EFFECT OF SAMPLE ORIENTATION ON HEAT DISTRIBUTION

A condition of heating power and treatment time that yielded the internal temperature of mango closest to 47°C from heat penetration study was selected for the study of heating uniformity. For each treatment, mango was positioned in either horizontal or vertical orientation (Fig. 2) and rotated while being MW heated. For treatment with horizontal position, mango was additionally rotated along its stem-apex axis manually due to the lack of rotating mechanism around x-axis. This manunal rotation was carried out by pausing the MW oven at half-time during each treatment, turning the sample over and restarting heating until finished. After each treatment, temperature profiles at 8 locations and 3 different depths underneath the skin were quickly acquired (10, 20 mm and at the pit ≈22.6 mm). For each measurement depth, experiment was triplicated. Internal temperature of the mango was mapped into a 3-D model with layers of temperature to demonstrate heat distribution at different depth inside the mango. Moreover, thermal images of treated mango were acquired using thermal scanning camera model IR Snapshot™ (Infrared Solutions, Inc. Plymouth, MN, USA) to accompany heat distribution pattern at the skin with internal temperatures of the mango.

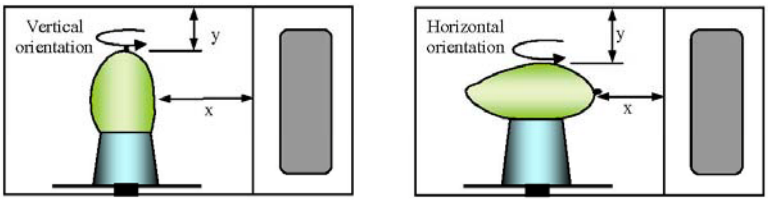

Figure 2. Positions of sample orientation and tri-axial distances between sample and cavity wall inside MW oven. The z-axis (not shown in the figure) was the inward distance between mango and cavity wall.

TEMPERATURE MEASUREMENT APPARATUS

Temperature measurement apparatus consisted of 8 custom-made temperature probes, a datalogger and a personal computer. Each temperature probe of 30 mm in length was assembled from a stainless steel needle gage 15, soldering tip with fine gage thermocouple type T (Omega Engineer Inc., Stamford, CT, USA), and filled with heat conductive paste. Temperature probes were connected to a datalogger model AI210 (Wisco, Co. Ltd, Bangkok, Thailand). Data were logged through a serial port into a personal computer using data acquisition software. Temperature measurement apparatus was calibrated with a certified mercury thermometer in a water bath. Accuracy of temperature measurement apparatus was found to be ±0.5°C within a range of 0-60°C (error less than 1%). It should be mentioned that all temperature measurements on MW-treated mangoes were performed quickly after the MW treatment. An in-placed temperature measurement during MW heating is possible via optic fiber temperature sensor without sample rotation; however, the equipment was not available during the course of our experiment and also did not match with the measurement configuration undergoing the rotation. Even though the post-treatment temperature measurement provided less accuracy, it provided all needs to evaluate the temperature history for to accomplish our desired temperature.

RESULTS

EFFECT OF MW POWER AND TREATMENT TIME ON HEAT PENETRATION

Internal temperatures of the mango at 22.6 mm underneath the cheek (point 6 in Figure 1) reached 35.7±0.7, 37.4±0.6, 45.1±0.6, and 52.3±1.7°C after the MW treatment with power of 50 and 100% for 20 and 40 s (Fig. 3). After 5 min of temperature measurement in ambient condition, internal temperature of the mango started to decay due to heat conduction, possibly outward to the skin. Since MW treatment with 50% power for 40 s increased internal temperature of the mango to 45.1°C (approaching target temperature of 47°C equivalent to effective temperature by VHT quarantine treatment), this treatment was selected for further heat distribution study. It should be noted that the lag time for temperature probe setup on mango was approximately about 60 s. During this lag time, actual temperature of mango was not known but can be estimated by 2nd polynomial model as follow:

$$Y = a \bullet X^2 + b \bullet X + c \qquad [2]$$

where Y is predicted temperature; X is time; and a, b, and c are constants from curve fitting. Even though the actual temperature history during the time of -120 to 0 s (period of MW heating plus setup lag time) was not accurately measurable, it may be of less interest than the information obtained after the actual measurement began ($t \geq 0$ sec).

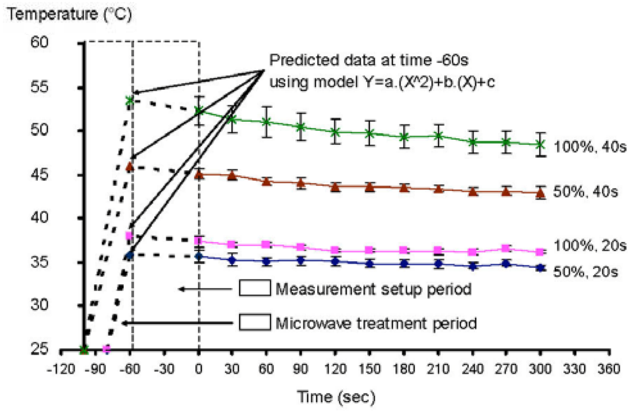

Figure 3. Internal temperature of mangoes closest to the pit (approximately 22.6 mm beneath the skin) after being treated with MW power of 50 and 100% for and 40 and 20 s. Each point represents a mean of 3 replications with error bars of 95% confident interval. The predictive model yields the r^2 of 0.93.

EFFECT OF SAMPLE ORIENTATION ON HEAT DISTRIBUTION

Figure 4 shows general trend of temperature distribution inside the mango and at its surface. The temperature of inside layer was hotter than the outer layer. With MW power of 50% treated for 40 s where mango was in vertical position (Fig. 4a), temperature distribution was not uniform. Heat from MW energy concentrated more at the areas near stem and apex than other parts. On the other hand, horizontal positioning mango (Fig. 4b) showed better heating uniformity with more consistent temperature pattern in each layer than did in vertical positioning one. Internal temperature of horizontal positioning mango distributed from the higher temperature near the pit to the lower temperature toward the skin. Thermogram also indicates that surface temperature of treated mango was more uniform in horizontal positioning mango than did in vertical positioning mango. Surface temperature of horizontal positioning mango varied within 7°C while that of vertical positioning mango varied up to 24°C, as shown in the associated color scale in each thermogram. This result confirms that orientation of the sample inside MW cavity significantly affected local heat absorption of treated mango. It seemed that electromagnetic field of MW inside oven cavity may be more intense near the top and the bottom parts of MW cavity wall than at the center so that stem and apex areas absorbed more heat than did in cheek area for the vertical positioning mango. For horizontal positioning mango, stem and apex areas were subjected to less MW intensity field because they were oriented away from the top and the bottom parts cavity wall. This resulted in the more even heat distribution in horizontal positioning mango than did in vertical one.

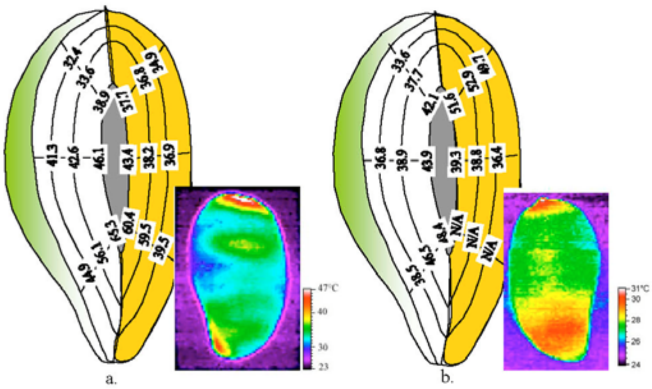

Figure 4. Sectional view of internal and surface temperature distributions of (a.) vertical and (b.) horizontal positioning mangoes treated with MW using 50% power for 40 sec. Each numeric temperature in the profile represents a mean of 3 measurements. Color of thermogram is coded in degree Celsius using color-scaled bar. N/A refers to not available data due to experimental error.

After mangoes were treated with MW under different conditions, half of them was stored at ambient condition (25°C/70%RH) while the other half was at 13°C/80%RH refrigerator for 72 hours before visual inspection. For vertical positioning treatment, mangoes stored at both conditions developed heat damages at stem and apex areas where heat were excessively absorbed (Fig. 5). For horizontal positioning treatment, no damage was observed in mangoes after storing at both conditions.

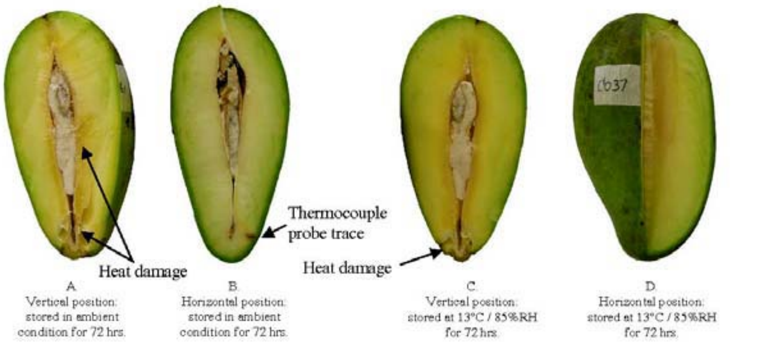

Figure 5. Visual appearances of MW-treated mango with 50% power for 40 s stored at ambient condition (25°C/70% RH) and in 13°C/85%RH refrigerator for 72 h. No heat damage was observed with horizontal positioning treatment.

DISCUSSION

MW energy in this experiment provided heat penetration through the depth of 23 mm inside mango, sufficiently to generate the desired internal temperature close to 47°C. As Fig. 4 illustrates, temperature of the inner layer is higher than of the outer one. Therefore, it seems that penetration depth of this MW configuration exceeds the theoretical value of 10.8 mm, possibly deeper than 23 mm. This phenomenon may be a consequence of MW focusing effect which is promising for the sample in spherical and cylindrical geometries. Spherically and cylindrically foods tend to concentrated MW energy at center when diameter is in the range of 20-60 mm as shown in Fig. 6 (Ducareau, 1992). Therefore, as MW energy propagated through mango, it focused at the center, causing d_p in this experiment possibly deeper than 23 mm.

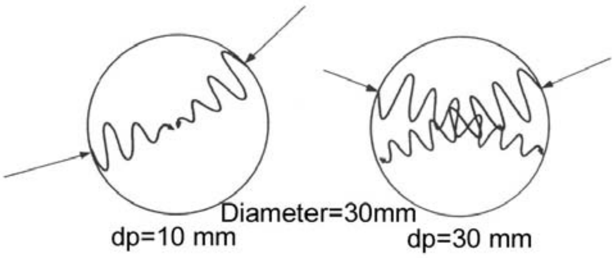

Figure 6. Focusing effect in spherical and cylindrical foods. Adapted from Buffler (1995).

Besides the focusing effect found in this work, it is possible to evaluate electric field intensity using the results from heat penetration study. An increase in temperature of a material due to dielectric heating can be calculated from (Wang et al., 2003):

$$\rho C_p \frac{\Delta T}{\Delta t} = 5.563 \times 10^{-11} f E^2 \varepsilon'' \quad [3]$$

where: C_p is specific heat of material in J/kg-°C, ρ is density of material in kg/m^3, E is electric field intensity in V/m, f is frequency (2,450,000 for household MW oven) in Hz, ΔT is temperature rise in material in °C, and Δt is treatment time in s. Using thermo-physical properties of the mango in Table 1 and temperature rise from heat penetration study (Fig. 3), together with ε" of 14 from the literature (Venkatesh and Raghavan, 2004), the E can be calculated. Table 2 shows that Es at the center of MW cavity for 50% and 100% MW power were 1,054 and 1,180 V/m, respectively. One should take into account that these numbers are not absolute since on-line temperature measurement was not available. However, it clearly illustrates that the higher the MW power, the greater the MW field strength, regardless of treatment time.

Table 2. Estimated electric field intensity at the center of MW oven cavity interacting with Chokanan mango.

MW power (%)	Treatment time (s)	Temperature rise (°C)	*E* (V/m)
50	20	10.7	1,070
50	40	20.1	1,037
		Average	1,054
100	20	12.4	1,152
100	40	27.3	1,209
		Average	1,180

Conclusion

MW treatment with power of 50% increased internal temperature of mango from 25°C to about 45°C within 40 s. Orientation of the sample inside MW cavity greatly affected the local heat absorption in mango where the closer distance from fruit to cavity wall was subjected to the higher heat absorption. Mango whose stem-apex axis positioned horizontally (more distance from the wall to the fruit) absorbed heat more uniformly than that positioned vertically. MW energy penetrated into mango (at least 23 mm) and was converted into heat, which later diffused outward to the skin. Therefore, the cold spot of the mango treated with MW was observed at the outer layer of fruit, which is opposite to those treated with VHT where cold spot is found near the pit inside mango. MW heating can overcome the slow come-up time of VHT (40 s by MW versus 100 min by VHT) and may be either a stand-alone process or a combined process with VHT to improve quarantine heat treatment efficiency. Further work may also be directed toward the design of MW cavity suitable for mango, quality evaluation of mango after MW treatment (e.g., sensory evaluation, firmness, nutrition degradation and ripening process) and completed process protocol of MW-based oriental fruit fly quarantine treatment.

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Microwave-Vapor Heating Technique for Mango Quarantine Treatment: Oriental Fruit Fly Mortality and Fruit Quality

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Abstract

The objective of this research was to develop a microwave-vapor heat treatment (MVHT) for 'Namdokmai Si Thong' mango (*Mangifera indica* L.) to quarantine oriental fruit fly (*Dacus dorsalis* H.). Mortality rate of egg and quality acceptability characterized by Thermal-Death-Time (TDT) and Thermal-Quality-Time (TQT) overlay plot was first obtained by hot-water immersion. Two treatments within a range of acceptable mango quality were selected for infestation experiment to confirm MVHT quarantine process. Results show that the effective quarantine temperature was higher than 48°C for a minimum time of 2 min. The MVHT using microwave for preheating followed by vapor for holding processes effectively disinfested oriental fruit fly egg up to 100%. Changes in physio-chemical properties, namely, color, titratable acid (TA), total soluble solid (TSS), TSS/TA, and firmness, of MVHT mango were not significantly difference ($p>0.05$) than those of the control. MVHT offered less percent of heat damage on mango than conventional VHT and shortened quarantine process time more than 90% during come-up period. MVHTs also retained equivalent or better lethality effect on oriental fruit fly eggs than did by the conventional VHT.

Keywords. Microwave-vapor heat, Quarantine treatment, Oriental fruit fly, Mango, Quality.

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