Scientia Horticulturae 225 (2017) 561–566

Contents lists available at ScienceDirect

Scientia Horticulturae

journal homepage: www.elsevier.com/locate/scihorti

Heat transfer, mass transport and horticultural commodity water loss during hypobaric storage

Stanley P. Burg*, Thomas L. Davenport

University of Florida, IFAS, Tropical Research and Education Center, 18905 SW 280 St., Homestead, FL 33031, United States

ARTICLE INFO

Keywords:
Hypobaric
Low pressure (LP)
Capillary condensation
Heat of condensation

ABSTRACT

Freedom red roses stored in a hypobaric warehouse at 11.1 mmHg, 2 °C, lost 6.78% of their water in 35 days. Respiratory heat only evaporated enough water from the flowers to cause a 2.5% weight loss. The low storage pressure promoted capillary water condensation in the non-waxed cardboard boxes used for flower distribution, increasing the cardboard's weight by 20%. Radiation and convection transferred the heat of capillary water condensation from the cardboard to the roses, and evaporative cooling caused the extra water loss moving heat from the roses to the chamber air. A weight increase due to capillary water condensation did not occur in cardboard boxes at atmospheric pressure, 85–90% RH, or in waterproof plastic boxes at 11.1 mmHg, 99.8% RH. Horticultural commodities lose more water during controlled atmosphere (CA) or normal atmosphere storage (NA) than during hypobaric storage (LP) in waterproof boxes because more respiratory heat is produced in CA and NA. Non waxed cardboard boxes should not be used for hypobaric storage.

1. Introduction

Many physical properties of gases, vapors, and liquids are pressure-dependent, e.g. specific volume; density; diffusion coefficient; Reynolds, Grashof and Prandtl numbers; convective heat transfer coefficient; convective coefficient for water vapor condensation; mean free path; boiling point of liquids. These allow hypobaric storage to extend storage life in ways that cannot be duplicated at atmospheric pressure. Laboratory experiments demonstrated a 3- to 4-fold increase in the storage-life of horticultural crops in LP compared to CA or NA (Table 1).

For more than 40 years academic publications have claimed that hypobaric storage causes an excessive horticultural commodity water loss (Tolle, 1972; Wu et al., 1972; Wu and Salunkhe, 1972; Sharples, 1974; Stenvers and Bruinsma, 1975; Salunkhe and Wu, 1973, 1975; Lougheed et al., 1977; Hughes et al., 1981; Staby et al., 1984; Paul et al., 2004; Lagunas-Solar et al., 2003, Lagunas-Solar et al., 2006; Li et al., 2006; An et al., 2009; Niblock, 2012; Thompson, 2010, 2015). Lougheed et al. (1978) reported that chamber leakage was responsible for the extra weight loss which sometimes occurred when apples were stored in LP. The lower the storage pressure, the more in-leaking air and water vapor expand, increase in volume, and decrease the humidity when they enter an evacuated chamber. At a lower pressure, leakage provides a greater part of the total air-change flowing through an LP system (Burg and Kosson, 1983) making it impossible to maintain the high humidity required to prevent excessive commodity water loss in LP. Decades later publications by Burg (2004, 2014a) and Burg and Zheng (2007) demonstrated that the extra horticultural commodity water loss which occurred during many laboratory hypobaric tests was caused by the experimental error of humidifying the LP system at atmospheric pressure. The humidity of water-saturated atmospheric pressure air decreases 76-fold, to 1.3% RH when the air expands entering a 10 mmHg LP chamber at the storage temperature. Burg (1975, 1976) warned that the pressure of the incoming LP air-change must be reduced to the storage pressure *before* the air is humidified. Instead, Hughes et al. (1981) flowed 86% RH atmospheric pressure air directly into CA and LP chambers, causing sweet peppers to become severely desiccated in LP, losing water 4 to 5 times faster than in CA. Ilangantileke (1989) found that mangoes humidified at atmospheric pressure and stored at 60 mmHg, 13 °C, lost 17.2% of their weight in 17 days, whereas mangoes humidified at 20 mmHg and stored at 99.5% RH, 13 °C, only lost 3% of their weight during 56 days (Davenport et al., 2006). The experimental error caused by humidifying LP with air saturated at atmospheric pressure also invalidates published results with potatoes, apricots, peaches, sweet cherries, apples, bananas, avocados, limes, guavas, pears and blueberries (Wu and Salunkhe, 1972; Salunkhe and Wu, 1973, Salunkhe and Wu, 1975; Wu et al., 1972; Jadhav et al., 1973; Al-Qurashi et al., 2005). Cold spots on an LP chamber's surface (Burg and Kosson, 1983), and defrost cycles (Burg, 2004) also lower an LP chamber's humidity. When all experimental errors are eliminated in

---

* Corresponding author. 3770 Kent Ct., Miami, FL 33133.
E-mail addresses: stanpburg@bellsouth.net (S.P. Burg), tldav@ufl.edu (T.L. Davenport).

http://dx.doi.org/10.1016/j.scienta.2017.07.026
Received 1 November 2016; Received in revised form 12 July 2017; Accepted 20 July 2017

Table 1
Maximum storage life (days) in NA, CA and LP (Burg, 2004).

Commodity	NA	CA	LP
Asparagus	14–21	21 + (slight benefit)	42
Avocado (Lula)	30	42–60	102
Banana	14–21	42–56	150
Carnation flower	21–42	No benefit	140
Cucumber	9–14	14 + (slight benefit)	49
Green bean	7–10	14	38
Green pepper	14–21	No benefit	50
Lime (Persian)	14–21	Juice loss, peel thickens	90 +
Mango (Haden)	14–21	21 + (slight benefit)	56
Mushroom	5	6	21
Papaya (Solo)	12	14	28
Pear (Bartlett)	60	100	200
Protea (flower)	7	No benefit	30 +
Rose (flower)	7–14	No benefit	60
Spinach	10–14	14 + (slight benefit)	50
Strawberry	7	7 + (off-flavor)	21

Table 2
Water loss from 'Golden Delicious' and 'Boskoop' apples during storage at 3 °C, in LP at 75 mmHg, or in NA (Bangerth, 1973). The % water loss to dispel respiratory heat is computed in Burg (2004) from areas under respiratory curves published by Bangerth (1973).

Variety	Storage Duration (months)	% Water Loss		% Water Loss to Dispel Resp. Heat	
		NA	LP	NA	LP
Golden Delicious	2	2.9	1.0	2.9	1.1
	5	6.3	3.5	7.6	3.2
Boskoop	2	2.1	0.8	3.2	0.8
	5	5.1	1.2	6.8	1.6

laboratory studies, and plant matter is stored without cardboard boxes, its weight loss is determined by the amount of respiratory heat the commodity produces (Burg, 2004; Burg and Zheng, 2007; Bangerth, 1973, Table 2),

Horticultural commodities are usually distributed in non-waxed cardboard boxes at atmospheric pressure. Waterproof boxes are preferred for high-humidity export shipments because they do not absorb enough water to weaken the stacking arrangement. During the past 47 years all shipments of horticultural commodities in hypobaric intermodal containers, and storages in hypobaric warehouses were carried out in non-waxed cardboard boxes provided by growers. The present research was undertaken to identify and eliminate the heat source that increased horticultural commodity water loss during prior hypobaric storages and shipments.

2. Materials and methods

Plant physiologists consider commodity water loss to be caused by a vapor-pressure gradient between plant matter and air passing over it (Burton, 1982). Thermodynamics examines water loss in a more comprehensive manner. Three inter-dependent variables interact to regulate the rate of evaporation: the availability of latent energy at the evaporating surface, the vapor pressure gradient that develops at equilibrium, and resistances in the water-vapor pathway (Slatyer, 1967; Raschke, 1960). Once the temperature distribution is known, the rates of heat transfer can be determined from laws relating heat flux to the temperature gradients. The combined effects of conduction, convection, radiation, and evaporation (or condensation) modulate the vapor pressure and temperature gradients that develop, and heat transferred by evaporative cooling determines the commodity water loss. Plant matter stored in a refrigerated space cannot remain at a constant temperature and lose more water than its respiratory heat evaporates unless it is receiving heat from its environment (Gac, 1956).

Fig. 1. Two VivaFresh 6 ft^3 (170 l) laboratory hypobaric chambers, installed in a 20–23 °C room.

Experiments were carried out in 6 ft^3 (170 l) Vivafresh laboratory hypobaric chambers (Fig. 1) or in an Atlas Technologies (305 Glen Cove Road, Port Townsend, WA 98368), Vivafresh 3332 ft^3 (94 m^{3})) commercial hypobaric warehouse (Fig. 2). The laboratory chamber's pressure controller, pressure measuring transducer, and vacuum pump were

Fig. 2. Vivafresh 3332 ft^3 (94 m^3) hypobaric warehouse, installed in a 2 °C cold-room. Internal dimensions = 8.3 × 10 × 40 ft.