Temperature measurement and analysis of postharvest agricultural products associated with thermal disinfestations

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Abstract: Hot air and hot water treatments are practical, environmentally-friendly and non-chemical heating methods, which are widely used for postharvest insect control and quality preservation in agricultural products. Taking apple and pear as representative fruits, this study mainly analyzed influences of their thermal properties, diameter, and medium speed on the heating rates of fruits through their real-time measured temperatures at surface and center. Based on the reported thermal death kinetic models of the target codling moth, the minimum heating time was estimated to achieve 100% insect mortality. The results showed that the heating rates in fruits decreased gradually with the increasing depth from the surface to the center. With increasing heating time, the heating rate became small. The apple was heated faster than the pear. Hot water was more effective than hot air in treating fruits. Increasing hot air speed increased the heating rate but increasing water circulating speed had no clear effects on the heating rate. Based on the measured temperature-time history of the fruit center, the minimum heating time could be effectively determined for codling moth control through the estimated total equivalent thermal lethal time. The results could provide reliable validation data for the computer simulation and a scientific basis to improve the hot air and hot water treatments.

Keywords: hot air, hot water, fruit, postharvest treatment, heating rates, temperature measurement, thermal disinfestation

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1 Introduction

China is a big fruit production country since both total cultivated area and production rank the top one in the world after 1993. In 2011, the cultivated area and production were about 12 million hectares and 23 billion tons, respectively. Especially, productions of apple and pear have been ranked in the top three countries for many years[1]. The fruit industry plays an important role in the national economy, which directly affects the development of agricultural economy and the increase of farmers' income. In the process of production, harvesting, shipping, and storage, the surface and interior of fruits are often infested by harmful microorganisms and insect pests (e.g. codling moth), which would cause negative influences on fruit quality and food safety. Besides, these plant diseases and insect infestation in

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fruits may result in biological invasions and quarantine regulations in international trade, which have a certain influence on the sustainable development of China's fruit export markets[2]. Therefore, reducing the occurrence of postharvest fruit diseases and pests is of great significance to provide high quality fruits, improve the fruit competitiveness in international markets, and increase farmers' incomes.

Most of postharvest fruits have been treated by using methyl bromide fumigation to control the microorganisms and pests for a long time. Since this fumigant is identified as an ozone depleter, developing countries such as China will ban its use in 2015 according to the international agreements[3]. With increased concerns on people's health and environmental protection, it is urgent to explore practical, environmental-friendly, no chemical residues and physical methods to replace the traditional chemical fumigation for controlling diseases and insects in fruits.

Having the advantages of no residues, easy to control and small equipment investment, hot air and hot water heating is considered to be a potential non-chemical method for pasteurizing and disinfecting fruits[4-7]. Adequate hot air treatments can reduce the respiratory intensity and ethylene release rate, increase the hardness and brittleness, and extend the shelf life of postharvest fruits and vegetables[8-11]. Hot water treatment can also accelerate the ripening speed of the fruit, inhibit the occurrence of diseases and pests effectively, maintain the fruit hardness and color, and prolong the fruit shelf life[12-18]. Without understanding of the heat transfer and precise temperature measurements during hot air and hot water treatments, long time and high temperature treatment would lead to fruit and vegetable quality damages, such as browning, softening or off flavors. For example, the flavor and appearance changes of grapes are reported when treated with hot air at 46℃ for 3 h[19], and surface browning of avocado appears after hot air heating at 43℃ for 3.5 h[20]. Internal breakdown and surface color change are found in apples after water bath heating at 46℃ for 45 min[21]. Therefore, insufficient or excessive heat treatments may result in either insect survival or fruit quality degradation.

The major factors influencing heat treatments include the final temperature, the heating rate and the heating time in the cold and hot spots of fruits, which are important to achieve the required insect control without damaging fruit quality. The precise determination of these factors is also needed to validate the computer simulation results[22]. Combining the temperature-time history with the reported thermal death kinetics of the target insects could optimize the heat treatment protocol and guide the selection of appropriate treatment time to achieve the required insect mortality in fruits, which has been solved by estimating the accumulated equivalent lethal time[23]. Therefore, a systematic study is required to precisely determine the heating rates as influenced by the possible heating factors, provide insight into the limitations of hot air and hot water heating methods, and explore reliable means of optimizing these treatments.

Choosing apple and pear as representative fruits, the objectives of this study were to measure their surface and center temperatures when subject to hot air and hot water heat treatments at 55℃, to analyze the effects of fruit diameter, medium, and medium speed on the heating rates of fruits, and to estimate the accumulated equivalent lethal time based on the temperature-time history in the fruit center and the reported thermal death kinetic model of the target codling moth.

2 Materials and methods

2.1 Materials

The varieties of fruit samples were "Red Fuji" apples and "White" pears, which were obtained from a local supermarket in Yangling, Shaanxi, China. To make the experimental results accurate and reliable and reduce the system error, all the samples were sorted and selected with approximately spherical shape, similar color and size (6-8 cm in diameter), and no mechanical damages or surface defects.

2.2 Temperature measurement

Samples were placed in an incubator (BSC-150, Shanghai Boxun Industry & Commerce Co., Ltd, Shanghai, China) at 20℃ for 4 h to obtain the uniform center and surface temperatures before the tests. The conducted experiments include: hot water heating of apple and pear, hot water and hot air heating of pear, and hot water heating of pear with different diameters. Hot water and hot air treatments were carried out by a numerically controlled constant-temperature water bath (SC-15, Scientz Biotechnology Co., Ltd., Ningbo, China) and an air drying oven (101-1AB, Taisite Instrument Co., LTD., Tianjin, China), respectively. To avoid the sample floating in the water bath, the samples were first fixed in a metal basket, which was immersed in the center of water bath during the water heating process. Since most of the insects could be killed at 55℃ for 1 min[24], this temperature was setup both for hot water and hot air treatments. The temperature measurement process was stopped when the fruit center temperature reached 55℃. Type-T thermocouple temperature sensor (TMQSS-020-6, Omega Engineering Ltd., CT, USA) was used to measure the fruit surface and center temperatures by inserting the sensor to these required positions. The measured temperatures were sampled every 5 s and recorded every 60 s by a data acquisition system (CR-1000, Campbell Scientific Inc., Logan, Utah, USA). Each test was repeated twice. The average and standard deviation values were calculated over the replicates in Excel software.

2.3 Effect of the medium speed on the heating rate

In conventional treatments, the air and water were generally considered as a heating medium surrounding the fruits. In the process of hot air and hot water heating, the heat was first transferred from the heating medium to the fruit surface by heat convection, and then from the surface to the fruit center by heat conduction. The thermal resistance of above two processes that affects the heating rate can be described by the biot number (Bi)[25], which is the ratio of the external thermal resistance to the internal one and expressed as:

$$Bi = \frac{\text{Internal resistance}}{\text{External resistance}} = \frac{hr_0}{k} \qquad (1)$$

where, r_0 is the fruit radius, m; k is the thermal conductivity of the fruit, W/(m·℃); and h is the surface heat transfer coefficient, W/(m·℃). With forced convection and turbulent flow and according to boundary layer similarity for a sphere, the convective heat transfer coefficient can be estimated as follows[22]:

$$h = 0.34\frac{k_f}{d}\left(\frac{ud}{v_f}\right)^{0.6} \qquad (2)$$

where, d is the sphere diameter, m; k_f is the thermal conductivity of the medium, W/(m·℃); u is the heating medium speed, m/s; and v_f is the kinematic viscosity of the medium, m^2/s. According to the energy balance, the fruit temperature is also function of the thermal properties of the fruit and the heating medium, which are listed in Table 1. For the effect of fruit thermal properties on heating rate, the general parameter, thermal diffusivity (α), which covers thermal conductivity (k), specific heat (c_p) and density (ρ), was taken into consideration.

Table 1 Thermal properties of selected fruits and heating medium[22,26]

Fruits and medium	Density (ρ) /kg m^{-3}	Specific heat (c_p) /J kg^{-1} ℃$^{-1}$	Thermal conductivity (k) /W m^{-1} ℃$^{-1}$	Thermal diffusivity (α) /$\times10^{-7}$ m^2 s^{-1}	Kinematic viscosity (v_f) /$\times10^{-6}$ m^2 s^{-1}
Apple	840	3600	0.513	1.70	-
Pear	1000	3700	0.595	1.61	-
Water	1000	4180	0.560	1.34	1.01
Air	1.2	1200	0.250	1.73	14.80

When Bi value is large (e.g., 10), it means that the external thermal resistance is small as compared to the internal one, the internal thermal resistance dominates the heating rate, and internal temperature gradients are significant. When Bi value is small (e.g., 0.1), it suggests that the external thermal resistance is greater than the internal one and the heating rate is greatly influenced by external thermal resistance. With the given thermal properties of the fruits and heating medium, the effect of the medium speed on the heating rate of fruits was analyzed by Equation (1).

2.4 Estimation of total cumulated thermal lethal time

Insect mortality is mainly determined by the total cumulated thermal lethal effect during the heat treatment process. When the actual temperature–time history at a specific location of fruit was measured, the cumulative thermal lethal effect of the treatment at this location can be estimated if thermal death kinetic model of the target insect pests is established. The most conservative or smallest insect mortality should be located at the cold spot of the fruit, that is, the fruit center in the hot air and hot water heating[23]. When the pests at the fruit center reach 100% mortality, the total cumulated thermal lethal time M_{ref} (min) at a reference temperature T_{ref} (℃) could be calculated as follows[24]:

$$M_{ref} = \int_0^t 10^{(T(t)-T_{ref})/z} dt \quad (3)$$

where, $T(t)$ is the center temperature (℃) at time t (min) in the process of heat treatment; z is the raised temperature (℃) required for a 10-fold decrease in thermal death time curve of the insects and the average value of 4℃ was used according to the thermal death kinetics of codling moth larvae mainly found in the fresh fruits. When reaching 100% mortality, the required minimum thermal lethal time t_{ref} (min) of codling moth could be estimated as follows[24]:

$$\log(t_{ref}) = 12.41 - 0.234T_{ref} \quad (4)$$

Based on the temperature-time history in the apple and pear center, Equation (3) can be used to predict the total cumulated thermal lethal time M_{ref} curve as a function of actual heating time in hot water and hot air treatments. As compared to the required minimum thermal lethal time t_{ref} for the codling moth in the center of fruit to achieve 100% mortality at the selected temperature using Equation (4), the heat process can be terminated at the crossing point between M_{ref} curve and the t_{ref}, which is the equivalent shortest heat treatment time t_{min} (min). This method may provide practical guidance to manage the heating process and stop the heating time timely, which could avoid insufficient heating for causing insect survivals or excessive heating resulted in fruit quality losses.

3 Results and discussion

3.1 Effects of different thermal characteristics on heating rate

Figure 1 shows the surface and center temperatures of apple and pear (d = 8 cm) as a function of the treatment time in the water bath at 55℃. The heating rate at the fruit surface was larger than that in the fruit center, because the surface layer was closer to the heating medium and heated up rapidly. The surface heating rate of apple was similar to that of pear, which needed 25 min and 35 min to reach 55℃, respectively. Due to thermal inertia, the fruit central parts were heated slowly at the beginning. After that, the temperature of the fruit center also increased rapidly due to the large temperature difference between the center part and the surface. However, when the central temperature approached the water bath temperature, the heating rate was reduced again. The heating rate in apple center was larger than that in the pear center, which took about 50 min and 70 min to reach 55℃ in water bath, respectively. This was probably caused by the slightly higher thermal diffusivity for apples as listed in Table 1, because the effect of other four basic parameters were not significant when temperature varied from 20℃ to 55℃[22]. Therefore, the heating rate and heating time may be estimated by the given thermal characteristics of the fruits.

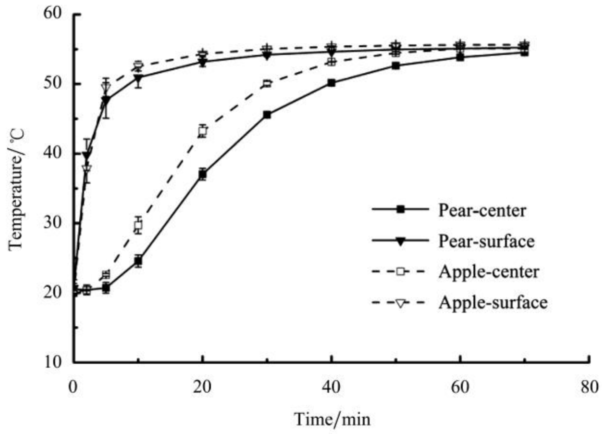

Figure 1 Center and surface temperatures of apple and pear (d = 8 cm) when subject to hot water heating at 55℃

3.2 Effects of different heating medium on heating rate

As shown in Figure 2, the surface and center temperatures of pear and apple (d = 8 cm) were compared between hot air and hot water heating at 55℃. The general trends were similar to Figure 1, but the heating rates both in the surface and the center of pear and apple under hot water heating were larger than those in hot air heating. For example, it took about 35 min and 70 min for pear surface and center to reach 55℃ in hot water heating, respectively; while for hot air heating, it needed about 125 min and 167 min for the fruit surface and center temperature to only reach 53℃ (Figure 2a). This was because the surface heat transfer coefficient (h) of the fruit was different for various heating media, which can be estimated by Equation (2). The surface heat transfer coefficient in water bath was 1 870 W/(m·℃), which was much higher than that (10 W/(m·℃)) in hot air heating. Due to the small surface heat transfer coefficient in hot air heating and small temperature difference between surface and center at the final stage, the heating rate in the pear and apple centers was very slow, resulting in long time to reach 55℃. Generally, the heating rate in hot water treatments was faster than that in hot air, suggesting that hot water treatment was more effective than hot air heating.

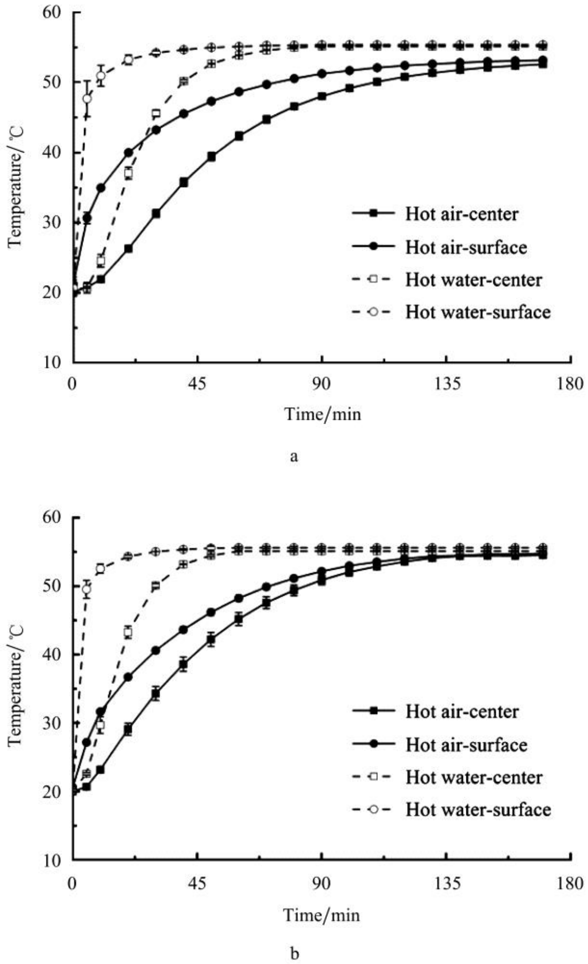

Figure 2 Center and surface temperatures of (a) pear and (b) apple (d = 8 cm) when subject to hot water and air heating at 55℃

3.3 Effects of fruit size on heating rate

Figure 3 shows the surface and center temperature profiles of pear and apple with different size when subject to hot water heating. The temperature profiles were similar both for pear and apple. As found in Figures 1 and 2, the surface and center temperatures increased with the heating time and the heating rate at the surface was larger than that in the fruit center. Reducing the fruit diameter from 8 cm to 6 cm, the heating rate of the pear and apple increased clearly, especially in the fruit center. For example, it took 35 min and 70 min for the surface and center of the large pear (d = 8 cm) to reach 55℃, which were reduced to 23 min and 50 min for the small size pear (d = 6 cm). With the same heating medium and thermal characteristics of fruits, the small fruit size difference (Δd = 2 cm) resulted in large differences in heating rates of pears and apples. For example, the maximum temperature difference was found to be more than 7℃ for pears, indicating that the fruit size was an important factor to affect the heating rate. Hence, the fruits should be sorted and carefully selected according to the size before heat treatment, which could improve the heating uniformity among the fruits in the practical heat treatments to ensure the insect control and reduce the quality loss of the fruits.

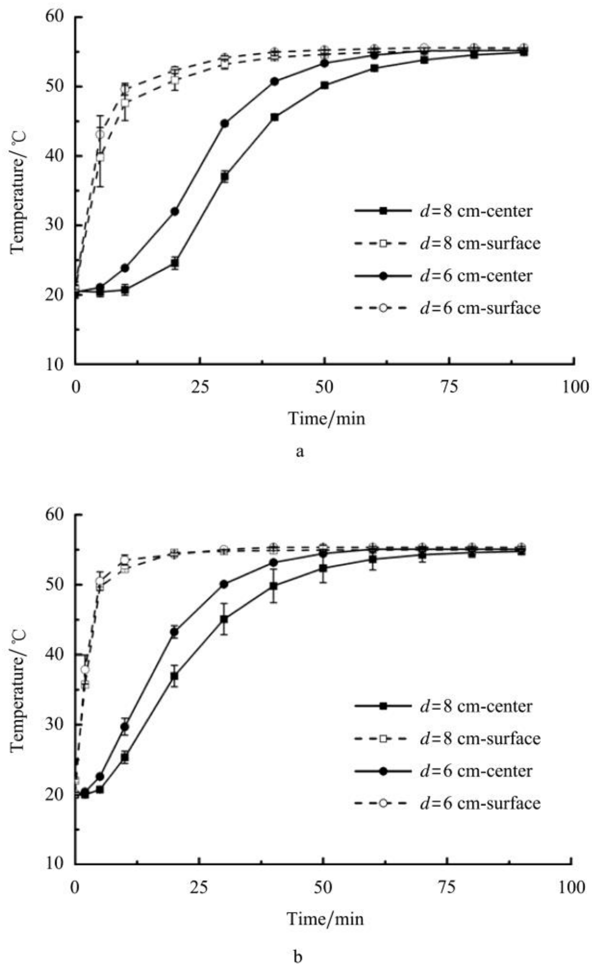

Figure 3 Center and surface temperatures of (a) pear and (b) apple with two diameters when subject to hot water heating at 55℃

3.4 Effects of heating medium speed on heating rate

Table 2 lists the estimated Bi values at two typical medium speeds when subject to hot air and hot water heating of apples and pears. The Bi values of hot air heating were small and close to 1.0, indicating that the external thermal resistance was similar to internal one and the heating rate was mainly influenced by the external heat transfer. Although absolute Bi value increased a little with increased hot air speed, the heating rate increased clearly since the external thermal resistance was reduced as compared to the internal one. Changing the air speed had influence on the heating rate of fruits. The Bi values in hot water heating were greater than 1.0, suggesting that the external thermal resistance was smaller than the internal one and the heat transfer was mainly limited by the heat conduction inside the fruit. Changing the water speed had little influence on the heating rate of fruits.

Table 2 The Bi value for different medium and medium speed around apples and pears (*d* = 6 cm)

Heating medium	Speed /m s^{-1}	Bi value	
		Apple	Pear
Hot air	0.5	0.80	0.69
	1.0	1.21	1.04
Hot water	0.5	95.98	82.75
	1.0	145.41	125.42

According to the results reported by Wang et al.[22], when using 50℃ hot air heating at a speed of 0.5, 1, 2 and 4 m/s, about 113, 81, 61 and 47 min heating time were needed to reach 50℃, respectively. This demonstrated that the speed of air significantly affected the heating rate of fruits. While using 50℃ hot water heating, the changed speed of water had little influence on heating time, which took about 23 min for all to reach 50℃. These results are in good agreement with what were observed in this study.

3.5 Total cumulated thermal lethal time

According to the thermal death kinetics of the codling moth, the required minimum thermal lethal time (t_{ref}) was about 0.35 min at 55℃ calculated from Equation (4). Figure 4a shows the total cumulated thermal lethal time for apples and pears when subject to hot air heating. The total cumulated thermal lethal time was close to zero after heating for initial 20 min, since the fruit center temperature increased slowly and had almost no effect on insect mortality. After that, the total cumulated thermal lethal time increased quickly with the heating time since the fruit center temperature was close to or higher than 48℃, which was lethal to the insects, indicating that when treated with the final target temperatures for a period of time was very effective to improve insect mortality. Generally, the total cumulated thermal lethal time increased faster in apple than in pear or in hot water than in hot air (Figure 4b). If some internal heating source, such as microwave or radio frequency energy, could be added, the come-up-time of the heating process would be greatly reduced, resulting in rapid increase in the total cumulated thermal lethal time. As compared to the horizontal line for 0.35 min of the required minimum thermal lethal time, the heat treatment could be stopped to avoid possible quality loss caused by excessive heating of fruits. The minimum equivalent shortest heat treatment time could be determined at the crossing point between M_{ref} curve and the t_{ref} line. For example, the corresponding shortest heat treatment time in apples and pears was about 83 min and 92 min in hot air heat treatment, respectively, and about 32 min and 41 min in hot water heat treatments, respectively when reaching 100% mortality ($M_{55℃}$ = 0.35 min) (Table 3).

According to the results reported by Tang et al.[27], the apple (*d* = 8 cm) was treated at 52℃ for 143 min by hot air at a speed of 1 m/s, which completely controlled the pests. This heating time was equivalent to 79 min at 55℃ based on Equation (3), which was close to the predicted shortest treatment time of 83 min in this study. As reported by Yang et al.[28], the insect pests inside apples were all killed when treated by hot water at 52℃ for 42 min, which was equivalent to 34 min at 55℃. This heating time was also in agreement with the minimum 27 min at 55℃ in this study. Therefore, estimating the cumulated thermal lethal time could be useful and helpful to guide the design of the heat treatment protocol. However, the effects of the proposed heat treatments on fruit quality need to be determined in future studies.

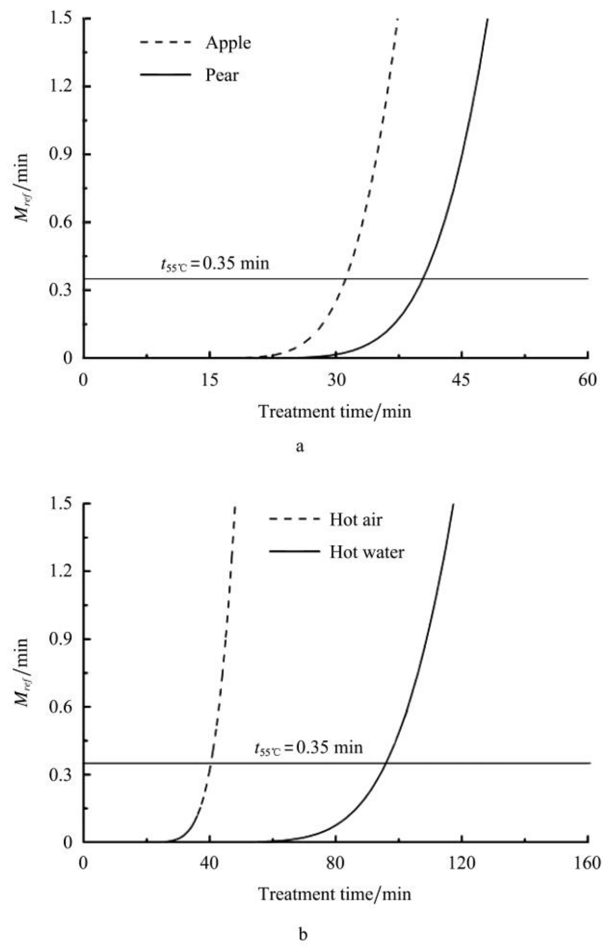

Figure 4 Total cumulated thermal lethal time as a function of treatment time of (a) apple and pear in air heating and (b) when subject to hot air and hot water heating at 55 ℃

Table 3 The minimum equivalent shortest heat treatment time for apple and pear when subject to hot air and hot water heating at 55 ℃

Medium	Hot air		Hot water	
Fruit	Apple	Pear	Apple	Pear
t_{min}/min	83	92	32	41

4 Conclusions

1) The thermal diffusivity affected clearly the heating rate of fruits in hot air and hot water treatments, suggesting that larger thermal diffusivity resulted in faster heating rate.

2) Hot water heating was more effective than hot air heating. Since the size of fruit had a great influence on the heating rate, sorting fruits with a similar size before heat treatment could improve the heating uniformity both in hot air and water treatments. Increasing the speed of hot air might increase heating rate, but the changed speed of hot water had little impact on the heating rate of fruits.

3) A reported method was further applied to calculate the total cumulated thermal lethal time of codling moth and the equivalent shortest heat treatment time during thermal processing. The corresponding equivalent shortest heat treatment times were about 83 min and 32 min for apple under hot air and hot water treatments, and 92 min and 41 min for pear under hot air and hot water treatments, respectively, to achieve 100% mortality of the codling moth at 55 ℃.

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