Design procedure for the silicone membrane system used for controlled atmosphere storage of leeks and celery

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The first part of this paper reports on the various applications of the silicone membrane for modified and controlled storage. Research results on the CO₂ and O₂ relation for leeks and celery storage, as well as how they relate to the ratio of membrane surface area to product mass (A/M), are presented in the second part.

THE SILICONE MEMBRANE SYSTEMS

The silicone membrane

The silicone membrane consists of fine Tergal net (52-54 g/m²) covered with a thin (about 90 µm) and uniform layer of silicone rubber (dimethylpolysiloxane). At one atmosphere, its permeabilities to CO₂, O₂ and C₂H₄ are respectively, 1750, 320 and 700 L/d·m²·Atm. At a given temperature, the amount of gas diffusing through the silicone membrane will depend on the membrane surface area, its permeability and the gas partial pressure difference across the membrane.

Commercial CA storage systems that utilize the silicone membrane are: the Pallet Package, the Marcellin and the Atmo-lysair systems. Although commercially utilized in many European countries, the silicone membrane systems are rarely used in North America.

The pallet package system

The first commercial application of the silicone membrane for long-term storage of fresh produce, “The Pallet Package System”, was developed by Marcellin (1978). This system consists of a pallet box wrapped in a heavy gauge polyethylene bag with a silicone membrane window installed to regulate gas exchange (Fig. 1). The advantages of this system are ease of manipulation and the possibility of marketing the stored produce progressively without affecting the atmosphere in the remaining pallet boxes. However, in order to work efficiently, the pallets need to be well spaced, thereby reducing the capacity of the storage room. Other disadvantages of this system are the amount of work required to wrap and unwrap each pallet and the special care required in handling the boxes. Although this application was initially developed for long-term storage of fruit, its limitations made it more suitable for short and medium term storage and for produce in transit.

The Marcellin system

The Marcellin system (Fig. 2) regulates the CA condition in a storage room with a series of rectangular bags of silicone rubber connected in parallel (Marcellin and Leteinturier 1966, 1967). The number of bags on the unit depends on the size of the cold storage room.
room, the storage temperature, and the type of produce stored. Analysis of the CA composition will indicate whether or not more bags should be used. To maintain an atmosphere of 3% CO₂ and 3% O₂, 50 m² of silicone membrane is required per 100 t of fruit at a bulk density of 200 to 250 kg/m³. These units can be installed inside or outside the cold room (Guertin 1979).

The Atmolysair system
A modified version of the Marcellin system has been developed in Canada by Atmolysair Ltd. (Fig. 3). The unit consists of gas diffusion panels enclosed in an airtight metallic container with two separate air flow paths and a control board (Raghavan et al. 1984). The gas diffusion panels are made of square frames in which the silicone membrane is fixed. They are banked side by side in an airtight arrangement so that the outside air and the CA flow on opposite sides of the membrane without direct mixing. The air circulation is maintained by centrifugal blowers operated by a timer. The main advantages of this system over the Marcellin system are its ease of management and its potential for complete automation.

The procedure to calculate the membrane surface area required to maintain the desired CA composition is described in Raghavan et al. (1982) and can be summarized by the following equation:

\[
\text{Area} = \frac{RR \times M}{P_{\text{co}_2} \times \Delta CO_2}
\]

where:
- \(\text{Area}\) = silicone membrane surface area (m²);
- \(P_{\text{co}_2}\) = permeability of the silicone membrane to CO₂ (1750 L/d-m²-Atm.);
- \(RR\) = respiration rate of the product stored under CA (L of CO₂/kg-d);
- \(\Delta CO_2\) = desired CO₂ partial pressure difference across the membrane (Atm); and
- \(M\) = mass of stored produce (kg).

When the \(RR\) of the produce stored under the desired CA is not known, it is estimated as 60–70% of its value under normal air composition, at the same temperature. Although it seems relatively simple to determine the required membrane area, this equation has two limitations. Firstly, the \(RR\) and respiratory quotient (RQ, volumetric ratio of the CO₂ produced to the O₂ consumed of the stored produce) of many commodities stored under CA are rarely available; and secondly, the equation does not consider the amount of O₂ consumed by the stored produce nor the level of O₂ to be maintained. For these reasons, new design procedures were derived from the data gathered from CA storage experiment on leeks and celery.

MATERIALS AND METHODS
Two sets of experiments were performed to assess the suitability of the silicone membrane system for long-term CA storage of locally grown leeks (Allium porrum L. cv. Alaska) and celery (Apium graveolens cv. Clean Cut). In this paper, they will be respectively referred as Alaska leeks and Clean Cut celery.

The chambers used in these experiments were made of sections of PVC pipe, 500 mm long and 250 mm in diameter (Fig. 4). The ends of each unit were closed with a square lid of clear acrylic, 6 mm thick, and held in place with six threaded rods. Neoprene gaskets were used on both ends to ensure near perfect airtightness. The silicone membrane was installed on the lid in a window-like fashion. The advantages of this design were: (i) Durability; (ii) Ease of construction; (iii) Near perfect airtightness; (iv) Quick and simple opening and closing procedures; (v) Possibility for visual assessment of the product during storage; (vi) Low maintenance requirement; and (vii) Ease of stacking.

The Alaska leeks were stored under four different CA compositions for 133 d and the Clean Cut celery under three dif-
RESULTS AND DISCUSSIONS

For both products studied, the progression of the CO$_2$ and O$_2$ concentrations followed a trend characteristic of the SMS and the levels maintained in the CA chambers depended on the membrane surface area. Figure 5 shows the progression of the CO$_2$ and O$_2$ concentrations in a chamber equipped with the silicone membrane. Additional information on the quality and physiological aspects are available in Gariépy and Raghavan (1983, 1985, 1986), and Gariépy et al. (1984, 1985, 1986).

For each product studied, a plot of the mean CO$_2$ and O$_2$ concentrations maintained in each CA chamber was obtained by integrating the gas concentration curve over the complete storage period.
Table I. Design parameters for the CA storage experiments on Alaska leeks and Clean Cut celery with the silicone membrane system

<table>
<thead>
<tr>
<th>Vegetable, cultivar</th>
<th>Initial mass (kg)</th>
<th>Treatment</th>
<th>Designed CO₂ level (%)</th>
<th>Membrane area (cm²)</th>
<th>Storage length (d)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Leeks, Alaska</td>
<td>3.5</td>
<td>A</td>
<td>3.0</td>
<td>130</td>
<td>133</td>
</tr>
<tr>
<td></td>
<td></td>
<td>B</td>
<td>4.5</td>
<td>91</td>
<td>133</td>
</tr>
<tr>
<td></td>
<td></td>
<td>C</td>
<td>6.0</td>
<td>70</td>
<td>133</td>
</tr>
<tr>
<td></td>
<td></td>
<td>D</td>
<td>9.0</td>
<td>36</td>
<td>145</td>
</tr>
<tr>
<td>Celery, Clean Cut</td>
<td>6.0</td>
<td>A</td>
<td>1.5</td>
<td>182</td>
<td>71</td>
</tr>
<tr>
<td></td>
<td></td>
<td>B</td>
<td>3.5</td>
<td>75</td>
<td>71</td>
</tr>
<tr>
<td></td>
<td></td>
<td>C</td>
<td>5.5</td>
<td>49</td>
<td>71</td>
</tr>
</tbody>
</table>

storage period (Figs. 6 and 7). These values were then plotted against their respective A/M ratio (Figs. 8 to 11). For the range studied, the relationship between A/M and CO₂ was found to be similar to that of O₂ and CO₂, while A/M appeared to be linearly related to O₂. The best fit curve equations were obtained from the regression analyses performed on the data using the following statistical models:

For the O₂:CO₂ and A/M:CO₂ relationships:

\[ Y = a + b \times X^{-1} + c \times X^{-2} + d \times X^{-3} + e \times \ln(x) \] (2)

For the A/M:O₂ relationship:

\[ Y = a + b \times X \] (3)

In these models, \( Y \) is the dependent variable (O₂ or A/M), \( X \) is the independent variable (CO₂ or O₂) and \( a, b, c, d, \) and \( e \) are the regression parameters. Results of the analyses are summarized in Tables II and III.

These graphs and equations can be used: (i) To estimate the required silicone membrane surface area to maintain a desired level of CO₂; and (ii) To obtain an estimate of the matching O₂ concentrations. For example, CA storage of Alaska leeks at 5% CO₂, in a storage facility equipped with the silicone membrane system, will require 1.15 m² of membrane per tonne of product and the O₂ concentrations maintained in the storage should be approximately 2.5%. These procedures also allow the user to obtain the required silicone membrane area from the desired O₂ concentrations. This was not possible with Eq. 1. One of the most promising applications of the CO₂:O₂ regression model is as a part of a computer program designed for the automatic control of silicone membrane systems such as the Atmolysair unit. The model could be used to predict gas concentrations and to determine the magnitude of the change in time of operation of the unit.

Disadvantages of the new procedure are: (i) It has to be obtained through experimentation; and (ii) Its utilization is limited to the range for which it has been established.

It was also observed that factors such as: cultivar, level of prestorage preparation, growing location and prestorage chemical treatments did affect the gas concentrations maintained in the chambers. However, the CO₂:O₂ combinations observed remained very close to the regression model. More research is required to better understand these phenomena and to broaden the range over which the models can be applied.

CONCLUSIONS

The silicone membrane system was found suitable for long-
Table II. Results from the regression analyses performed on the O₂:CO₂ and A/M:CO₂ data from the experiments on CA storage of leeks and celery with the silicone membrane system. The statistical model used for the analyses was:

\[ Y = a + b \times X^{-1} + c \times X^{-2} + d \times X^{-3} + e \times \ln(X) \]

<table>
<thead>
<tr>
<th>Vegetable, cultivar</th>
<th>Variables</th>
<th>Regression parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( Y )</td>
<td>( X )</td>
</tr>
<tr>
<td>Leeks, Alaska</td>
<td>O₂</td>
<td>CO₂</td>
</tr>
<tr>
<td>Celery, Clean Cut</td>
<td>A/M</td>
<td>CO₂</td>
</tr>
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</table>

Figure 8. Membrane requirement per unit mass of leeks as a function of the mean O₂ concentration. The best fit curve equation is: \( A/M = 1.1 + 0.42 \times \%O_2 \).

Figure 9. Membrane requirement per unit mass of leeks as a function of the mean CO₂ concentration. The best fit curve equation is: \( A/M = 9.11 + 325 \times (\%CO_2)^{-3} \).

Figure 11. Membrane requirement per unit mass of celery as a function of the mean CO₂ concentration. The best fit curve equation is: \( A/M = 31.8 - 21.2 \times \ln(\%CO_2) \).

Figure 10. Membrane requirement per unit mass of celery as a function of the mean O₂ concentration. The best fit curve equation is: \( A/M = -5.8 + 2.5 \times \%O_2 \).

new procedures have been derived for the design of the silicone membrane system for long-term storage of leeks and celery. With the new parametric relations, the design of the silicone membrane system can be based on either the desired O₂ or CO₂ concentrations.
Table III. Results from the regression analyses performed on the
$\text{AIM}:O_2$ data from the experiments on CA storage of leeks and
celery with the silicone membrane system. The statistical model
used for the analyses was: $Y = a + b \times X$

<table>
<thead>
<tr>
<th>Vegetable, cultivar</th>
<th>Variables</th>
<th>Regression parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$Y$</td>
<td>$X$</td>
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<td>Leeks, Alaska</td>
<td>$A/M$</td>
<td>$O_2$</td>
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<td>$O_2$</td>
</tr>
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