1. Introduction

The export of Thai mango (*Mangifera indica* L.) exhibits increasing trend due to the high value added to the commodity. In 2004, the export value per kilogram of mango increased about 58% compared to the export value in 2003 (Office of Agriculture Economics, 2005). This increasing trend initiates the awareness of Thai agro-industries about the regulation of trading countries. One of the major threats to the premium markets such as Japan and Australia for Thai mango is the presence of oriental fruit fly (*Dacus dorsalis* H.) inside the fruit. Since cancellation of ethylene dibromide (EDB) fumigation from the past two decades, non-chemical quarantine treatments, e.g., vapor heat treatment (VHT) and hot water dipping became the common methods to control this pest. Recently, an interest of electromagnetic treatments, for instant, microwave and radio frequency, to control oriental fruit fly in fruits has emerged. Microwave rapidly generates heat in food materials and may be used as an alternative to conventional VHT which has drawback due to its slow come-up period.

According to Thai regulation for mango export, general guideline to disinfest oriental fruit fly in mango using VHT was accomplished by monitoring the cold spot of mango at 47°C for 20 min during VHT. This treatment achieved thermal death time higher than $5D$ (equivalent to $LT_{99.999}$) for the first instars (16.45 min) and the egg of oriental fruit fly (<8.91 min) (Jang, 1986), but slightly lower than $5D$ for the third instars (22.3 min) (Jang, 1991). An increase in internal temperature of mango up to 47°C by VHT would take longer than 45 min, hence the fruit would be susceptible to heat damage. With rapid heating by microwave, a concept of high-temperature-short-time (HTST) treatment is possible to shorten treatment time while retaining lethality effect higher than $5D$. The HTST concept is extensively used in food processing to minimize thermal degradation of food quality (Stumbo, 1973; Lund, 1977; and Holdsworth, 1997) and may be applicable for insect quarantine process. Tang et al. (2000) proposed the HTST thermal quarantine methods using radio frequency to control codling moth larvae in in-shell walnuts to be a temperature range of 50-54°C. The third instars codling moth in cherry was also studied (Ikediala et al., 1999). The 915 MHz microwave treatment on cherries can achieve the fruit temperatures of 45, 50, and 55°C but quality of fruit was promising with treatments of temperature less than 50°C.

With regard to mango quarantine treatment, HTST could give several advantages over the conventional heating in term of shortening of come-up time, equivalent or better quality retention, energy minimization, and insect mortality assurance due to high temperature treatment. Varith and Kiatsiriroat (2004) studied the microwave heating on Chokanan mango with 2,450 MHz / 800 W-microwave oven and found an increase of internal temperature up to 46°C within 40 s. Heat distribution inside the fruit depended on fruit orientation, microwave power and treatment time. The horizontal positioned mango treated with 50% microwave power yielded better heat distribution than the vertical one. Continuing to this work, our purpose was to develop a full microwave-vapor heat treatment (MVHT) for oriental fruit fly quarantine process in Namdokmai Si Thong mango which is the export variety. The first experiment explored the lacking information of thermal death and quality kinetics at temperature higher than 48°C. The MVHT process was then developed based on thermal death and quality kinetics. Finally, experiments were conducted to confirm the MVHT quarantine method along with measurement of changes in mango quality after the MVHT process.

2. Materials and Methods

2.1 Materials

Namdokmai Si Thong mangoes freshly harvested from two orchards in Chiang Mai, Thailand, were used in this research. The first orchard provided domestic-graded mango while the second orchard offered export-graded one. The domestic-graded mangoes were primarily used for insect mortality study while the export graded-mangoes were used for a study of changes in quality after MVHT. During fruiting stage, intact export-graded mango was enfolded with horticultural envelope while the domestic graded one was enfolded with the regular white paper. This yielded a major difference in color of skin where domestic-graded mango dominated the green color while the export-graded mango dominated the yellow one (Table 1). Other physical-chemical properties of mango between two orchards were not different. After harvesting, each lot of mango was stored at 13°C / 90%RH for 48 h prior to the experiment. The experiment was accomplished within 72 h to avoid effect of ripening. Each mango weighed between 300-330 g/fruit with maturity of 80% (commercially estimated). Firmness was characterized with two parameters; failure force at rupture point and apparent elastic modulus (ASAE Standards, 2003). Details of firmness measurement were discussed further. Eight hours prior to the test, the samples were equilibrated in room condition of 25°C / 60%RH. Thermo-physical properties of domestic- and export-graded mangoes measured at the room condition (25°C / 60%RH) are presented in Table 1.

2.2 Mass rearing of oriental fruit fly

Oriental fruit fly pupae were reared in the Department of Plant Protection, Maejo University, in screen cages at 25-27°C / 70%RH. Flies that emerged were provided with sugar, hydrolyzed yeast protein, and water. Eggs were collected from mature females (10-14 days old) during 1-h period. Eggs used in mortality study were transferred into agar gel box (size of 30x55x20 mm) while those used in infestation experiment were transferred in the mango fruit.

2.3 Preliminary study of mortality rate and quality acceptability

Mortality rate of oriental fruit fly eggs were studied using hot water immersion technique. Two hundred eggs were incubated on a thin layer of agar gel inside the plastic boxes (fifty eggs each). For each treatment, four incubated boxes were immersed into water bath model MD16-G (Julabo Labortechnik GmbH, Germany) with an accuracy of ±0.5°C under the controlled temperature of 46, 48, 51, and 55°C for 2, 5, 12 and 20 min. This resulted in a total of 3200 eggs. It is noted that an increase in medium temperature within ±0.5°C of the desired temperature required approximately 10 min. Therefore, all mortality treatments were subjected to the additional come-up time of 10 min; bringing on the actual immersion time of 12, 15, 22 and 30 min. It was also assumed that thermal lethality effect on insect during come-up period was less significant than that during holding period and was negligible.

For quality acceptability, four mangoes (domestic graded) per treatment were immersed in hot water bath under the desired temperatures of 46, 48, 51, and 55°C for 2, 5, 12 and 20 min, equivalent to the mortality study. The experiment was replicated twice, resulting in a total of 128 fruits. To reach temperature within ±0.5°C of the designated temperature, the extra five minutes were required so that the actual elapsed time were 7, 10, 12 and 20 min. After hot water immersion, treated mango was hydro-cooled with 25°C sprayed water for 30 min. All treated mangoes were then stored at 13°C / 90%RH for 3 days before assessing the heat damage by percent of browning area. Details of heat damage assessment are discussed in section 2.6.

To quantify the acceptable temperature and time for quarantine treatment, Thermal-Death-Time (TDT) plot of insect mortality was established, overlaying with Thermal-Quality-Time (TQT) plot. TDT plot exhibited ranges of insect mortality while TQT plot indicated percent of damage area on mango peel. Acceptable quarantine process was an area in overlay plot where the insect was 100% killed and no damage on mango. Treatments of acceptable temperature and time were selected for further full-quarantine process development in the next experiment.

2.4 Development of MVHT Quarantine Process

For MVHT process development on mango, preheat during come-up period was accomplished by microwave treatment adapted from Varith and Kiatsiriroat (2004) where Chokanan mango treated with MW power of 400 W for 40 sec increased its internal temperature at the cheek area up to 46°C. Export-graded mango was treated with MW power of 50% using 2,450 MHz / 800 W microwave oven model R-254 (Sharp Co., Ltd., Japan). MW preheat treatment was divided into 2 steps. Firstly, the mango was placed in horizontal position on a polypropylene support at center of the oven and rotated while being heated with MW power of 400 W for 40 s (Figure 1a). Secondly, the mango was placed approximately 20 mm away from the exit of waveguide without rotation (Figure 1b). The

25°C water of 1800 cm^3 was placed beside the mango to absorb microwave after penetrating through the mango and to reduce the microwave reflection back to the mango. This step provided a virtual 1-D radiation focusing at the mango cheek which was the thickest part and subjected to the slowest heating during conventional VHT heating. Finally, mango was transferred to a vapor (saturated steam) cabinet for VHT holding process where temperature inside was controlled at 55±1°C using temperature controller and solid state relay. During treatments, mangoes were sampled in 4-5 periods and cut in-half for a thermography imaging. Then, thermography images of the sectional mangoes were quickly taken for step-wised heat distribution during MW and VHT periods using thermal imaging camera model IR FlexCam™ (Infrared Solutions, Inc., MN, USA). After MW treatment, the slowest heating spot during MVHT process was identified and used as a reference for holding temperature during VHT. After preheating and holding period of MVHT, the mango was cooled down with showering water of 25°C for 30 min. All MVHT preliminary experiments were replicated six times with six mangoes each. Treated mangoes were stored at 13°C / 90%RH for 24 h for assessment of percent damage on peel and flesh. Figure 1 schematically demonstrated the steps of MVHT quarantine treatment on mango.

2.5 Confirmation experiments on MVHT and VHT quarantine processes: insect mortality and fruit quality

Two selected time-temperature combination in acceptable range of TDT and TQT curve were selected for the infestation experiment. Each domestic-graded mango was infested with fifty eggs onto the flesh slice, about 23 mm deep from the peel, and sealed with clear tape to prevent leakage of water into infested area. Two MVHTs and one conventional VHT using 55°C saturated vapor were selected for quarantine treatments. Experiment was replicated twice which led to a total of 48 mangoes with 2,400 eggs. Treated mangoes were then stored at 25°C / 70% RH to observe an emergence of larvae. Morality rate of oriental fruit fly egg (reciprocal of percent of egg emergence) was reported.

For quality changes over a period of storage time, two selected MVHT and one VHT treatments were performed on 48 export-graded mangoes with two replications of six fruits per treatment. After treatment, mangoes were stored at 13°C / 80%RH for 15 days. Quality measurements, namely, color of peel and flesh, firmness, tritratable acid (TA), total soluble solid content (TSS) and ratio of TA/TSS were determined on two mangoes from each replication for every third day. Quality parameters were analyzed using Analysis of Variance (ANOVA) using StatView™ version 5.0 (SAS Institute, Inc., NC) with 95% confident interval. Quality parameters were reported significantly different when $p<0.05$.

2.6 Quality measurement methods

Color: Spectroscopy model MiniScan XE (Hunter Associates Laboratory, Inc., Reston, VA) was used to measure color of mango. Measuring condition was set using 10/45° angle with D65 illuminant. Spectroscopy was standardized with white and black plates following the factory protocol. CIE scale (L*-a*-b*) was reported as the color parameters. Measured parameter L* indicated lightness with scale from 0 to 100; a* indicated red (-a*) to green (+a*); and b* indicated yellow (-b*) to blue (+b*) scale.

Firmness: Firmness of mango was determined by two means under penetration test; 1. maximum force at rupture; and 2. apparent elastic modulus followed the guideline of ASAE S386.4 DEC00 (ASAE Standards, 2003). Stainless steel probe with a diameter of 6 mm and radius of curvature of indenter about 66.9 mm was used to penetrate mango flesh to 10 mm in depth. Cross-head speed was set at 1 mm/s. Apparent elastic modulus (E) was calculated using Equation 1 as:

$$E = \frac{0.338 K_u^{\frac{3}{2}} F (1-\mu^2)}{D^{\frac{3}{2}}} \left(\frac{4}{d} \right)^{\frac{1}{2}} \qquad [1]$$

where E= apparent modulus of elasticity (Pa); D=deformation (m); μ=Poisson's ratio (assumed to be 0.45); F=force (N); K_u=dimensionless factor (=1.351 for a flat surface-indenter test); and d=diameter of curvature of the spherical indenter.

Tritratable acid (TA): TA was determined by indicator method followed the guideline of AOAC 942.15. (AOAC, 1996).

Total soluble solid content (TSS): TSS was determined by hand refractometer model N-1α (Atego Co., Ltd, Japan).

Heat damage assessment: Heat damaged on treated mango was assessed from percent of browning area of the peel or whitening area of the flesh. While being placed on a graphical paper, the mango was captured by a digital camera and then transferred into Adobe® Acrobat Professional® version 6.0 for the area determination using area measuring tool (Figure 2). Percent of damage and non-damage on each mango was assessed from:

$$\%\ damage = \frac{Browning\ or\ whitening\ area\ of\ damage}{Total\ area} \qquad [2]$$

3. Results and Discussion

3.1 Preliminary study on mortality rate and quality acceptability

Table 2 shows that oriental fruit fly in egg stage was susceptible to heat tolerance at 46°C up to 12 min. Our results agreed with the data presented by Jang (1986) that gave a calculated lethality time in egg stage of 8.91 min and yielded thermal death rate of 5*D* ($LT_{99.999}$). However, the thermal death rate data of egg above 48°C were absent. Since our result indicates that the temperature higher than 48°C with holding time at least 2 min yielded 100% mortality, these treatments were promising for the holding condition for further MVHT quarantine treatment of mango.

Table 3 indicates that the mangoes undergoing treatment at 51°C with holding time up to 12 min were not damage due to heat. Mangoes subjected to heat at 51°C for 20 min and 55°C for 5 min were slightly susceptible to damage less than 5%. With temperature of 55°C for holding time longer than 5 min, heat damage on mango increased no more than 15%. The TDT and TQT overlay plot (Figure 3) shows the shaded area of quarantine treatment. Therefore to assure non-damaged quarantined fruit, the upper boundary of quality acceptance was approximately at 55°C for short period of time for 2

