Modeling Respiration of Apple Slices in Modified-Atmosphere Packages

R. Lakakul, R. M. Beaudry, and R. J. Hernandez

ABSTRACT

Modified-atmosphere packaging was used to provide respiratory data for apple (*Malus* x*domestica* Borkh.) slices at 0, 5, 10 and 15°C. The maximum rate of O_2 uptake increased with increasing temperature. The lowest O_2 partial pressure to which fruit could be exposed without fermentation also increased with increasing temperature. A mathematical model of film permeability data characterized the effect of fruit mass, film permeability to O_2, activation energy of O_2 permeation, temperature, and the film type, area, and thickness on O_2 partial pressure for hermetically packaged apple slices. The model identified a minimum (fruit mass × film thickness)/(film area) ratio for apple slices, which would simplify package design calculations.

Key Words: fermentation, lightly processed, permeability, activation energy, apple

INTRODUCTION

FRESH APPLE SLICES HAVE THE POTENTIAL TO BE A HIGHLY popular lightly processed product (Hoag, 1995). Sliced apple products will likely be hermetically sealed in packages to maintain sterile conditions. Produce respiration inside a package with an air-tight seal alters the atmosphere within the package. For apple, modifying both O_2 and CO_2 may be useful to retard textural and flavor changes and reduce browning (Jurin and Karel, 1963; Lee et al., 1991). Alternatively, modified atmospheres can also induce fermentation and the generation of off-flavors (Kader et al., 1989). Information is needed on the effect of packaging on the atmosphere in the package and the effect of the atmosphere on quality and physiology of the product. Ranges of nondamaging O_2 and CO_2 levels have been published for several commodities (Kader, 1993; Meheriuk, 1993; Saltveit, 1993); however, the levels of O_2 and CO_2 required to avoid tissue damage or quality loss are unknown for apple slices.

Modified-atmosphere packaging (MAP) can be designed to maintain nondamaging partial pressures of O_2 and CO_2 over a range of temperatures (Beaudry et al., 1992; Cameron et al., 1994). According to Fick's Law, the respiration-driven reduction in O_2 partial pressure and increase in CO_2 partial pressure creates gradients that cause O_2 to enter and CO_2 to exit the package at rates proportional to the gradient. Steady-state O_2 levels can be achieved in the package when the O_2 uptake by the product is equal to that permeating into the package (Jurin and Karel, 1963). Similarly, steady-state CO_2 levels in the package are achieved when CO_2 production by the product equals CO_2 flux out of the package. The steady-state levels of both gases are dependent on interactions of respiration of the product and permeability properties of packaging film (Cameron et al., 1989; Kader, 1989; Beaudry et al., 1992). Increases in temperature are related to decreases in O_2 partial pressure in modified-atmosphere packages (Beaudry et al., 1992; Cameron et al., 1994). This has been attributed to the higher temperature responsiveness of respiration relative to O_2 permeation (Beaudry et al., 1992; Cameron et al., 1994).

MAP design can be improved by developing mathematical descriptions of the effects of temperature and O_2 on respiration. A Michaelis-Menton type model has been used to describe the influence of temperature and O_2 on respiration of blueberries (*Vaccinium corymbosum* L.) (Cameron et al., 1992), strawberries (*Fragaria* × *ananassa* Duch.) (Joles, 1993), raspberries (*Rubus idaeus* L.) (Joles et al., 1994) and broccoli (*Brassica oleracea* L. Botrytis Group) florets (Talasila et al., 1994). Respiratory models incorporating Arrhenius equations describing the temperature sensitivity of film permeability to gases predict package O_2 partial pressure as a function of temperature, fruit mass, surface area and film thickness (Cameron et al., 1994; Cameron et al., 1995). This approach can be used to design an MA package that can generate aerobic O_2 partial pressures across a range of temperatures. The respiration of apple slices (O_2 uptake) as a function of temperature and O_2 partial pressure has not been reported.

Our objective was to collect data needed to design MA packages of sliced apple fruit that would generate an atmosphere minimizing fermentation. We collected data for development of a respiratory model for sliced apple, then combined package permeability characteristics with the respiratory model to develop a packaging model to predict effects of temperature, film thickness, and fruit mass on package O_2. We also attempted to develop a simplified approach for designing packages that would remain aerobic across a broad temperature range and validate the model by packaging sliced apple fruit, comparing resultant O_2 levels with those predicted.

MATERIALS & METHODS

Film permeability

The permeability of 76.2 μm- and 101.6 μm-thick low density polyethylene (LDPE) film (LDF 550, The Dow Chemical Company, Midland, MI) and a polyolefin plastomer (POP) film made from a proprietary resin (Affinity PF 1140, The Dow Chemical Company, Midland, MI) to O_2 and CO_2 were determined on three random film samples at 0, 10 and 20±0.05°C according to the method of Beaudry et al. (1992). Concentration data were converted to partial pressures (1% O_2 (v/v) = 1.013 kPa at atmospheric pressure) to determine the permeability coefficients. Values of permeability as a function of temperature were fitted by the Arrhenius equation:

$$P_j = P_{0j}\ e\ \exp(-E_a^{Pj}/RT) \qquad (1)$$

where P_j is the permeability coefficient (mol m m^{-2} Pa^{-1} s^{-1}) of gas j, $P_{0,j}$ is the Arrhenius constant (mol m m^{-2} Pa^{-1} s^{-1}), R is the gas constant (8.3144J mol^{-1} K^{-1}), E_a^{Pj} is the activation energy (J mol^{-1}) and T is the temperature (K).

Plant material

Apple fruit of the numbered selection 'NY 674' were harvested at

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commercial maturity from plantings at the New York State Agricultural Experiment Station (Geneva, NY) and shipped overnight (no temperature control) to Michigan State University in October, 1993 for collecting respiratory data to construct the packaging model. 'NY 674' fruit for the model validation test were harvested at the Clarksville Horticulture Experiment Station (Clarksville, MI) in October, 1994. In both years, harvested fruit were held under elevated humidity (RH >85%) at 3±0.5°C for 7 days prior to use. Apples were cut into wedges using a stainless steel knife and the core material was removed. The skin was not removed from the wedge. Each piece was 1.5 cm wide measured at the skin side.

Package design

The initial step in the designing process involved determining rate of O_2 uptake (r_{O_2}) for apple slices at ambient O_2 partial pressure (20.7 kPa, 20°C). Apple slices (100g) were placed in a glass jar ventilated with air at a flow rate of 30 mL min^{-1} and the rate of CO_2 production (r_{CO_2}) measured. We assumed that r_{O_2} was similar to r_{CO_2} and was estimated to be 278, 194, 139 and 83 pmol g^{-1} s^{-1} at 15, 10, 5 and 0°C, respectively, by assuming a Q_{10} of 2 (Hardenburg et al., 1986). Using these estimates of r_{O2}, the fruit mass and film area for 76 µm-thick LDPE packages needed to generate 16 kPa O_2 in the package headspace for each temperature was calculated using Eq (2). The O_2 partial pressure of 16 kPa was assumed to saturate the respiratory demand for O_2. To achieve a range of lower O_2 levels, packages for the study possessed combinations of greater fruit mass, greater film thickness and/or decreased area. Film thicknesses were 76 and 102 µm, film areas were 800 and 1250 cm^2 and fruit mass varied from 19 to 587g. Four replications of each of 12 different combinations of film thickness, film area, and fruit mass were made for each temperature.

Respiration rate of apple slices

Apple wedges were placed on a plastic tray and inserted into packages subsequently hermetically sealed using a heat sealer. A small amount of silicone adhesive on a short strip of electrical tape was attached to the surface of the package for gas sampling (Boylan-Pett, 1986). To accelerate steady-state gas concentrations, a portion of the headspace air was removed by vacuum and replaced with N_2 prior to placing packages in controlled temperature chambers. Initial atmospheres contained 5 kPa O_2. Packages with holes or containing fruit with decay lesions were discarded and no fungicide treatment was used.

Gas samples were drawn from each package through the self-sealing silicone septum using a 0.5-mL syringe. Two 100-L gas samples were analyzed from each package at each evaluation using a paramagnetic O_2 analyzer (Series 1110, Servomex Co., Sussex, England) and CO_2 analyzer (225-MK3, Analytical Development Co., Hoddesdon, England) connected in series, with N_2 as the carrier gas (flow rate = 100 mL min^{-1}). A third gas sample was taken if any difference was noted between the first two samples. The gas composition of the headspace in individual packages was monitored daily until the partial pressures for O_2 (p_{i,O_2}) and CO_2 (p_{i,CO_2}) no longer changed and they were assumed to have reached steady-state. Steady-state gas levels were reached in 3, 4, 8 and 12 days at 15, 10, 5, and 0±0.5°C, respectively.

The respiration rate of the apple slices was determined using measured film permeabilities to O_2 and CO_2 as follows:

$$r_{O_2} = (p_{o,O_2} - p_{i,O_2})(P_{O_2}A/ml) \qquad (2)$$

$$r_{CO_2} = (p_{i,\,CO_2} - p_{o,CO_2})(P_{CO_2}A/ml) \qquad (3)$$

where r_{O_2} and r_{CO_2} are the respiration rate (mol g^{-1} s^{-1}) for O_2 and CO_2, respectively, p_i and p_o are the partial pressure (Pa) inside and outside the package, respectively, of O_2 and CO_2 (p_{o,O_2} was 21 kPa and p_{o,CO_2} was 0.04 kPa), A is the area (m^2) of the package exposed to gas transfer, m is the mass (g) of the apple slices and l is the thickness (m) of the packaging film. P_{O_2} and P_{CO_2} are the O_2 and CO_2 permeabilities (mol m m^{-2} Pa^{-1} s^{-1}), respectively, for the film.

The data describing the relationship between r_{O_2} and p_{i,O_2} were fitted with the Michaelis-Menten type model:

$$r_{O_2} = (V_{max}P_{i,O_2})/(K_{1/2} + P_{i,O_2}) \qquad (4)$$

where V_{max} (mol g^{-1} s^{-1}) is the maximal rate of O_2 uptake and $K_{½}$ (Pa) is the O_2 partial pressure at one half of V_{max}. The respiratory quotient (RQ) was calculated as r_{CO_2} divided by r_{O_2}. Data were plotted as the dependence of r_{O_2} and RQ on p_{i,O_2} at four temperatures. The fermentation threshold was determined as the O_2 partial pressure below which the RQ was estimated to increase above 1.3. The temperature dependence of V_{max} and $K_{½}$ was determined by fitting the respiratory data for all four temperatures to Eq (4) using SAS statistical analysis software (SAS Institute Inc., Cary, NC) as described (Cameron et al., 1994). The fitted equation was employed to determine the effect of temperature on O_2 uptake at constant p_{i,O_2}, calculating temperature sensitivity of the respiratory process in a manner comparable with the activation energy of the permeation process.

Package ethanol

The ethanol content of the package headspace was measured as described (Beaudry et al., 1993). Two 1-mL gas samples were withdrawn after packages had reached steady-state for O_2 and CO_2. Quantitation was by comparison to a gaseous standard. The standard gas sample was from a static headspace that was in equilibrium with a solution of water and ethanol of known concentration and temperature (Pesis and Avissar, 1990). A gas chromatograph (Carle AGC series 400, Carle Instruments Company, Fullerton, CA) fitted with a packed column (Hayesep N, 3 mm i.d., 45.7 cm length, with gas flow rates of 40, 40 and 200 mL min^{-1} for H_2, He and air, respectively) and an FID was used for analysis. The column was maintained at 120°C.

Package model

The mathematical model of Cameron et al. (1994) was used to describe the dependence of package O_2 levels on temperature and package characteristics for apple slices. Initially, O_2 flux through the package (Eq 2) was set equal to the respiratory rate determined from the respiratory model (Eq 4) such that:

$$(P_{O_2}A/mL)[p_{o,O_2} - p_{i,O_2}] = [(V_{max}p_{i,O_2})/(K_{½} + p_{i,O_2})] \qquad (5)$$

Which is valid only under steady-state conditions. This relationship was solved for p_{i,O_2}:

$$P_{i,O_2} = ½ \,[\![\{[K_{½} + (ml/P_{O_2}A)V_{max} - p_{o,O_2}]^2 + 4\, p_{o,O_2}K_{½}\}^{½} - [K_{½} + (ml/P_{O_2}A)V_{max} - P_{o,O_2}]]\!] \qquad (6)$$

Equation (6) was used to determine the effect of temperature on $p_{i,O2}$ when the activation energy of film permeability to O_2 ($E_a^{PO_2}$, Eq 1) was changed while the other package variables (m, l, A and $p_{o,\,O_2}$) were constant. Equation (6) was also used to evaluate film types for their film thickness suitability for gas exchange design criteria of 100g of sliced fruit in a 120 cm^2 package. The package model was used to predict the effects of varying the ml/A ratio for packages composed of LDPE containing apple slices.

RESULTS

Film permeability

An Arrhenius plot of permeability data indicated that ln(permeability) for both gases depended linearly on the reciprocal of temperature (Fig. 1, inset) with $r^2 = 0.99$ ($P<0.01$) for both O_2 and CO_2. Regression analysis of the Arrhenius plots, P_{O_2} and P_{CO_2} of LDPE yielded the following equations:

$$P_{O_2} = 2.49E - 9e^{(-37000/RT)} \quad (\text{mol m m}^{-2}\ \text{s}^{-1}\ \text{Pa}^{-1}) \qquad (7)$$

$$P_{CO_2} = 4.14E - 9e^{(-35000/RT)} \quad (mol\ m\ m^{-2}\ s^{-1}\ Pa^{-1}) \quad (8)$$

$E_a^{P_{O_2}}$ for LDPE was 37 kJ mol^{-1}. The activation energy of the permeation of CO_2($E_a^{P_{CO_2}}$) through LDPE was 35 kJ mol^{-1}. The permeability of the POP (Affinity PF 1140) film to O_2 and CO_2 was, respectively, 3.5 and 4-fold higher than for LDPE (data not shown). The activation energy for O_2 and CO_2 permeation through the POP film was 37.4 and 33.1 kJ mol^{-1}, respectively.

Respiratory model

Steady-state $p_{i,O2}$ was reached for all packages for each temperature. and ranged from approximately 0.1 to 15 kPa (Fig. 2). The r_{O2} (Fig. 2) and r_{CO2} (data not shown) calculated from film permeability to O_2 and CO_2, respectively, increased with increasing temperature and $p_{i,O2}$. V_{max} increased exponentially with temperature, while $K_{½}$ increased linearly:

$$V_{max} = 1.67E - 10e^{0.069T} - 1.06E - 10 \quad (mol\ g^{-1}\ s^{-1}) \quad (9)$$

$$K_{1/2} = 50T + 660 \quad (Pa) \quad (10)$$

where T is temperature in °C. The data fit the respiratory model with a coefficient of determination (R^2) of 0.94. The V_{max} for 'NY-674' apple slices was calculated to be 64, 139, 222 and 367 pmol g^{-1} s^{-1} for apple slices held at 0, 5, 10 and 15°C, respectively. This increase in respiration was equivalent to Q_{10}≈3.

At $p_{i,O2}$ < 1 kPa, RQ increased above its aerobic value (Fig. 3). Ethanol concentration in the package headspace increased when the RQ was ≥1.3 (data not shown) indicating fermentative metabolism. The $p_{i,O2}$ at which the RQ increase occurred increased as temperature increased. Fermentation threshold estimates for 0, 5, 10, and 15°C were 0.2, 0.25, 0.3 and 0.4 kPa O_2 (Fig. 3) and empirically fitted the exponential equation:

$$p_{i,O_2} = 195\ e^{(0.047T)} \quad (Pa) \quad (11)$$

where T is temperature in °C (r^2 = 0.99). A 'practical' lower O_2 limit three times higher than the fermentation threshold was established (Fig. 4).

Package model

The respiratory data enabled calculation of an apparent activation energy of respiration (apparent $E_a^{r_{O_2}}$), expressing the respiratory tem-

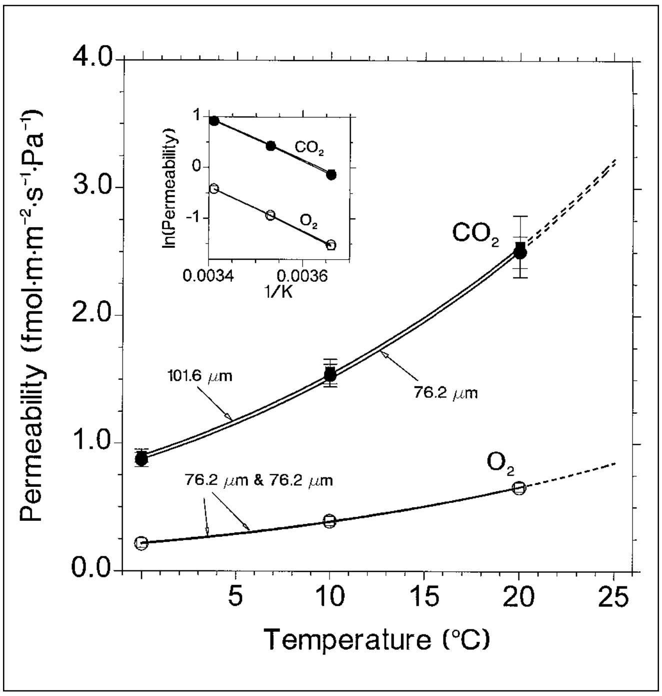

Fig. 1—Effect of temperature on film permeability to O_2 (open symbols) and CO_2 (solid symbols) for 76.2 µm (○,●) and 1.016 µm (□,■) thick LDPE films used in packaging. Inset: Arrhenius plot of O_2 and CO_2 permeability for LDPE film used in packaging experiments (r^2 = 0.99 for both O_2 and CO_2).

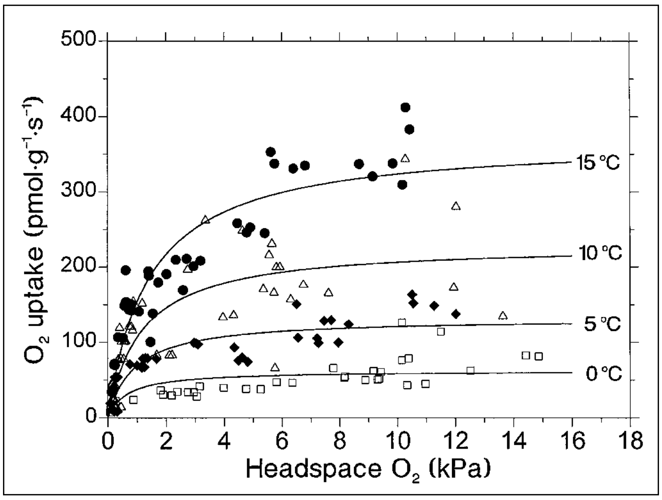

Fig. 2—Effect of steady-state O_2 partial pressure and storage temperature on the rate of O_2 uptake of apple slices (numbered selection 'NY674') in sealed LDPE packages. Curves depict the respiratory model (Eq 4) for 0 (□), 5 (△), 10 (◆), and 15 (●) °C .

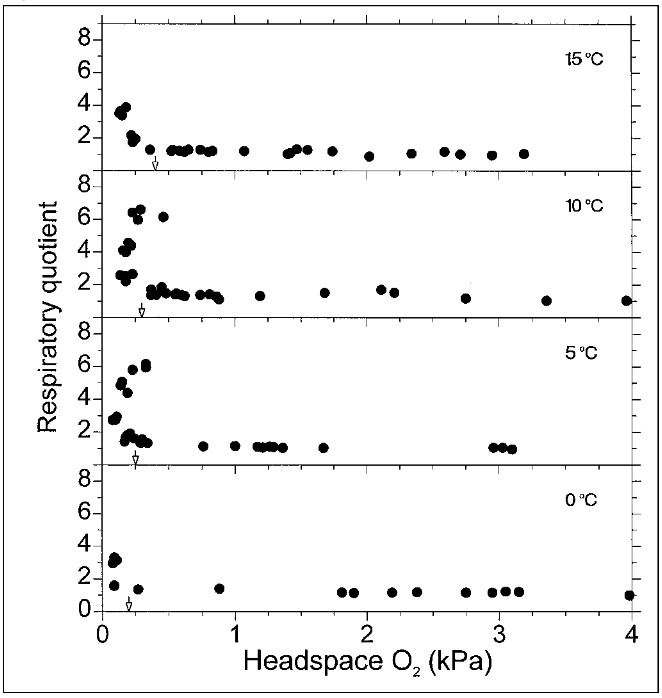

Fig. 3—Effect of steady-state O_2 partial pressure on the respiratory quotient of apple slices in sealed LDPE packages held at different temperatures. Fermentation thresholds are indicated by arrows and are estimated to be 0.2, 0.25, 0.3, and 0.4 kPa at 0, 5, 10, and 15°C, respectively.

perature sensitivity comparable to that for O_2 permeability (inset, Fig. 4). The apparent E_a^{rO2} for fruit at 16 kPa O_2 was 75 kJ mol^{-1} and at 0.5 kPa O_2 was 55 kJ mol^{-1}. Thus, the E_a^{PO2} of LDPE (37 kJ mol^{-1}) was lower than the apparent E_a^{rO2} of apple slices for O_2 partial pressures from 0.5 to 16 kPa.

The package model developed from apple slice data was used to determine how E_a^{PO2} affects p_{i,O_2} and temperature-induced anaerobiosis by substituting differing values of E_a^{PO2} for the permeability coefficient in Eq (6). When predictions for p_{i,O_2} were constrained to yield 1.2 kPa at 15°C, as E_a^{PO2} decreased, the p_{i,O_2} predicted at 0°C increased (Fig. 4). When the permeability coefficient E_a^{PO2} was near that of the respiratory response (60 kJ mol^{-1}), a low O_2 partial pressure was predicted across the temperature range. This was slightly higher than the practical lower O_2 limit established, and remained above the fermentation threshold.

Predictions of film thickness needs were made based on $P_{0,O2}$ and E_a^{PO2} data from Pauly (1989) for Saran® (poly[vinylidene chloride]), PVC (poly[vinyl chloride]) and PP (poly[propylene]) and from laboratory measurements on LDPE and POP (Affinity PF 1140) for theoretical packages (Fig. 5). Predicted film thickness ranges needed to maintain aerobic conditions across the temperature range of 0 to 15°C were 0.0066 to 0.109 µm for Saran®, 0.0775 to 0.96 µm for PVC, 0.533 to 5.51 µm for PP, 0.858 to 14.1 µm for LDPE and 3.15 to 25.4 µm for POP (Affinity PF 1140).

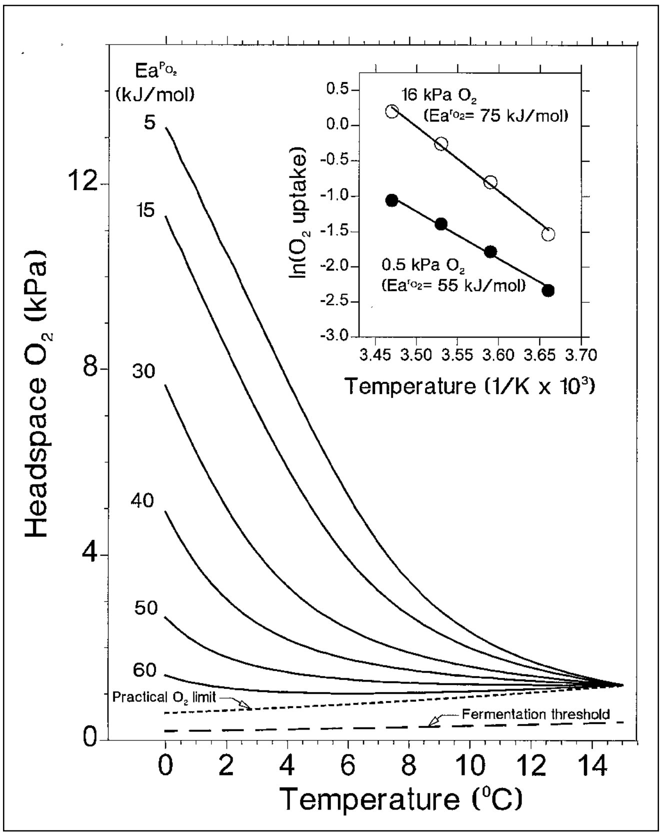

Fig. 4—Dependency of $p_{i,O2}$ on temperature for packages of sliced apple according to Eq (6). The constraint of $p_{i,O2}$ = 1.2 kPa at 15°C is imposed for hypothetical films differing in E_a^{PO2}. The practical O_2 limit is 3× the fermentation threshold and is represented by the exponential equation: Practical O_2 limit (kPa) = $0.587e^{0.047T}$, where T is temperature in °C. Inset: The relationship between the natural logarithm of O_2 uptake and the inverse of temperature (1/K) when $p_{i,O2}$ is 0.5 (●) and 16 (°) kPa. The apparent E_a^{PO2} for sliced apple fruit is 75 kJ mol^{-1} at of 16 kPa and 55 kJ mol^{-1} at 0.5 kPa O_2.

DISCUSSION

THE RESPIRATORY RATE OF APPLE SLICES WAS ABOUT 2 TO 3 TIMES that reported for whole fruit (Gran, 1993; Kader et al., 1989), due to effects of wounding, not a reduction in diffusive resistance produced by slicing. Since diffusive resistance of whole fruit resulted in an O_2 partial pressure gradient of only 2 to 5 kPa (Rajapakse et al., 1989), the interior O_2 level was sufficiently high to very nearly saturate the respiratory response (Tucker and Laties, 1985). Thus, the reduced diffusive resistance provided by slicing should not have resulted in an increase in O_2 uptake relative to whole fruit. The shapes of the respiratory curves were similar to those reported for blueberry (Beaudry et al., 1992) since both the $K_{½}$ and V_{max} increased with temperature in linear and exponential fashions, respectively.

The increase in RQ with declining p_{i,O_2} represents the lower O_2 limit in some studies and has been referred to as the RQ breakpoint, extinction coefficient or as the fermentation threshold (Beaudry et al., 1992; Gran and Beaudry, 1993; Yearsley et al., 1996). The fermentation threshold of apple slices was about half that of whole fruit reported by Gran and Beaudry (1993). The low fermentation threshold was likely not a function of the cultivar, but resulted from partial removal of the skin gas exchange barrier, coupled with a reduced diffusion path length. Hence, O_2 partial pressure in the surrounding atmosphere could be lower for a slice than for whole apple with internal O_2 partial pressure just above the fermentation threshold.

Like whole apple (Gran and Beaudry, 1993), blueberry (Beaudry et al., 1992), raspberry and strawberry (Joles, 1993; Joles et al., 1994) fruit, the fermentation threshold for apple slices increased with temperature. It was associated with the accumulation of ethanol in a manner consistent with previous results (Beaudry et al., 1992; Gran, 1993). The hypothesis that fermentation was linked to off-flavors and/or tissue damage in apple slices was supported indirectly by the correlation between RQ and the development of off-flavors in highbush blueberry fruit in a MAP system (Dostal et al., 1991). Fermentation should probably be avoided in packaged apple slices.

The package model could be used to design a package to minimize fermentation and predict the headspace atmosphere composition for sliced apples in packages composed of any polymer film of known permeability, thickness, area and fruit mass. The fruit must physically fit within the container and with sufficiently small headspace to permit rapid attainment of steady state. In addition to providing a suitable headspace atmosphere during storage, package material should maintain non-injurious p_{i,O_2} and p_{i,CO_2} over a range of temperatures and limit CO_2 injury. Treatment of apple slices with CO_2 resulted in the development of brown lesions in the fruit cortex when p_{i,CO_2} was near 10 kPa (Lakakul, 1994). An optimal package design therefore, should maintain p_{i,O_2} in the aerobic range and p_{i,CO_2} below the range causing injury.

The commercially acceptable lower O_2 limit may be higher than the fermentation threshold (Fig. 4). Cameron et al. (1993) measured variation in product respiration and package permeability and modeled the effects on p_{i,O_2}. They determined there was an estimable risk of the p_{i,O_2} falling below the O_2 limit, resulting in fermentation. They showed that for broccoli, packages must be designed to generate a p_{i,O_2} well above the fermentation threshold to ensure aerobic conditions. We used a practical lower O_2 limit 3 times higher than the fermentation threshold as a package design criterion (Fig. 4).

The apparent E_a^{rO2} for blueberry fruit ranges from 40 to 60 kJ mol^{-1} under aerobic conditions, similar to the range reported here (55 to 75 kJ mol^{-1}). The apparent E_a^{rO2} for strawberry fruit is 60 kJ mol^{-1}, lettuce, ~53 kJ mol^{-1} and broccoli, ~90 kJ $mole^{-1}$ (Cameron et al., 1995). It appears that the E_a^{rO2} for many horticultural crops tends to be greater than the E_a^{PO2} for LDPE. Thus, the flux of O_2 gas into the commodity has a higher temperature sensitivity than the flux of O_2 through the polymer film. Therefore as temperature increases, the respiration rate of the commodity would increase relatively more than P_{O_2}. That is, packaging systems with higher E_a^{PO2} would undergo smaller declines in O_2 as temperature increased. Generally, polymer films with lower temperature sensitivities are predicted to exert progressively less 'control' over p_{i,O_2} (Cameron et al., 1994; Cameron et al., 1995). A package that relies solely upon perforations would have an $E_a^{PO_2}$ 5 kJ mol^{-1} and, thus less 'control' than systems relying on O_2 permeation through polymers, with greater fluctuations in p_{i,O_2} with temperature changes. A polymeric package with a $E_a^{PO_2}$ of 60 kJ mol^{-1} would be expected to maintain low O_2 levels across the range 0 to 15°C. The need for a temperature-adaptive package is minimized if temperature can be controlled within a range of 1 to 2°C of the target temperature (Cameron et al., 1994; Cameron et al., 1995).

The package model could be rearranged to predict a suitable thickness range for packaging films for which design criteria have been established (e.g., 100g of fruit, 120 cm^2) such that the atmosphere in the package would remain aerobic from 0 to 15°C (Fig. 5). While many kinds of food-compatible polymer films are available, the predicted film thicknesses suggest not all would be suitable for apple slices. Among these polymers, a Saran® copolymer has a desirably high $E_a^{PO_2}$, however its P_{O_2} is very low, so film thickness would necessarily be much thinner than most machining capabilities (S. Jenkins, The Dow Chemical Company, Midland, personal communication) and use of Saran® copolymer would not be an option. Moreover, a thin monolayer film may not provide enough strength for the package. The POP film had a P_{O_2} about 3.5 times higher than that of LDPE, but a similar $E_a^{PO_2}$. The elevated P_{O_2} enables the use of greater film thickness than standard LDPE. For example, 25.4 µm-thick film would yield P_{i,O_2} of 6 kPa at 0°C (film area 120 cm^2 and 100g of apple slices) and would safely remain aerobic up to 15°C.

A more generally applicable form of the model can be derived using a ratio of the ml/A of each polymer film type (e.g., LDPE, PVC, EVA, etc.) to predict p_{i,O_2} dependency on temperature. From our model, an apple slice package composed of LDPE would be predicted to maintain aerobic conditions within the range from 0 to 15°C when the ml/A ratio is less than 5.65E-2g m^{-1}. For example, for a 100-g apple slice fruit pack using LDPE film thickness of 12.7 µm, the film area would have to be >225 cm^2 to avoid risk of fermentation.

To validate the model, packages composed of LDPE with ml/A ratios of 2.0E-02 and 3.575E-02 g m m^{-2} were constructed and stored at 0, 3, 5, 10, and 12°C. Package O_2 was expressed as a function of temperature (Fig. 6). The data were close to predicted values represented by the solid lines ($r^2 = 0.76$, $P < 0.05$), suggesting the model was functional and accurate.

Decay and browning remain as obstacles in the commercial production of apple slices (Lee and Smith, 1995). In our study or in parallel CA studies, neither decay nor browning were controlled by the atmospheres generated in the packages. Decay was observed on the apple slices in packages within 5 days at 15°C and 8 days at 10°C and browning was considered unacceptable within 24h of packaging at all temperatures.

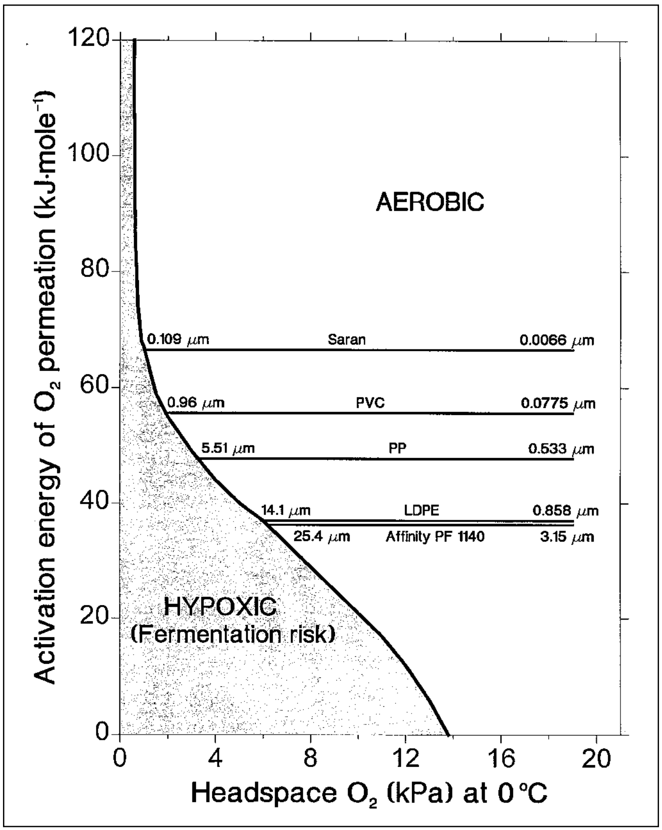

Fig. 5—Interrelationship between film E_a^{PO2} and thickness on the ability of a theoretical package to maintain aerobic O_2 partial pressures between 0 and 15°C. Thickness data are expressed as a function of $p_{i,O2}$ at 0°C. Curves were generated from Eq (6) with substitution of different $p_{i,O2}$ and E_a^{PO2} obtained experimentally or from Pauly (1989). The theoretical package film surface area was 120 cm^2 and fruit mass was 100g.

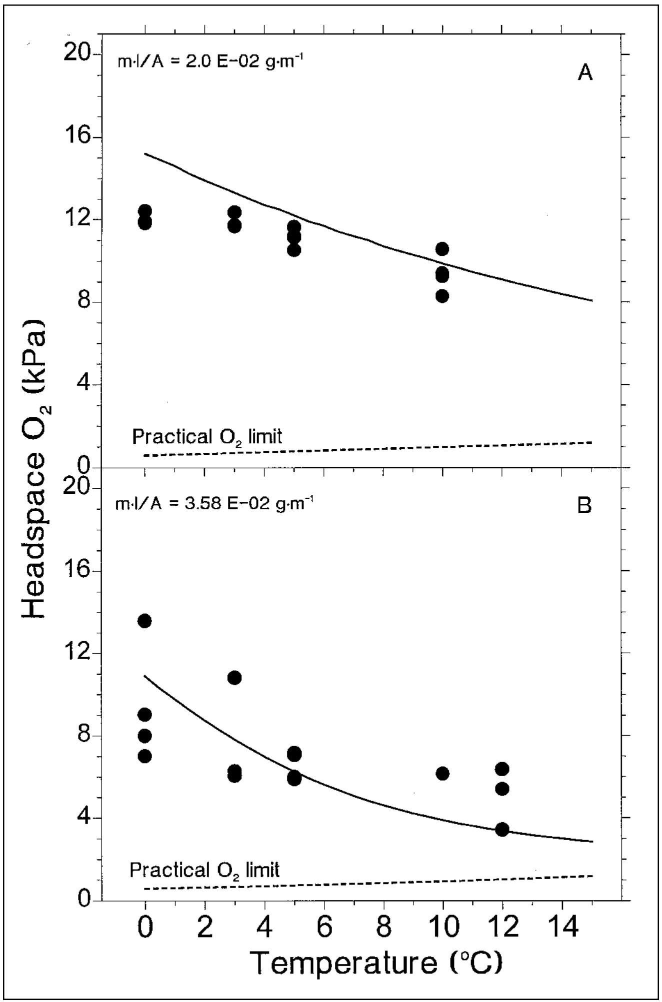

Figure 6—Package headspace O_2 achieved in packages designed to have a ml/A of either 3.58E-02 or 2.0E-02. The practical O_2 limit is 3× the fermentation threshold and is represented by the exponential equation: Practical O_2 limit (kPa) = $0.587e^{0.047T}$, where T is temperature in °C.

CONCLUSIONS

MATHEMATICAL MODELS FOR RESPIRATORY RESPONSES TO O_2 and temperature and the permeation of O_2 through various films could be combined for the design of MA packages for apple slices. The effects of environmental factors such as temperature on O_2 partial pressure in the packages could be predicted, enabling the evaluation of film types without the need for conducting numerous packaging experiments. The simplified approach of using the film-specific ml/A ratio should facilitate package design for MAP.

REFERENCES

Beaudry, R.M., Uyguanco, E.R., and Lennington, T.M. 1993. Relationship between headspace and tissue ethanol levels of blueberry fruit and carrot roots in sealed LDPE packages. Proc. Sixth Intl. Controlled Atm. Res. Conf., Ithaca, N.Y., June 15-17, 1993, p. 87-94.

Beaudry, R.M., Cameron, A.C., Shirazi, A., and Dostal-Lange, D.L. 1992. Modified-atmosphere packaging of blueberry fruit: Effect of temperature on package O_2 and CO_2. J. Amer. Soc. Hort. Sci. 117: 436-441.

Boylan-Pett, W. 1986. Design and Function of a Modified-atmosphere Storage on Browning and Softening Reactions in ‘Delicious’ Apples. PhD dissertation, Michigan State Univ., East Lansing.

Cameron, A.C., Boylan-Pett, W. and Lee, J. 1989. Design of modified atmosphere packaging systems: Modeling oxygen concentrations within sealed packages of tomato fruits. J. Food Sci. 54(6): 1413-1416, 1421.

Cameron, A.C., Patterson, B.D., Talasila, P.C., and Joles, D.W. 1993. Modeling the risk in modified-atmosphere packaging: A case for sense-and-respond packaging. Proc. Sixth Intl. Controlled Atm. Res. Conf., Ithaca, N.Y., June 15-17, 1993, pp. 95-102.

Cameron, A.C., Beaudry, R.M., Banks, N.H., and Yelanich, M.V. 1994. Modified-atmosphere packaging of blueberry fruit: modeling respiration and package oxygen partial pressures as a function of temperature. J. Amer. Soc. Hort. Sci. 119(3): 534-539.

Cameron, A.C., Talasila, P.C., and Joles, D.J. 1995. Predicting film permeability needs for modified-atmosphere packaging of lightly processed fruits and vegetables. HortScience, 30(1): 25-34.

Dostal Lange, D.L. and Beaudry, R.M. 1991. The effects of modified atmosphere packaging and temperature on postharvest storage life of three high bush blueberry cultivars. HortScience 23: 742.

Gran, C.D. 1993. Fruit Respiration and Determination of Low Oxygen Limits for Apple (Malus Domestica Borkh.) Fruit. M.S. dissertation, Michigan State Univ., East Lansing.

Gran, C.D. and Beaudry, R.M. 1993. Determination of the low oxygen limit for several commercial apple cultivars by respiratory quotient breakpoint. Postharvest Biol. Technol. 3(3): 259-267.

Hardenburg, R.E., Watada, A.E., and Wang, C.Y. 1986. The Commercial Storage of Fruits, Vegetables and Florist and Nursery Stocks. rev. ed., USDA Handbook 66.

Hoag, D. 1995. Fresh-cut fruit flowers in an array of ways. Produce Business: 35, 38, 40, 42, 44, 45.

Jenkins, S. 1994. Personal communication. The Dow Chemical Company, Midland, MI.

Joles, D.W. 1993. Modified-atmosphere Packaging of Raspberry and Strawberry Fruit: Characterizing the Respiratory Response to Reduced O_2, Elevated CO_2 and Changes in Temperature. M.S. dissertation, Michigan State Univ., East Lansing.

Joles, D.W., Cameron, A.C., Shirazi, A., Petracek, P.D., and Beaudry, R.M. 1994. Modified-atmosphere packaging of ‘Heritage’ red raspberry fruit: respiratory response to reduced oxygen, enhanced carbon dioxide, and temperature. J. Amer. Soc. Hort. Sci. 119: 540-545.

Jurin, V. and Karel, M. 1963. Studies on control of respiration of McIntosh apples by packaging methods. Food Technol. 17: 104-108.

Kader, A.A. 1993. A summary of CA requirements and recommendations for fruits other than pome fruits. Proc. Sixth Intl. Controlled Atmosphere Res. Conf., June 15-17, 1993, Ithaca, NY., p. 859-887.

Kader, A.A., Zagory, D., and Kerbel, E.L. 1989. Modified atmosphere packaging of fruits and vegetables. Crit. Rev. Food Sci. 28(1): 1-30.

Lakakul, A. 1994. Modified-atmosphere Packaging of Apple Slices: Modeling Respiration and Package Oxygen Partial Pressure as a Function of Temperature and Film Characteristics. M.S. dissertation, Michigan State Univ., East Lansing.

Lee, C.Y. and Smith, N.L. 1995. Minimal processing of New York apples. Bulletin 145, New York State Ag. Exp. Stn., Geneva, NY.

Lee, D.S., Haggar, P.E., Lee, J. and Yam, K.L. 1991. Model for fresh produce respiration in modified atmospheres based on principles of enzyme kinetics. J. Food Sci. 56(6): 1580-1585.

Meheriuk, M. 1993. CA storage conditions for apples, pears and nashi. Proc. Sixth Intl. Controlled Atmosphere Res. Conf., June 15-17, 1993, Ithaca, NY, p. 819-858.

Pauly, S. 1989. Permeability and diffusion data. Ch. IV in Polymer Handbook, 3rd ed., J. Brandup and E.H. Immergut (Ed.), p. 435-449, Wiley, New York.

Pesis, E., and Avissar, I. 1990. The effect of postharvest application of acetaldehyde vapour on strawberry decay, taste, and certain volatiles. J. Sci. Food Agric. 52: 377-385.

Rajapakse, N.H, Hewett, E.W., Banks, N.H., Cleland, D.J., and Austin, P.C. 1989. Oxygen diffusion in apple fruit flesh. Proc. Fifth Intl. Controlled Atmos. Res. Conf., June 14-16, 1989, Wenatchee, WA, p. 13-21.

Saltveit, Jr., M.E. 1993. A summary of CA and MA requirements and recommendations for the storage of harvested vegetables. Proc. Sixth Intl. Controlled Atmosphere Res. Conf., June 15-17, 1993, Ithaca, NY, p. 800-818.

Talasila, P.C., Cameron, A.C., and Joles, D.W. 1994. Frequency distribution of steady-state oxygen partial pressures in modified-atmosphere packages of cut broccoli. J. Amer. Soc. Hort. Sci. 119(3): 556-562.

Tucker, M.L. and G.G. Laties. 1985. The dual role of oxygen in avocado fruit respiration: Kinetic analysis and computer modeling of diffusion-affected respiratory oxygen isotherms. Plant, Cell Environ. 8: 117-127.

Yearsley, C.W., Banks, N.H., Ganesh, S., and Cleland, D.J. 1996. Determination of lower oxygen limits for apple fruit. Postharvest Biol. Technol. 8(2): 95-109.

Ms received 1/12/98; accepted 6/15/98.

This research was funded by the Crop and Food Bioprocessing Center at Michigan State University and was supported in part by the Michigan Agricultural Experiment Station. We thank Dr. Susan Brown of Cornell University for supplying fruit and Jessica Townsend and Eric Gay of Michigan State University for technical assistance.