Vapor Heat Research Unit for Insect Quarantine Treatments

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ABSTRACT A vapor heat facility was designed and constructed for use in research on heating fruits for insect quarantine treatments. Air was heated to temperatures between 40 and 50°C by direct addition of steam at atmospheric pressure, resulting in relative humidities near 100%. This conditioned air was circulated directly through spaces between fruits by making the fruit load an integral part of the airflow path. With this method, fruits were heated to temperatures lethal to fruit fly eggs or larvae in 3–4 h compared with previous vapor heat treatment periods of up to 14 h.

KEY WORDS Insecta, vapor heat, quarantine treatments, fruit flies

VAPOR HEAT is a method of heating fruit with warm air saturated with water vapor at temperatures between 40 and 50°C to kill fruit fly eggs and larvae as a quarantine treatment before shipment on the fresh market (APHIS 1985). Heat is applied directly to the surface of fruits by condensation of water vapor on the fruit. Other methods of heating fruit include immersion in hot water or circulation of high-temperature forced air. Properly designed vapor heat systems should be able to heat fruit much faster than with warm air and nearly as fast as with hot water. The vapor heat method was first developed and used commercially in Florida in 1929 to prevent the spread of the Mediterranean fruit fly, *Ceratitis capitata* (Wiedemann) (Baker et al. 1944). This technique was later approved by the USDA Animal and Plant Health Inspection Service as a quarantine treatment for grapefruit infested with *Anastrepha ludens* (Loew) in Texas (Hawkins 1932).

Numerous types of fruit were treated experimentally with vapor heat in many areas of the world in the 1930s, including citrus, stone fruits, and pome fruits in Australia (Weddell 1931); apples, avocados, citrus, dates, figs, grapes, melons, nectarines, peaches, pears, persimmons, plums, and pomegranates in California (Mackie 1931); mangos and guavas in Puerto Rico (Sein 1935); and citrus, plums, and mangos on Formosa (Koidsumi 1937). Later, the process was studied for Hawaiian papayas (Jones 1940, Balock & Kozuma 1954); for grapefruit and oranges in Texas, and for mangos imported to the United States from Mexico (Balock & Starr 1945, Stone et al. 1951, Baker 1952); for California citrus and avocados (Sinclair & Lindgren 1955); and for deciduous fruits in California (Claypool & Vines 1956). Vapor heat treatments also were studied in Washington as a method to kill bulb flies and mites in narcissus bulbs (Latta 1932) and in Oregon for killing microorganisms in seeds (Miller & McWhorter 1948).

Ethylene dibromide (EDB) was tested as a fumigant for fruit infested with fruit fly eggs and larvae in the early 1950s and was approved as a quarantine treatment in 1953. Use of vapor heat soon declined in favor of the simpler and quicker EDB fumigation method. Further research and use of vapor heat was very limited. In 1969, the vapor heat treatment was approved by Japan for importation of Hawaiian papayas. However, because of technical problems with the vapor heat machinery and damage to treated fruit, vapor heat was abandoned in 1971 (Sugimoto & Sunagawa 1987). In 1972, the vapor heat method was tested in Hawaii as a treatment against eggs and larvae of the oriental fruit fly, *Dacus dorsalis* Hendel, in papayas (Seo et al. 1974). Research on vapor heat treatment of green peppers was begun on Okinawa in 1978 because chemical fumigation caused phytotoxicity to the commodity (Sugimoto et al. 1983). The vapor heat treatment also was studied in Japan on eggplant (Furusawa et al. 1984), mango (Sunagawa et al. 1987) and bitter nomordica fruit (Sunagawa et al. 1988).

The Environmental Protection Agency banned the use of EDB on all fruit intended for consumption in the United States effective 30 September 1987 (Anonymous 1986). Therefore, further research on vapor heat treatments against tephritid fruit flies is needed to increase the use of this nontoxic quarantine technology. Here, we describe a vapor heat research facility designed with improved methodology and constructed at the USDA Subtropical Horticulture Research Station in Miami, Fla., for use in developing vapor heat quarantine treatments for hosts of the Caribbean fruit fly, *Anastrepha suspensa* (Loew).

Materials and Methods

When water vapor comes in contact with a fruit surface having a temperature lower than the dewpoint temperature of the vapor, condensation oc-

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curs, the vapor releases its latent heat of vaporization, and the fruit surface is heated almost instantaneously to the dewpoint temperature of the water vapor surrounding the fruit. Theoretically, if water vapor surrounding the fruit can be maintained at the desired saturation temperature, fruit can be heated as rapidly as by hot-water immersion. As condensation occurs during the vapor heat process, water vapor is removed from the air, thus lowering the dewpoint temperature. Therefore, to continue the process at the desired temperature, water vapor must be added back to the air at a rate equal to that being lost to condensation.

A number of methods have been used to condition the air for vapor heat. Baker et al. (1944) described the process as the circulation of air, saturated water vapor, and water in the form of a fine mist in large volumes throughout the load. According to Baker (1952), the earliest equipment (first used in 1929) consisted of a combination of water sprays and steam sprays mixed together in a metal mixing box. A blower pulled the mixture across baffles to remove the drops of water. Balock & Starr (1945) supplied heat with electric heating elements. A current of air was drawn or blown across the elements, and a fine water spray was injected into the air current. The mixture of air, water vapor, and mist was then forced through the load. Claypool & Vines (1956) used the system of injecting live steam into a reservoir of water and then spraying the warm water into a conditioning chamber through which the circulating air was passed.

In much of the earlier research, no attempts were made to measure the amount of water vapor in the air or to measure relative humidity, dewpoint temperature, or wet-bulb temperature. Mackie (1931) discussed dewpoint temperature, and Weddell (1931) and Sinclair & Lindgren (1955) measured wet-bulb temperatures. Most researchers assumed that the air was saturated to 100% RH by the fine water mist. Control was based on maintaining the water temperature or the air temperature at the desired final fruit temperature. Inspection of curves for fruit surface temperature indicates that the air was not saturated with water vapor in many of these early studies because the fruit surface took several hours to heat instead of heating rapidly to the air temperature. For commercial treatment, the fruit was placed in large wooden boxes in large rooms. The fruit at the center of the boxes was heated by condensation only after water vapor had moved to the interior regions of the boxes by diffusion, a slow process at best. Currently available vapor heat quarantine treatment procedures of up to 14 h in duration (APHIS 1985) were based on this previous research.

Improved Methods. Our vapor heat system was designed to condition an insulated walk-in room (2.4 m wide, 2.8 m deep, 2.5 m high) (Fig. 1) to a dewpoint temperature equal to the desired final fruit temperature by direct injection of saturated steam at 100°C into the room. The large amount of water vapor available in the room provided a steam storage effect that was advantageous in maintaining the necessary close control of the condition of the air entering the fruit load.

Fruit was placed in a horizontal container 1.8 m in length. Experiments on vapor heat should be conducted with a fruit depth in the direction of airflow at least equivalent to the maximum fruit dimension that would be used commercially. In this way, research results can be applied to commercial systems, whereas results from tests on a smaller scale often are impossible to extend to commercial application. The length of the fruit test section was 1.2 m, allowing the results from the tests to be applied to commercial scale systems moving air through up to two 0.6-m-deep pallet boxes. The inside cross section for holding fruit was 0.44 m by 0.44 m with 2-cm-thick polystyrene insulation around the periphery, thus giving a square fruit cross section of 0.4 m on each side. The fruit container was made an integral part of the airflow path (Fig. 1) so that the moisture-laden air was forced to travel through the interstices between the fruit to return to the fan.

The rate of airflow through the fruit influences both the uniformity of heating and the power requirements for the fan. Because water vapor condenses as it moves through the load, the dewpoint temperature of the air is reduced as the air moves downstream, resulting in slower heating of downstream fruit compared with those fruits at the entrance. The magnitude of this effect is related to airflow; very low airflow rates can result in large differences in the rate of heating between fruits at the entrance and exit of the air path. Higher rates of airflow can carry a proportionately higher amount of moisture and thus a proportionately higher amount of heat because the heat is being carried into the bed in the form of water vapor. The airflow through the fruit should be large enough to minimize non-uniformity in fruit heating; however, higher airflows result in greatly increased fan horsepower requirements. The required fan horsepower increases approximately with the cube of the airflow rate. Therefore, each doubling of the airflow will increase the required fan power by approximately eight times.

A mathematical model for heat and mass transfer in fruits (Chau & Gaffney 1990) was revised to describe the vapor heat process. Results of mathematical modeling indicated that a minimum air velocity approaching the fruit of 1 m/s would be desirable to minimize the differences in fruit heating rates along the path of airflow. The fan chosen for this system was a Dayton model 2C889 blower (Dayton Electric Manufacturing Company, Chicago, Ill.) with a ⅓-HP motor operating at 1,750 rpm. This unit was rated at 0.23 m^3/s at 2.33 mm Hg static pressure. With our fruit cross section, this rate of airflow would provide an effective approach velocity of 1.44 m/s at this pressure. Actual air

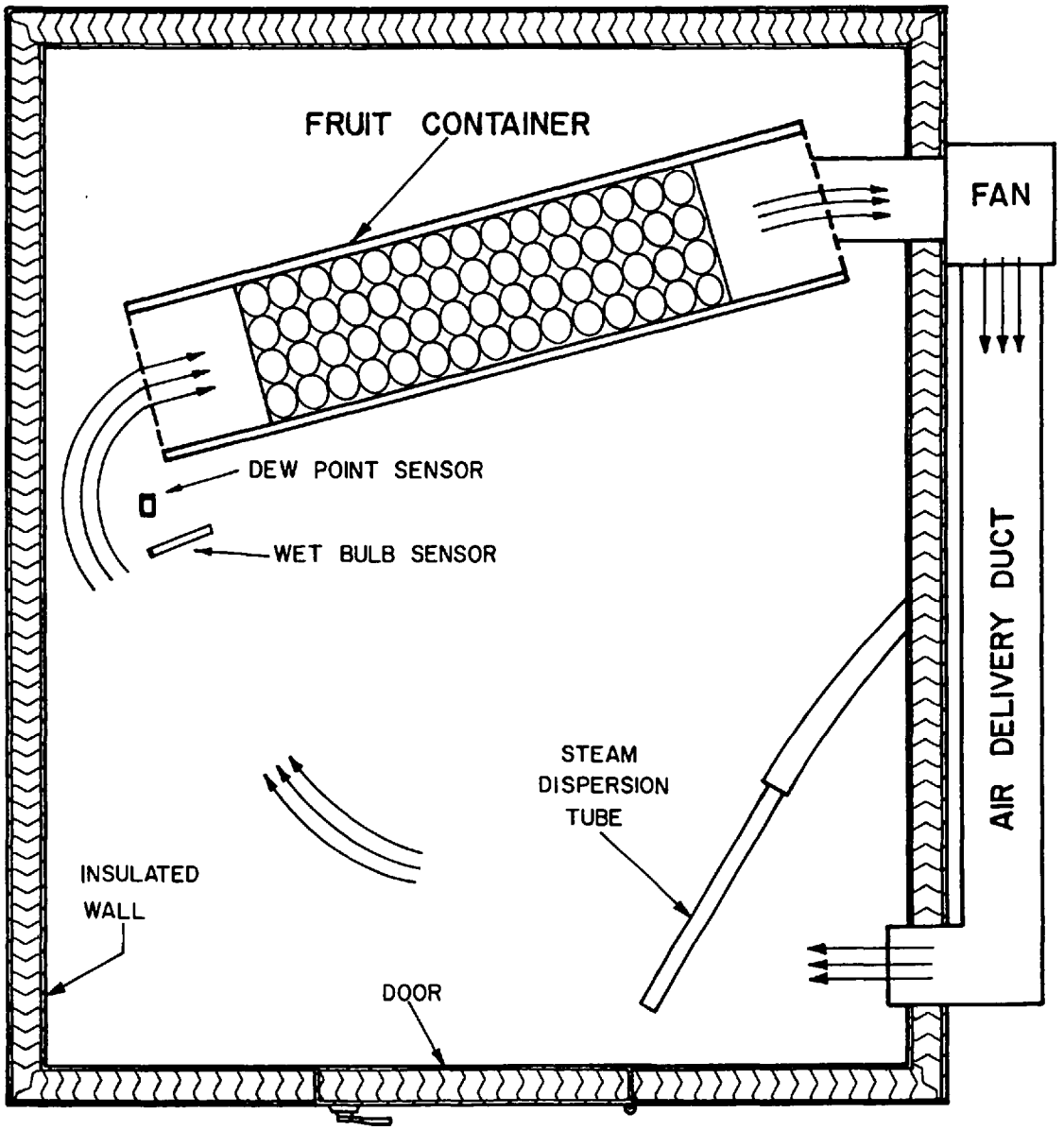

Fig. 1. Diagram of vapor heat research facility.

velocity during operation will depend upon the airflow resistance characteristics of the fruit as determined by fruit size, shape, stacking arrangement, and length of airflow path.

The dewpoint temperature of the air in the room was conditioned by adding 100°C steam at atmospheric pressure by means of an electrically heated steam generator (Vapormist Model VM-10DI DRISTEEM, Hopkins, Minn.) with a rated steam output of 13.6 kg/h. The steam mixed with the air in the room to provide a temperature for the air entering the fruit load at any desired setpoint between 40 and 50°C and at 100% RH. The major effect resulting from addition of steam to air is to raise the water vapor content of the mixture. However, a small amount of heat is added to the air in the room when the steam cools from 100°C to the desired control temperature. Some heat also is added by the fan energy. Unless this heat is removed from the system, the dry-bulb temperature will be higher than the dewpoint and the air will not be saturated. In our system, this small heat removal was accomplished by heat loss through the insulated room walls and through the insulated metal duct on the outside of the room. The steam generator was fitted with a float so that the unit could fill continuously, thus avoiding the interruption of steam output characteristic of intermittent fill systems caused by the temporary but sudden lowering of the water temperature during the fill. The steam was trans-

ported through a 3.8-cm-diameter flexible hose connected to a stainless steel steam dispersion tube located within the room near the fan outlet.

The end of the fruit container exposed to the conditioned room air was closed off by a urethane foam plug (0.4 m square, 0.1 m thick) during initial warming of the room to prevent heating the fruit before the air reached the desired initial test condition. When the room reached the desired conditions to begin a test, the plug was pulled from the end of the container holding fruit, and the fan was turned on to circulate the saturated warm air through the fruit.

Instrumentation. The steam generator control system consisted of a time-proportioning modulating circuit (TP modulator, DRISTEEM, Hopkins, Minn.), which controlled the "on" time of the steam generator in a proportional manner based on the deviation of the actual dewpoint from the desired dewpoint. The TP modulator required an input signal (proportional to the dewpoint temperature) of between 6 and 9 V dc. The dewpoint temperature in the room was sensed with a model M2 Optical Condensation dewpoint hygrometer (General Eastern Corporation, Watertown, Mass.). This instrument had an analog output that increased with dewpoint temperature and had a scaling of 0 V dc at 0°C and 5 V dc at 50°C. An interface circuit was designed to connect the signal from the dewpoint instrument to the TP modulator to control the steam output. This interface circuit consisted of a precision zener voltage reference, an operational amplifier operating in the inverting mode, and two unity gain operational amplifiers to buffer the input and output signals. The desired setpoint was displayed on a digital panel meter to a resolution of 0.1°C and was adjustable between 40 and 50°C by means of a 10-turn potentiometer. The proportional band could be set at either 0.5 or 1.0°C by a switch that controlled the gain of the inverting amplifier. The interface circuit thus converted the voltage output from the dewpoint instrument to give a signal varying between 6 V (full off) and 9 V (full on) when the dewpoint varied by either 0.5 or 1.0°C corresponding to the proportional band setting. Air dry-bulb temperatures and fruit surface and center temperatures were measured at up to 14 locations in the load of fruit with 36-gage copper–constantan thermocouples and recorded on a Fluke Model 2285B digital data logger (John Fluke Manufacturing Company, Everett, Wash.).

In some instances, we controlled the wet-bulb temperature in the room rather than the dewpoint temperature. This was done by providing a control signal proportional to wet-bulb temperature to the TP modulator for control of steam output. The wet-bulb temperature was measured with a MINCO model S200PD miniature platinum resistance thermometer element (MINCO Products, Inc., Minneapolis, Minn.) (1 mm diameter, 11 mm long) wrapped with a fine cotton wick. The small size of this unit resulted in a rapid response time. The sensor was placed in a 2-cm PVC pipe with an airflow past the sensor of 2.5 m/s provided by a Rotron blower Model 606NS (Rotron Manufacturing Company, Woodstock, N.Y.). The wet-bulb element was connected to the ambient channel of the dewpoint instrument, and the output signal was used to control the steam generator. Under saturated conditions, control of either dewpoint or wet-bulb temperature should provide the same results because the dewpoint, dry-bulb, and wet-bulb temperatures are all equal at saturation. Measurement of dry-bulb temperature with a sensor located within a room heated by live steam may not be accurate initially because the sensor will be wetted when the water vapor condenses as the room is heating up. If the relative humidity is high, the sensor will dry very slowly and will tend to measure the wet-bulb temperature until it dries completely.

Results and Discussion

The system worked very well in controlling either the dewpoint temperature or the wet-bulb temperature of the air in the room at the desired setpoint fixed temperature (Fig. 2). The system typically took about 10 min to heat and humidify the air from an initial condition of 28°C and 65% RH to a desired condition of 43°C and 100% RH at the beginning of a test. Once the room heated up to the desired setpoint, the foam plug was removed and the fan was turned on to circulate the conditioned air through the fruit. Thereafter, the stability of the entering air was maintained within ±0.5°C of the desired setpoint temperature. During the initial heating period, a small amount of water vapor condensed on the room walls and other interior surfaces, causing them to warm rapidly. This moisture evaporated once the air had reached the setpoint, and the room remained dry for the duration of the experiment.

Fig. 3 shows temperatures measured at the surface and center of grapefruit at the air entry end (front) and the exit (rear) of the fruit chamber during heating with a saturation temperature of 43.3°C and an approach air velocity of 0.87 m/s. The surfaces of fruit at the exit heated at a slightly slower rate than those at the entrance because of the lowered dewpoint of the air surrounding these fruit that results from condensation occurring as the air moves along the path of fruit. After about 100 min, the fruit surfaces at the entrance and exit reached the temperature of the saturated air being circulated through the load of fruit, and surface temperatures at both positions were maintained at the setpoint temperature for the duration of the test. Differences in fruit center temperatures reflect the influence of the different rates of heating of the fruit surfaces. Fortunately, the lag in temperature response at the fruit centers caused by the time required for heat to travel by conduction to the center of fruits results in very little difference

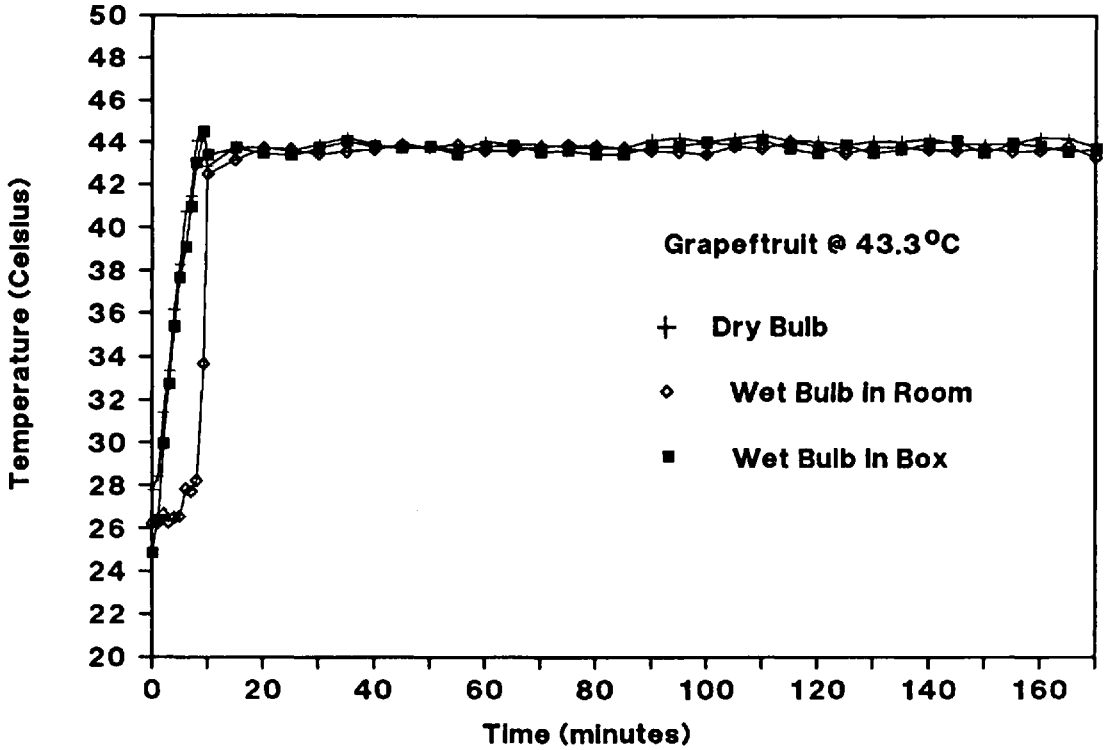

Fig. 2. Stability of air dry bulb and wet bulb temperatures during vapor heating of grapefruits.

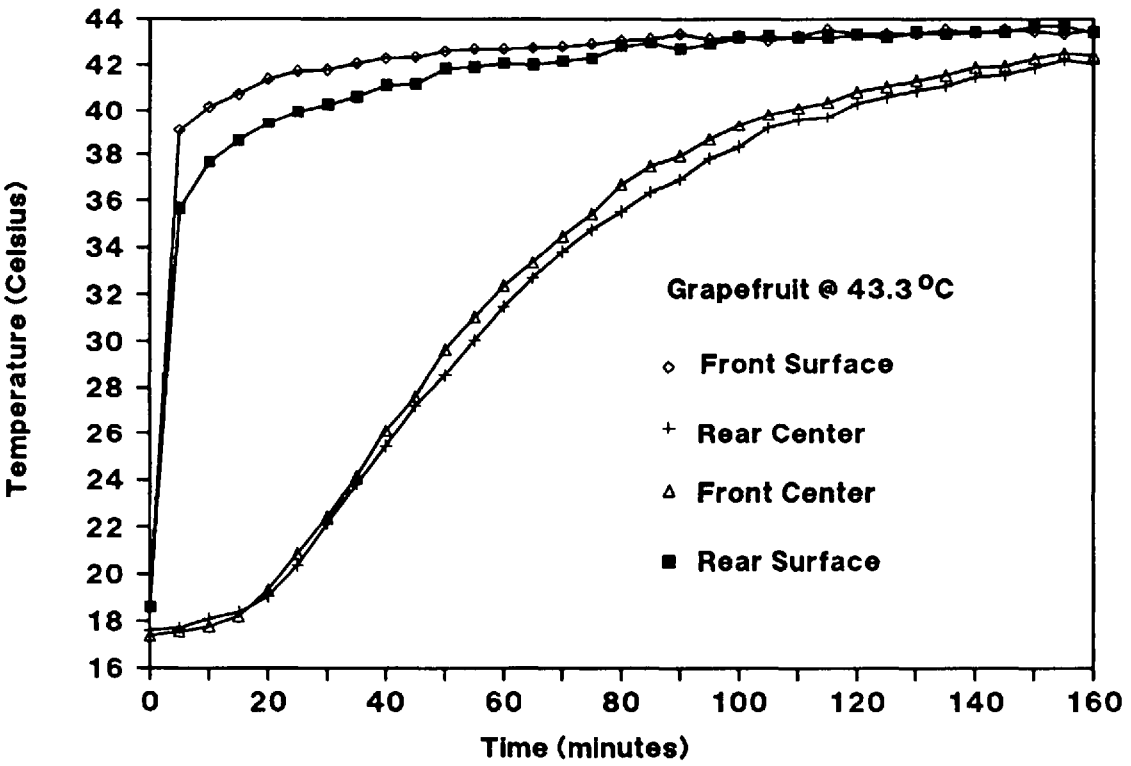

Fig. 3. Temperatures measured at the surface and center of grapefruits during vapor heating with saturated air at 43.3°C and an approach air velocity of 0.87 m/s.

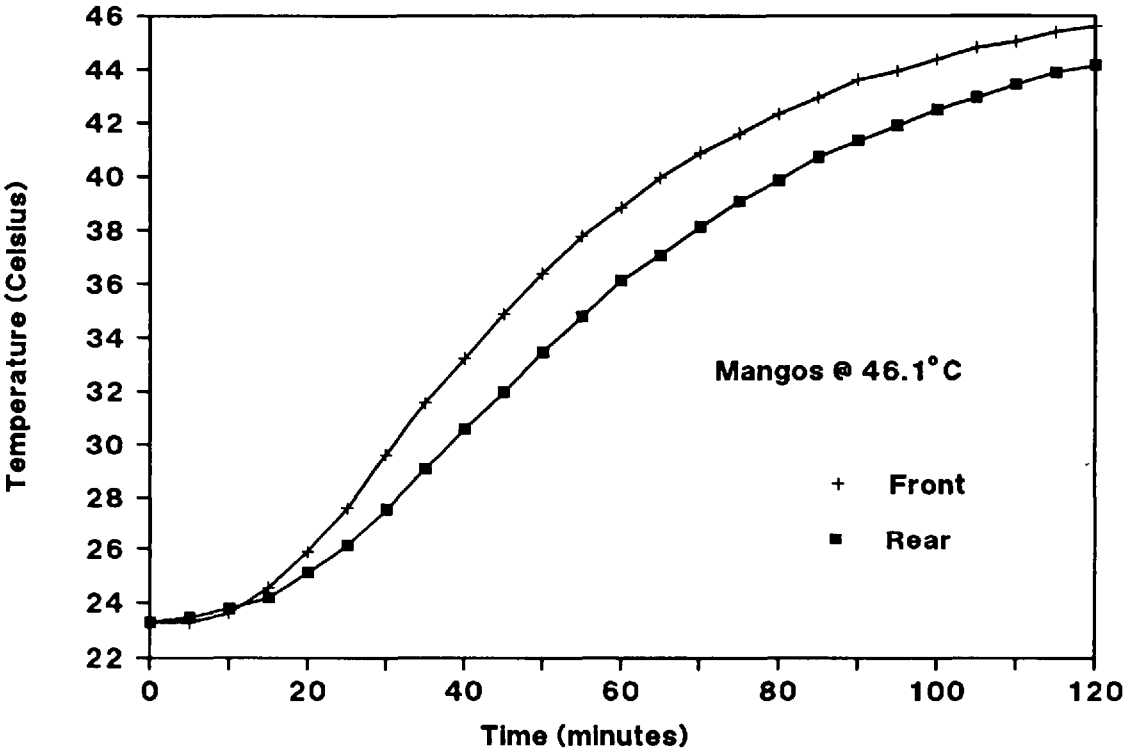

Fig. 4. Temperatures measured in the center of mangos during vapor heating with saturated air at 46.1°C and an approach air velocity of 0.61 m/s.

between fruit center temperatures at the front and rear of the load.

Fruit center temperatures measured during heating of mangos at a saturation temperature of 46.1°C and an approach air velocity of 0.61 m/s are shown in Fig. 4. Note the greater difference in fruit center temperatures between the front and rear of the load at this lower airflow compared with the grapefruit center temperature response shown in Fig. 3. All fruits will not heat at the same rates as those shown here. In addition to airflow, initial fruit temperature and fruit size and shape influence the temperature response of specific fruits during heating with the vapor heat method.

Our vapor heat facility includes a number of improvements over those which were used earlier. Previous investigators used various combinations of air heating devices along with heated or unheated water mists or sprays. Our research has shown that air can be both heated and saturated at temperatures between 40 and 50°C by direct injection of 100°C saturated steam at atmospheric pressure. No additional heating or misting devices are necessary.

Further, instead of relying on diffusion of water vapor into the interior of large boxes, we made the fruit load an integral part of the air circulation system. The fruit chamber was positioned at the inlet to the fan so that the air could proceed through the circulation path only by passing through the interstices between the fruit. In this manner, the conditioned air was forced directly through the entire load of fruit, resulting in more rapid and direct contact between the water vapor and the fruit. We raised the center temperatures of grapefruit (size 36) to 43.3°C in about 4 h compared with 8 h or longer in previous studies. The approach of making the fruit load part of the air circulation path has found widespread application in recent years in the commercial cooling of fruits and vegetables with a system called pressure cooling (Mitchell et al. 1972, Gaffney 1977). Commercial systems for vapor heating of fruits also could be designed on the same principles.

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