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Research Paper

Evaluating the storage environment in hypobaric chambers used for disinfesting fresh fruits

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Low pressure (LP) treatment has potential as an alternative non-chemical postharvest disinfestation method for fresh fruits. A validated computer simulation model was used to determine the thickness of foam insulation needed to cover the hypobaric chamber walls in order to stabilise the air temperature within the hypobaric chambers that were housed in a cold storage room with fluctuating air temperatures. The stability of pressure, temperature and relative humidity levels in the LP system was evaluated together with various O_2 concentrations, evacuation, venting and leakage rates. Results showed that the added foam covering the chambers maintained the temperature variation of the hypobaric chamber wall to within ±0.2 °C and inside air to within ±0.1 °C. The regulating system kept pressure to within ±1% of the set point, and maintained relative humidity at nearly saturated levels (>98%) under various air exchange rates and pressures, with a chamber leakage rate of 0.009 kPa h^{-1} and LP system leakage rate of 0.480 kPa h^{-1}. Given that the hypobaric chamber displayed adequate performance characteristics, further studies will be conducted to evaluate LP treatment efficacy for fresh fruits.

1. Introduction

Because the process is completely organic, chemical free, and environmentally sustainable, low pressure (LP) has been considered as a non-chemical alternative to chemical fumigants for disinfestation of agriculture products. LP is achieved by evacuating air from a chamber holding the stored product to be treated to proportionally reduce the partial pressures of individual atmospheric gases, especially O_2. Most LP systems targeting fresh fruits and vegetables utilise a method to maintain high humidity, thus water loss, commodity respiration, and production of the ripening hormone ethylene are reduced under LP conditions to prevent wilting and fruit ripening during storage (Burg, 2004). In addition, LP discourages commodity deterioration caused by bacterial and fungal decay and is capable of killing all life stages of many insects infesting agricultural commodities (Burg, 2004). Insect mortality increases with increasing storage time in LP, and is

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Nomenclature

A	surface area, m^2
C	O_2 concentration, %
C_a	ambient O_2 concentration, %
C_{O_2}	final O_2 concentration, %
C_p	specific heat, J kg^{-1}°C^{-1}
h_1	external surface heat transfer coefficients, W m^{-2}°C^{-1}
h_2	internal surface heat transfer coefficients, W m^{-2}°C^{-1}
k	thermal conductivity, W m^{-1} °C^{-1}
l	material thickness, m
P	pressure, kPa
P_0	ambient air pressure at sea level, kPa
RH	relative humidity, %
t	time, s
T	temperature, °C
V	volume, m^3
x, y	distances (m) along the axial direction, m
α	thermal diffusivity, m^2 s^{-1}
ρ	density, kg m^{-3}

Subscripts

a	interior air
c	chamber wall
d	dry-bulb
f	foam
set	total inside the hypobaric chamber
sv	saturated vapour
o	outside air
v	vapour
w	wet-bulb
0	reference

strongly temperature and humidity dependant (Johnson, 2010; Mbata, Phillips, & Payton, 2004). In order to develop a disinfestation treatment for fresh fruits using LP, its impact on insect mortality must be evaluated. However, it is essential to firstly evaluate the stability of the storage environment in hypobaric chambers before conducting future efficacy tests.

The effect of low pressure on insects has been investigated since the 1880s (Back & Cotton, 1925). Attempts to use LP for disinfesting a variety of agricultural commodities began with Back and Cotton (1925), followed by studies by Bare (1948), Calderon, Navarro, and Donahaye (1966), and Calderon and Navarro (1968). More recently, the need to find non-chemical treatments to kill quarantine insects in transhipped loads of imported and exported commodities has increased interest in the use of LP technology for disinfestation (Burg, 2010; Chen, White, & Robinson, 2005; Davenport, Burg, & White, 2006; Johnson & Zettler, 2009; Mbata & Philips, 2001; Navarro et al., 2001, 2007). LP storage provides the added benefit of preserving the fresh-picked quality of fully mature fruits and vegetables for months (Burg & Burg, 1966; Davenport et al., 2006; Knee & Aggarwal, 2000; Li, Zhang, & Wang, 2008). For example, Challot and Vincent (1977) used a treatment of 80.0 kPa to preserve cacao bean quality in polyethylene bags. Li and Zhang (2006) achieved an extension in shelf-life of green asparagus with a pressure of 15.0 ± 5.0 kPa.

Stability of pressure, temperature and relative humidity is an important performance characteristic of LP systems for fresh produce. Except for the influence of the vacuum pump, pressure stability mainly depends on chamber tightness, precision of the pressure sensor and regulator, and the air exchange system. The air exchange system is not only important in maintaining the desired relative humidity and pressure, but by allowing the continuous intake of fresh air and removal of metabolic gases produced by the fruit, it prevents the build-up of respiratory byproducts and ethylene within the hypobaric chamber. Since hypobaric chambers are generally located in temperature-controlled incubators, cold storage rooms or plant growth chambers (Chen et al., 2005; Davenport et al., 2006; Navarro et al., 2007), the temperature variations of the chamber walls and air inside the chambers are largely influenced by the precision of the surrounding temperature-controlled environment. A large temperature variation results in condensation and evaporation cycles on the inner surface of chamber walls and product surfaces, which could cause unexpected water loss from products and even damage to product quality, especially in the water-saturated air necessary for storing fresh fruits. To avoid condensation and evaporation cycles, the surrounding air temperature variation should be maintained within ±0.5 °C (Davenport et al., 2006) and the hypobaric chamber wall temperature should remain within ±0.2 °C in the temperature range of −17 °C to 49 °C (Burg, 2004). A practical solution could be to use insulating foam around the chamber and humidifier to reduce air temperature variation, thus maintaining the saturated humidity in the hypobaric chamber.

It is difficult in most laboratory LP systems to achieve leak-free low pressures, and usually leaks are not evident because pressures are maintained at the set value using pressure regulators (Burg, 2004). Leakage is a major problem in lab-scale LP systems, resulting in higher than desired pressure and most importantly lower relative humidity which may cause more water loss of products. To avoid excess water loss in LP-treated products, the leakage rate should be kept below 0.6, 1.0, 1.5 and 5.0 kPa h^{-1} at pressures of 1.3, 2.0, 2.7 and 5.3 kPa, respectively (Burg, 2004).

Insect mortality under LP is predominantly caused by low O_2 concentrations (Navarro & Calderon, 1979), although it has been reported that low relative humidity can also enhance the lethal effect of LP on insects (Johnson, 2010; Navarro, 1974, p. 118). When insects are placed into a hypoxic environment for a sufficient duration, adenosine triphosphate production is reduced, resulting in increasing membrane phospholipid hydrolysis (Herreid, 1980). Cell and mitochondrial membranes then become permeable, causing cell damage or death (Freidlander & Navarro, 1983; Mitcham, Martin, & Zhou, 2006). Effective control of insects has been observed at O_2 concentrations less than 6.6%, and especially at 0.15%–0.30% (Burg, 2004). Thus, it is essential to estimate the level of O_2 concentration in hypobaric chambers as influenced by pressure, temperature and relative humidity.

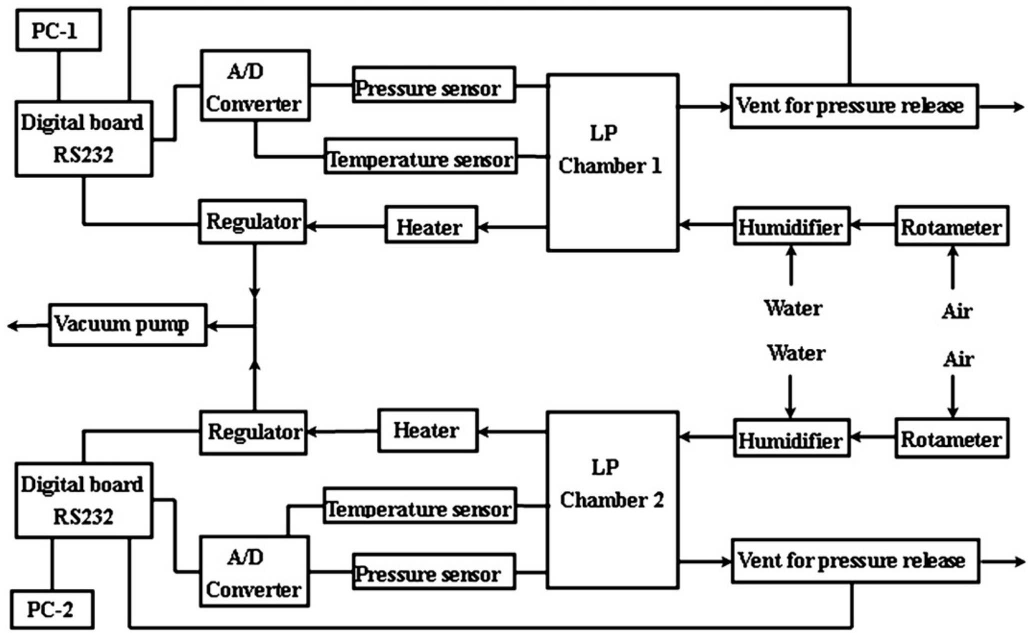

Fig. 1 – Diagram of the low pressure (LP) system, including vacuum, air exchange, pressure release and measurement systems (lines with an arrow indicate the gas flow through plastic soft pipe and those without an arrow indicate signal transmission via wire).

The objectives of this research were firstly to reduce the variations of air temperature in a hypobaric chamber housed in a cold storage room by using a validated energy balance model, and to evaluate the stability of pressure, temperature, and relative humidity in the chambers. Secondly, to determine O_2 concentrations as influenced by pressure, temperature, and relative humidity in the chambers. Finally, to determine the leakage rate of ambient air into the LP system.

2. Materials and methods

2.1. *LP system*

Two laboratory scale, VivaFresh™ (Model RDC-0005, Atlas Technologies, Port Townsend, WA, USA) LP systems using identical aluminium chambers (0.61 L × 0.43 W × 0.58 H m^3) were used in the present study. Low pressure was achieved with a two-stage rotary vacuum pump (Model RV5, Edwards, Tewksbury, MA, USA) regulated by a compact proportional solenoid valve (Model PVQ33, SMC Co., Tokyo, Japan) controlled by a proportional/integral/derivative (PID) computer control system. Chamber pressure was monitored with a digital pressure gauge (Model HPS902, MKS Vacuum Technology, Boulder, CO, USA). A rotameter (Model FL-3841G, OMEGA Engineering Inc., Stamford, CT, USA) was used to adjust the air exchange rate, and the ingoing rarefied air was passed through a humidifier (Atlas Technologies, Port Townsend, WA, USA) before entering the hypobaric chamber in order to keep the relative humidity near saturation (100%). The relative humidity was calculated by measuring wet-bulb and dry-bulb temperatures using calibrated YSI 55000 Series GEM thermistors (Therm-x of California, Hayward, CA, USA) having relatively high accuracy (±0.1%) (Wang, Tang, & Younce, 2003). Similar thermistors were used to measure the temperatures inside the chamber and the exterior chamber wall. All data from temperature and pressure sensors in the LP system were digitised and sent to a computer control and recording system via an RS-232 serial port. The diagram of the system is shown in Fig. 1.

2.2. *Model development*

Based on preliminary tests, air temperature variation in the cold storage room was ±1.1 °C, which exceeded the required surrounding air temperature variation (±0.5 °C) for hypobaric chambers (Davenport et al., 2006). To reduce the influence of air temperature variations from the cold storage room, polyurethane foam insulation was used to completely cover the hypobaric chambers. A heat transfer model was developed and validated to determine an adequate thickness of foam insulation.

The computer simulation model consisted of energy balance equations for the interior air, the chamber wall, and the foam insulation (Fig. 2). It included convective heat transfer from the cold room air to the foam, conductive heat transfer through the foam and the chamber wall, and convective heat transfer from the chamber wall to the interior air. For heat conduction in the rectangular-shaped objects, the following governing equation was used:

$$\frac{1}{\alpha}\frac{\partial T}{\partial t} = \left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2}\right) \quad (1)$$

where α is thermal diffusivity ($m^2\ s^{-1}$), T is the temperature (°C), t is time (s), x and y are the distances (m) along the axial direction. Thermal diffusivity (α) is derived from $k/\rho C_p$, where

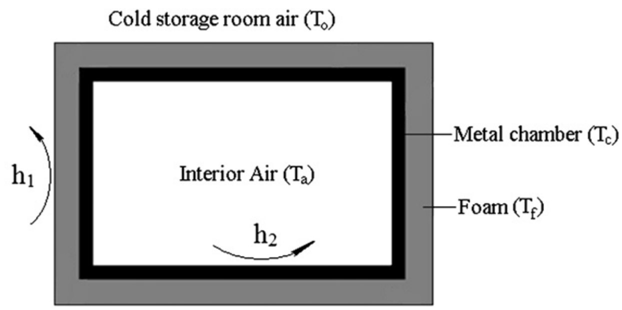

Fig. 2 – Diagram of the heat transfer model in an insulated metal chamber in a cold storage room (h_1 – external surface air convection coefficient, h_2 – internal surface air convention coefficient).

k is the thermal conductivity ($W\ m^{-1}{}^{\circ}C^{-1}$), ρ is the density ($kg\ m^{-3}$), and C_p is the specific heat ($J\ kg^{-1}{}^{\circ}C^{-1}$). The boundary conditions were represented by the following heat exchange equation describing convection from the ambient medium (air) and the foam surface (f):

$$\underset{\text{Heat exchange flow at foam surface}}{-k\frac{\partial T_f}{\partial l}\Big|_{l=l_o}} = \underset{\text{Heat exchange flow from the exterior}}{h_1\left[T_f(t) - T_0\right]} \tag{2}$$

where l is the material thickness (m), h_1 is the external surface heat transfer coefficients ($W\ m^{-2}{}^{\circ}C^{-1}$) and T_f is the temperature of the foam (°C).

The energy balances for the interior air, chamber and foam were described below:

$$\rho_a C_a V_a \frac{dT_a}{dt} = h_2 A_a (T_c - T_a) \tag{3}$$

$$\rho_c C_c V_c \frac{dT_c}{dt} = \frac{K_c}{l_c} A_c (T_f - T)_c - h_2 A_c (T_c - T)_a \tag{4}$$

$$\rho_f C_f V_f \frac{dT_f}{dt} = h_1 A_f (T_o - T_f) - \frac{K_f}{l_f} A_f (T_f - T_c) \tag{5}$$

where A is the surface area (m^2), V is the volume (m^3), subscripts a, c, f and o represent interior air, chamber wall, foam, and outside air, respectively; h_1 and h_2 are the external and internal surface heat transfer coefficients ($W\ m^{-2}{}^{\circ}C^{-1}$), respectively. Forced and natural convections for the external and internal heat convections were considered. The values of h_1 and h_2 were selected to be 50 and 10 $W\ m^{-2}{}^{\circ}C^{-1}$ based on the literature (Chung, Wang, & Tang, 2007). The properties of the various materials in the system were shown in Table 1 and the thickness of the aluminium chamber wall was 0.006 m. The partial differential Eqs. (3)–(5) were reduced to algebraic equations using the finite difference method. Each material was assumed to have a homogenous and uniform temperature distribution. Temperatures of each material were calculated at a time interval of 1 s using the Gauss-Seidel numerical method coded in Quick Basic (v4.5, Microsoft Co., WA, USA) software.

2.3. *Model validation and application*

To validate the proposed heat transfer model, a stainless steel rectangular box with the interior dimension of $0.29\ L \times 0.15\ W \times 0.045\ H\ m^3$ and with chamber wall thickness of 0.001 m was placed in a cold storage room, and the box was wrapped with insulation foam using a thickness of 0.013 m. Two type-T thermocouples connected to a data logger (DL2e, Delta-T Devices Ltd., Cambridge, U.K.) were used to measure the air temperatures in the cold storage room and the box. The measured air temperature of the cold storage room was used as input for the model, while the resulting calculated air temperature for the box interior was compared with the measured data to validate the simulation model. The validated model was used to predict the influence of foam thickness on the hypobaric chamber wall and inside air temperature variations. Foam thickness ranging from 0.001 m to 0.03 m was considered and the corresponding hypobaric chamber wall and inside air temperature variations were simulated. The thickness of foam insulation which can reduce the temperature variation of the hypobaric chamber wall to within ±0.2 °C would be used for subsequent studies.

2.4. *Stability of pressure and temperature in the hypobaric chambers*

After the hypobaric chambers were covered with the optimal thickness of foam insulation derived from the above model, the pressure and temperature stability within the two hypobaric chambers was determined at 4 °C and 1.3, 3.3 and 6.7 kPa with air exchange rates of 0–2.0, 0–0.5, 0–0.2 volumes h^{-1}, respectively. The pressure was reduced to the set-point by the fully open vacuum pump, then held for more than 24 h, and finally released by opening the release valve. The evacuation or venting rates were estimated by dividing the difference

Table 1 – Thermal properties of different materials used in the current model simulation.

Materials	Density ρ ($kg\ m^{-3}$)	Specific heat C_p ($J\ kg^{-1}{}^{\circ}C^{-1}$)	Thermal conductivity k ($W\ m^{-1}{}^{\circ}C^{-1}$)	Thermal diffusivity α ($m^2\ s^{-1}$) $\times 10^{-7}$
Air[a]	1.2	1010	0.02	168
Foam[a]	32	1300	0.03	7.2
Stainless steel[a]	7900	477	14.9	39.5
Aluminium 6061 alloy[b]	2710	1256	167	491

a Data collected from Çengel. (2006).
b http://www.engineersedge.com/properties_of_metals.htm.

Table 2 – Environmental parameters measured in the hypobaric chamber held at 4 °C under different pressures and air exchange rates (mean ± SD).

Pressure set point (kPa)	Air exchange rate (volumes h^{-1})	Measured pressure (kPa)	Relative humidity (%)	Evacuation rate (kPa min^{-1})	Venting rate (kPa min^{-1})
1.3	0	1.336 ± 0.005	99.20 ± 1.13	2.733 ± 0.027	14.972 ± 0.080
	1	1.341 ± 0.007	99.30 ± 0.85	2.546 ± 0.240	14.745 ± 0.400
	2	1.343 ± 0.007	99.00 ± 1.41	2.386 ± 0.120	15.185 ± 0.240
3.3	0	3.329 ± 0.008	99.20 ± 1.13	4.573 ± 0.067	15.452 ± 0.560
	0.2	3.326 ± 0.011	98.40 ± 1.14	4.906 ± 0.027	14.919 ± 0.120
	0.5	3.330 ± 0.011	98.80 ± 0.85	4.666 ± 0.173	14.652 ± 0.773
6.7	0	6.631 ± 0.028	99.35 ± 0.78	6.439 ± 0.320	15.719 ± 2.160
	0.1	6.639 ± 0.029	99.10 ± 0.80	5.760 ± 0.267	14.359 ± 0.160
	0.2	6.638 ± 0.032	98.45 ± 0.78	5.920 ± 0.293	14.039 ± 0.027

between the ambient pressure and the set-point by the time needed to reach the set point or ambient pressure, the average values and standard deviations were calculated based on the two chambers.

2.5. O_2 concentration and relative humidity in the hypobaric chambers

Relative humidity (RH, %) was calculated using the measured dry-bulb and wet-bulb temperatures inside the hypobaric chamber according to the following equation (Lide, 1996):

$$RH(\%) = \frac{6.1078e^{17.269\times T_w/(T_w+237.3)} - 0.66\times(T_d - T_w)}{6.1078e^{17.269\times T_d/(T_d+237.3)}}\times 100 \quad (6)$$

where T_w and T_d are the wet-bulb and dry-bulb temperature in °C, respectively.

The saturated vapour pressure (P_{sv}, kPa) is a function of the air temperature (T_a, °C) and can be calculated with the Antoine equation as follows:

$$P_{sv} = 0.133324\times 10^{8.07131-\frac{1730.63}{233.426+T_a}} \quad (7)$$

The partial pressure of vapour is:

$$P_v = RH\times P_{sv} \quad (8)$$

Since the atmosphere in the hypobaric chamber can be considered as a mixture of gases, including water vapour, the total pressure is the sum of the partial pressures of the components in the mixture based on Dalton's Law. The partial pressure of air (P_a, skPa) in the hypobaric chamber is:

$$P_a = P_{set} - P_v \quad (9)$$

where P_{set} is the total pressure inside the hypobaric chamber. According to the ideal gas law, the final O_2 concentration (C_{O_2}, %) is:

$$C_{O_2} = \frac{C_a\times P_a}{P_0} \quad (10)$$

where C_a is the ambient O_2 concentration (~21%),P_0 is the ambient air pressure at sea level, $P_0 = 101.3$ kPa.

According to Eqs. (9) and (10), O_2 concentration depends on the set-point pressure and the vapour pressure, which is a function of the air temperature and relative humidity in the chamber. The O_2 concentration was calculated at a temperature range of 0–20 °C, and three pressures of 1.3, 3.3 and 6.7 kPa. Relative humidity was derived from measurements taken under different temperatures and pressures (Table 2) and was considered to be 99%.

2.6. Determining LP system leakage rate

A reliable method to determine the leakage rate of LP systems is to reduce the pressure to a typical level, then turn off the

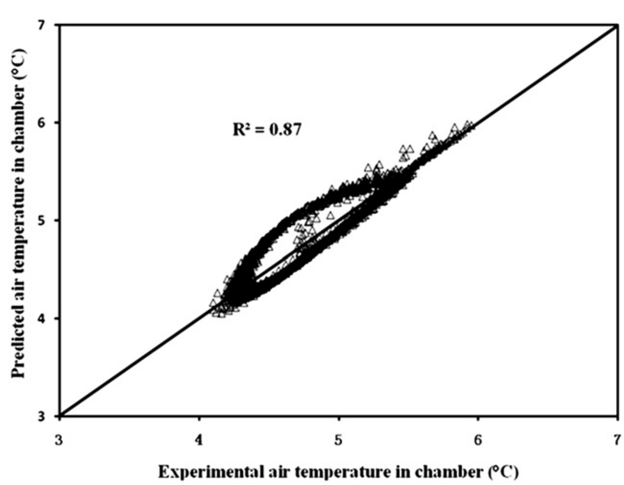

Fig. 3 – Comparison between predicted and experimental air temperatures in the chamber.

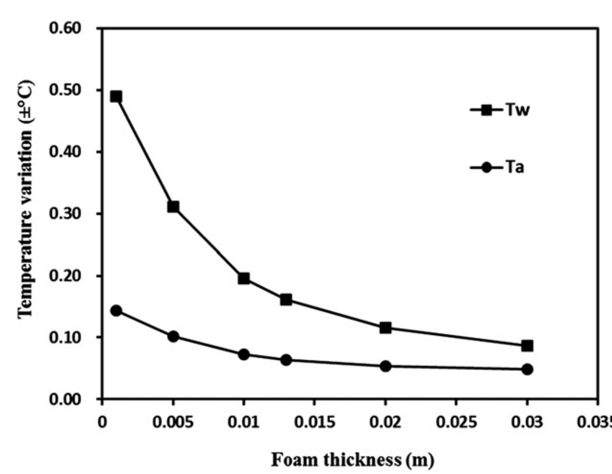

Fig. 4 – Simulated temperature variations for the hypobaric chamber wall (T_w) and inside air (T_d) under different insulation foam thicknesses.

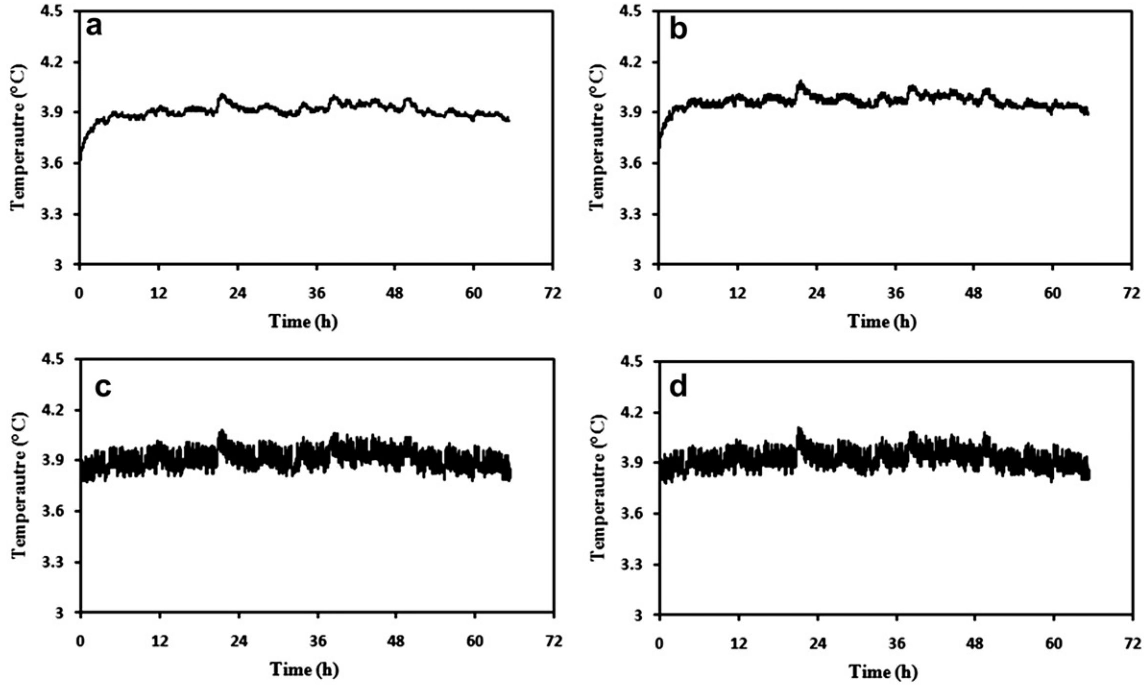

Fig. 5 – Temperature variation measured by four thermistor sensors at the set point temperature of 4 °C and 6.7 kPa pressure with 0.1 volumes h^{-1} air exchange rate in one hypobaric chamber, (a) Wet-bulb temperature; (b) Dry-bulb temperature; (c) interior chamber wall temperature; (d) exterior chamber wall temperature.

vacuum pump, isolate the system, and finally measure the rate of pressure rise (Burg, 2004). In the current study, the pressure was first reduced to 1.3 kPa at 4 °C and then the rate of pressure increase was measured under three different conditions: (A) close off the vacuum system and the air exchange system, (B) close off the vacuum system but the air exchange system was set to 1.0 volumes h^{-1}, (C) open the vacuum system but shut down the air exchange system.

3. Results and discussion

3.1. *Model validation and application*

Figure 3 compares the air temperature data measured inside the small box to the temperatures predicted from the computer simulation heat transfer model over about 17 h. Since the proposed model fitted the experimental data well (coefficient of determination $R^2 = 0.87$), the established simulation model was used to predict the influence of the foam thickness on temperature variation inside the hypobaric chamber. Figure 4 shows the predicted variation of hypobaric chamber wall and inside air temperatures when the chamber was covered by different insulation foam thicknesses and housed in a 4 °C cold storage room. Temperature variation of the inside air was less than that of the hypobaric chamber wall, and both temperature variations decreased with increasing foam thickness. The results showed that the hypobaric chamber wall temperature variation could be reduced to within ±0.2 °C and the inside air temperature could be maintained within ±0.1 °C when the foam thickness was >0.01 m (Fig. 4). The results indicated that a layer of insulation foam at least 0.01 m thick can be used in the current study to maintain a relatively stable temperature of the hypobaric chamber walls. To ensure suitable stability in subsequent studies, commercially available polyurethane insulation foam (McMaster-Carr Supply Co., Los Angeles, CA, USA) 0.013 m thick was used.

3.2. *Control stability of temperature and pressure*

Figure 5 shows the variation of wet-bulb, dry-bulb, interior chamber wall and exterior chamber wall temperatures versus time at the set temperature of 4 °C for the cold storage room.

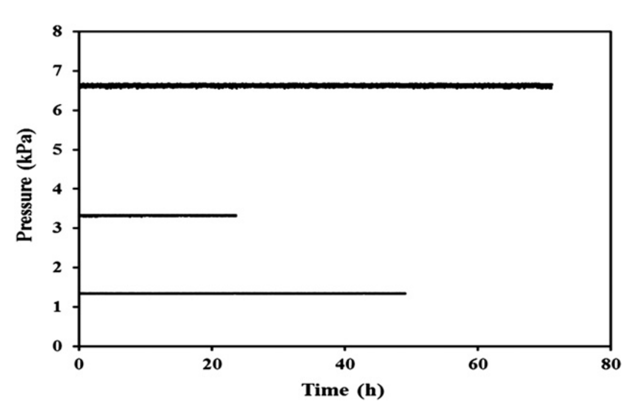

Fig. 6 – Stability of different pressures (1.3, 3.3, and 6.7 kPa) in the hypobaric chamber at 4 °C with the air exchange rate of 1, 0.2, and 0.1 volumes h^{-1}, respectively.

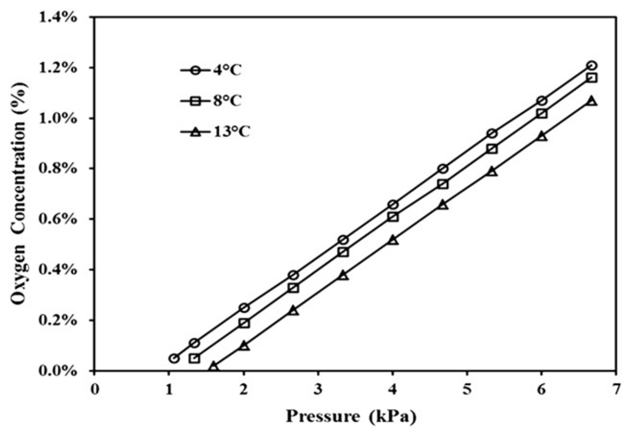

Fig. 7 – The estimated O_2 concentrations in the LP systems as a function of pressures at three different temperatures.

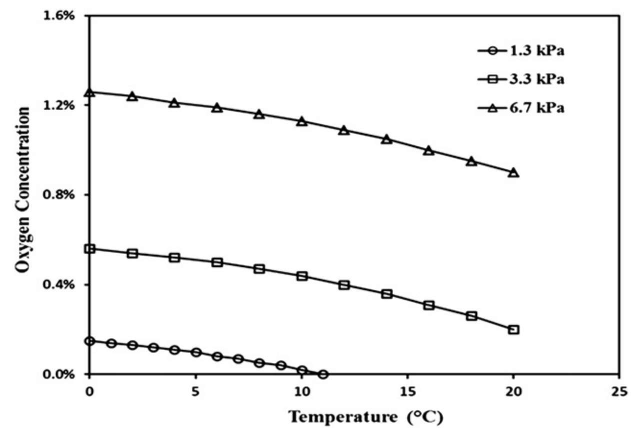

Fig. 8 – The O_2 concentration in LP systems as related to temperature at three different pressures.

The pressure was set to 6.7 kPa with 0.1 volumes h^{-1} air exchange rate in one empty hypobaric chamber. The experimental variation of the inside air temperature was within ±0.04 °C, which was a little smaller than the predicted value (±0.06 °C), probably due to the slightly overestimated heat convection coefficient. With a temperature variation of ±0.04 °C there were no condensation and evaporation cycles on the inner surface of hypobaric chamber walls, which was consistent with the literature (Burg, 2004). Addition of fruit stored at room temperature could cause temporary alteration in chamber temperature, but this should be of short duration and can be avoided by pre-cooling the fruit.

Figure 6 presents the pressure stability under different air exchange rates at 4 °C. The pressures were relatively stable at the set point with an accuracy of 1%, which is better than other systems mentioned in the literature (Chen et al., 2005; Davenport et al., 2006; Li & Zhang, 2006). Detailed statistical results were listed in Table 2 together with the evacuation and venting rates of the LP system. The pressure venting rate was much higher than the evacuation rate for all conditions (Table 2). The time for pressure to reduce from 93.3 kPa to all three tested pressures (1.3, 3.3, and 6.7 kPa) was 14–42 min, but the pressure venting time was less than 7 min for all of the tested pressures. These transient times during evacuating and venting are relatively short compared with the total LP treatment time, which usually takes several days for disinfestation. The evacuation and venting rates are constant parameters and are mainly dependent on the vacuum pump and air vents. Determining evacuation and venting rates will allow estimation of the time needed for increasing or decreasing pressure in the current LP system.

There were no clear differences under different air exchange rates (Table 2), since the flow rate was so small for the air exchange system compared with that of the vacuum pump or the vent for reducing or releasing pressure. The air exchange system is very important for maintaining fruit quality by removing metabolic gases generated by fruits (Burg, 2010) and keeping a relatively stable, low O_2 environment without ethylene. However, excessive air exchange rates have no benefits to the LP system, making the air difficult to saturate and causing a pressure drop in the pipe connected with the humidifier to the hypobaric chamber (Burg, 2004).

3.3. *Relative humidity and O_2 concentration in the hypobaric chambers*

Relative humidity, based on the measured wet-bulb and dry-bulb temperatures inside the hypobaric chamber at 4 °C under the different pressures and air exchange rates, is listed in Table 2. The humidifier installed in the current LP system maintained relative humidity inside the chamber at nearly saturated levels (>98%) under different pressures and air exchange rates. This saturated environment inside the hypobaric chamber would benefit fruit quality by reducing water loss (Burg, 2004). Even through the high relative humidity in hypobaric environments may encourage fungal growth (Lougheed, Murr, & Bérard, 1978), near saturated humidity conditions have been found to inhibit mould growth on most plant commodities (Burg, 2004; van den Berg & Lentz, 1978).

Calculated O_2 concentrations are shown in Figs. 7 and 8 at a temperature range of 0–20 °C and at three pressures (1.3, 3.3 and 6.7 kPa). O_2 concentration proportionally increased with pressure at each temperature (Fig. 7). At the same pressure, the O_2 concentration decreased with increasing temperature

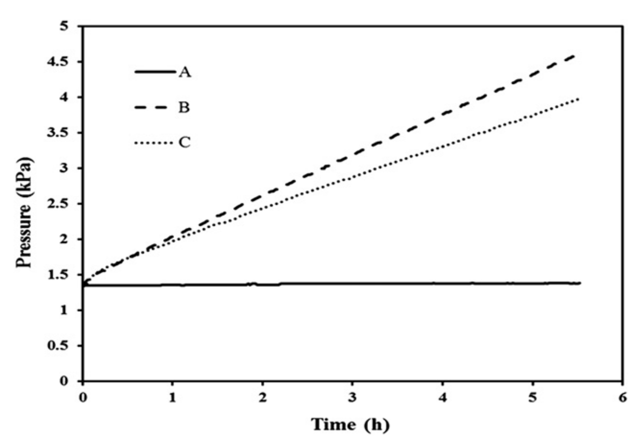

Fig. 9 – The leakage rates of hypobaric chamber under three different conditions at the temperature of 4 °C (A: Chamber only; B: With air exchange rate of 1 volumes h^{-1}; C: With vacuum system).

(Fig. 8). There was a limit for temperature reduction of O_2 concentration at each pressure level. For example, at 1.3 kPa O_2 concentrations reached 0% when the air temperature in the hypobaric chambers was increased to 11 °C (Fig. 8). O_2 concentrations were 0–0.2, 0.2–0.6, and 0.9–1.3% for 10, 25 and 6.7 kPa, respectively. Low O_2 concentration is the dominant mechanism for LP technology to control insects and <4.5% O_2 is necessary for effectively controlling the most susceptible stored-product insects (Navarro, 1978).

3.4. *LP system leakage rate evaluation*

Figure 9 shows the changes in hypobaric chamber pressure under three different conditions at 4 °C. The rate of increase in chamber pressure was 0.6 kPa h^{-1} under an air exchange rate of 1 volumes h^{-1}; and was 0.5 kPa h^{-1} when the air exchange system was shut down and the vacuum system was connected, and open, but the pump was turned off. When both the vacuum and air exchange systems were closed, the chamber pressure rose from 1.33 to 1.39 kPa in 5.5 h, indicating that the leakage rate was 0.01 kPa h^{-1} for the hypobaric chamber. These chamber leakage rates were lower than those of the VacuFresh^{SM} container reported by Burg (2004). Thus, the current hypobaric chambers would be expected to provide a useful system to further study the insect control and fruit quality preservation.

4. Conclusions

The good fit between the predicted results from the simulation and the experimental data suggests that the model could be useful in predicting temperature variability and the thickness of insulation needed for a variety of chambers. The model showed that insulation with a thickness of more than 0.01 m can reduce the temperature variation of hypobaric chamber wall to within ±0.2 °C and inside air to within ±0.1 °C. Experimental temperature data from the hypobaric chamber showed that with an insulation thickness of 0.013 m, temperature variation was well within the required levels, thereby avoiding condensation and evaporation cycles on the inner surface of the chamber walls. The LP system had the ability to control the pressure within 1% of the set point and maintained relative humidity at a nearly saturated level (>98%). O_2 concentration could be controlled at low levels (<0.6%) when the pressure was less than 3.3 kPa. These concentrations are well within the insecticidal range. The leakage rate of the hypobaric chamber was 0.01 kPa h^{-1} and the whole LP system was 0.5 kPa h^{-1} which was in the acceptable range. The good performance of the hypobaric chambers may provide a solid basis for future efficacy studies to develop non-chemical disinfestation treatments.

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