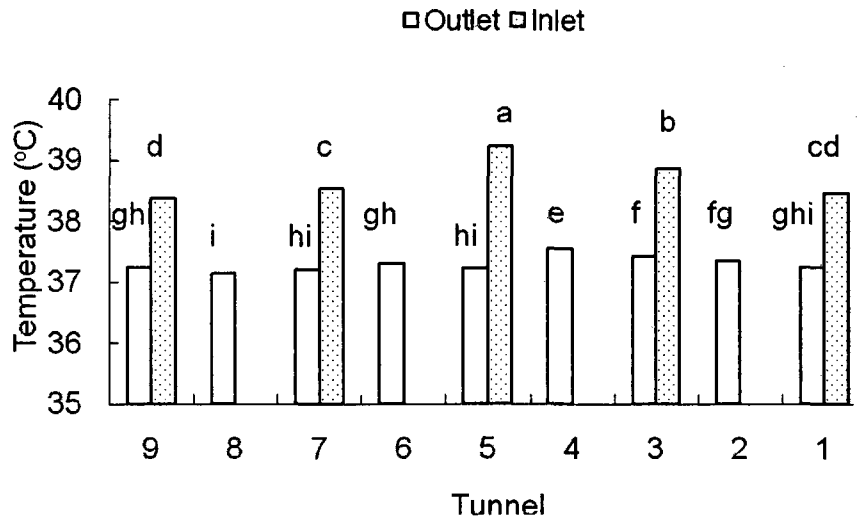


Figure 4.19: Comparison of air temperature among tunnel inlets and outlets. Letters above the bar indicate the result of Duncan's Multiple Range Test. Treatments indicated by the same letter are not significantly different at $\alpha = 0.05$.

Air temperature close to the centerline at tunnel outlets such as that of tunnel 4 showed statistically significant difference from that of the other tunnels, with a maximum difference of 0.4°C. Similarly, differences in inlet temperatures were found between tunnels 3 and 5, with a maximum difference of 0.84°C. However, compared with the difference between the temperature mean of inlet and outlet air, the difference between tunnels for either outlet or inlet air temperatures were almost negligible. So the uniformity of temperature among tunnels is physically acceptable.

No significant differences in air flow rate (Fig. 4.20) were identified between tunnels for the measurement taken at either inlet or at the middle of tunnels. The result validated the effectiveness of the air distributor in our design.

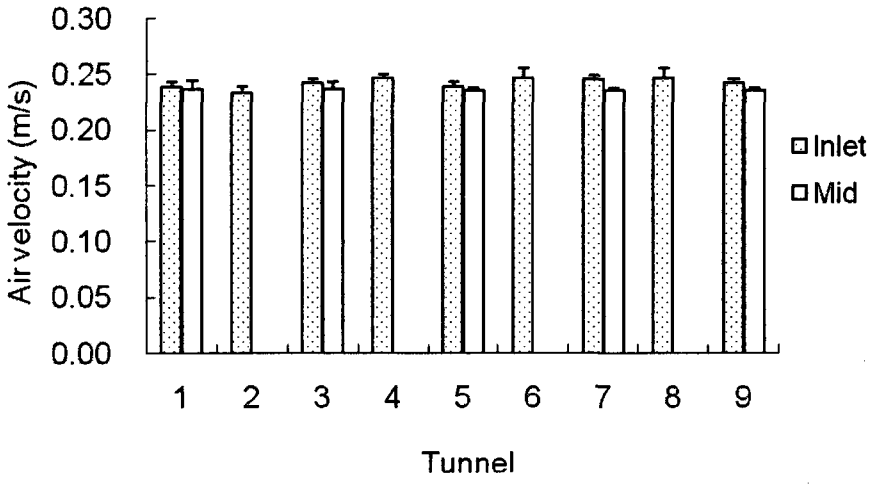
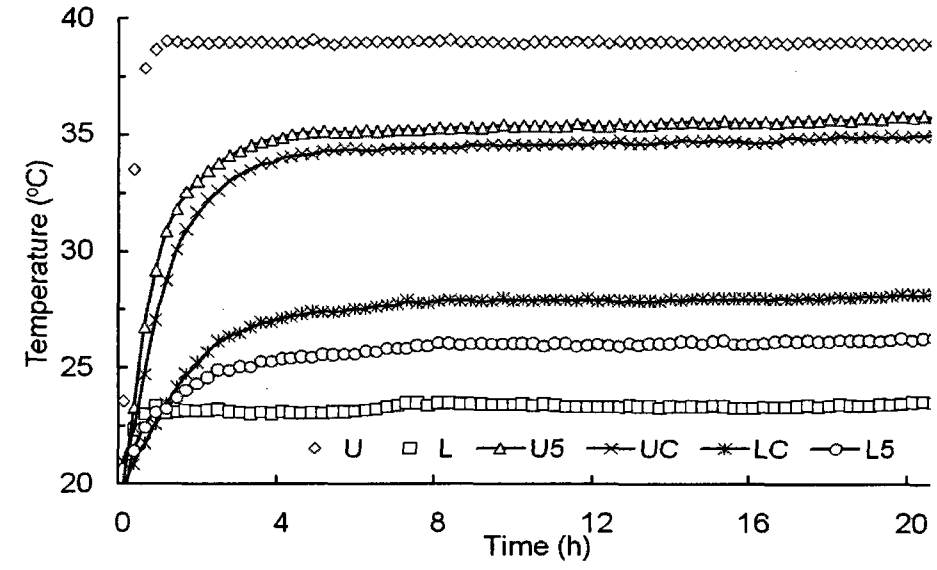
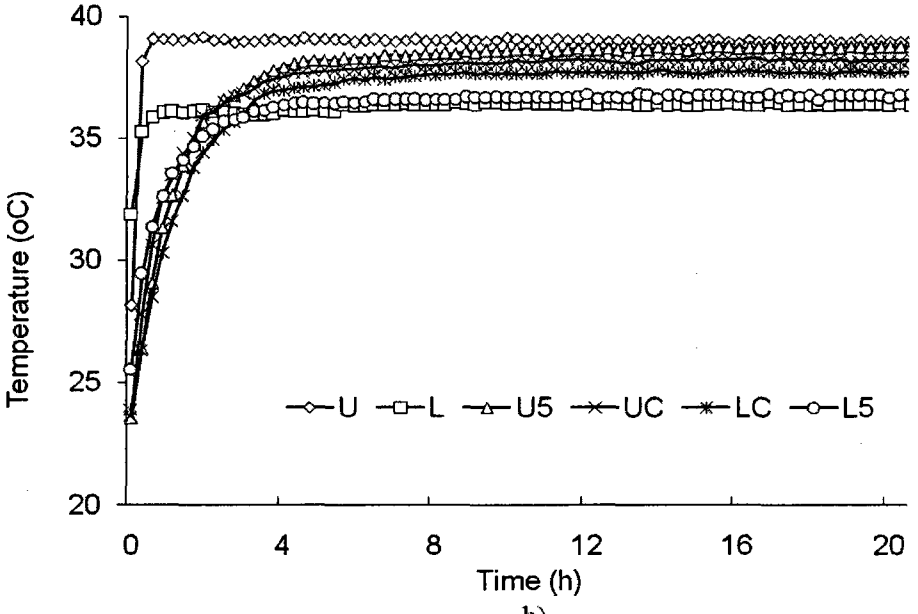


Figure 4.20: Comparison of air velocity among tunnels inlets and middles.

Temperature gradients within non-uniformly treated tomatoes (Fig. 4.21) were compared to those resulting from uniform treatments. The gradient within each individual heated tomato was greater as the air temperature between upper and lower chambers increased.



a)



b)

Figure 4.21: Temperature profile of air and tomato exposed to heterogeneous treatment where air temperature in upper chamber was controlled at 39°C and that of lower chamber was at (a) 23°C or (b) 36°C. U refers to air temperature in upper chamber, L refers to air temperature in lower chamber, U5 or UC refers to temperature at 5 or 20 mm

beneath the top surface of the tomato, L5 or LC refers to temperature at 5 or 20mm above the bottom surface of the tomato.

When the air temperatures of the upper and lower tunnels were controlled at 39°C and 36°C respectively, the temperature profile of tomatoes was very similar to that of tomatoes exposed to uniform temperatures, and the value of U5 was close to that of U (Fig. 4.21). As long as the air temperature difference between chambers increased (Fig. 4.21a), the temperature at a 5 mm depth was lower than the air temperature it was exposed to, and of its counterpart when the air temperature difference was lower (Fig 4.21b). This further confirmed the results of simulation.

4.5 Conclusions

The general trend of the simulated temperature profile matched the measured temperature quite closely, which was indicated by Nash-Sutcliffe efficiencies (>0.91). Thus, the simulation model could be used to accurately predict measured temperature. The air humidity has significant effect on heat treatment, and specifically for the temperature gradient generated in our design. Tomato position, referring to the length of tunnel, is another factor which should be considered when designing a new experimental device. Moreover, while the air velocity is a factor affecting heat treatment uniformity, tomato orientation did not show a significant effect. This simulation method and experimental set up could also be used for other fruits.

The experimental results also indicated that for all tunnels, the air temperature at the outlet was significantly lower than that at the inlet, implying the existence of a temperature gradient along the direction of air flow. Compared to the difference between the mean temperature of inlet and outlet air, the difference among tunnels for either measurements of outlet or inlet was almost negligible. The uniformity of temperature among tunnels was considered as physically acceptable.

A temperature gradient within non-uniformly treated tomato fruits was generated, and was compared to the difference resulted from those submitted to uniform treatments

at the same temperature. The gradient within each differentially-heated tomato was larger as the difference in air temperature between upper and lower chambers increased.

4.6 Acknowledgements

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CONNECTING STATEMENT 3

Chapter IV presented and validated the forced-air-twin-chamber experimental set up to generate the temperature gradient for intact tomatoes. In chapter V, this set up will be used to check the non-uniformity effect of heat treatment on disease control.

The intended manuscript has been submitted to the *Transactions of ASABE*. It is authored by:

Jianbo Lu*, Vicky Toussaint, Marie Thérèse Charles**, Clément Vigneault**, G. S. Vijaya Raghavan*.** The title is **Effect of Heat Treatment Uniformity on the Control of *Botrytis cinerea* on Harvested Tomato.**

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Contributions made by different authors are as follows:

The first author, the Ph.D. student did the experimental work and prepared the manuscript; the second author provided the laboratory equipment and guidance during the experimental process; the third author provided the scientific support on the plant physiology aspect; the forth and fifth authors are the supervisors who guided the research work.

CHAPTER V. EFFECT OF HEAT TREATMENT UNIFORMITY ON THE CONTROL OF *BOTRYTIS CINEREA* ON HARVESTED TOMATO

5.1 Abstract

Surface-sterilized breaker-stage tomato (*Lycopersicon esculentum* Mill. cv. DRW 453) fruit were randomly divided into seven lots: four lots of fruits were fully exposed to circulating air at 23°C (control), 36°C, 38°C or 39°C, respectively, whereas the remaining three were treated in a custom-designed insulated twin-chambered forced-air unit which allowed half (bisected along stem- to blossom-scar plane) of each tomato to be exposed to 39°C air, at the same time the other half was, in respective experimental runs. Following the 23 h exposure to different temperatures, fruits were cooled by room temperature forced-air for 2 h, and then inoculated with week-old *Botrytis cinerea* Pers mycelium agar plugs. After 24 h storage at 23°C, inoculated tomatoes were stored at 13°C for 48 h before the plugs were removed; the fruit then remained under the same storage conditions for a further 72 h. To assess the effect of the heat treatment combinations on *B. cinerea* development, the occurrence of hypersensitive response (HR), of tissue breakdown, lesion diameter and the abundance of mycelia (4-point subjective scale) were assessed on the 6th day after inoculation. A non-parametric one-way procedure followed by ANOVA and Duncan's multiple range test was conducted to investigate the effect of treatment conditions on the parameters assessed. The single-temperature heat treatment(s) to be most effective in limiting pathogen development varied according to the parameters measured: 38°C for HR, 36°C, 38°C or 39°C for tissue breakdown and mycelium abundance, and 38°C or 39°C for lesion size. The ideal heat treatment effect was only obtained when the material to be treated was exposed to a particular temperature for a designed duration. Within the temperature range investigated, bilateral differences in temperature across the fruit significantly affected disease control: decreasing temperature differences significantly improved the uniformity for disease control. The importance of improving the uniformity of heating media among treated fruits and around each individual fruit is addressed.

Keywords. *Botrytis cinerea*, disease control, gray mould, heat treatment, inoculation, postharvest, temperature, tomato, uniformity.

5.2 Introduction

Research efforts to develop laboratory- and industrial-scale postharvest heat treatments for disinfestation, disinfection, chilling injury control and retardation of the ripening process (Lurie 1998) in various fresh crops has been steadily increasing in recent decades. Hot water, radio frequency (RF), microwave and hot air methods have been used. Hot air has been used for both fungal and insect control (Tang et al. 2000; Yahia and Ortega-Zaleta 2000; Jacobi et al. 2001a; Mitcham et al. 2004; Hoa et al. 2006). Lurie (1998) reviewed hot air heat treatment and concluded that exposure to high temperatures in forced or static air can decrease fungal infections. The potential of hot air treatment as both a means of beneficially affecting commodity physiology and preventing insect and fungal invasion, justifies further development of these treatments (Lurie 1998). However, a common difficulty with hot air or hot water heating methods is the slow rate of heat transfer, requiring hours of treatment time, especially for large fruits (Wang et al. 2001).

The overall quality of fresh produce treated at optimal heat treatment temperatures and exposure duration has been shown to be significantly better than that of an untreated control (Fallik 2004). Several studies have demonstrated the potential of heat treatment to interact with both constitutive and induced defence mechanisms (Schirra et al. 1999; Terry and Joyce 2004). Hot water brushing brings about a clear redistribution of the epicuticular wax layer, part of the constitutive defence system, and a significant reduction in cuticular cracks, thus improving physical barriers to pathogen penetration (Ben-Yehoshua 2003; Fallik 2004). It is well established that heat treatment favours wound healing by leading to the deposition of lignin-like material (enhancement of a constitutive defence) at wound sites, hindering pathogen invasion. Lurie et al. (1997) demonstrated that heat treatment prevents the deterioration of enzymes such as anionic peroxidases, which play an important role in the constitutive defence of tomato (Lycopersicon esculentum Mill.) fruit against Botrytis cinerea Pers (Lurie and Sabehat 1997). In many fruit and vegetables, heat treatments inhibit biochemical pathways involved in ripening and other processes, thereby contributing to maintenance of juvenility and resistance. Heat treatment promotes the synthesis and accumulation of induced antimicrobial compounds and of enzymes associated with induced resistance through their ability to degrade fungal cell walls (Pavoncello et al. 2001; Ben-Yehoshua 2003).

Although heat treatment can provide a number of benefits to the fruit or vegetable treated, inappropriate heat treatment can cause damage. Lurie and Sabehat (1997) found that temperatures higher than 38°C were not generally as effective as 38°C and that 24 h exposure to 42°C or 46°C caused heat damage of tomato. Mangoes (Mangifera indica L. cv. Manila) showed severe skin scalding when forced-air heated at temperatures of 45°C or higher, but no damage at 43°C, indicating the existence of a threshold temperature for skin injury to develop (Ortega-Zaleta and Yahia 2000). Tissue damage caused by heat will also result in increased decay development (Lurie 2006).

Under bulk processing, it is nearly impossible for individual commodity items subjected to a heating field to receive exactly the same exposure, leading to the non-uniformity of the treatment. A number of studies have investigated bulk heating issues for scaling up RF (Birla et al. 2004; Wang et al. 2006a) and hot water treatments (Bollen and Dela Rue 1999; Birla et al. 2004; Fallik 2004; Wang et al. 2006b). However, little research has been conducted regarding hot air treatment and mass heat treatment processing.

Compared to electromagnetic waves, conventional media such as air and water have low specific heat capacity and their poor heat transfer ability can cause problems making it difficult to obtain uniform heating within each individual fruit. It has been found that the part of apples within the cavity created by two adjacent abutted fruits and effectively sealed off from the heating medium was shown to delay the achievement of target temperatures (Bollen and Dela Rue 1999).

Heterogeneity exists not only within each single fruit but also among fruits: initial temperature and size of the produce, along with its positioning within the treatment chamber have a marked influence on the effectiveness of treatment (Narayannasamy 2006). The half-cooling time variance was shown to increase as the total area of openings on the walls of a container declined and that the variance at the minimum opening configuration was significantly increased as the airflow rate decreased (Vigneault and de Castro 2005). Large differences in heat transfer coefficient values were observed since the airflow is not uniform, when spherical objects were packed in stacked bins and cooled by forced air convection (Alvarez and Flick 1999a; Alvarez and Flick 1999b).

Given that their tissues and composition are spatially variable, the horticultural crop thermal properties are heterogeneous. Given this non-uniformity of fresh commodities, resulting variations in radio frequency (RF) fields, which should be uniform if a uniform heating is to be attained (Wang et al. 2003), have proved a major obstacle in developing postharvest treatments (Mitcham et al. 2004). Thus, further research is needed to optimize heating temperature and the duration of its application for different treatment media and to devise a way of maintaining a fairly uniform micro-media environment for individual commodities. Before scaling-up a postharvest heat treatment a better understanding of the effect of heat uniformity on the quality of the treated commodity is required. In addition, an understanding of the physiological and pathological processes occurring in the fruit and vegetable tissue during and following this non-uniform heat treatment should aid in developing successful treatments.

Because of its ability to grow effectively at temperatures just above freezing, *B. cinerea* is a major pathogen of fruits and vegetables during cold storage and subsequent shipment. The greatest damage inflicted by *B. cinerea* occurs in senescing fruit tissues after harvest since they are then most vulnerable to infection and pathogen development. Symptoms include a grey to brown discoloration, water soaking, fuzzy whitish grey to tan mould (mycelium and conidia) growing on the surface of affected tissue and restricted lesions (Elad et al. 2004).

The objective of this research was to observe and quantify the effect of non-uniformity in heat treatment on the control of *B. cinerea* on tomatoes by pre-exposing them to: a) hot air chambers set at different temperatures; and b) differentially heating of portions of individual tomato fruit.

5.3 Materials and methods

5.3.1 Experimental set-up

An insulated twin-chambered forced-air device (Fig. 5.1) was built in order to generate a heterogeneous heat treatment for tomatoes, where one half (bisected along stem- to blossom-scar plane) of each intact tomato was exposed to a constant controlled temperature, whilst the other half was exposed to a different constant, controlled temperature. One hemisphere of individual tomatoes was exposed for 23 h to an effective

disinfection treatment of 39°C at an air flow rate of 0.24 m s^{-1}, whereas the other half hemisphere was exposed to temperatures of 23°C, 36°C or 38°C, at the same air flow rate for the same period of time.

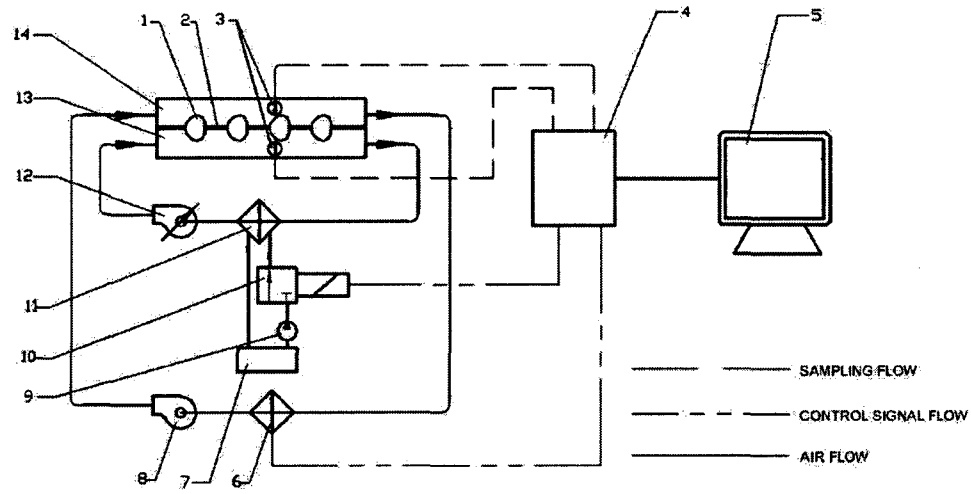

Figure 5.1: Schematic of experimental set-up consisting of a forced air twin-tunnel allowing a 9 × 4 matrix of produce to be exposed to heterogeneous environmental conditions as follows: 1- Produce; 2-Microcell™ and plastic supporting plate; 3-Thermocouples; 4-Data acquisition board; 5-Computer; 6-Heater; 7-Water bath; 8- Fan for upper chamber; 9-Pump; 10- Solenoid valve; 11- Heat exchanger; 12-Adjustable fan for lower chamber; 13- Lower chamber; 14- Upper chamber.

The upper chamber was equipped with 8 incandescent bulbs (8×100W) as heater since the air in upper chamber should be higher than ambient temperatures. As a wider range of air temperatures (23-39°C) were to be implemented in the lower chamber, a radiator-like heat exchanger which could function as either a heater or cooler, circulated by hot or cold water from VWR Signature™ Heated/Refrigerated Circulator (VWR International, West Chester, PA, USA), was employed. Hot or cold water from the circulator, which served to control the temperature, passed through the core's winding tube. Fins attached to the core tubes served to increase the surface area for heat transfer to the air forced past them by a fan, thereby heating or cooling the produce.

Temperature control for both chambers was achieved through electronic control and chambers were separated from each other by 12 mm-thick insulation material (Microcell^{TM}, Foam N' More, Inc., Michigan) supported by a 5 mm-thick plastic plate. The two chambers were divided into 9 parallel tunnels in order to expose sufficient samples to a relatively uniform airflow. Tunnels were separated by steel partitions as steel's high heat conductivity increased uniformity of the air temperature between adjacent tunnels. An aluminum mesh plate coated with adhesive-bonded fabric covered the tunnel entrance to achieve uniform airflows among tunnels. Holes of appropriate size corresponding to the longitudinal cross-section of tomato were cut in the Microcell^{TM} to receive the fruit during treatment, and larger holes (82 mm diam.) were cut in the plastic plate separating the twin chambers in order to position the tomato fruits along the center of the tunnel, and simultaneously expose each hemisphere of a tomato to different conditions.

5.3.2 Instrumentation and control

Four channels of an 8-channel data acquisition system (Personal Daq/3001, IOtech Inc., Cleveland, Ohio, USA) were used for sampling and controlling the temperature of the upper chamber and lower chamber, and the other four channels were used to record the temperature profile of the representative sample of non-uniformly treated tomatoes. The control program was made using DASYLab V 9.0 (National Instruments Corporation, Austin, TX, USA). Temperature was recorded at 4-min interval.

5.3.3 Tomato fruit

Breaker stage tomato fruit (*Lycopersicon esculentum* Mill cv. DRW 453) of uniform size were manually harvested from a local commercial greenhouse and surface-sterilized for 3 min using a dilute bleach solution [0.1% Cl_2 (w/w) as sodium hypochlorite], then thoroughly rinsed with tap water for a further 3 min, and left on filter paper to drain and air dry as recommended by Polenta et al. (2006).

5.3.4 Experimental design

The study was set up in a completely randomized design with 3 sub-experiments (Table 5.1): (i) examining the effect of uniform temperature treatments at different temperatures; one half of each tomato was inoculated with a single plug, and the non-

inoculated half was treated as an independent group, (ii) assessing the effect of a temperature difference between two hemispheres of heterogeneously-treated tomatoes through a pair-wise comparison, and (iii) identifying the difference between induced effects and a combination of thermal and induced effects. Experiments were repeated three times.

Table 5.1: Experimental Design.

	Treatment		Inoculation on day 1		Storage
Sub-experiment		Level (°C)	Plugs per tomato	Before inoculation	After inoculation
1	Control (C1 and C2)	20, 23	1	N/A	1 d at 23°C and 2 d at 13°C before plug removal; another 3 d at 13°C after plug removal (or treatment of pre-heat). RH = 90-95%.
	Uniform	36, 38, 39			
	Heterogeneous (H/C)*	39/23			
2	Control	23	2		
	H/C	39/23, 36, 38			
3	Control	23	1	13°C for pre-heat groups. RH=90-95%.	
	Uniform	38, 39			
	Heterogeneous (H/C)	39/23, 36	2		

* H/C = Hot side air temperature / Cold side air temperature

5.3.4.1 Treatment

Surface-sterilized breaker stage tomato fruits were randomly divided into seven lots, and individual lots submitted to the following treatments according to the experimental design (Table 5.1):

(i) Non-treated controls (C). C1, control for the first sub-experiment, fruit stored in a 20°C chamber immediately after surface sterilization, no forced air circulation. C2, same as C1, but fruit exposed to circulating air at 23°C

(ii) Uniformly treated at 36°C for 23 h in a chamber (U36)

(iii) Uniformly treated at 38°C for 23 h in a chamber (U38)

(iv) Uniformly treated at 39°C for 23 h in a chamber (U39)

(v) Heterogeneously treated for 23 h, with imposed air temperatures of 39°C and 23°C in the upper and lower chambers, respectively (H23, C23)

(vi) Heterogeneously treated for 23 h, with imposed air temperatures of 39°C and 36°C in the upper and lower chambers, respectively (H36, C36).

(vii) Heterogeneously treated for 23 h, with imposed air temperatures of 39°C and 38°C in the upper and lower chambers, respectively (H38, C38).

5.3.4.2 Inoculation of tomato fruits

Given its importance as a post-harvest pathogen of tomatoes, *B. cinerea* was selected as the pathogenic fungi used in this study. The strain was isolated from a tomato in the laboratory of bacteriology and post harvest pathology at the Horticultural Research and Development Centre of Agriculture and Agri-Food Canada in St-Jean-sur-Richelieu, QC, Canada. The strain was identified using fungal identification keys. For long-term storage, the strain was kept in inoculated soil and stored at 4°C. To produce fresh inoculum, an aliquot of infected soil was spread on PDA (DifcoTM Potato Destrose Agar, Becton, Dickinson and Company, Sparks, MD 21 152 USA), and after one week's growth at room temperature, agar plugs containing fresh mycelium were sub-cultured on PDA. Inoculated plates were used to inoculate tomatoes before the fungi produced spores. To inoculate a tomato, a 7 mm diameter plugs bearing mycelia was cut from the margin of an actively growing 7-day-old culture and placed on the tomato at mid distance between the stem scar and equator, i.e., the equivalent of 45°N lat.

5.3.4.2.1 Paired inoculation for partially heated tomatoes

To investigate the effect of temperature differences on disease control, specifically that existing between one tomato fruit hemisphere's exposure to 39°C and the other's exposure to a lower temperature, one mycelial plug was inoculated on each hemisphere, at the equivalent of 45°N lat., and 180° apart in longitude. The lots with single-side inoculation are referred to as the independent comparison, whilst the two-side inoculation lots are referred to as the matched pair comparison. In the latter case, the Wilcoxon Matched-Pairs Signed Rank Test was employed to determine differences between groups of paired data.

5.3.4.2.2 Post-heat treatment inoculation and storage

Post-heat treatment inoculations were done after tomatoes had received the heat treatment, and were designed to study whether heat treatment of one portion of the tomato induced pathogen growth inhibition effect in a portion of the same fruit having received a lower temperature treatment.

Immediately after treatment, fruits were cooled with 23°C forced air for 2 h, and then inoculated with 7-day-old *B. cinerea* mycelium agar plugs. As the temperature to which the fungus is submitted following inoculation constitutes a limiting factor in disease development, to insure the adherence of mycelial plugs to tomato skin and allow the fungus the possibility to invade the tomato tissue, inoculated tomatoes were maintained at 23°C for 24 h. This is close to the optimal temperature for *B. cinerea* infection. Fruits were then transferred to a 13°C storage room, where they remained for 48 h. Mycelial plugs were then removed (72 h after their initial application) and tomatoes were stored at 13°C for an additional 72 h. This temperature is midway between the optimal temperature for *B. cinerea* growth and that for best tomato conservation (Elad et al. 2004).

5.3.4.2.3 Pre-heat treatment inoculation and storage

To identify differences between induced effects and the combination of thermal and induced effects, pre-treatment inoculation was also conducted. In this sub-experiment, tomato fruits were divided into two lots: one lot was submitted to post-heat treatment inoculation as described above. The other lot was kept in 13°C storage room for

one day while the post-heat inoculated groups were submitted to heat treatment, then cleaned and inoculated on the same day as were the post-heat treatment inoculation fruits. The fruits of the lot having received no heat treatment were cleaned and dried, then inoculated with either one plug of mycelium (as for control and uniformly treated groups), or one plug for each side of the fruit as for the heterogeneously treated groups. Tomato fruits from the uniform and control inoculation were then randomly divided into three plastic containers, and the two-side inoculation tomato fruits into a further two containers. Each tomato was put in a medium-sized plastic pot to avoid contact with the wet paper placed at the bottom of the container to maintain a high relative humidity around the tomato fruits. The containers were covered with a black plastic bag and kept at room temperature (23°C) and 95% RH for 24 h. The containers were then transferred to 13°C storage room and kept for another 48 h before removing the agar plugs. After plug removal, one lot of tomato fruits was exposed to circulated room temperature air, and two others to 38°C or 39°C air temperatures in heated chambers. The partially-treated tomato fruits lots were treated in the twin chamber apparatus, with the upper chamber air at 39°C and that of the lower chamber set at 23°C or 36°C in respective runs. All heat treatments were conducted for 23 h, and treated tomato fruits were cooled down at room temperature for 2 h before placing them back in 13°C storage chambers for another 72h before evaluation.

5.3.5 Disease evaluation

The severity of infection was evaluated using different parameters (Table 5.2):

(i) hypersensitive response (HR), consisting in small spotted necrosis on the tomato skin. A tomato was considered HR positive in the presence of these symptoms only if the presence of mycelium and tissue rotting was not visibly present. The tomato could be still considered marketable.

(ii) evaluation of the presence of tissue break-downs (cracks) on tomato skin.

(iii) abundance of mycelium, and

(iv) the area of lesion 6 days after inoculation.

Table 5.2: Evaluation of *Botrytis cinerea* infection at day 8.

Parameters	Values	Symptom
Hypersensitive response (HR)	0	No lesion type HR apparent
	1	Small lesion resembling necrosis, black, mottled appearance
Tissue breaking-down (Crack)	0	No presence of lesions on the skin, or mycelium area cell lysis
	1	Skin is split, and the internal tissues appear water-soaked and could be seen on the fruit surface.
Mycelium abundance	0	No visible mycelium
	1	Launch of mycelium, difficult to see
	2	Mycelium visible, but little dense and / or not raised
	3	Mycelium visible, very dense and / or elevated
Lesion area	The lesion area, $A = \pi ab$, where A is surface area of a near-elliptical water-soaked lesion, a and b are the ellipse's semimajor and semiminor axes, respectively (i.e. half the width and half the height). a and b were determined from the arc lengths of the lesion segment using a flexible measuring tape graduated in millimetres.	Tomato fruits infected by *B. cinerea* presented initially with soft water-soaked areas that became grayish or yellowish green with lighter margins. Affected areas appeared darker than the healthy portions of fruits (Barkai-Golan 2001; Narayannasamy 2006).

Infected tissues became soft and water-soaked, and ultimately the lesion surface became abundantly covered with mycelium and gray-brown-conidia sometimes accompanied by black sclerotia. The affected areas appeared darker than the uninfected healthy portions of fruits as observed by Barkai-Golan (2001) and Narayannasamy (2006). The skin of some fruits was split, and the internal tissue turned water-soaked and was seen on the fruit surface. A considerable proportion of the rots caused by B. cinerea

spread during storage by contact between infected and sound fruits (Barkai-Golan 2001), which emphasized the importance of investigating the induced heat treatment effect since such an induced effect could lead to *B. cinerea* control during storage.

5.3.6 Statistical analysis

The normality and homoscedasticity of the residuals were evaluated using the Shapiro-Wilk's test. As most of the investigated parameters were categorical, and the value of lesion area was not normally distributed, a nonparametric one-way procedure followed by ANOVA and Duncan's multiple range test was conducted for the parameters investigated. Kruskal-Wallis was used for multiple-groups comparison and Wilcoxon for the un-matched comparison.

Statistical analysis was performed with the GLM non-parametric one-way procedure of SAS (SAS institute, 1999) and treatment differences based on the mean score of ranking were separated using the Duncan Multiple Range Test. Wilcoxon Matched-Pairs Signed Ranks Test (Univariate) was used to determine the difference of all parameters investigated between heated and less heated parts of fruit receiving the heterogeneous treatment. The Wilcoxon Rank Sum Test was employed to compare the effect of heat treatment between pre-heating inoculation and post-heating inoculation at each temperature setting. This test was used to compare the locations of two populations, and to determine if one population was shifted with respect to another. In order to quantify the difference between H23 and C23 for future modeling work, a marginal significance level of α=0.1 was selected.

5.4 Results and discussion

Some tomatoes showed hypersensitive response. Here, the hypersensitive response consisted on the development a spotted necrosis on the tomato skin at the inoculation point, without mycelium or rotting development. The tomato could be still considered marketable. In other tomatoes, infected tissues were soft and water-soaked, and ultimately lesion surface become abundantly covered with mycelium and gray-brown-conidia sometimes accompanied by black sclerotia. The affected areas appeared darker than the uninfected healthy portions of fruits as observed by Barkai-Golan (2001) and Narayannasamy (2006). The skin of some fruits was split, and the internal tissue

turned water-soaked and was seen on the fruit surface. A considerable proportion of the rots caused by *B. cinerea* spread during storage by contact between infected and sound fruits (Barkai-Golan 2001), which emphasized the importance of investigating the induced heat treatment effect since induced effect could lead to *B. cinerea* control during storage.

5.4.1 Effect of heat treatment uniformity

Among the uniform temperature treatments, hypersensitive response, tissue break-down, mycelium abundance, and water-soaked lesion dimension showed significant differences (Kruskal-Wallis test; P = 0.00429, 0.0302, 0.0084, 0.0001 respectively). The ranking result was further grouped using Duncan's Multiple Range Test (Figs. 5.2-5.3).

The hypersensitive response (Fig. 5.2) was enhanced in tomatoes exposed to hot air; however only those treated at 38°C showed a significant difference compared to control groups C1 and C2, but was not significantly different from tomatoes in 39°C heated group. The 39°-treated side of heterogeneously-treated tomatoes showed a higher HR than their lower temperature counterpart, but this difference was not significant. Hypersensitive cell death indicates that metabolic activities of the host are accelerated in response to the pathogen. The resulting necrosis of cells surrounding the site of attempted penetration impaired disease development (Narayannasamy 2006). Our data indicate that heat treatment likely impaired gray mold rot through the death of HR cells.

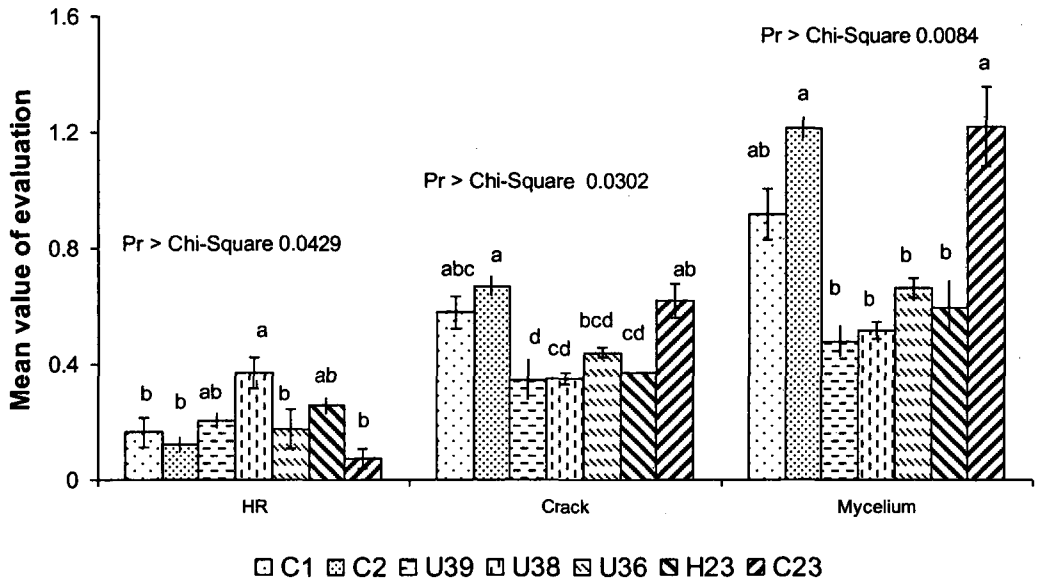

Figure 5.2: The comparison of hypersensitive response (HR), tissue breaking down (Crack), and mycelium abundance (Mycelium). The value and error bars represent the mean value and standard error mean, respectively, for HR, Crack, and Mycelium for each group. The letters above the bar indicate the result of Duncan's Multiple Range Test grouped by the mean rank score of nonparametric one way. Treatments indicated by the same letter are not significantly different at $\alpha = 0.05$. C1, fruit stored at 20°C immediately after cleaning, no forced air circulation; C2, fruit exposed to circulating air at room temperature; U39, U38, U36, fruits uniformly treated for 23 h at 39°C, 38°C, or 36°C respectively; H23, C23, heterogeneously treated for 23 h, with imposed air temperatures of 39°C and 23°C in the upper and lower chambers, respectively.

Break-down of tomato fruit tissue infected by *B. cinerea* is attributable to the hydrolytic action of fungal enzymes namely, cutinase, pectinase and cellulase (Charles et al. 2008a). These enzymes, which digest the fruit cuticle and cell walls, play a significant role in pathogenicity, development of the water-soaked area and tissue break-down. Less tissue break-down (Fig. 5.2) was observed for the heated tomatoes than control groups, suggesting that heat treatment interfered with the action of these hydrolases. Tomatoes heated at 36°C, 38°C, 39°C significantly differed from control groups. Tissue breakdown

tended to be less severe on the heated side of heterogeneously-treated tomato in comparison with their unheated side.

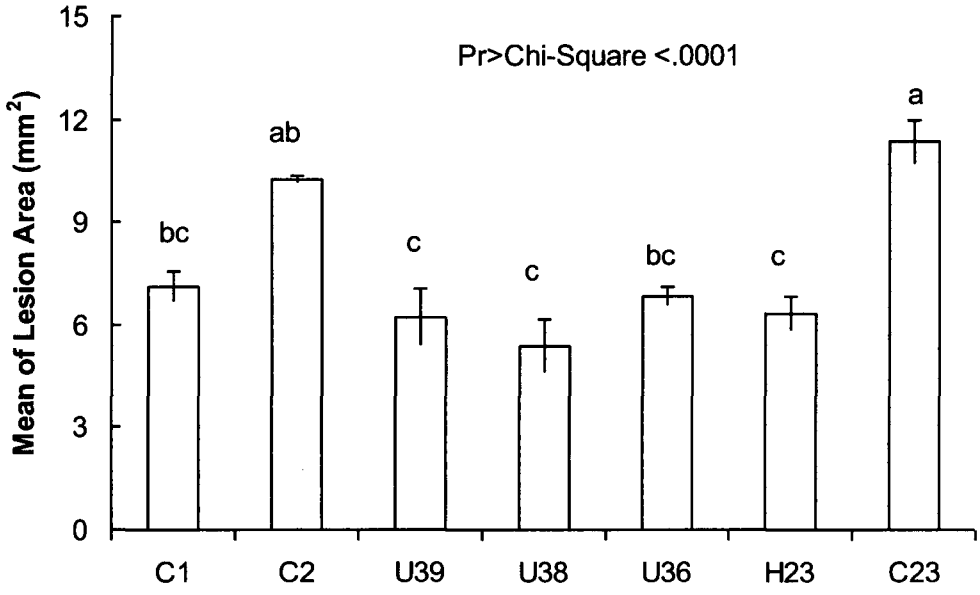

Figure 5.3: The comparison of lesion area. The value and error bars represent the mean value and standard error mean, respectively, for HR, Crack, and Mycelium for each group. The letters above the bar indicate the result of Duncan's Multiple Range Test grouped by the mean rank score of nonparametric one way. Treatments indicated by the same letter are not significantly different at $\alpha = 0.05$. C1, fruit stored at 20°C immediately after cleaning, no forced air circulation; C2, fruit exposed to circulating air at room temperature; U39, U38, U36, fruits uniformly treated for 23 h at 39°C, 38°C, or 36°C respectively; H23, C23, heterogeneously treated for 23 h, with imposed air temperatures of 39°C and 23°C in the upper and lower chambers, respectively.

The most important role of the hydrolytic enzymes secreted by pathogenic fungi is to liberate unit molecules that sustain mycelium growth and conidia production. In all heated groups, mycelium abundance (Fig. 5.2) was significantly lower than that of the control group in which tomatoes were exposed to circulating air flow at 23°C; however,

no significant difference was identified between the two control groups. Similarly, significantly less mycelium grew on the heated side of heterogeneously-treated tomatoes than on its counterpart. Lesion size tended to follow a trend similar to that of mycelium abundance (Fig. 5.3). Heat treatments at 38°C directly suppressed spore germination of *B. cinerea* within 24 h following their exposure to heat stress. Heat treatments inhibited hyphal growth and prevented colony expansion (Fallik 1993; Barkai-Golan 2001). *B. cinerea* is a necrotrophic fungus known to use several toxins to cause cell death ahead of the site of initial penetration (Rebordinos et al. 1996; Charles et al. 2008a). The reduction in lesion size, along with the lower abundance of mycelium in heat treated fruit are evocative of a slower diffusion of fungal hydrolases but also of a reduced effect of fungal toxins in causing cell death. Moreover, it is not unlikely that heat treatment improved resistance of the fruit cell walls against the degrading action of the hydrolases through structural reinforcement by lignin and other phenol derivatives. Significant increase in the activity of anionic peroxidases, catalyzing the polymerization of cinnamyl groups into lignin and suberin, was putatively linked to the resistance of heat treated tomato to *B. cinerea* (Lurie et al. 1997). In heat treated citrus fruits, lignin-like substances were clearly identified as a component in decay prevention (Nafussi et al. 2001). Similarly the biological basis of UV-C-induced resistance of tomato fruits to *B. cinerea* was associated with reinforcement of cell walls by lignin and suberin (Charles et al. 2008b).

The optimum for growth is not necessarily identical to the optimum for germination. The farther from the latter's optimal temperature the longer the time required for initiation of germination and mycelial growth, and the longer the duration of the incubation period of the disease (the time until the appearance of decay symptoms). The retardation of gray mold development in tomatoes infected with *B. cinerea* spores is a consequence of shifting the temperature away from the germination optimum (17-20°C). It was shown that heat treatments at 38°C directly suppressed *B. cinerea* spore germination for 24 h following their exposure to heat stress (Barkai-Golan 2001). In the present study, although the optimal heat treatment temperature varied in terms of efficacy for induction HR (38°C), tissue break-down inhibition (36°C to 39°C), mycelium abundance and lesion size reduction (36-39°C and 38-39°C respectively); the ideal heat treatment effect could be obtained only if treated material was exposed to a particular

temperature for a designed duration. Otherwise, heat treatment could not result in the expected effect, which emphasizes that all fruits should be treated at a designated temperature, i.e. uniformly treated. Similarly, it is quite important for each individual fruit to be uniformly exposed to the heating media.

Under the uniform treatment, mycelium growth and lesion expansion on tomato fruits heated with 38°C or 39°C hot air, were significantly inhibited compared to tomatoes in circulated room-temperature air. However, the latter did not differ from tomatoes stored at 20°C storage room with intermittent air flow. Similarly, the unheated part of heterogeneously-treated tomato fruits showed similar symptoms to the two control groups except for lesion size where the unheated portion was similar to control fruits with circulated room temperature air but not with those stored at 20°C without air circulation. This could be explained by the fact that forced air stress might increase the sensitivity of tomato fruits to susceptibility to disease as observed by stress provoked by UV (Charles et al. 2008c). More weight loss of tomatoes exposed to circulating room temperature air was observed compared with those kept in 20°C storage chamber, and water stress causes a response that is similar in some cases to oxidative stress such as UV or ozone. Thus, the higher sensitivity of tomatoes treated with circulated room temperature air could be the result from such an oxidative stress. The data presented here highlight that when the beneficial heat level is not reached, there is a possible risk that disease development is not controlled but rather disease sensitivity is increased. This finding implies that the commodities should be heated by media controlled at an effective temperature range in order to achieve expected heat treatment effects.

Heat damage and tolerance to heat exposure is influenced by species, cultivar, harvest maturity stage, growing conditions and handling between harvest and treatment (Lurie 2006). Temperatures of 35–40°C have been found to be effective, depending upon the commodity (Lurie 1998). Lurie & Sabehat (1997) found that temperatures higher than 38°C were not generally as effective as 38°C, but caused heat damage in tomato. 'Manila' mangoes showed severe skin scalding when forced-air heated at temperatures of 45°C or higher, slight skin scalding from heating at 44°C and no damage at 43°C, indicating the presence of a threshold temperature for skin injury to develop (Ortega-Zaleta and Yahia 2000). Tissue damage caused by heat will also result in increased decay development.

In the present study, the effective temperature range affecting tissue breaking-down and mycelium abundance (36-39°C) and lesion size (38-39°C) are wider than the temperature range affecting and hypersensitive response (38°C), which could be explained by the fact that in our experiment mycelium plugs were used instead of a spore suspension. These two types of fungal structures differ considerably, which might have an impact on heat treatment response. Spores' sensitivity to heat is also dependent on their physiological state. Germinated fungal spores are markedly more sensitive to heat than non-germinated spores (Barkai-Golan 2001).

5.4.2 Effect of temperature gradient

The temperature gradient affected all disease indices (Tables 5.3-5.6). The beneficial effect of heat treatment (H39) was generally reduced when the temperature gradient was high. Hypersensitive response tended to be stronger in H39 portion, compared to the control part, independently of the level of the gradients; however the difference was significant only for largest gradient (16°C) (Table 5.3). Physical containment represented by fungal growth and development, measured in terms of restriction of tissue break down (Table 5.4), mycelium abundance (Table 5.5) and lesion area (Table 5.6), was most effective in a 3°C H39 gradient. Clearly a non-systemic mode of action of heat treatment reduced disease development. This mode of action of heat treatment could be anticipated from the difference in ripening rate of tomato fruit portions exposed to higher heat regimes compared to their less heated counterparts (Lu et al. 2007b). It is likely that the protection afforded through heat treatment evolved from mechanisms that are triggered differently than the activation of host defence via elicitors of systemically acquired resistance (Feys and Parker 2000). One possibility might be that heat treatment act as a local activator of host defences in a manner similar to the action of UV-C treatment (Mercier et al. 2000). Heat treatment may also have directly inhibited fungal growth (Fallik 1993).

Table 5.3: Comparison of hypersensitive response (HR) by Kruskal-Wallis test and Wilcoxon Matched-Pairs Signed Ranks Tests.

		Independence		Matched pairs		
Temperature Difference between upper and lower tunnel	Treatment	Mean ± Std Error Mean	Pr > Chi-Square	Mean±Std Error Mean	Pr > Chi-Square	Signed Rank Pr ≥|S|
16°C	Ctrl	0.140 ± 0.053^{ab}	0.0202	0.719 ± 0.081^{A}	0.0752	0.0391
	H	0.256 ± 0.067^{aDE}		0.500 ± 0.090^{ABC}		
	C	0.070 ± 0.039^{bE}				
3°C	Ctrl	0.08 ± 0.044^{b}	0.8929	0.51 ± 0.083^{ABC}	0.2483	0.2266
	H	0.300 ± 0.073^{aCD}		0.432 ± 0.083^{ABC}		
	C	0.286 ± 0.077^{aBCD}				
1°C	H			0.613 ± 0.089^{ABC}	0.7943	1.0000
	C			0.645 ± 0.087^{AB}		

Lowercase letters show the difference among treatments at each temperature difference set-up and between two set-ups according to the Duncan's Multiple Range Test result after Kruskal-Wallis test; uppercase letters in the same row show the relationship between effect of one-side inoculation and two-side inoculation. Treatments indicated by the same letter are not significantly different at $\alpha = 0.05$.

Table 5.4: Comparison of tissue break down (cracks) by Kruskal-Wallis and Wilcoxon Matched-Pairs Signed Ranks Tests.

		Independence		Matched pairs		
Temperature Difference between upper and lower tunnel	Treatment	Mean ± Std Error Mean	Pr > Chi-Square	Mean±Std Error Mean	Pr > Chi-Square	Signed Rank Pr ≥|S|
16°C	Ctrl	0.674 ± 0.072^{a}	0.0183	0.156 ± 0.06^{B}	0.0037	0.001
	H	0.372 ± 0.074^{cAB}				
	C	0.627 ± 0.074^{abA}		0.500 ± 0.090^{A}		
3°C	Ctrl	0.684 ± 0.076^{a}	0.8034	0.297 ± 0.076^{AB}	0.3333	0.2891
	H	0.300 ± 0.078^{cAB}				
	C	0.429 ± 0.084^{bcAB}		0.405 ± 0.082^{AB}		
1°C	H			0.290 ± 0.083^{AB}	1.0000	1.0000
	C			0.290 ± 0.083^{AB}		

Lowercase letters were the Duncan's Multiple Range Test result after Kruskal-Wallis test, showing the difference among treatments at each temperature difference set-up and between two set-ups; uppercase letters in the same row show the relationship of the effect of one-side inoculation and two-side inoculation. Treatments indicated by the same letter are not significantly different at $\alpha = 0.05$.

Table 5.5: Comparison of mycelium abundance by Kruskal-Wallis test and Wilcoxon Matched-Pairs Signed Ranks Test.

		Independence		Matched pairs		
Temperature Difference between upper and lower tunnel	Treatment	Mean ± Std Error Mean	Pr > Chi-Square	Mean ± Std Error Mean	Pr > Chi-Square	Signed Rank Pr ≥|S|
16°C	Ctrl	1.209 ± 0.150^{a}	0.0003	0.063 ± 0.043^{D}	0.1280	0.0625
	H	0.581 ± 0.111^{bB}		0.281 ± 0.103^{CD}		
	C	1.302 ± 0.147^{aA}				
3°C	Ctrl	1.026 ± 0.133^{a}	0.1132	0.189 ± 0.065^{CD}	0.7740	1.0000
	H	0.325 ± 0.083^{bCD}		0.216 ± 0.069^{CD}		
	C	0.629 ± 0.143^{bBC}				
1°C	H			0.097 ± 0.054^{D}	0.6226	1.0000
	C			0.064 ± 0.045^{D}		

Lowercase letters were the Duncan's Multiple Range Test result after Kruskal-Wallis test, showing the difference among treatments at each temperature difference set-up and between two set-ups; uppercase letters in the same row show the relationship of the effect of one-side inoculation and two-side inoculation. Treatments indicated by the same letter are not significantly different at $\alpha = 0.05$.

Table 5.6: Comparison of lesion area by Kruskal-Wallis test and Wilcoxon Matched-Pairs Signed Ranks Test.

		Independence		Matched pairs		
Temperature Difference between upper and lower tunnel	Treatment	Mean ± Std Error Mean (mm^2)	Pr > Chi-Square	Mean ± Std Error Mean (mm^2)	Pr > Chi-Square	Signed Rank Pr ≥|S|
16°C	Ctrl	10.211 ± 1.220^{a}				
	H	6.380 ± 0.976^{bB}		1.17 ± 0.465^{E}	0.0931	
	C	11.437 ± 0.956^{aA}	0.0006	2.77 ± 0.81^{CDE}		0.0638
3°C	Ctrl	9.44 ± 0.947^{a}				
	H	3.978 ± 0.752^{bBCD}		1.93 ± 0.470^{DE}	0.5848	
	C	4.799 ± 0.836^{bBC}	0.4323	1.99 ± 0.415^{CDE}		0.8368
1°C	H			1.04 ± 0.430^{E}	0.5919	
	C			1.15 ± 0.411^{E}		0.8794

Lowercase letters were the Duncan's Multiple Range Test result after Kruskal-Wallis test, showing the difference among treatments at each temperature difference set-up and between two set-ups; uppercase letters in the same row show the relationship of the effect of one-side inoculation and two-side inoculation. Treatments indicated by the same letter are not significantly different at $\alpha = 0.05$.

5.4.3 Effect of inoculums

Compared with independent comparison when only one side of partially heated tomato was inoculated, the hypersensitive response (Table 5.3) of either side of matched pairs was significantly greater when both sides of a partially heated tomato were inoculated with mycelium plugs as less heated part was exposed to air at 23°C. This could be explained by the fact that the mycelial plug-induced reaction might be systematic rather than localized. Similar result was reported by (Mercier et al. 2000). However, when the temperature difference between H and C was reduced, the difference between these two inoculation methods was not significant.

Similarly, when the temperature difference between H and C was greater as C was controlled at 23°C, mycelium abundance (Table 5.5) and lesion development (Table 5.6)

under two-sided were significantly lower than its one-sided counterpart due to inoculation-induced resistance. Moreover, when the temperature difference decreased, the difference between these two inoculation methods was not significant.

Although when C was controlled at 23°C, less tissue breakdown (Table 5.4) occurred for two-side-inoculated tomatoes than that for one-side-inoculated fruit, the difference between these two inoculation methods was not significant.

The mean score of ranking for matched-pair inoculation differed from that of one-side inoculation, and this difference was significant for most of investigation when the temperature gradient between H and C was greatest. However, the difference as a result of the effect of temperature gradient could be identified by pairwise comparison due to the powerful effect of the matched pair comparison.

5.4.4 Comparison of post-heat and pre-heat treatment inoculation.

For all parameters compared, the two control groups showed no significant differences between pre- and post-heat treatment inoculation, implying that no significant difference came from the timing of inoculation. Significant differences were identified between control and uniformly heated groups for both post-treatment inoculation and pre-treatment inoculation groups, which implied that heat treatment had a significant effect on disease control in terms of hyper-resistance response, reduction of tissue break down, mycelium growth, and lesion development, no matter whether the inoculation was conducted before or after heat treatment. The overall quality of treated fruits was significantly better than that of control for both pre-heat inoculation and post-heat inoculation groups, and this concurs with similar results obtained when water was used as the treatment medium (Fallik 2004).

Stronger hyper-resistance response (Fig. 5.4) appeared on pre-treatment inoculation group than on its corresponding post-treatment inoculation group for all uniformly treated groups. Significantly stronger response was also demonstrated on halves of heterogeneously-treated tomatoes heated after inoculation than their counterparts exposed to heat treatment before inoculation. Interestingly, even less heated portions of pre-heat groups showed a better effect than those of post-heat ones. It might

be that the relatively dry air (RH<30%) in these treatments dehydrated the inoculums, hence to some extent directly inactivated infection.

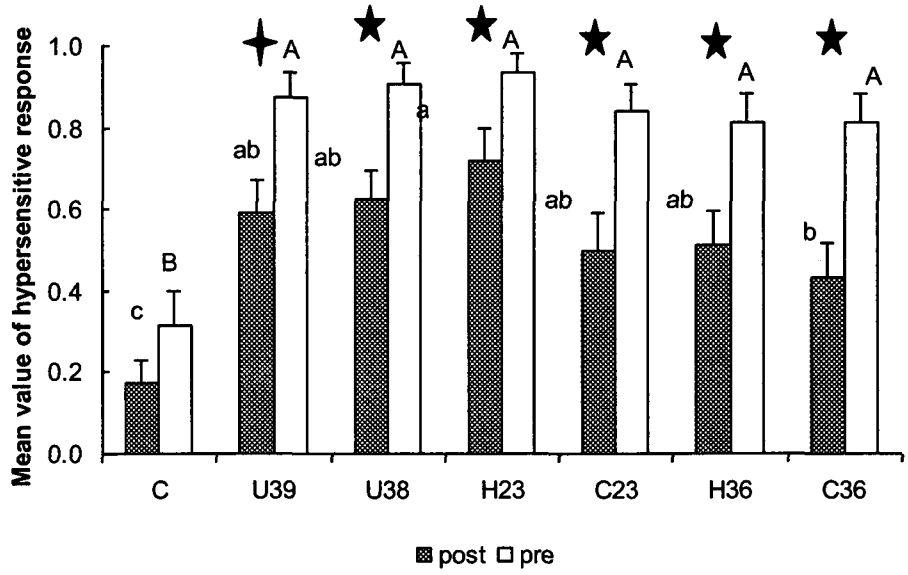

Figure 5.4: Comparison of hypersensitive response (HR) between pre-inoculation and post-inoculation treatments. The value and error bars represent the mean value and standard error of the mean, respectively, for each group. Letters above the bar indicate the result of Duncan's Multiple Range Test grouped by the mean rank score of nonparametric one way tests. Treatments indicated by the same letter are not significantly different at $\alpha = 0.05$. the four-pointed or five-pointed star indicated the marginal or significant difference, respectively, between pre-heat inoculated group and its correspondent post-heat inoculated one at each temperature setting, as assessed by Wilcoxon Rank Sums Test. C, fruit exposed to circulating air at room temperature; U39 or U38, fruits uniformly treated for 23 h at 39°C or 38°C respectively; H23, C23, heterogeneously treated for 23 h, with imposed air temperatures of 39°C and 23°C in the upper and lower chambers, respectively; H36, C36, heterogeneously treated for 23 h, with imposed air temperatures of 39°C and 36°C in the upper and lower chambers, respectively.

The mean value for tissue break-down of pre-heat treatment inoculated groups was lower than that of post-heat treatment inoculated ones (Fig. 5.5), which indicated that the combination of thermal suppression and an induced effect on reduction of tissue breakdown was greater than the induced effect alone; however, Wilcoxon Rank Sums Test results showed that this difference in effect was only significant for C23, H36, and C36. This difference could then be attributed to the fact that the air circulated during the entire treatment duration for heterogeneously treated groups, whilst air was only intermittently circulated during uniform treatment. Another possibility might be that heat transfer was better as a result of sufficient exposure to heat for uniform treated groups compared to heterogeneously-treated ones; resulting in a sufficiently large induced effect that regardless of pre-heat or post-heat treatment, differences were eliminated between the two.

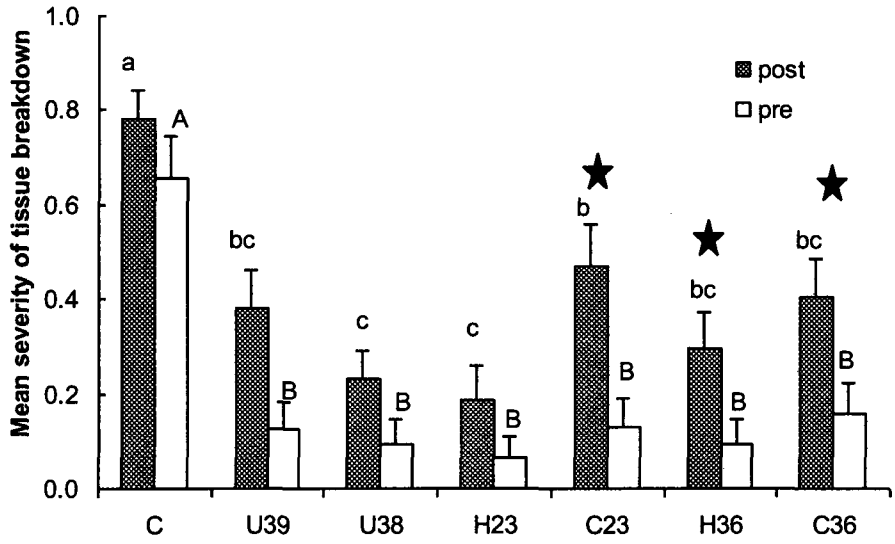

Figure 5.5: Comparison of tissue breakdown (cracks) between pre-inoculation and post-inoculation. The value and error bars represent the mean value and standard error of the mean, respectively, for each group. Letters above the bar indicate the result of Duncan's Multiple Range Test grouped by the mean rank score of nonparametric one way tests. Treatments indicated by the same letter are not significantly different at $\alpha = 0.05$. the five-pointed star indicated the significant difference ($\alpha = 0.05$) between pre-heat inoculated

group and its correspondent post-heat inoculated one at each temperature setting by Wilcoxon Rank Sums Test. C, fruit exposed to circulating air at room temperature; U39 or U38, fruits uniformly treated for 23 h at 39°C or 38°C respectively; H23, C23, heterogeneously treated for 23 h, with imposed air temperatures of 39°C and 23°C in the upper and lower chambers, respectively; H36, C36, heterogeneously treated for 23 h, with imposed air temperatures of 39°C and 36°C in the upper and lower chambers, respectively.

Similarly, although the mean value of tissue breakdown of the pre-heat group was lower than that of its correspondent post-heat group, ranking score results indicated that no significant difference existed between the post-heat inoculated group and its pre-heat inoculated counterpart in terms of mycelium abundance (Fig. 5.6), with the exception of C36, which showed a marginal difference.

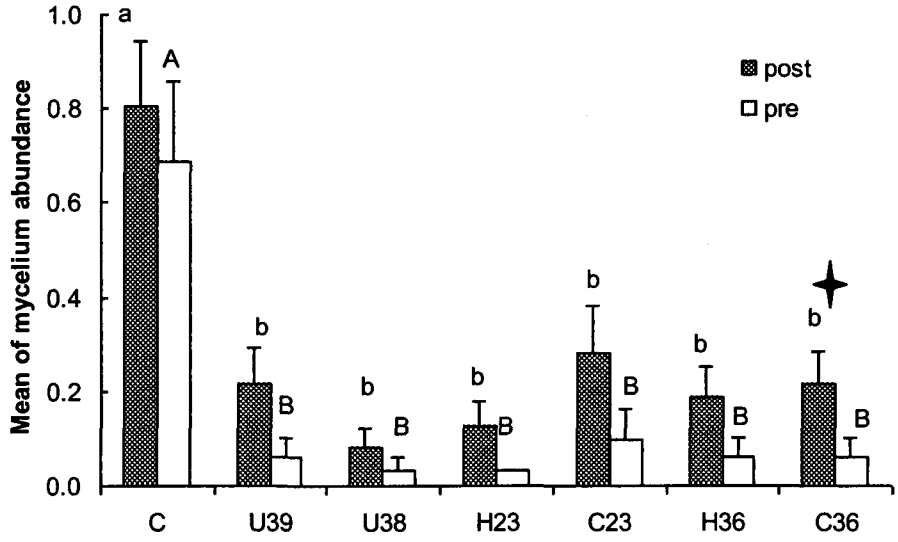

Figure 5.6: The comparison of mycelium abundance (Mycelium) between pre-inoculation and post-inoculation. The value and error bars represent the mean value and standard error of the mean, respectively, for each group. Letters above the bar indicate the result of Duncan's Multiple Range Test grouped by the mean rank score of nonparametric one way tests. Treatments indicated by the same letter are not significantly different at $\alpha = 0.05$.

The four-pointed star indicated the marginal difference (α = 0.10) between pre-heat inoculated group and its correspondent post-heat inoculated one at each temperature setting by Wilcoxon Rank Sums Test. C, fruit exposed to circulating air at room temperature; U39 or U38, fruits uniformly treated for 23 h at 39°C or 38°C respectively; H23, C23, heterogeneously treated for 23 h, with imposed air temperatures of 39°C and 23°C in the upper and lower chambers, respectively; H36, C36, heterogeneously treated for 23 h, with imposed air temperatures of 39°C and 36°C in the upper and lower chambers, respectively.

Pre-heat treatment inoculated groups showed significantly less lesion development (Fig. 5.7) than post-heat treatment inoculated ones, implying a strong combination of physical and induced effects.

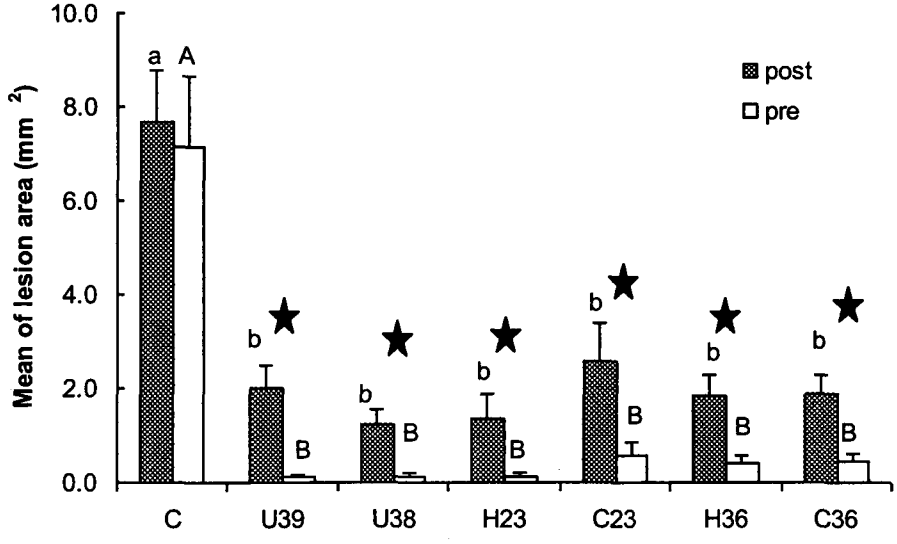

Figure 5.7: The comparison of infect lesion area between pre-inoculation and post-inoculation. The value and error bars represent the mean value and standard error of the mean, respectively, for each group. Letters above the bar indicate the result of Duncan's Multiple Range Test grouped by the mean rank score of nonparametric one way tests. Treatments indicated by the same letter are not significantly different at α = 0.05. The

five-pointed star indicated the significant (α = 0.05) difference between pre-heat inoculated group and its correspondent post-heat inoculated one at each temperature setting by Wilcoxon Rank Sums Test. C, fruit exposed to circulating air at room temperature; U39 or U38, fruits uniformly treated for 23 h at 39°C or 38°C respectively; H23, C23, heterogeneously treated for 23 h, with imposed air temperatures of 39°C and 23°C in the upper and lower chambers, respectively; H36, C36, heterogeneously treated for 23 h, with imposed air temperatures of 39°C and 36°C in the upper and lower chambers, respectively.

Postharvest heat treatment has been shown to be an effective non-chemical disease management strategy, acting by directly inhibiting pathogen growth, activating the natural resistance of the host, and slowing down the ripening process (Narayannasamy 2006). Heating, aimed at suppressing storage decay, could act directly by inactivating the pathogen, or indirectly via physiological and biochemical changes in the host, which enhances the resistance of the tissues to the pathogen (Barkai-Golan 2001).The inducible mechanisms of defence are of four types: (1) generation of signals; (2) structural barriers; (3) hypersensitive cell death (hypersensitive response, HR); and (4) inhibitors of pathogen growth (Barkai-Golan 2001). In our research, the inducible effect was apparent in the results of the post-heat inoculation groups, since the inoculum was not submitted to heat, and the results of pre-heat inoculated groups showed the combination effect of direct pathogen inactivation and activated resistance of the host by heat treatment. The difference between pre-heat and post-heat inoculation might be explained by the direct effect of heating on the pathogen. Our results showed that HR, and lesion development were highly affected by the direct effect of heat treatment; whilst mycelium growth was less affected; it might be mostly affected by induced defence mechanisms.

Several studies have demonstrated the potential of heat treatment to interact with both constitutive and induced defence mechanisms (Schirra et al. 1999; Terry and Joyce 2004). The mode of action of hot water dips on decay development appears to occur in interaction with fungal pathogens, as was exhibited by the inhibition of spore germination and germ-tube elongation of *Botrytis cinerea* and *Alternaria alternata*, the two main

fungi responsible for postharvest decay of peppers (Barkai-Golan 2001). However, unlike hot water treatment whose primary mode appears to limit decay development through direct inhibition of pathogen growth and by physically removing inoculum from the fruit surface, hot air could only directly inhibit pathogen growth. Hot water brushing brings about a clear redistribution of the epicuticular wax layer, part of the constitutive defence system, and a significant reduction in cuticular cracks, thus improving physical barriers to pathogen penetration (Ben-Yehoshua 2003; Fallik 2004). Works by Lurie et al. have demonstrated that heat treatment prevents the deterioration of molecules such as anionic peroxidases, which play an important role in the constitutive defence of tomato fruit against *B. cinerea* (Lurie et al. 1997; Lurie and Sabehat 1997). Heat treatments inhibit biochemical pathways involved in ripening and other processes in many fruit and vegetables and therefore, contribute to maintenance of juvenility and resistance. Heat treatment promotes the synthesis and accumulation of phytoalexins (induced antimicrobial compounds) and of chitinases and β-1,3-glucanases, enzymes associated with induced resistance through their ability to degrade fungal cell walls (Pavoncello et al. 2001; Ben-Yehoshua 2003).

Temperature differences between treated fruits could be decreased by mixing or increasing water circulation for water treatment, and using an RF or microwave treatment in combination with water (Birla et al. 2004). Air would obviously show the same problem, but no studies give a direct answer. The down side of moving a commodity in hot air is obvious, leading to mechanical injury due to the lack of buoyancy and water lubrication; and bruising can enhance the invasion of pathogen during storage. It's technically possible to get a relatively uniform treatment by reducing treating load, such as using a one layer layout; but this method is not economically feasible. If in-bin processing is necessary, some research results (Alvarez and Flick 1999a; Alvarez and Flick 1999b; Vigneault and de Castro 2005) of postharvest forced-air cooling might be shared for hot air treatment after validation.

5.5 Conclusion

The effective heat treatment temperature varied in terms of HR (38°C), tissue break-down and mycelium abundance (36-39°C), and lesion size (38-39°C); the ideal

heat treatment effect could be obtained only if treated material was exposed to a specific set temperature for a designed duration. Commodities should be heated by media controlled at an effective temperature range in order to achieve expected heat treatment effects. Otherwise; heat treatment might not result in the expected effect, which emphasizes that all fruits should be treated under this set temperature, i.e. uniformly treated. Similarly, it is quite important for each individual fruit to be uniformly exposed to heating media.

The temperature difference between H and C did affect the disease control reaction of tomatoes induced by heat treatment except for HR; however, this difference did not change too much after the temperature difference decreased to less than 3°C. Decreasing temperature difference between upper and lower chambers significantly improved the uniformity for disease control.

The overall quality of treated fruits was significantly better than for controls for both pre-heat and post-heat inoculation groups, and pre-heat groups showed a more marked effect than post-heat groups, implying the strength of the combined effect of direct physical effects and induced effects.

It is technically possible to get relatively uniform treatment by reducing treating load, such as using one layer layout. However, if in-bin processing is necessary, some research results of postharvest forced-air cooling package based on simulation might be used for hot air treatment after validation.

5.6 Acknowledgements

The authors are grateful to the NSERC (Natural Sciences and Engineer Research Council of Canada) and AAFC (Agriculture and Agri-Food Canada) for their financial supports. We also appreciate the assistance of Marie Ciotola, Bernard Goyette, Jérôme Boutin, and Dominique Roussel during the experimental portion of the study.

CONNECTING STATEMENT 4

So far the effect of heat treatment uniformity on disease control of harvested tomatoes has been studied. Starting from this chapter, the effect of heat treatment uniformity on quality and chilling injury control will be investigated.

The intended manuscript is to be submitted to *Postharvest Biology and Technology.*

Jianbo Lu*, Clément Vigneault, Marie Thérèse Charles**, G.S.Vijaya Raghavan*, Bernard Goyette**. Effect of Heat Treatment Uniformity on Tomato Ripening and Chilling Injury.**

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Contributions made by different authors are as follows:

The first author, the Ph.D. student did the experimental work and prepared the manuscript; the second and fourth authors are the supervisors who guided the research work; the third and fifth authors gave scientific and technical support.

CHAPTER VI. EFFECT OF HEAT TREATMENT UNIFORMITY ON TOMATO RIPENING AND CHILLING INJURY

6.1 Abstract

An experimental set-up consisting of an insulated forced-air twin-chambered device was built to investigate the effect of heat treatment uniformity on color, firmness, titratable acidity, total soluble solids and severity of chilling injury (CI) in tomato fruits. The design allows one to submit tomato fruits to a non-uniform heat treatment by exposing one hemisphere of the tomato in one chamber to a heated airflow maintained at 39°C and a velocity of 0.24 m s^{-1}, while the other hemisphere is exposed in another chamber to a temperature of 23°C, and air velocity of 0.24 m s^{-1}. Suitable instrumentation was used to control the temperature of both chambers and provide the desired fixed airflow rate. The test tomatoes were randomly divided into five lots: one was used as control, two were uniformly treated, and the other two were non-uniformly treated. Immediately after treatment, the fruits were transferred to storage at one of three different temperatures: 14°C (regular storage), 20°C (ripening) or 4°C (CI). Color, firmness, TA, TSS and severity of CI were evaluated at predetermined times. A significant difference was found between the heated and unheated half-tomatoes in terms of color and CI. No significant difference was found in the taste indicator: sugar/acid ratio (TSS/TA). Results suggest that, in the heated tomato halves, the postharvest ripening process was delayed and that this delay was similar to the difference in ripening period between the uniformly heated tomato halves and the corresponding control. The observed difference gives support to a localized rather than a systemic effect of heat treatment on post-harvest quality parameters of tomato and that ensuring uniform heat conditions is of paramount importance in attaining the desired beneficial impact of post-harvest heat treatment.

KEY WORDS: Non-uniform, heat treatment, chilling injury, firmness, color, tomato, taste.

6.2 Introduction

Postharvest heat treatments are being used for disinfestation and disinfection of an increasing variety of crops, including fresh flowers, fruits and vegetables (Lurie 1998; Soto-Zamora et al. 2005). During the past few years, there has been an increasing interest in the use of heat treatment to control insect pests, prevent fungal rots, retard or minimize commodity response to temperature extremes. Part of this interest relates to the growing pressure from consumers for a reduction in the quantities of postharvest chemicals used against pathogens and insects. Heat treatment is considered a relatively safe physical treatment that can be used as an alternative to chemical control.

Fruits and vegetables are important sources of carbohydrates, proteins, organic acids, vitamins and minerals for human nutrition. When humans use plants or plant parts, whether for food or for aesthetic purposes, there is always a postharvest component that leads to loss (Fallik 2004). The susceptibility of fresh-harvested produce to postharvest disease increases during prolonged storage, as a result of physiological changes that enable pathogens to develop in the fruit.

Insect infestation of commodities is a major problem in the production, storage, marketing and exportation of agricultural commodities. Very few countries have the ability to produce enough fresh fruits and vegetables to meet their domestic needs during every week of the year, and this situation has created opportunities for trade. In 2002, world exports of fresh vegetables reached $7.5 billion, up 11% from 2001 and 19% from 1999, according to Global Trade Atlas statistics (USDA 2004). Phytosanitary restrictions have been developed to protect agricultural regions from the introduction of damaging insects (Kader 2003), diseases and non-native pest species. Many importing countries require inspection certificates attesting to the absence of live targeted pests in a shipment after a pre-approved postharvest "sanitation" treatments (Tang et al. 2000; Ikediala et al. 2002).

In a time of increased consumer awareness and concern that many of the chemical treatments applied to fruits and vegetables to control insects, diseases, and physiological disorders are potentially harmful to humans, there is an urgent need to develop effective, relatively safe physical treatments for insect disinfection and disease control in fresh

horticultural products. Among non-chemical technologies such as irradiation, hypobaric treatment or modified atmosphere packaging, heat treatment appears to be one of the most promising methods for postharvest control of decay (Fallik, 2004). Heat treatments can also be used to inhibit ripening processes, induce resistance to chilling injury (CI), and decrease external skin damage during storage, in order to extend shelf life and marketing potential. Many of the effects of heat treatment on fruits and vegetables have been studied. Most of the investigations have involved lab-scale experimentation and analytical or empirical equation models applied to the treatment of one type of produce at a time. Providing the level of heat treatment uniformity required to attain uniform results is one of the primary obstacles to industrialization of new approaches of this kind.

While some studies have investigated uniformity during the cooling process (de Castro et al. 2005; Vigneault and de Castro 2005), few studies have looked at the effect of heat treatment uniformity. Large differences in heat transfer coefficient values (up to 40%) were observed after measuring temperature evolution at the center of spherical sensors used as produce simulators (Alvarez and Flick 1999a; Alvarez and Flick 1999b). The differences resulted from local heat transfer coefficients associated with non-uniform airflow conditions (velocity and turbulence). During bulk processing, the heating field to which each commodity item is exposed can rarely be perfect. This is why treatment differences can be observed among commodities and even within the different parts of a given commodity. Some researchers have studied bulk heating issues in connection with scaling-up of radio frequency and hot water treatments (Bollen and Dela Rue 1999; Birla et al. 2004; Fallik 2004; Wang et al. 2006b). For conventional media, low specific heat capacity and poor heat transfer ability can cause problems, making it difficult to obtain uniform heating within individual fruits. It has been found that, for portions of apples located within cavities created by two adjacent fruits, which are effectively sealed off from the heating medium, heating to within 1°C of the target temperature is delayed by 25 min in a hot water drench and by 70 min in a forced-air heating system, because the heating rate is similar to that for the fruit core (Bollen and Dela Rue 1999). Moreover, fresh commodities are structurally, compositionally and morphologically heterogeneous, and hence a uniform heating effect is difficult to achieve. Although the problem of non-uniformity of heat transfer has been studied, it is still not clear what impact heating

differences have in terms of the response of treated horticultural produce. It is therefore important to investigate the physiological processes occurring in fruit and vegetable tissues during and following a non-uniform heat treatment to get a better understanding of the response of individual commodities to heat treatment uniformity. Development of methods that take this aspect into account should help to pave the way for commercial applications of heat treatments.

The objectives of the present research were to study the effect of heat treatment uniformity on a) quality attributes of tomato; and b) chilling injury in tomato fruits, by subjecting only one half of each fruit to a specific treatment and evaluating the effect of the treatment on the two halves separately.

6.3 Materials and methods

6.3.1 Experimental set-up

An experimental set-up (Fig. 6.1) consisting of an insulated forced-air twin-chambered device was built to generate a non-uniform heat treatment. This device was used to expose one hemisphere of a tomato fruit to heat treatment conditions in one chamber, while the other hemisphere was exposed to unheated, controlled conditions in the other chamber. Temperature control for both chambers, along with the desired airflow rate, was achieved using suitable instrumentation.

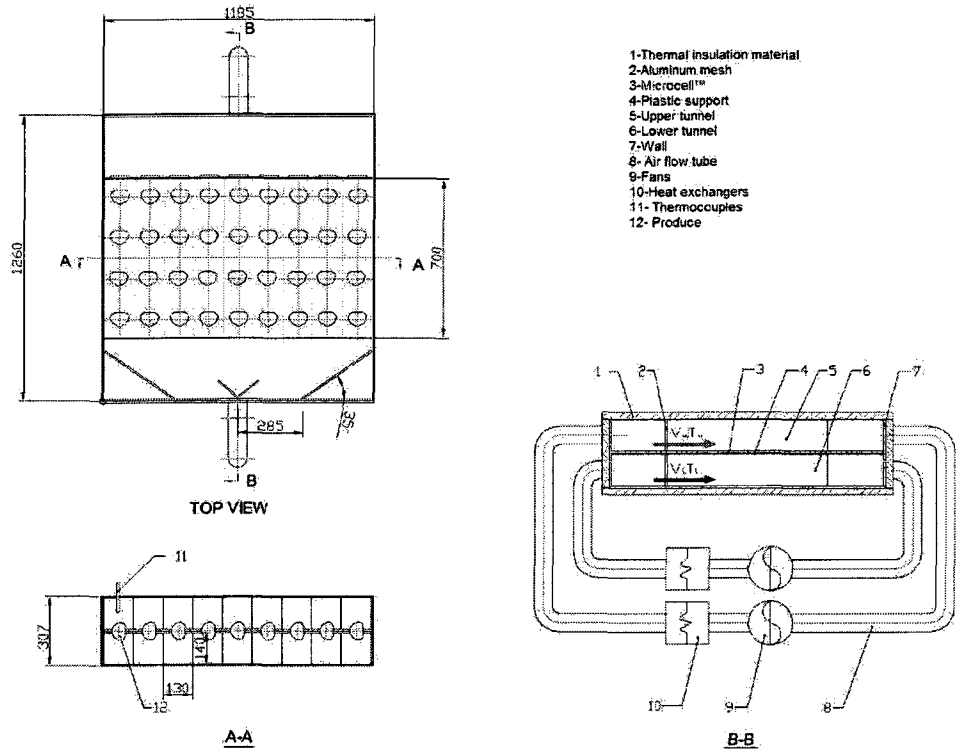

Figure 6.1: Experimental set-up consisting of a 1260 mm-wide × 1185 mm-long × 307 mm-high forced-air twin-tunnel allowing a produce matrix to be exposed to non-uniform environmental conditions.

The experimental device was separated upper (heated) and lower (non-heated) chambers by a 12-mm-thick insulation material (Microcell^{TM}) supported by an 8-mm-thick plastic plate. Each of the twin chambers was further divided into 9 tunnels in order to expose the test tomato fruits to relatively uniform airflow. The 0.700 m length of the tunnels kept the tomato fruits from being subjected to an airflow gradient along the flow direction. Steel sheeting was chosen as the tunnel separation material because of its high heat conductivity, thus helping to increase uniformity of air temperature conditions between adjacent tunnels. Aluminium mesh plate (68.3% open) coated with a porous adhesive-bonded fabric was placed over the entrance of the tunnel to ensure uniformity of airflows among tunnels.

Holes of similar size (equivalent diameter of 66 mm) to the longitudinal cross-section of tomato fruits were cut in the Microcell™ to hold the fruit during treatment, and bigger holes (82-mm-diameter) were cut in the plastic plate separating the twin chambers in order to position the tomato fruits along the center of the tunnel and to simultaneously expose half of each fruit to the conditions of one chamber and the other half to the conditions of the other chamber. Although Microcell™ is quite flexible, allowing for adjustment to the size variability of the tomato fruits, it was still difficult to guarantee air tightness between the twin chambers. Therefore, the same air velocity was used for both chambers to balance the pressure and decrease air infiltration between the chambers.

During the non-uniform treatment, one half of each tomato was exposed to 39°C air, while the other half was exposed to air at ambient temperature (23°C). The air velocity at the inlet was 0.24 m s^{-1}. By contrast, during the uniform treatment, both parts of each tomato were exposed to air heated to 39°C.

6.3.2 Instrumentation and control

Two channels of an 8-channel data acquisition system (Strawberry Tree, Sunnyvale, CA, USA) were used to control the experimental conditions. The control program was written using WorkBench PC for Windows (Strawberry Tree, Sunnyvale, CA, USA). The Agilent data acquisition system (34970 Data Acquisition/Switch Unit – Agilent Technology, HP, Palo Alto, CA, U.S.A.) was employed to simultaneously monitor the 18 air tunnels. The acquisition program uses custom software written using Labview language (National Instruments Corporation, Austin, TX, U.S.A.). Temperature was recorded at 3-min intervals.

6.3.3 Material

Tomato fruits (*Lycopersicon esculentum* Mill. cv. DRW 453) of uniform size at breaker stage (USDA, 1976) were picked directly from a commercial greenhouse. The fruits were first surface-sterilized for 3 min with a chlorine solution (150 mg of Cl_2 kg^{-1} as sodium hypochlorite), then thoroughly rinsed with tap water for another 3 min, and finally left on filter paper to drain, as described by Polenta et al. (2006).

6.3.4 Treatment

Clean tomato fruits were divided into five lots. Each lot was subjected to one of the following treatments:

(i) Not treated and referred to as the control unit (C)

(ii) Uniformly treated for 6 h (U6)

(iii) Uniformly treated for 23 h (U23)

(iv) Non-uniformly treated for 6 h (H6 and C6 = heated and unheated parts, respectively)

(v) Non-uniformly treated for 23 h (H23 and C23 = heated and unheated parts, respectively).

After each treatment, the tomato fruits were divided into three groups to be stored at different temperatures (4°C, 14°C, and 20°C) and at a relative humidity (RH) of 90–93%, in order to measure the effect of the treatments on chilling injury (CI) and the ripening process. Color, firmness, titratable acidity (TA) and total soluble solids (TSS) were measured on days 0, 4, 7 and 11 for the tomato fruits stored at 14°C and 20°C. An additional measurement of all these parameters was taken on day 15 for tomato fruits stored at 14°C. After 21 days, the fruits stored at 4°C were transferred to a storage room at 20°C and RH 90–93% for another 11 days and then evaluated for CI, using the approach described by Lurie and Sabehat (1997). Three replications were performed for all treatments. The quality parameters were measured on four tomato fruits from each treatment on each predetermined day.

6.3.5 Color

Color was measured according to the Commission Internationale de l'Éclairage (CIE). The value was determined with a Minolta Chroma Meter CR-400 (Konica Minolta, Japan) at two locations between equator and blossom end, as well as at four locations on the equatorial region, for both uniform and control treatments. For the non-uniform treatment, the values were measured at one location between the equator and the blossom end, and at two locations on the equatorial region of each half of the fruit. The values were recorded as L (Lightness), hue, and C (chroma). The mean value derived from all

measured locations on each tomato fruit was used in the statistical analysis of each parameter, as suggested by Ali et al. (2004).

6.3.6 Fruit firmness

Firmness (resistance to compression) was determined using a universal testing machine (Lloyd Instruments, LRX). This machine was equipped with a load cell of 100 N fitted with a standard 11.025-mm-diameter hemispherical-tip probe driven downwards at 0.416 mm s^{-1} to a depth of 5.5 mm. Firmness of individual fruit was measured twice on opposite sides at the equator for the uniform (U) treatment and for the control (C) group. For H6, C6, H23, and C23, the firmness measurements were performed on two adjacent zones at the equator level and around the top on both the heated and unheated parts of the tomato fruits. For each treatment, the mean value of two measurements was used for statistical analysis.

6.3.7 Titratable acidity and total soluble solids

Four tomato fruits from each treatment were sampled on the predetermined days. A 10-mm-wide pericarp strip was cut off at the equator on four tomato fruits from each treatment. The pericarp tissue was homogenized in a Waring blender and centrifuged at 4500 rpm for 5 min at 2°C (Beckman AccuSpin FR). The supernatant juice was used for TA and TSS measurements. TA was determined using a Titrino 719S automatic titrator (Metrohm, Switzerland) with 2 mL of tomato juice diluted in 30 mL of distilled water. Titration was done with 0.1 N sodium hydroxide to pH 8.1. Titratable acidity is expressed as g of citric acid/mL of tomato juice. Three readings were taken for each treatment on each predetermined day, and the mean of these readings was used for statistical analysis.

Total soluble solids (TSS) content of the full strength juice was determined by the AOAC method (1984) using a hand-held refractometer (ATAGO ATC-1E, Japan) at room temperature. A representative drop from well-shaken juice was placed on an absolutely dry and clean refractometer prism and readings were taken directly. Total soluble solids content is expressed as percentage on the Brix scale.

6.3.8 Chilling injury (CI)

Tested tomato fruits were stored at 4°C (Lurie and Sabehat 1997) for 21 days before being allowed to ripen at 20°C, and the two most clearly documented symptoms of chilling injury (Cheng and Shewfelt 1988) susceptibility to decay and alteration of ripening pattern, evidenced by inadequate color development, were used to assess CI in tomato fruits. Chilling injury, estimated visually as surface lesions on the fruit, pitting, decay and fruit color from green to red, was determined on day 11 on all fruits in the 7–10 replicates of each treatment after the tomato fruits were transferred to storage at 20°C. Fruits were evaluated for physiological disorders such as pitting, stress scar, cracking and severity of irregular ripening, as well as for pathological indicators, such as number and size of lesions and appearance of typical colony. An assessment was performed by two evaluators using a 0–5 scale (0 = free of defects, 5 = extremely susceptible).

6.3.9 Statistical analysis

Experiments were performed according to a factorial design with time and treatments as the factors. Statistical analysis was performed with the GLM procedure of SAS (SAS Institute Inc., 1989), and the treatment differences were separated using Duncan's Multiple Range Test. A two-tail paired *t*-test was used to determine the difference between heated and unheated parts for the non-uniform treatment.

6.4 Results and discussion

Preliminary tests indicated that tomato fruits exposed to a temperature of 36°C or higher for 23 h showed heat treatment effects in terms of ripening delay, chilling injury control, and disease control; however tomato fruits were damaged when exposed to a temperature of 40°C or higher. Between 36°C and 39°C, the higher the air temperature and longer the duration of treatment, the more significant the effects were. In order to shorten the experiment, a temperature of 39°C was applied for 23 h, while a 6-h period was used to investigate the effect of exposing the treated material to non-uniform conditions for a shorter heating duration. The uniform treatment ensured that each whole tomato was treated uniformly at the predetermined temperature.

6.4.1 Color

A delay in red color development, represented by a higher hue value compared with the control values (C) (Table 6.1), was observed in uniformly heated tomato fruits (U6 and U23) held at 14°C and in U23 held at 20°C. The delay was greater with longer treatment duration. Uniformly heated tomato fruits (U6 and U23) showed significantly higher lightness values than the control group under 14°C and 20°C storage conditions. A significant difference in chroma was found between control and treated groups when stored at 14°C, whereas no difference was identified for those stored at 20°C. The tomato halves heated for 6 h did not differ from the unheated parts in terms of lightness, chroma, or hue. All color parameters of both H6 and C6 were similar to those of the control group, suggesting that there was no heat treatment effect owing to the insufficient duration of this treatment. This would explain the difference between heated and unheated parts. After 23 h of heat treatment, H23 fruit halves showed a significant delay in red color development at 14°C; they were also shinier than C23 tomato fruits stored at 14°C and 20°C, but their color was less vivid at 14°C.

The color parameter values of the unheated parts of H6 and H23 tomato fruits were identical and did not differ from those of the control group. On the other hand, the heated parts (H23 and H6) differed from each other in terms of lightness at 20°C, chroma at 14°C, and hue at 14°C, and significant color parameter differences were found between H23 and the control, with the exception of lightness at 14°C and chroma at 20°C.

Table 6.1: General effect of heat treatment on color, firmness, titratable acidity (TA), total soluble solids (TSS) and TSS/TA ratio of treated tomato fruits from day 4 to day 11 for 20°C storage, and from day 4 to day 15 for 14°C storage.

Trt	Color						Firmness		TA		TSS				Sugar acid ratio	
	L		C		hue		Fmax (N)		(g/L)		(%)					
	20	14	20	14	20	14	20	14	20	14	20	14	20*	14*	20	14
C	37.56^{d}	41.60^{cd}	23.92^{a}	23.01^{a}	34.97^{c}	37.56^{d}	10.90^{a}	12.78^{a}	4.49^{b}	4.83^{c}	4.24^{b}	4.11^{c}	4.27^{a}	4.11^{b}	9.44^{a}	8.58^{ab}
U6	41.63^{c}	42.41^{b}	22.30^{a}	20.76^{b}	37.65^{bc}	41.63^{c}	10.39^{ab}	12.40^{ab}	4.73^{ab}	4.92^{abc}	4.32^{ab}	4.23^{abc}	4.33^{a}	4.24^{abc}	9.14^{a}	8.56^{ab}
U23	49.32^{a}	43.16^{a}	22.09^{a}	19.49^{c}	44.05^{a}	49.32^{a}	10.17^{b}	12.03^{b}	4.90^{a}	5.01^{abc}	4.48^{a}	4.37^{a}	4.45^{a}	4.33^{a}	9.37^{a}	8.93^{b}
H6	39.11^{cd}	41.97^{bcd}	22.95^{a}	22.55^{a}	37.51^{bc}	39.11^{cd}	10.42^{ab}	12.07^{b}	4.60^{ab}	5.05^{abc}	4.27^{b}	4.23^{abc}	4.33^{a}	4.22^{abc}	9.27^{a}	8.45^{a}
C6	38.88^{cd}	41.51^{d}	23.20^{a}	23.13^{a}	37.80^{bc}	38.88^{cd}	10.46^{ab}	12.24^{b}	4.53^{ab}	4.92^{bc}	4.22^{b}	4.16^{bc}	4.30^{a}	4.19^{ab}	9.31^{a}	8.40^{a}
H23	45.18^{b}	42.21^{bc}	21.75^{a}	21.10^{b}	41.24^{ab}	45.18^{b}	10.09^{b}	12.05^{b}	4.87^{a}	5.23^{a}	4.41^{ab}	4.31^{ab}	4.42^{a}	4.28^{ab}	9.04^{a}	8.31^{a}
C23	392^{cd}	41.33^{d}	23.44^{a}	23.30^{a}	38.13^{bc}	39.2^{cd}	10.35^{b}	11.97^{b}	4.6^{ab}	5.1^{ab}	4.26^{b}	4.23^{abc}	4.28^{a}	4.19^{abc}	9.13^{a}	8.36^{a}

Means followed by the same letter in the same column are not significantly different according to Duncan's Multiple Range Test ($\alpha = 0.05$).

* Without considering day 7 at 20°C or day 4 at 14°C.

The results of paired *t*-tests, shown in Table 6.2 (20°C) and Table 6.3 (14°C), illustrate the differences between the heated and unheated parts of tomato fruits, and the significance of the difference on each evaluation day. A significant delay in color development ($\alpha = 0.05$) for the heated tomato parts, as represented by a higher hue value, was seen right after 23 h of heat treatment, and this delay was even more pronounced on the subsequent sampling days: day 4 ($\alpha=0.01$) at 20°C; day 4 ($\alpha = 0.001$), day 7 ($\alpha = 0.001$), and day 11 ($\alpha = 0.01$) at 14°C. However, the delay vanished on day 7 and subsequently at 20°C, and on day 15 at 14°C. Lightness and chroma did not differ between H23 and C23 right after treatment; however, on day 4 a significant difference in lightness ($\alpha = 0.05$) and chroma ($\alpha = 0.01$) was identified between H23 and C23 for storage at 14°C and at 20°C. The difference in lightness values was also found on day 11 at 20°C and on day 7 at 14°C with a higher significance level ($\alpha = 0.01$); the difference in chroma continued throughout the observation period for both storage conditions. H6 and C6 were not significantly different in terms of lightness and hue for either 20°C or 14°C storage; however, a significant difference was observed for chroma on day 4 at 20°C and on day 7 at 14°C at $\alpha = 0.01$ and $\alpha = 0.05$, respectively.

The inhibition of red color development was consistent with the results of cherry tomato treated by hot air alone or combined with MA (Ali et al. 2004), 'Sunbeam' tomato (McDonald et al. 1999) treated by hot water, tomato (Cheng et al. 1988; Inaba and Chachin 1988; Mitcham and McDonald 1992; Sozzi et al. 1996; Soto-Zamora et al. 2005; Polenta et al. 2006) treated by hot air, and strawberry (Vicente et al. 2002; Vicente et al. 2003) treated by hot air.

Table 6.2: Effect of heat treatment on color, firmness, titratable acidity (TA), total soluble solids (TSS) and TSS/TA ratio on different sampling dates for tomatoes stored at 20°C.

Day		Color						Firmness		TA		TSS		Sugar acid ratio	
		L		Hue		C		Fmax(N)		(g/L)		(%)			
		6	23	6	23	6	23	6	23	6	23	6	23	6	23
1	Heated	51.17	47.49	99.42	80.32*	20.61	18.92								
	Unheated	50.70	46.97	95.80	70.74*	19.45	19.07								
4	Heated	42.78	43.70*	41.78	50.91**	20.40**	19.44**	11.57	11.29	4.87	5.04	4.40	4.50	9.04	8.94
	Unheated	42.22	42.31*	41.09	41.78**	21.25**	21.17**	11.42	11.58	4.80	4.97	4.33	4.37	9.02	8.79
7	Heated	40.67	40.81	35.72	37.82	23.22	21.92***	10.37	9.57	4.44	4.96	4.13	4.40	9.32	8.91
	Unheated	40.33	40.74	36.50	36.63	23.14	24.06***	10.55	9.90	4.41	4.67	4.07	4.20	9.23	9.00
11	Heated	39.72	38.92**	35.04	34.94	25.25	23.88**	9.05	9.12	4.45*	4.62*	4.27	4.33	9.49	9.39
	Unheated	39.47	39.36**	35.81	35.88	25.21	25.14**	9.14	9.30	4.38*	4.34*	4.27	4.20	9.74	9.71

Mean values obtained on the same day and followed by *, ** or *** are significantly different at $\alpha = 0.05$, 0.01 or 0.001, respectively, according to two-tail paired t-tests.

For tomato, a climacteric fruit which depends upon ethylene for coordinated ripening, the high temperature inhibition of ethylene production can inhibit many ripening processes, including fruit softening, color changes and aroma development. The synthesis of ethylene, which synchronizes the ripening processes of climacteric fruits, is inhibited at temperatures near or above 35°C. The inhibition of ripening due to lack of ethylene is reversible if the heat treatment is not too extended and does not cause damage, so that regular biosynthesis of aromatic compounds and lycopene occurs (Lurie 2006).

In our experiment, in contrast to the comparison of fully heated tomato fruits with control fruits during storage, the color of the heated portion did not significantly differ from that of the unheated portion of partially treated tomato fruits. One reason for this might be that the two halves of partially treated tomato fruits were under the same storage environment, so the greater ethylene release in the faster ripening halves would induce the ripening process of the unheated part, thus eliminated the difference in ripening process between the two parts. This hypothesis was verified by the very similar coloring at the end of storage (Table 6.2 and Table 6.3).

Table 6.3: Effect of heat treatment on color, firmness, titratable acidity (TA), total soluble solids (TSS) and TSS/TA ratio on different sampling dates for tomatoes stored at 14°C.

Day		Color						Firmness		TA		TSS		Sugar acid ratio	
		L		Hue		C		Fmax(N)		(g/L)		(%)			
		6	23	6	23	6	23	6	23	6	23	6	23	6	23
1	Heated	51.17	47.49	99.42	80.32*	20.61	18.92								
	Unheated	50.70	46.97	95.80	70.74*	19.45	19.07								
4	Heated	45.53	45.90*	47.07	62.16***	18.99	17.41***	12.65	12.41	5.42	5.34	4.27	4.40	7.88	8.25
	Unheated	44.75	44.00*	47.11	46.59***	19.70	20.50***	12.32	12.11	5.37	5.43	4.13	4.37	7.64	8.05
7	Heated	42.39	43.14**	37.61	45.04***	21.96*	19.44***	12.27	12.18	5.27	5.10	4.33	4.30	8.22	8.43
	Unheated	41.66	42.16**	37.04	40.06***	23.07*	21.91***	12.17	12.07	5.21	4.98	4.20	4.23	8.07	8.51
11	Heated	40.23	40.21	35.83	37.01**	23.96	23.45**	11.52	11.81	4.97	5.28	4.27	4.40	8.59	8.36
	Unheated	40.18	39.74	35.03	34.91**	24.58	24.97**	11.60	11.40	4.92	5.05	4.27	4.30	8.68	8.53
15	Heated	39.73	39.9	35.92	36.53	25.26	24.11**	11.20	11.15	4.38	5.00	4.07	4.13	9.28	8.29
	Unheated	39.48	39.41	36.78	36.49	25.20	25.82**	11.35	11.14	4.33	4.78	4.10	4.03	9.47	8.44

Mean values obtained on the same day and followed by *, ** or *** are significantly different at $\alpha = 0.05$, 0.01 or 0.001, respectively, according to two-tail paired t-tests.

Contrary to the diminished fruit lightness of strawberry after 3 h hot air treatment (Vicente et al. 2002), in our research, the overall lightness of uniformly treated tomato fruits was higher than that of control, and a similar tendency was observed for 23h partially heated tomato fruits.

6.4.2 Firmness

The heat treatment using hot air reduced the firmness of tomato fruits compared to the control (Table 6.1). The longer the treatment, the softer the tomato fruits became. The U23 fruit were significantly softer than control fruit under both storage conditions; U6 fruit also tended to be softer than the control fruit during storage at 14°C and 20°C; however, these differences were not significant. The significance could be identified right after heat treatment or on the first observation day, but the difference tended to diminish along with storage as a result of the lesser softening rate of heated fruits (data not shown). This finding was also reported by Lurie and Klein (1992). The differential softening rate is probably associated with the different ethylene production rates shown by control and heated fruit (Budde et al. 2006).

When stored at 14°C, all treated tomato fruits were softer than the control fruit, without any marked difference being noted between heated and unheated parts for the non-uniformly treated fruits. When held at 20°C, H23 tomato fruits were softer than the control ones and showed similar firmness to U23 fruit; however, no significant difference was found between unheated and heated parts. There was no significant difference in firmness between H6, C6 and U6.

No significant difference was found between H6 and C6, or between H23 and C23 on any of the sampling days for storage at 14°C or 20°C (Table 6.2 and Table 6.3).

The present results confirm the conclusion that most cultivars of tomato fruits become significantly softer after heat treatment than fruits maintained at 20°C during the same period (Manzano-Mendez et al. 1984). It also concurs with the finding for 72 h hot air treated tomato fruits (Polenta et al. 2006). A similar trend towards softness has also been found for Dragon fruits (*Hylocereus* sp.) after hot air disinfestations (Hara et al.

1997), and oranges [Citrus sinensis (L.) Osbeck] heated by hot air (Plaza et al. 2003; Schirra et al. 2004). However, others have shown that the firmness of heated tomato fruits was not significantly softer or was even higher than that of control fruit, immediately after heat treatment (Lurie and Klein 1992; Lurie and Sabehat 1997).

Mitcham and McDonald pointed out that loss of firmness during hot air treatment may have been related to moisture loss, and the increase in weight loss of tomatoes by heat treatment might also be caused by an increased rate of respiration (Inaba and Chachin 1988) or an increased vapor pressure deficit at the higher temperature (Mitcham and McDonald 1992).

6.4.3 Titratable acidity

The effect of heat treatment on TA is presented in Table 6.1. When stored at 20°C, heat-treated tomato fruits, whether uniformly or non-uniformly treated, showed higher acid levels than controls, and this difference was significant for U23 and H23 in comparison to the controls. However, there was no significant difference among heat treatments. Under 14°C storage conditions, H23 fruits maintained the highest level of acidity and differed from the controls, but generally not from C23. The TA for H23 was statistically greater than that of C6. Nonetheless, no significant difference was found among the other treatments.

Based on the results of paired *t*-tests (Tables 6.2 and 6.3), a significant decrease in the acidity was observed. It is generally known that hot air treatment induced an increase of the fruit's basal metabolism, particularly accelerating the catabolic rate of this organic acid (Tucker 1993). In the present research, TA was represented by citric acid, not malic acid as under normal conditions; hence, the predominant acid of ripened tomato fruits is citric acid, with malic acid being the next most abundant material. Changes in TA have generally been attributed either to changes in citric acid alone, or to changes in both, citric and malic acids (Hobson and Davies 1971). This could partially explain the different trend of our results to others'.

Another reason might be the effect of ripeness slowing down following heat treatment which has been indicated by delayed coloring. The present research did not check the TA right after treatment, while the TA reductions in previous researches were

measured immediately after heat treatment; the data in Table 6.1 reflected the mean value of parameters measured from day 4 of storage. It might be that decelerating metabolism as the result of delay ripening resulted in the higher TA level for heated tomato fruits.

6.4.4 Total soluble solids

Over the whole storage period, U23 and H23 showed significantly higher TSS content than the control tomatoes when stored at 14°C (Table 6.1). For storage at 20°C, there was no difference between any of the treatments and the control, with the exception of U23. For the fruits stored at 14°C, U23 and H23 showed significantly higher TSS than the control, but no difference was found between U6 and U23, or between heated parts and unheated parts, after 6 h or 23 h of non-uniform treatment.

The range of TSS values was greatest on day 4 for fruits stored at 14°C (Fig. 6.2b) and on day 7 for storage at 20°C (Fig. 6.2a). TSS values generally decreased toward the end of the storage period. The TSS content of heated tomato fruits (U6 and U23) or heated parts (H6 and H23) was higher than that of the controls and the unheated parts (C6 and C23). When the maximum range values are omitted (day 7 at 20°C or day 4 at 14°C) (Table 6.1), all of the above-mentioned differences disappear at the end of the storage period (Fig. 6.2a and 6.2b), except that a constant difference is observed between U23 and the control when stored at 14°C.

TSS of heated parts (H6, H23) was higher than the corresponding value for unheated parts (C6, C23) on each day, whether stored at 14°C or 20°C; however no significant difference was identified (Tables 6.2 and 6.3).

The ripening of heated tomato fruits was delayed, and the heated groups showed slower decreasing levels of TSS compared to controls (Fig. 6.2a and 2b). Similarly to TA, this result might be related to a lower consumption of sugars as the result of slowing down of ripening during storage following heat treatment. Thus, heated fruits kept a higher sugar content. The increased sugar content of heated tomato fruits was consistent with the results of Lurie and Klein (1992) who found that at the end of storage and shelf-life the heated tomato fruits had higher soluble solids content than control tomatoes.

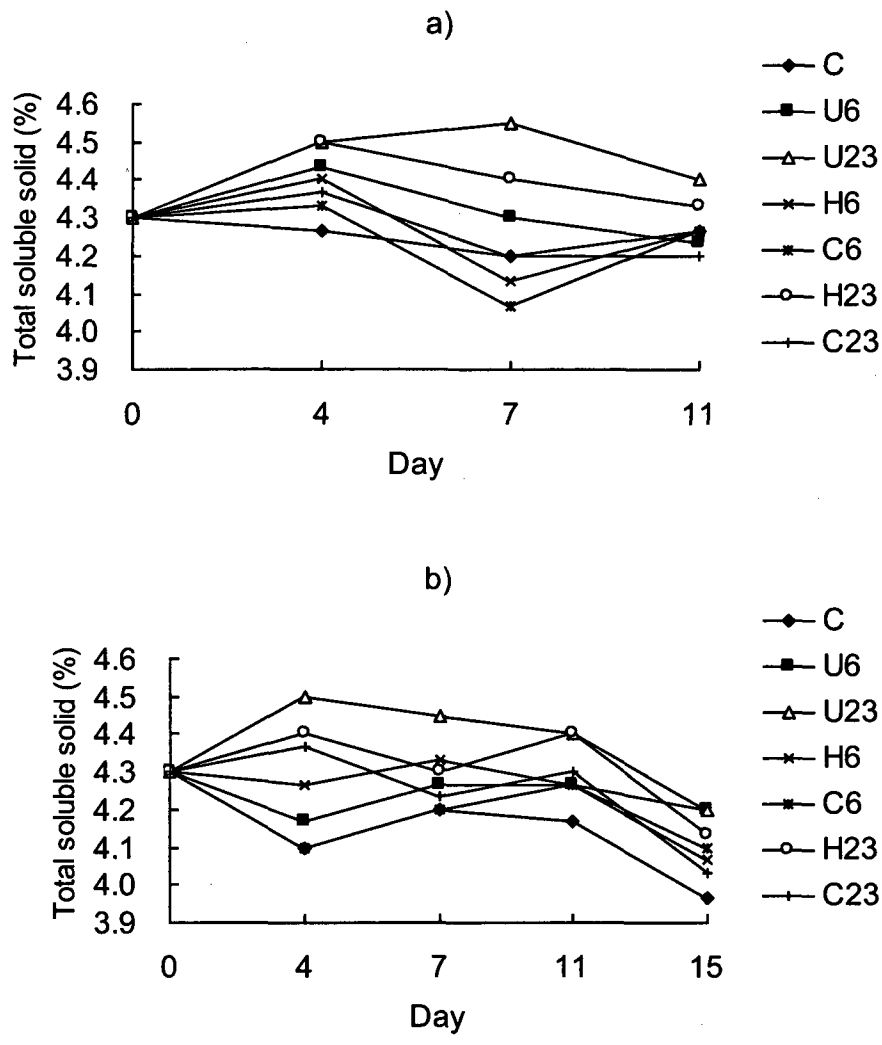

Figure 6.2: Effect of different heat treatments on total soluble solids (TSS) of tomatoes stored at 20°C (a) or 14°C (b) and treated as follows: untreated (C), uniformly treated for 6 h (U6) or 23 h (U23); heated part of fruit non-uniformly treated for 6 h (H6) and unheated part for 6 h (C6); heated part of non-uniform treatment for 23 h (H23), and unheated part of non-uniform treatment for 23 h (C23).

6.4.5 TSS/TA ratio

The sugar/acid ratio is an important taste factor and an indicator of maturity and/or ripeness in some mature fruit-type vegetables such as tomatoes (Malundo et al.

1995). There was no significant difference in TSS/TA ratio among the treatments and the control group at 20°C. Fruits held at 14°C, the C, U6 and U23 groups tended to display higher ratios than the other treatments. However, only U23 showed a significantly higher TSS/TA ratio than the non-uniform treatments. Since heat treatment increased both TSS and TA, the sugar/acid (TSS/TA) ratio was not affected. Similar results have been reported (Shellie and Mangan 1996; Porat et al. 2000b) for grapefruit (*Citrus* × *paradisi* Macfad.) heated by hot air or hot water.

There was no significant difference of TSS/TA ratio overall (Table 6.1) or on any particular observation day (Table 6.2, Table 6.3) between the heated parts and the non-heated parts of non-uniformly treated tomatoes regardless of the treatment duration or of the post-treatment storage temperature. This finding suggests that heat treatment did not have a marked effect on the sweet-sour taste characteristic of tomatoes.

6.4.6 Chilling injury

Compared to the control (Fig. 6.3), H23 showed significantly more resistance to chilling injury, whereas H6 did not differ from the control or from C6. Even with the paired *t*-tests, no significant difference in severity of CI was found between the H6 and C6 fruits (Table 6.4). However, the C23 portions showed significantly more pronounced symptoms than the H23 portions, especially with respect to pitting on the stem scar side, discoloration, and susceptibility to disease.

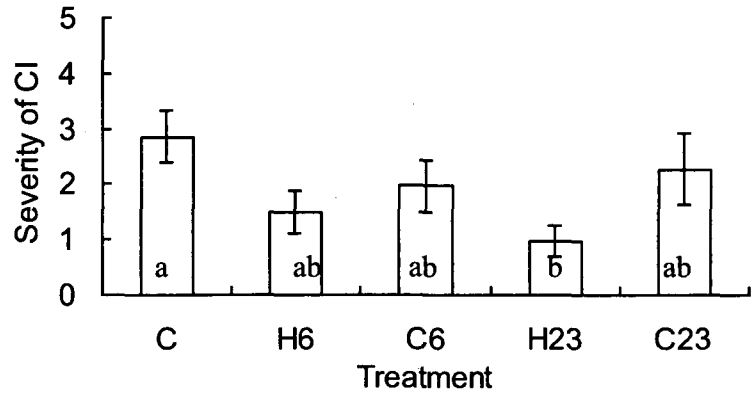

Figure 6.3: CI severity of untreated tomatoes (C), heated parts of non-uniformly treated for 6 h (H6), unheated 6 h (C6), heated part of non-uniform treatment for 23 h (H23), and unheated part of non-uniform treatment for 23 h (C23); letters in the column indicate the results of Duncan's Multiple Range Test, treatments indicated by the same letter are not significantly different at $\alpha = 0.05$.

Table 6.4: Effect of heat treatment on chilling injury severity of heated and unheated parts of tomatoes after 21 days at 4°C followed by 11 days at 20°C.

Tomato part	Treatment duration (h)	
	6	23
Heated	1.55^{a}	0.98^{b}
Unheated	2.02^{a}	2.50^{a}

Note: Means followed by the same letter in the same column are not significantly different at $\alpha = 0.05$ according to two-tail paired t-tests.

This result verified the reports (Lurie and Sabehat 1997; McDonald et al. 1999; Soto-Zamora et al. 2005; Yahia et al. 2007) that 2-3 d exposure to 38°C allowed mature green tomatoes to ripen normally without CI after 2-4 weeks at 2°C. In our research, CI was significantly reduced, but not eliminated. This could be the result of insufficient exposure duration to heat: tomato fruits were heated less than 1 d (23 h), while in

previous studies fruits were treated 2-3 d. The effect of treatment duration could be further verified by the comparison of H23 and H6. Additionally, we could conclude that the CI control effect of heat treatment is localized since this effect was only observed on heated halves of partially-treated tomatoes.

6.5 Conclusions

A significant difference in redness, represented by hue, was identified between heated parts and unheated parts of tomato fruits immediately after 23 h of non-uniform heat treatment; and the differences persisted when the tested tomato fruits were stored at 14°C and 20°C. Although a difference in lightness and chroma was not observed right after non-uniform treatment, a significant difference was noted on day 4 under both 20°C and 14°C storage conditions. However, there was no difference in redness towards the end of storage, suggesting that the delay in ripening did not have an irreversible effect on lycopene synthesis.

Compared with the control group, the heat-treated tomato fruits tended to be softer, although fruit firmness did not differ between heated and unheated parts.

Delay in ripening caused by heat treatment was evidenced by the higher TA and TSS values of U6, U23, H6 and H23. This effect declined by the end of storage. As a result of the consistently higher TA and TSS values, no significant difference in the taste indicator, sugar/acid ratio, was observed. This suggests that the basic tomato taste may be the same in heated and unheated parts of non-uniformly treated tomato fruits. The results indicate that uniformly heated tomato fruits may also have a basic taste similar to the control.

The overall quality of non-uniformly heated tomato fruits was better than that of the control. The heated parts of tomato fruits that were non-uniformly treated for 23 h showed a stronger resistance to chilling injury. Furthermore, the unheated parts did not differ from the control group, showing the importance of uniform treatment conditions even for each fruit.

Some of the effects of heat treatment on tomato fruits that were investigated in this experiment, such as color development and resistance to chilling injury, appear to be localized rather than systemic. Consequently, our findings show that providing uniform

heat conditions for material during heat treatment is the only way to attain optimal benefits. It is important to choose media that allow for more uniform treatment, such as water, RF or microwaves (Karabulut and Baykal 2002; Birla et al. 2004; Mitcham et al. 2004), to ensure optimal fruit positioning during treatment with conventional media.

6.6 Acknowledgements

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CONNECTING STATEMENT 5

As the continuation of this study, the effect of heat treatment uniformity on tomato quality was further quantified within normally effective treatment temperature range (36°C to 39°C), and the effect of some factors such as temperature and air velocity were investigated.

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Effect of Thermodynamic Parameters on Tomato Ripening and Chilling Injury under Heterogeneous Heat Treatment.

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The first author, the Ph.D. student did the experimental work and prepared the manuscript; the second and fourth authors are the supervisors who guided the research work; the third and fifth author gave scientific and technical support.

CHAPTER VII. EFFECT OF TEMPERATURE AND AIR VELOCITY ON QUALITY OF TOMATO FRUIT UNDER HETEROGENEOUS HEAT TREATMENT

7.1 Abstract

An insulated twin-chambered forced-air device was built to generate heterogeneous heat treatment for tomato fruit. This treatment insured that one hemisphere of the tomato resided in one chamber to be exposed to warm air at a controlled temperature of 39°C and uniform circulation rate of 0.24m s^{-1}; while the other hemisphere, in the other chamber, was exposed to a lower temperature of 36°C or 37°C under 0.24m s^{-1}, or at 36°C under 0.12 m s^{-1}. Temperature control for both chambers was achieved using suitable instrumentation, while the air velocity could be modified and fixed at a desired rate. Tomato fruits were randomly divided into four lots: one was used as control, two were uniformly treated, and the other was heterogeneously treated. Immediately after treatment the fruits were transferred to regular storage conditions at 14°C, to ripening at 20°C or to chilling injury (CI) inducing temperatures at 2°C. Under all storage conditions, relative humidity was maintained high at 90-93%. Color, firmness, titratable acidity (TA), total soluble solid (TSS) and severity of CI were measured or evaluated subjectively at designed time. Results indicated that temperature differences between the two chambers have significant effects on the uniformity of color—especially on chroma and redness as represented by hue—and a slight effect on firmness, TA and sugar acid ratio in the temperature range investigated. Decreasing the temperature difference between the two chambers or relatively increasing the air flowrate of the upper (39°) chamber significantly improved the uniformity of quality, addressing the importance of improving the uniformity of heating media around each individual treated fruit.

Keywords. heterogeneous, heat treatment, temperature, air velocity, tomato

7.2 Introduction

Heat treatment has been used for disinfestations and disinfection of an increasing variety of crops (Lurie 1998). No country produces all of the fresh fruit and vegetables

that its citizens demand on a year-round basis, creating the opportunity for trade, and thus the possibility of introducing insects to importing regions. Phytosanitary restrictions have been developed to protect a region's agricultural industry from the introduction of damaging insect pests (Kader 2003). Many importing countries often require inspection certificates assuring the absence of targeted live pests in a shipment after a pre-approved postharvest 'sanitation' treatment (Ikediala et al. 2002). Due to consumer requirements, environmental concerns and regulatory issues (Mulas and Schirra 2007), a potential non-damaging physical treatment substitute for chemical prevention is needed. Heat treatment appears to be one of the most promising means for postharvest quarantine and control of decay (Fallik 2004). Heat treatments can also be used to inhibit ripening processes or to induce resistance to chilling injury (CI) and external skin damage during storage, thus extending storability and marketing.

However, non-uniformity of heat transfer is one of the largest obstacles in the way to industrialization of heat treatment. Under bulk processing, the heating field to which each commodity is exposed can hardly be the same, leading to treatment differences among commodities and even within a single unit. Some researchers have studied these bulk heating issues for scaling up radio frequency (Birla et al. 2004; Wang et al. 2006b) or hot water treatments (Bollen and Dela Rue 1999; Birla et al. 2004; Fallik 2004; Wang et al. 2006a). For conventional media, low specific heat capacity and its poor heat transfer ability can cause problems, making it difficult to obtain uniform heating within each individual fruit. It has been found that the part of apples within cavities created by two fruit butted together and effectively sealed off from the heating medium would, due to its similar heating rate as the fruit core, delay by 25 min the apple tissue reaching within 1°C of the target temperature when exposed to a hot water drench and for 70 min in a forced air heating system (Bollen and Dela Rue 1999). Heterogeneity exists not only within each single fruit but also among fruits exposed to air treatment. Vigneault and de Castro (2005) evaluated the applicability of using instrumented balls as an indirect measurement of air velocity which was inferred as a function of the simulator locations relative to the air entrance. Their results demonstrated that the variance in temperature distribution increased as the container opening area shrank below 25%, and that the airflow rate had a significant effect on the half-cooling time variance at the minimum opening configuration

(Vigneault and de Castro 2005). The effect of non-uniformity of heat transfer on the effect of heat treatment for treated commodities should be further investigated in order to pave the scaling-up of heat treatment applications by correlating the engineering parameters with the quantified heat treatment effects. Differences attributable to those differences—in terms of quality, anti-pathogen, anti-CI—among commodities can be studied by exposing commodities to different target temperatures within the effective ranges. It is also important to check how and to what extent non-uniformity of heat transfer within an individual commodity influences the heat treatment effects (Lu et al. 2006; Lu et al. 2007a).

7.3 Materials and methods

7.3.1 Experimental set-up

The experimental setup (Fig. 7.1), consisting of an insulated twin-chambered forced-air device was built to generate a heterogeneous heat treatment. This treatment insured that one hemisphere of the tomato in one chamber was exposed to warm air at a controlled temperature of 39°C and uniform circulation at a velocity of 0.24 m s^{-1}; while the other hemisphere in the other chamber was exposed to heating at relatively lower temperatures (36°C or 37°C respectively), or under slower air circulation conditions (0.12 m s^{-1}; 36°C). Temperature control for both chambers was achieved using suitable instrumentation. The setup was separated into two chambers by a 12 mm-thick insulation material (Microcell^{TM}) supported by a 5 mm-thick plastic plate: the upper (heated) and the lower (less heated). The separate twin chambers were further divided into 9 tunnels in order to expose tested tomato fruits to a relatively uniform airflow. The 0.700 m length of tunnel prevented the tomato from being exposed to an airflow gradient along the flow direction. Steel was chosen as the tunnel separation material for its high heat conductivity, increasing the uniformity of the air temperature between adjacent tunnels. Aluminum mesh plate coated with adhesive-bonded fabric covered the entrance of the tunnel to equalize airflows among tunnels.

Holes of similar size with the longitudinal cross-section of tomato were cut in the Microcell^{TM} to receive the fruit during treatment, and bigger holes (82 mm diameter) were cut on the plastic plate separating the twin chamber to position the tomato fruits

along the center of the tunnel and expose half part of each of them to the two conditions simultaneously.

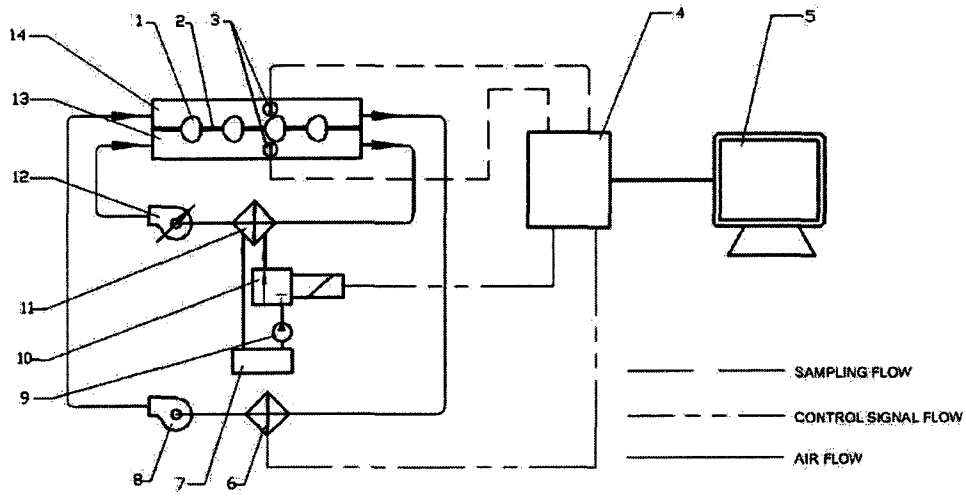

Figure 7.1: Schematic of experimental set-up consisting of a forced air twin-tunnel allowing a matrix of produce to be exposed to heterogeneous environmental conditions as follow: 1- Produce; 2-Microcell^{TM} and plastic supporting plate; 3-Thermocouples; 4-Data acquisition board; 5-Computer; 6-Heater; 7-Water bath; 8- Fan for upper chamber; 9-Pump; 10- Solenoid valve; 11- Heat exchanger; 12-Adjustable fan for lower chamber; 13-Lower chamber; 14- Upper chamber.

7.3.2 Instrumentation and control

Four channels of an 8-channel data acquisition system (Personal Daq/3001, IOtech Inc., Cleveland, Ohio, USA) were used for sampling and controlling the temperature of the upper chamber and lower chamber, and the other four channels were used to record the temperature profile of one representative non-uniformly treated tomato. The control program was written in a graphical flow chart program (DASYLab V 9.0, National Instruments Corporation, Austin, TX, USA). Temperature was recorded at 4-min intervals.

7.3.3 Material

Breaker stage tomato fruits (*Lycopersicon esculentum* Mill. cv. DRW 453) of uniform size were picked directly from a commercial greenhouse. Fruits were first surface-sterilized for 3 min using a chlorine solution (150 mg kg^{-1} Cl_2 as sodium hypochlorite), then thoroughly rinsed with tap water for another 3 min, and finally left on filter paper to drain and air dry as recommended by Polenta et al. (2006).

7.3.4 Treatment

Cleaned tomato fruits were then divided into four lots. Whole tomato fruits or tomato hemispheres were exposed for a given time to one of desired air flows. Each lot was submitted to one of the following treatments:

I: Not treated and referred to as the control unit (C)

II: Uniformly treated at 39°C for 23 h (U39)

III: Uniformly treated at 38°C or 36°C for 23 h (U38 or U36)

IV: Heterogeneously treated for 23 h (H23 and C23 = part heated at upper chamber and heated in lower chamber, respectively), where the temperature of the upper chamber was kept at 39°C (0.24 m s^{-1} flow rate), and the lower chamber was kept at 36°C (0.24 m s^{-1} flow rate) — T1; 36°C (0.12 m s^{-1} flow rate) — T2; or 38°C (0.24 m s^{-1} flow rate) — T3. The treatments T1, T2, and T3 were repeated three times as were treatments I, II, and III.

After any treatment, the tomato fruits were divided into three groups to be stored at different temperatures (2°C, 14°C, or 20°C) and at a fixed RH 90-93%, so as to measure the effect of the treatments on chilling injury (CI) and maturity processes. For fruit quality investigations, color, firmness, titratable acidity (TA) and total soluble solids (TSS) were measured at day 0, 4, 7, 11 for those stored at 14°C, and 20°C. One further measurement of all these parameters was taken at day 15 for tomato fruits stored at 14°C. After 21 days at 2°C, refrigerated fruits were transferred to a storage room (20°C, RH 90-93%) for another 10 days and then evaluated for CI symptoms (Lurie and Sabehat 1997).

7.3.5 Color

Color is one of the most important quality factors associated with the evaluation of most horticultural produce. It was measured according to Commission Internationale de l'Éclairage (CIE) methods. The values were determined with a Minolta chromameter (CR-400, Japan) at two locations between equator and blossom end, and at 4 locations on the equatorial region for both uniform and control treatments. For heterogeneous treatment, the values were measured at one location between equatorial and blossom end, and two locations on the equatorial region for each demarcated hemisphere of the fruit. The values measured were L, indicating lightness, hue which decreases in value indicating the color change in the tomato from green to red, and C (chroma) expressing the saturation of colors, with high-saturated colors being vivid and low-saturated colors dull. The means of all locations from each sampled tomato were taken for the statistical analysis (Ali et al. 2004).

7.3.6 Fruit firmness

Firmness (resistance to compression) was determined by using a universal testing machine (Lloyd Instrument, LRX). This machine was equipped with a load cell of 50 N fitted with a standard 11.025 mm diameter hemispherically-tipped probe driven downwards at 0.416 mm s^{-1} to a depth of 5.5 mm. Firmness of individual fruit was measured twice on opposite sides at the equator for the U treatment fruits and the C group. For H23 and C23, the firmness measurements were performed on two adjacent zones at the equator level and around the top on the heated and less heated part of tomato. Mean values of two replications were used for statistical analysis for each treatment.

7.3.7 Titratable acidity and total soluble solid

Four tomato fruits of each treatment were sampled. A 10 mm wide pericarp strip was cut off at the equator of four tomato fruits from each treatment. The pericarp tissue was homogenized in a Waring blender and centrifuged at 4500 rpm for 5 min at 2°C (Beckman AccuSpin FR). The juice was used for TA and TSS measurements. TA was determined using an automatic titrator, Titrino 719S (Metrohm, Switzerland) with 2 mL of tomato juice diluted in 30 mL distilled water. Titration was with 0.1N sodium hydroxide to pH 8.1. Titratable acidity is expressed as g citric acid/mL tomato juice. Total

soluble solids of the full strength juice was determined by the recommended method of (AOAC 1984), using a handheld refractometer (ATAGO ATC-1E, Japan) at room temperature. The representative sample of tomato juice was placed on absolutely dry and clean refractometer prism, and readings were taken directly. Total soluble solids are expressed as a percentage on the Brix scale. Mean values were obtained from four lots of four fruits each, three reading for each lot.

7.3.8 Chilling injury

Tested tomato fruits were stored at 2°C (Lurie and Sabehat 1997) for 21 days before ripening at 20°C. The two most clearly documented symptoms of chilling injury in tomato fruit are susceptibility to decay and alteration of ripening pattern as evidenced by inadequate color development (Cheng and Shewfelt 1988). Chilling injury, estimated visually as surface lesions on the fruit, pitting, decay and fruit color from green to red, was determined on all fruits in each treatment at day 10 after the fruit were transferred to 20°C. Fruits were rated for physiological disorders such as pitting, stress scar, cracking, severity of irregular ripening; and pathological severity indicators such as number and size of lesions, appearance of typical colony. Assessment was determined by 2 assessors using a 0-5 scale (0-free of defect, 5-extremely susceptible).

7.3.9 Statistical analysis

Experiments were performed according to a factorial design, time and treatments being the factors; additionally, a pairwise comparison was conducted for the heterogeneous treatment. Statistical analysis was performed with the GLM procedure of SAS (SAS 1999) and the treatment differences were separated using the Duncan Multiple Range Test. Two-tailed paired *t*-test was used to determine the difference of all parameters investigated between heated and less heated parts for the heterogeneous treatment. In order to quantify the difference between H23 and C23 for future modeling work, the significant level started at α=0.1.

7.4 Results and discussion

Results of pairwise comparisons are listed in table 7.1 to table 7.6. The change in level of significance and occurrence of significant differences on particular observation days were employed to compare the effect of thermal conditions on quality and CI of

treated produce; where the change from T1 to T2 represents the effect of air flowrate, and the change from T1 to T3 represents the effect of temperature difference.

7.4.1 Color

The difference between H23 and C23 was most significant for the higher flow rate. The significance of differences and the frequency of significant difference being identified at specific observation days changed along with treatments. Results indicated that both the difference in temperature (T1 *vs.* T3) and that in airflow rate (T1 *vs.* T2) had effects on coloring, although results for ripening at 20°C differed slightly from those at 14°C.

At 20°C, differences in lightness (Table 7.1), chroma (Table 7.2), and hue (Table 7.3) between H23 and C23 didn't show any difference under T2 conditions; whereas significant overall differences were identified for all the three parameters, namely pronounced differences in lightness on day 4 (α=0.01) and day 11 (α=0.1) under T1 conditions; while a difference of relatively low significance was shown on day 4 (α=0.1) under T3 conditions. This result indicated that air flow rate had an effect on color index. The chroma showed a similar tendency as lightness, where significant differences appeared both overall and at peculiar days (day 4 and 11 for T1, and day 1 for T3); moreover, the significance and frequency were greater when the temperature difference between upper and lower chamber was greater (T1) than when the temperature difference was lesser (T3). The overall hue value showed differences at the same level (α=0.05) for T1 and T3; however, differences occurred on two days (day 1 and day 4) for T1 conditions, compared to only one day (day 4) under T3 conditions, implying that there was an effect of temperature difference between two chambers on redness as represented by hue value difference.

Table 7.1: Paired Student's *t*-test result of lightness for different treatments.

Day		14°C			20°C		
		T1	T2	T3	T1	T2	T3
1	H23	52.88	48.82	47.94	52.88	48.82	47.94
	C23	53.10	49.31	48.20	53.10	49.31	48.20
4	H23	52.42	48.06^{+}	47.61	48.38**	47.15	46.21^{+}
	C23	52.43	48.97	47.94	49.57	47.31	47.28
7	H23	49.85	47.55	46.49	44.35	44.52	43.18
	C23	50.23	48.15	46.94	44.76	43.90	42.85
11	H23	46.76	44.38	44.83	40.62^{+}	40.22	40.66
	C23	46.87	44.84	44.34	42.07	40.88	40.58
15	H23	44.17	42.20	43.04			
	C23	44.79	42.44	42.21			
Overall		ns	*	ns	**	ns	ns

The significance indicated by overall refers to the paired *t*-test taking the pairwise data obtained for all observed days of each parameter as samples to show the general tendency during the whole observed period.

+, *, **, *** showing significant differences in the investigated parameters between C23 and H23 treatments at α=0.1, 0.05, 0.01 and 0.001 respectively; ns refers to not significant.

Table 7.2: Paired Student's *t*-test results for chroma under different treatments.

Day		14°C			20°C		
		T1	T2	T3	T1	T2	T3
1	H23	23.68	20.85	20.70*	23.68	20.85	20.70*
	C23	23.14	20.76	19.76	23.14	20.76	19.76
4	H23	22.37	18.79	17.95	21.75*	17.77	17.99
	C23	20.55	19.87	18.28	20.85	17.77	17.22
7	H23	20.26	18.49	17.62	23.83	19.86	18.86
	C23	20.15	17.97	17.30	23.48	19.58	18.46
11	H23	22.86	17.11^{+}	17.44	27.00**	22.92	23.31
	C23	22.34	18.10	17.26	26.16	22.99	22.75
15	H23	24.64	20.21	18.52			
	C23	24.22	20.48	18.37			
Overall		*	ns	ns	**	ns	*

The significance indicated by overall refers to the paired *t*-test taking the pairwise data obtained for all observed days of each parameter as samples to show the general tendency during the whole observed period.

+, *, **, *** showing significant differences in the investigated parameters between C23 and H23 treatments at α=0.1, 0.05, 0.01 and 0.001 respectively; ns refers to not significant.

At 14°C, overall differences in hue for all the three treatments were all significant but with different significance levels (0.001, 0.01, and 0.1 for T1, T3, and T2, respectively). Similarly, differences were identified most frequently for T1 followed by T3, indicating that both the temperature difference and air flowrate had effects on hue. Although an overall difference in Chroma was only found for T1, significant differences were found at day 1 for T3 (α=0.05) and day 11 for T2 (α=0.1). No significant differences in lightness difference were found for T1 or T3.

Table 7.3: Paired Student's *t*-test results for hue under different treatments.

Day		14°C			20°C		
		T1	T2	T3	T1	T2	T3
1	H23	103.37^{+}	106.47	108.81	103.37^{+}	106.47	108.81
	C23	101.88	105.64	107.53	101.88	105.64	107.53
4	H23	89.64*	98.19	99.36	72.78^{+}	81.68	90.91*
	C23	84.22	99.76	98.17	69.42	80.97	83.71
7	H23	64.03	88.24^{+}	91.20^{+}	43.26	58.60	57.13
	C23	62.14	81.35	87.56	42.65	53.97	56.10
11	H23	49.33*	56.85	65.88	37.32	39.34	40.65
	C23	45.40	53.24	65.19	36.98	39.03	40.41
15	H23	41.98	45.42	58.04**			
	C23	41.37	44.96	52.46			
Overall		***	+	**	*	ns	*

The significance indicated by overall refers to the paired *t*-test taking the pairwise data obtained for all observed days of each parameter as samples to show the general tendency during the whole observed period.

+, *, **, *** showing significant differences in the investigated parameters between C23 and H23 treatments at α=0.1, 0.05, 0.01 and 0.001 respectively; ns refers to not significant.

These results indicate that direct reduction of the temperature difference between H23 and C23 or the relative increase in air flow rate of H23 significantly reduced the color difference between H23 and C23, implying that the difference of color as a result of thermal difference between H23 and C23 could be significantly reduced by improving the uniformity of temperature around each individual treated fruit, or by appropriately improving the air circulation.

7.4.2 TA and TSS

Only a slightly significant difference (α=0.1) in TA was identified (day 7 or 11, at 20°C or 14°C) when the temperature difference was highest (T1), and this difference

disappeared when the media temperature difference decreased (T3) or when the C23 side air flow rate was slower (T2), with the exception for day 4 when a significant difference was identified after storage at 20°C (Tables 7.4 and 7.5).

Table 7.4: Paired Student's *t*-test results for TA, TSS, and Sugar acid ratio for different treatments at 14°C.

Day		TA (g/L)			TSS (%)			Sugar Acid Ratio		
		T1	T2	T3	T1	T2	T3	T1	T2	T3
4	H23	4.09	4.34	4.35	4.70	4.37	4.10	11.49+	10.08	9.41
	C23	4.23	4.20	4.20	4.67	4.43	4.10	11.01	10.57	9.73
7	H23	4.22	4.26	4.31	4.70	4.57	4.27	11.17	10.71	9.89
	C23	4.37	4.05	4.29	4.70	4.53	4.33	10.75	11.19	10.11
11	H23	4.04+	4.31	4.31	4.77	4.60	4.20	11.81+	11.19	9.72
	C23	4.24	4.06	4.21	4.83	4.57	4.13	11.41	11.19	9.78
15	H23	4.01	4.24	4.44	4.67	4.53	4.27	11.66	10.69	9.66
	C23	4.02	4.24	4.47	4.73	4.47	4.27	11.81	10.87	9.60
Overall		**	**	ns	ns	ns	ns	*	**	ns

The significance indicated by overall refers to the paired *t*-test taking the pairwise data obtained for all observed days of each parameter as samples to show the general tendency during the whole observed period.

+, *, ** showing significant differences in the investigated parameters between C23 and H23 treatments at α=0.1, 0.05, and 0.01 respectively; ns refers to not significant.

In terms of the overall level of TA, H23 did not differ from C23 under 20°C or 14°C storage (T3), whereas significant difference (α=0.01) were apparent under T1 and T2 conditions at 14°C and under T2 conditions at 20°C. This result suggests that maintaining the uniformity of heating media around each individual fruit, especially the uniformity of temperature is very important in obtaining uniform TA for any part of treated fruit.

No significant differences of TSS were identified for all the treatments either at the overall level or at any given day.

Table 7.5: Paired Student's *t*-test results for TA, TSS, and Sugar acid ratio for different treatments at 20°C.

Day		TA (g/L)			TSS (%)			Sugar Acid Ratio		
		T1	T2	T3	T1	T2	T3	T1	T2	T3
4	H23	4.17	4.10*	4.48	4.73	4.47	4.13	11.36	10.90	9.33
	C23	4.24	3.87	4.27	4.73	4.37	4.13	11.17	11.30	9.71
7	H23	3.84+	4.34	4.20	4.50	4.63	4.13	11.76*	10.67	10.23
	C23	3.94	4.10	4.21	4.53	4.53	4.27	11.54	11.10	10.12
11	H23	3.67	4.18	4.31	4.77	4.70	4.30	13.14	11.32	10.01
	C23	3.70	4.09	4.31	4.77	4.70	4.23	12.99	11.62	9.90
Overall		ns	*	ns	ns	ns	ns	*	ns	ns

The significance indicated by overall refers to the paired *t*-test taking the pairwise data obtained for all observed days of each parameter as samples to show the general tendency during the whole observed period.

+, * showing significant differences in the investigated parameters between C23 and H23 treatments at α=0.1, and 0.05 respectively; ns refers to not significant.

7.4.3 Sugar acid ratio

For the sugar to acid ratio, which is used to evaluate fruit taste, differences were consistent with those of TA since no significant difference was measured for TSS. Higher temperature differences between H23 and C23 affected the sugar to acid ratio, which was shown by the slightly significant difference illustrated on day 4 and day 11 and at overall level for 14°C (Table 7.4) and the significant difference on day 7 at 20°C (Table 7.5) for T1 conditions. However, these differences vanished under T2 and T3 conditions, suggesting an effect of the decrease in temperature difference between H23 and C23 or the change of air flow rate.

7.4.4 Firmness

Heat treatment had less effect on firmness (Table 7.6) in comparison to its effect on color, and the change of temperature difference between H23 and C23 didn't significantly affect the difference between H23 and C23. At 14 °C, the overall difference was significant only for T1 conditions, and T2 did not show any significant difference between H23 and C23 both at the overall level and for any given day. This indicated that the change in air velocity affected the firmness uniformity between H23 and C23. Compared with T1 conditions, T2 conditions showed uniform improvement as a result of the relatively lower air flow rate on the C23 side, which convectively removed less heat transferred conductively from the H23 hemisphere, leading to a lower temperature difference between the H23 and C23 portions of treated tomato fruits. Although a difference was observed on day 4 for both T1 and T3 (α=0.1), the uniformity of overall firmness was indicated by the reduction of overall significance from T1 (α=0.05) to T3 (ns).

Results didn't show any difference for T2 conditions at any sampling day at 20°C, but the overall difference was slightly significant (α=0.1). T1 and T3 conditions showed no difference overall, but H23 differed from C23 on day 7 for both T1 and T3 conditions. Thus, the temperature difference did not affect firmness at 20°C.

Table 7.6: Paired Student's *t*-test result of firmness [F_{max} (N)] for different treatments.

Day		14°C			20°C		
		T1	T2	T3	T1	T2	T3
4	H23	14.66^{+}	15.54	13.02^{+}	12.00	11.76	12.61
	C23	13.39	14.80	14.15	11.84	12.59	12.05
7	H23	14.56	13.73	14.65	9.85*	10.24	10.68*
	C23	13.86	13.88	14.36	10.05	10.37	10.41
11	H23	14.18	12.78	14.58	9.36	8.70	9.17
	C23	13.44	12.90	13.57	9.43	10.07	9.43
15	H23	13.09	11.51	13.08			
	C23	13.12	11.62	13.01			
Overall		*	ns	ns	ns	+	ns

The significance indicated by overall refers to the paired *t*-test taking the pairwise data obtained for all observed days of each parameter as samples to show the general tendency during the whole observed period.

+, * showing significant differences in the investigated parameters between C23 and H23 treatments at α=0.1, and 0.05 respectively; ns refers to not significant.

7.4.5 Chilling injury

No significant differences were identified between H23 and C23 for T1, T2, and T3 (Figure 7.2); however, the severity of CI for both H23 and C23 was lower than that of the control, indicating a significant effect of heat treatment on reducing chilling Injury.

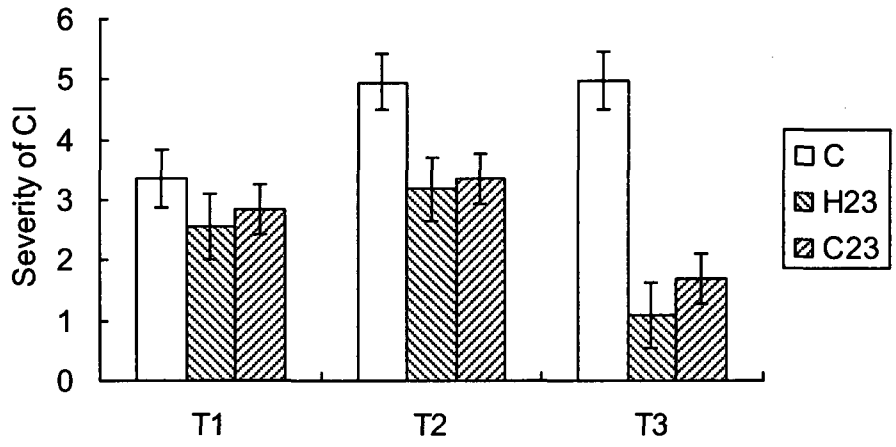

Figure 7.2: Mean severity of chilling injury (CI) evaluated at day 10 of storage at 20°C after 3 weeks' storage at 2°C after 23 h hot air treatment: the probability of significance between H23 and C23 is $P = 0.40$, $P = 0.86$, $P = 0.22$ for T1, T2, T3 respectively

The lack of significant difference between H23 and C23 could be explained by the results of the uniform treatment (Fig. 7.3). It indicates that after 23 h heat treatment at 36°C or 38°C, CI symptoms were significantly reduced compared to that of the control group, and no significant difference was identified between treatments at 36°C and at 38°C. This result implies that the effective temperature range for anti-CI is quite wide. On the other hand, results indicated that an extreme high temperature is critical for CI control: when tomato fruits were heated at 39.5°C for 23 h, slight heat damage— scalding— was observed on some treated tomato fruits, resulting in a decrease in the effect of heat treatment on CI control. Among the three temperatures investigated, tomato fruits treated at 38°C showed the best effect followed by those treated at 36°C. For non-uniform treatment, heating tomato fruits under T3 conditions gave the best CI controlling effect compared with T1 or T2 conditions, which could be explained by the fact that the temperature of tomato fruits must be in a range between 39°C and 37 °C, to which the H23 and C23 portions were exposed. For the same reason, tomato fruits under T2 conditions would have shown better performance than under T1 conditions; however, results did not indicate this because chilling injury temperature was around 4°C for T1 but at 2 °C for T2 and T3.

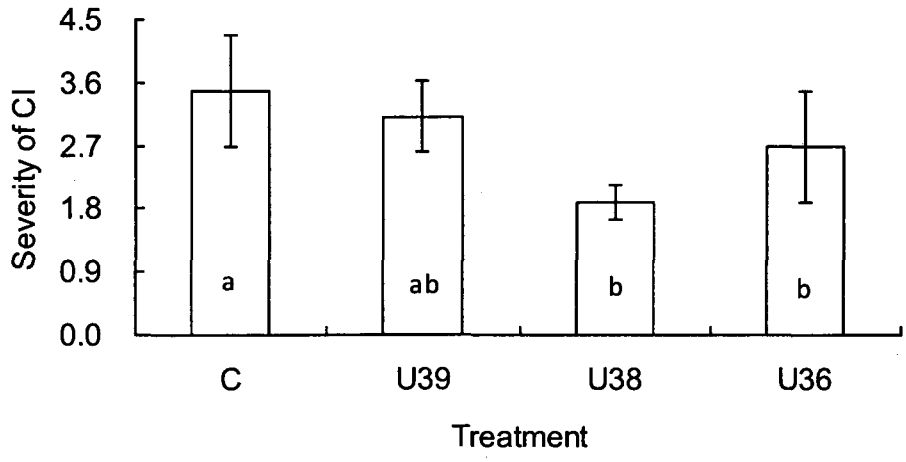

Figure 7.3: Mean severity of chilling injury of tomato fruits evaluated after 10 days of post-chilling storage (3 weeks at 2°C) at 20°C after a pre-chilling 23 h uniform hot air treatment at 39.5°C (U39), 38°C (U38), 36°C (U36), or untreated (C); letters in the column indicate the results of Duncan Multiple Range Test, treatments indicated by the same letter are not significantly different at $\alpha = 0.05$

7.5 Conclusion

The temperature difference between H23 and C23 had a significant effect on the uniformity of color—especially on chroma and redness as represented by hue; and a slight effect on lightness, firmness, TA, and sugar acid ratio in the temperature range investigated. No significant change was identified on CI and TSS when temperature difference decreased or a different air flow was used. The effective temperature range to control CI (36°C to 38°C) was wide for the investigated fruit, tomato, but temperatures above 39.5°C for 23 h hot air treatment could lead to heat scalding and poor CI control.

Directly decreasing the temperature difference between H23 and C23 or relatively increasing the air flow rate of H23 significantly reduced the color and firmness differences between H23 and C23, addressing the importance of improving the uniformity of air flow around each individual treated fruit. Furthermore, this improvement could be achieved by managing air temperature and appropriately improving the air circulation.

7.6 Acknowledgements

The authors appreciate the assistance of Dominique Roussel during experimentation.

CHAPTER VIII. GENERAL SUMMARY AND CONCLUSIONS

The importance of the uniformity of heat transfer with respect to the effect of heat treatment on treated commodities should be investigated further to pave the way for the scale-up of heat treatment applications by correlating the engineering parameters with the quantified heat treatment effects. Those differences in effect in terms of quality, anti-pathogen and anti-chilling injury properties among commodities can be studied by exposing commodities to different target temperatures within the effective range. It is also important to evaluate how and to what extent the non-uniformity of heat transfer within an individual commodity influences the effects of heat treatment.

A research tool consisting of an insulated twin-chambered forced-air device was built to investigate the effect of heat treatment uniformity. This research tool ensured that half of a horticultural produce was positioned in one chamber and was exposed to warm air at the desired temperature and velocity, while the other half was in another chamber and exposed to controlled standardized ambient temperature circulated at a lower air velocity.

In the study of disease control, results showed that the effective heat treatment temperature varied in terms of hypersensitive response (38°C), tissue break-down and mycelium abundance (36-39°C), and lesion size (38-39°C); the ideal heat treatment effect could be obtained only if treated material was exposed to particular temperature for a designed duration. Commodities should be heated by media controlled within an effective temperature range in order to achieve expected heat treatment effects. Otherwise; heat treatment might not result in the expected effect, which emphasizes that all fruits should be treated at the design temperature, i.e. uniformly treated. Similarly, it is quite important for each individual fruit to be uniformly exposed to heating media.

The temperature difference between the heated and less heated portions did affect the disease control reaction of tomatoes induced by heat treatment except for hypersensitive response; however, this reaction did not differ when the temperature difference was decreased to less than 3°C. A decreasing temperature difference between upper and lower chambers significantly improved the uniformity of disease control.

The overall quality of treated fruits was significantly better than that of control for both pre-heat and post-heat inoculation groups, and pre-heat groups showed a more marked effect than post-heat treated ones, implying the strength of the combination effect of direct physical and induced effects.

Some of the effects of heat treatment on tomatoes that were investigated in this experiment, such as color development and resistance to chilling injury, appear to be localized rather than systemic. A significant difference in redness, represented by hue, was identified between heated parts and unheated parts of tomato fruits immediately after 23 h of non-uniform heat treatment; and the differences persisted when the tested tomatoes were stored at 14°C and 20°C. Although a difference in lightness and chroma was not observed right after non-uniform treatment, a significant difference was noted on day 4 under both 20°C and 14°C storage conditions. However, there was no difference in redness towards the end of storage, suggesting that the delay in ripening did not have an irreversible effect on lycopene synthesis.

Compared with the control group, the heat-treated tomatoes tended to be softer, although fruit firmness did not differ between heated and unheated parts.

Delay in ripening caused by heat treatment was evidenced by the higher TA and TSS values of heated tomatoes or heated portion of partially heated tomatoes. This effect declined by the end of storage. As a result of the consistently higher TA and TSS values, no significant difference in the taste indicator, sugar/acid ratio, was observed. This suggests that the basic tomato taste may be the same in heated and unheated parts of non-uniformly treated tomatoes. The results indicate that uniformly heated tomatoes may also have a basic taste similar to the control.

The heated parts of tomatoes that were non-uniformly treated for 23 h showed a stronger resistance to chilling injury, showing the importance of uniform treatment conditions even for a single fruit. The temperature difference between H23 and C23 had a significant effect on the uniformity of color—especially on chroma and redness as represented by hue; and a slight effect on lightness, firmness, TA, and sugar acid ratio in the temperature range investigated. The effective temperature ranges from 36°C to 38°C to control CI for the investigated commodity, tomato, but at temperatures higher than

39.5°C at 23 h hot air exposure could lead to heat scalding, resulting in an adverse effect on CI control.

Directly decreasing the temperature difference between H23 and C23 or relatively increasing the air flow rate of H23 significantly reduced the color and firmness differences between H23 and C23 treatments, addressing the importance of improving the uniformity of air flow around each individual treated fruit. Furthermore, this improvement could be achieved by managing air temperature and appropriately improving the air circulation.

Consequently, our findings show that providing uniform heating conditions for material during heat treatment is the only way to attain optimal benefits. It is important to choose media that allow for more uniform treatment, such as water, RF or microwaves, to ensure optimal fruit positioning during treatment with conventional media.

In addition, research into a protocol for the adoption of different heat treatment methods in the postharvest chain is needed for the purposes of disinfestation, disinfection or quality control.

CHAPTER IX. CONTRIBUTIONS TO KNOWLEDGE AND RECOMMENDATIONS FOR FUTURE STUDIES

9.1 Contributions to knowledge

The major contributions to knowledge of this study are:

For the first time an approach of artificially heterogeneous heating experimental device was developed to investigate the effect of a temperature gradient on intact fruits. This concept and device can also be used for similar investigation of other commodities.

A simulation scheme was established and validated by using finite element approach (COMSOL). This simulation was used to design the heterogeneous treatment and to find out the factors affecting the uniformity of heat treatment effect. This simulation method could be used for simulating the effect for commodities other than tomato by modifying its properties without tedious experiments.

Through the investigation of heat treatments' effects on quality parameters of tomato following heterogeneous treatment, the effect of heat treatment on slowing ripening and chilling injury control of tomato was determined to be localized. Hence we theoretically verified the importance that a micro-heat environment should be created in order to benefit the heat treatment.

Through the investigation of heat treatment effects on tomato pathology following heterogeneous treatment, some of the spatially distinct effects of heat treatment, such as the inhibition of tissue break down, mycelium growth, and lesion development on disease control of tomato were described. The single- effective heat treatment temperature in limiting pathogen development varied according to the parameters measured.

By quantifying the effect of thermodynamic factors on the effect of heat treatment on quality of tomato, it was demonstrated that air velocity and temperature were the two main factors affecting the effectiveness of heat treatment.

9.2 Recommendations for future research

Other commodities should be tested to verify localized effects in terms of quality and disease control.

The simulation work presented here did not consider the effect of tomato surface temperature jump, and water loss during heating. Some of the assumption to simplify the model during simulation could be further investigated experimentally to improve the accuracy of simulation result, provided that the computer was powerful enough.

A mathematical model should be designed that would correlate physiological and pathological effects with heat treatment temperature and duration so that they can be used in the simulation program.

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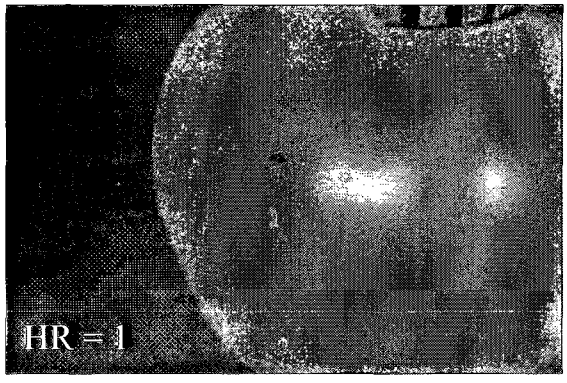
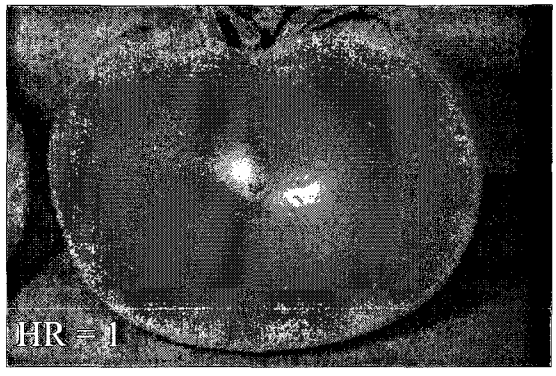
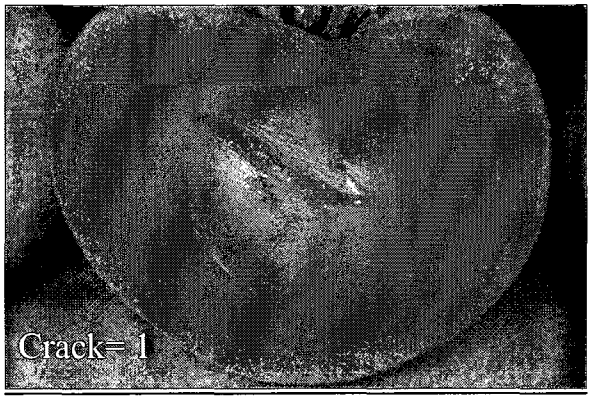
APPENDIX 1 Evaluation of *Botrytis cinerea* infection on tomato

Hypersensitive Response (HR)





Tissue Breakdown (Crack)



Mycelium Abundance

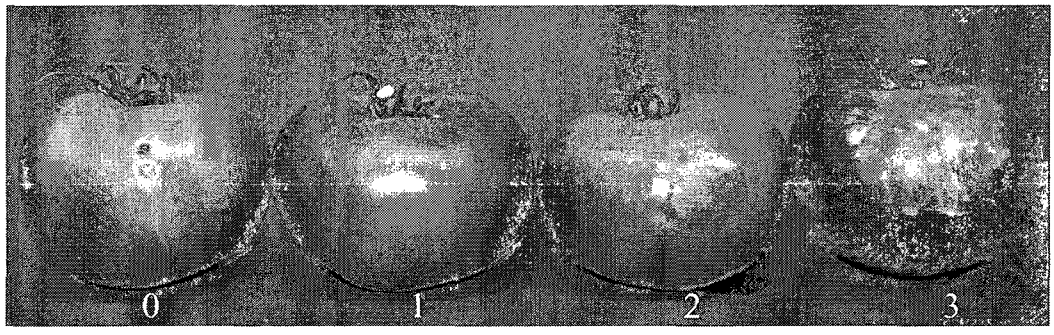
Score: 0, 1, 2 or 3

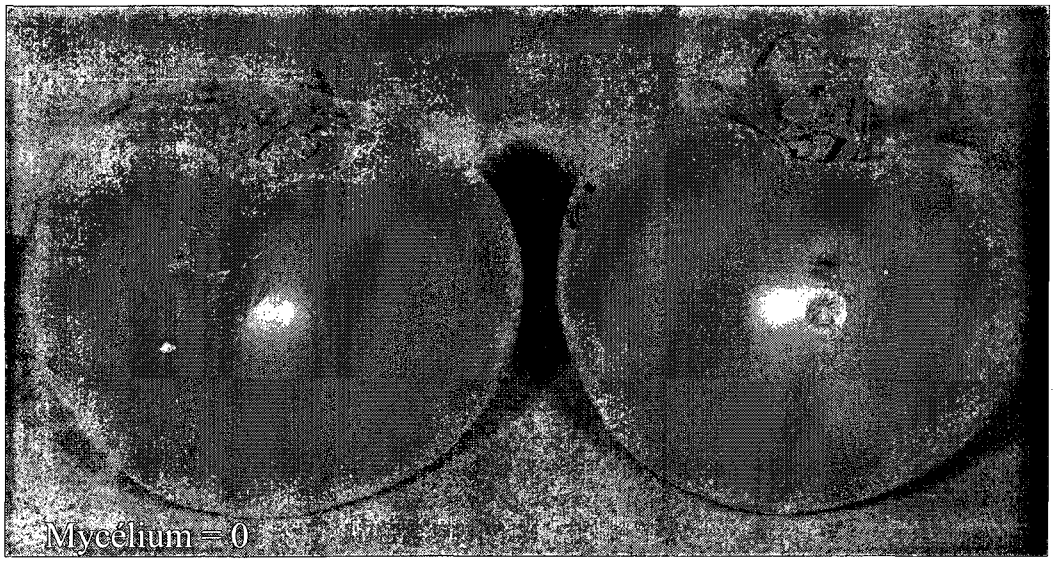
0 : Aucun mycélium visible

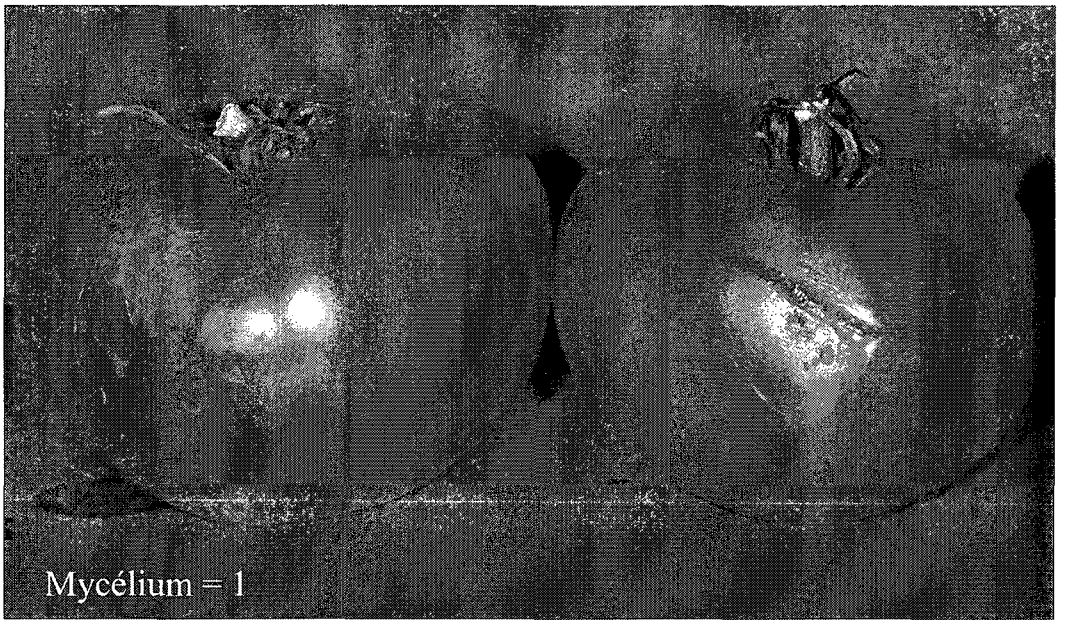
1 : Début de mycélium, difficile à voir

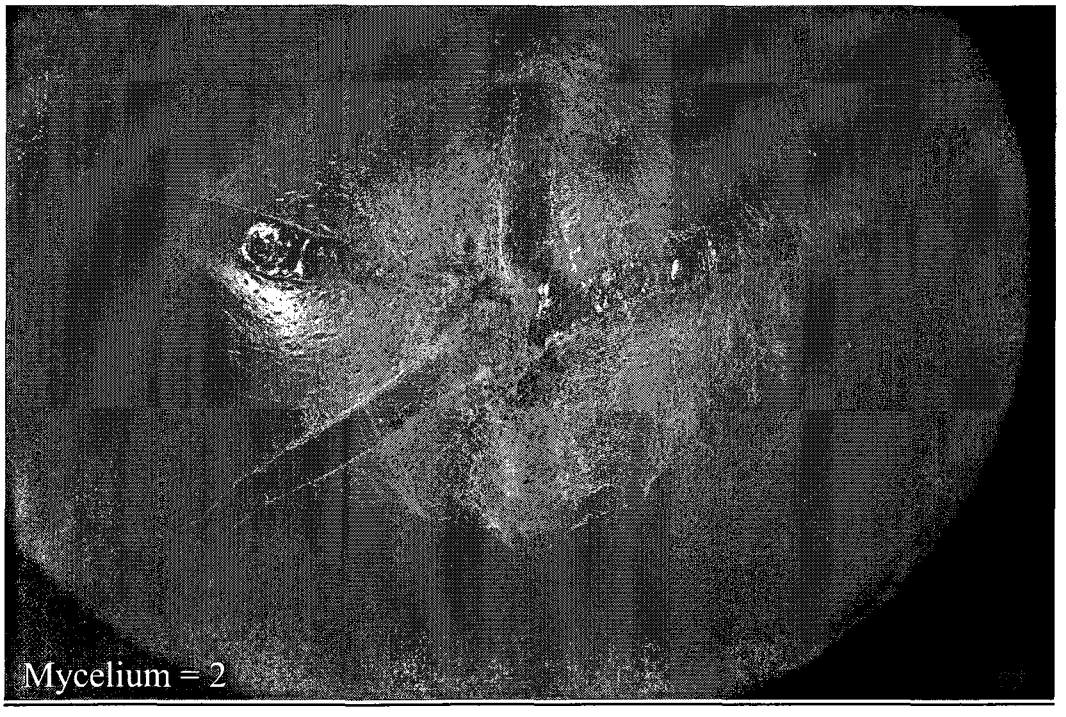
2 : Mycélium visible, mais peu dense et/ou pas surélevé

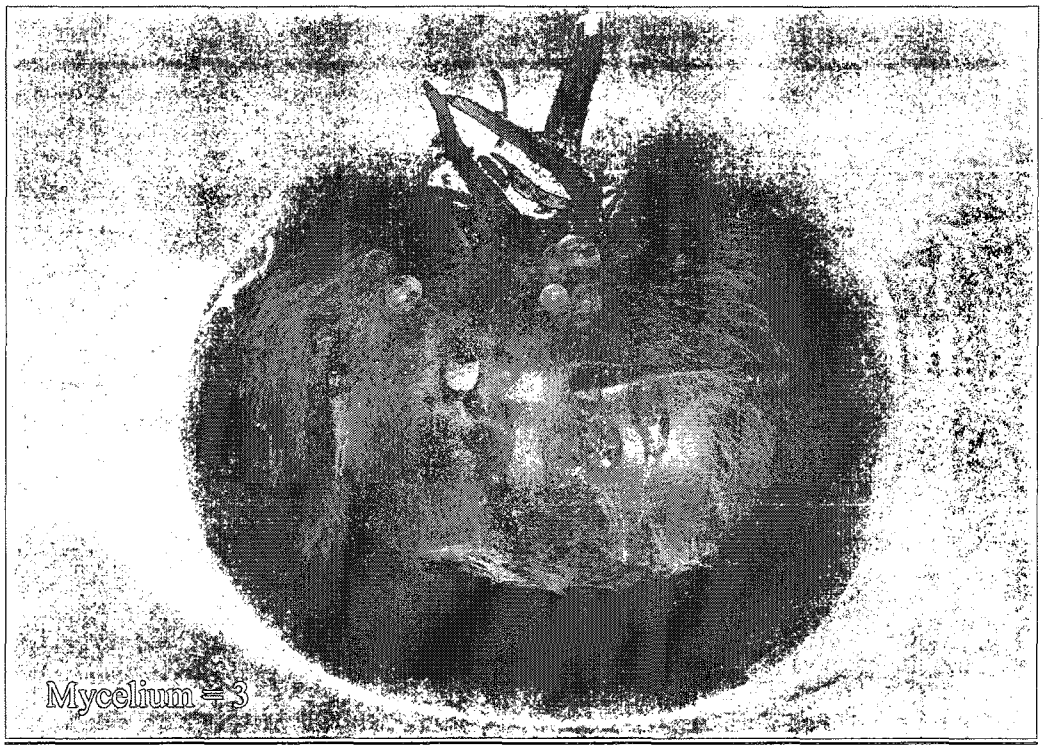
3 : Mycélium visible, très dense et/ou surélevé






Mycélium = 1

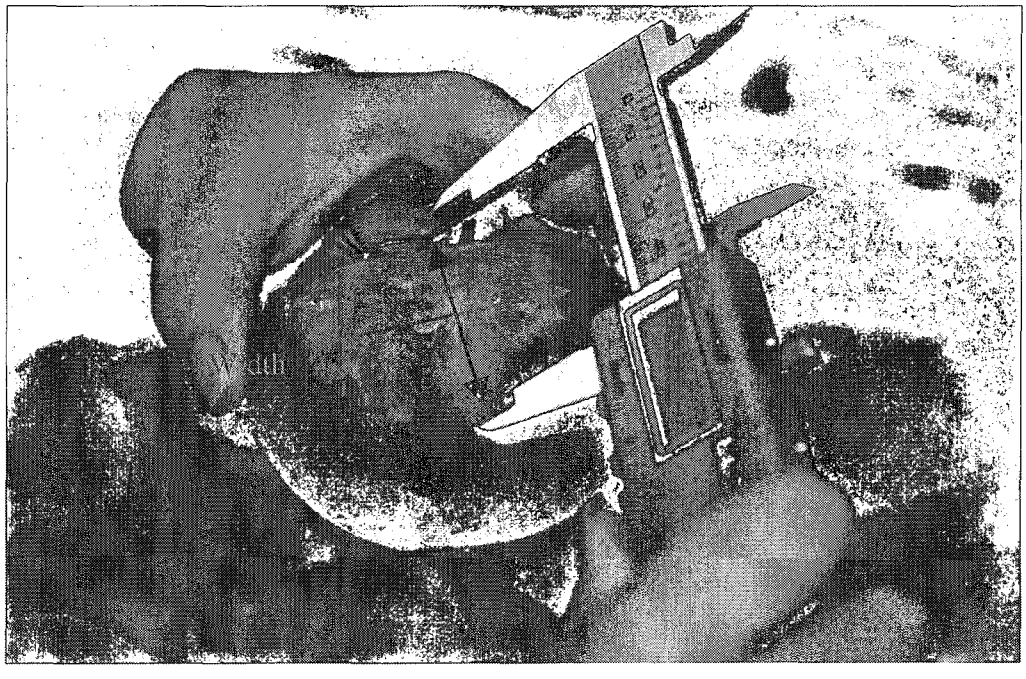

Mycelium = 2



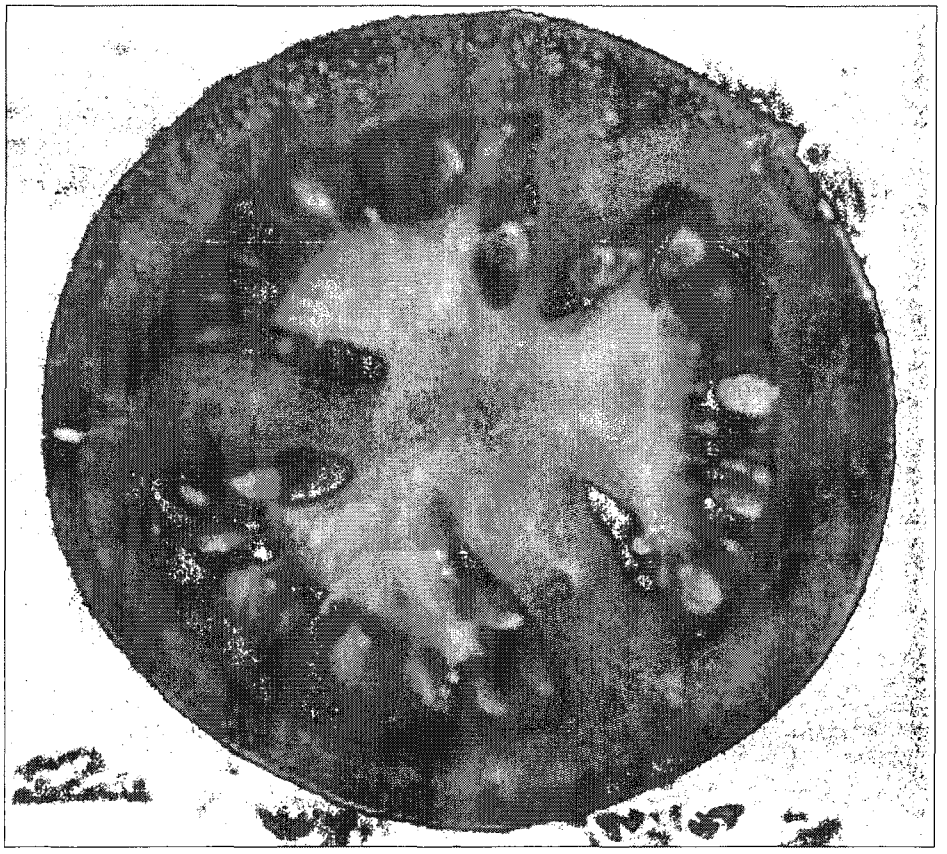
Diamètre

Cote : mesure en mm à l'aide d'un Vernier. Arrondie au mm près.

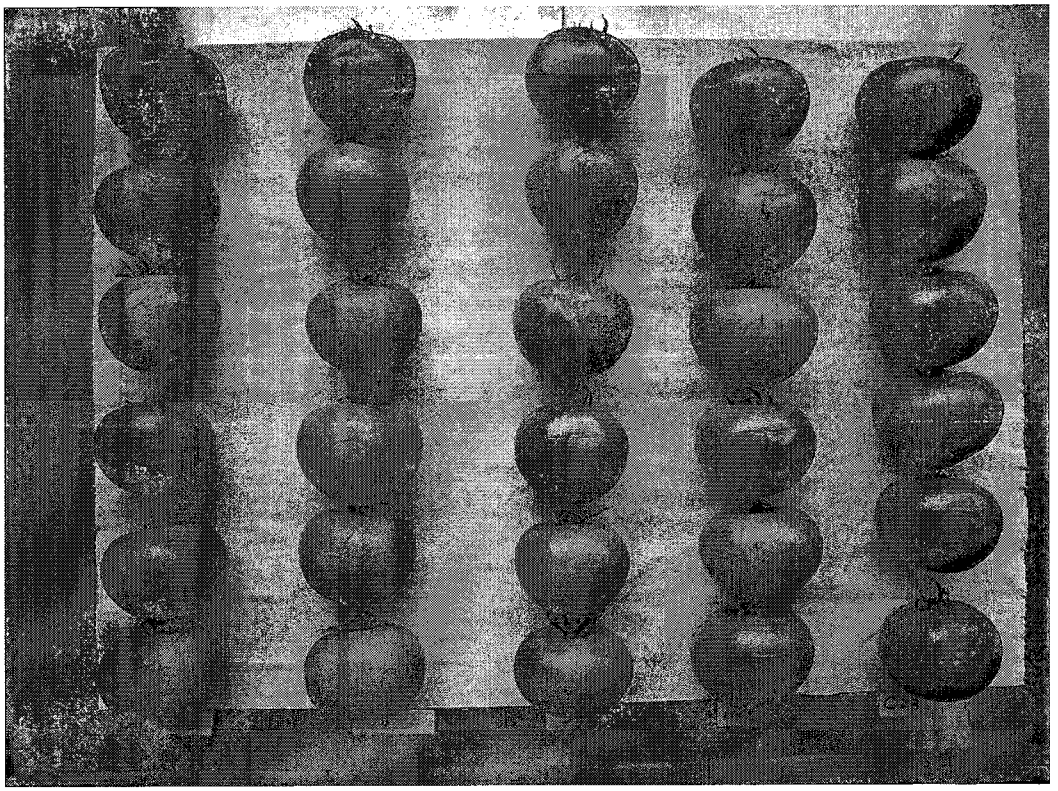
Le diamètre doit être mesuré en largeur et en hauteur.

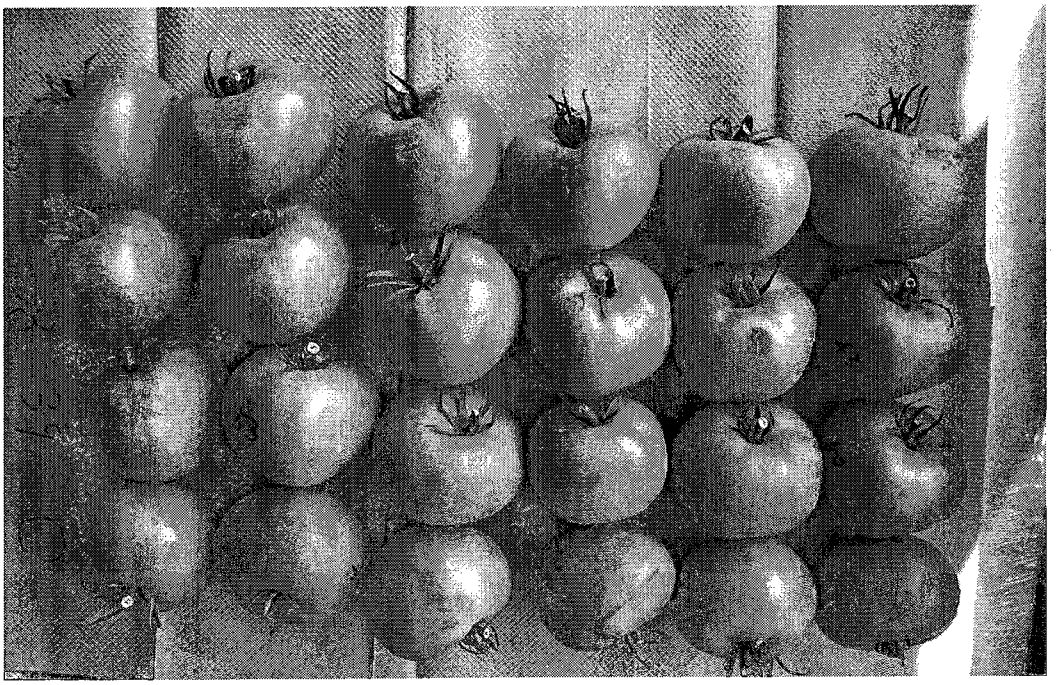


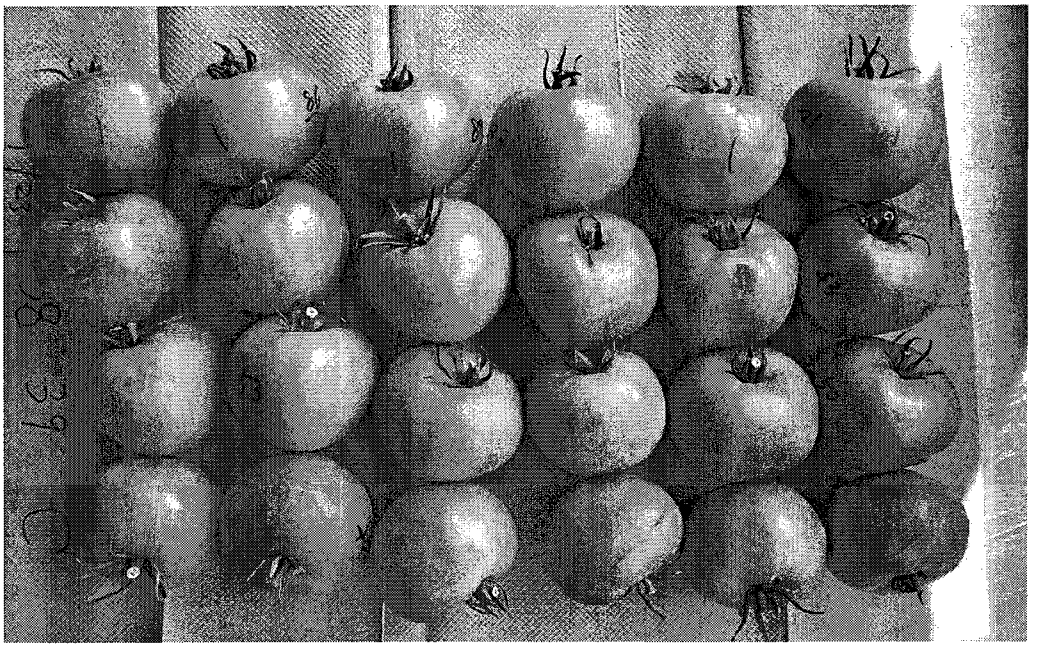
APPENDIX 2 The transverse section of multiloccular tomato fruit



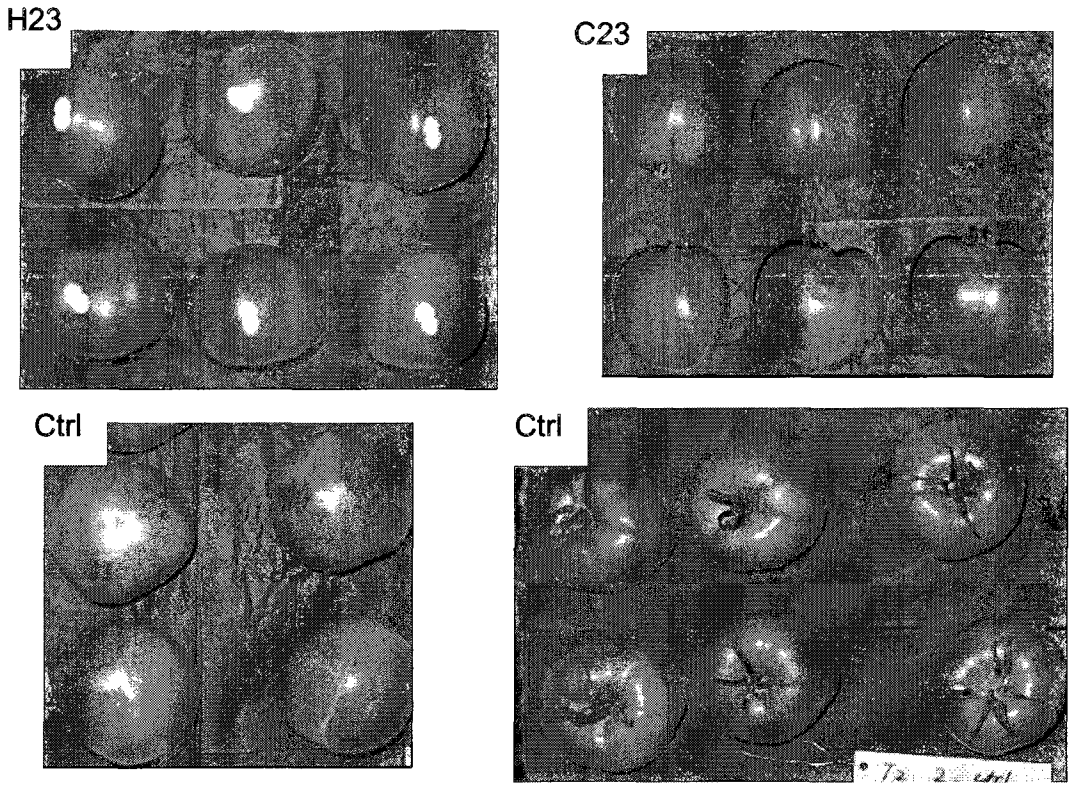
APPENDIX 3 Comparison of severity of *B. cinerea* infection at day 8



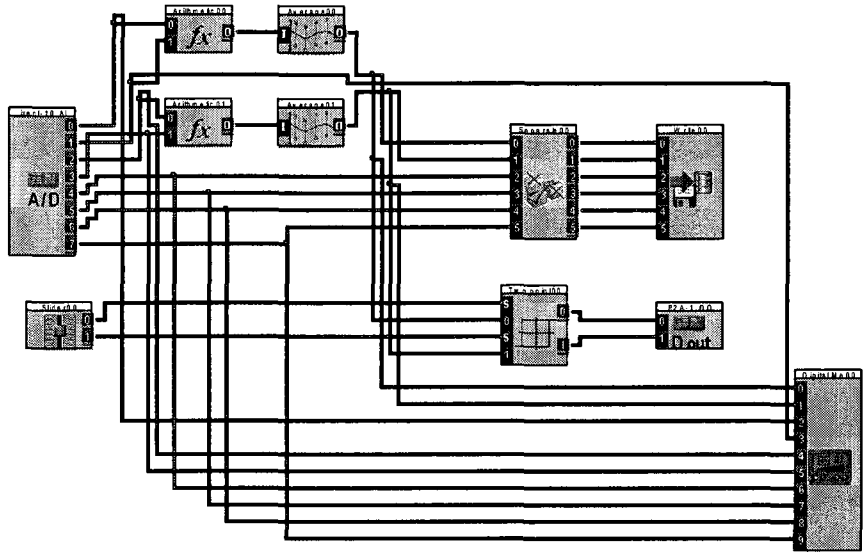


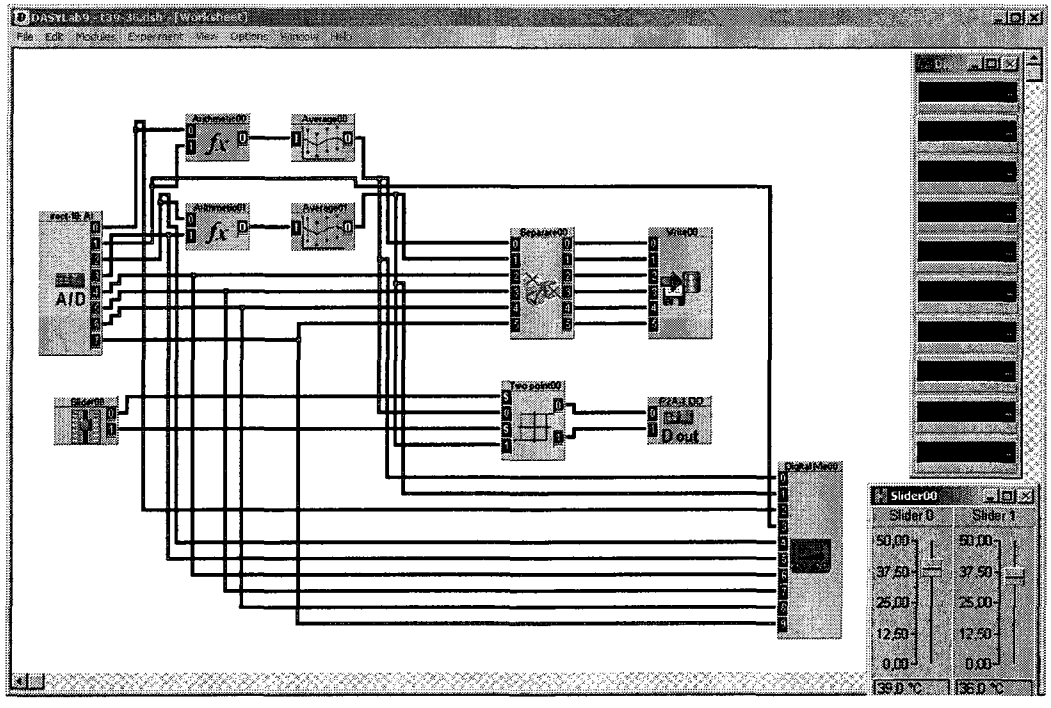


APPENDIX 4 Comparison of severity of chilling injury at day 10 following heat treatment



APPENDIX 5 Control program made using DASYLab V 9.0





APPENDIX 6 Non-parametric SAS program

```
data sample ;
input BATCH rep group hr ck my ar;
output ;
cards ;

proc print;
run;

proc univariate;
class group;
var hr;
run;

/*FREQ*/
proc freq ; /*the correct result is "row mean scores differ"*/
tables group*hr/ scores = rank cmh2 noprint;
run;

/*NPAR1WAY*/
proc npar1way wilcoxon;
class group; /* Chi-Square= 18.13*/
var hr;
run;

/*RANK+ANOVA*/
proc rank data =sample out = a ;
var hr;
ranks r;

proc GLM;
class  rep group ;
model r =rep group ;
means rep group/duncan; /*LSD*/
run;
quit;
```

APPENDIX 7 Standard deviations of temperature measurement inside tomato (°C)

Air temperature difference		Location of thermocouples			
		5 mm beneath top surface of tomato	20 mm beneath top surface of tomato	20 mm above bottom surface of tomato	5 mm above bottom surface of tomato
16	Max	1.08	0.68	1.25	1.22
	Mean	0.88	0.44	0.91	0.88
	Min	0.61	0.15	0.29	0.06
3	Max	1.10	0.90	1.25	1.29
	Mean	0.58	0.64	0.37	0.68
	Min	0.40	0.45	0.00	0.21