Gas Diffusion Tube Dimension in Sensor-Controlled Fresh Produce Container System to Maintain the Desired Modified Atmosphere

Yun Hee Jo, Duck Soon An and Dong Sun Lee*

Department of Food Science and Biotechnology, Kyungnam University, Changwon 631-701, Korea

Abstract Modified atmosphere (MA) of reduced O\textsubscript{2} and elevated CO\textsubscript{2} concentrations has been used for keeping the quality of fresh produce and extending the shelf life. As a way to attain the beneficial MA package around the produce, a gas diffusion tube or perforation can be attached onto the container and controlled on real time in its opening/closing responding to O\textsubscript{2} and CO\textsubscript{2} concentrations measured by gas sensors. The timely-controlled opening of the gas diffusion tube can work in harmony with the produce respiration and help to create the desired MA. By use of the mathematical modeling, the effect of tube dimension on the controlled container atmosphere was figured out in this study. Spinach and king oyster mushroom were used as typical commodities for designing the model container system (0.35 and 0.9 kg in 13 L, respectively) because of their respiration characteristics and the optimal MA condition (O\textsubscript{2} 7~10%/CO\textsubscript{2} 5~10% for spinach; O\textsubscript{2} 2~5%/CO\textsubscript{2} 10~15% for mushroom). With a control logic for the gas composition to stay as close as possible to optimum MA window without invading injurious low O\textsubscript{2} and/or high CO\textsubscript{2} concentrations, the atmosphere of the sensor-controlled container could stay at its lower O\textsubscript{2} boundary or upper CO\textsubscript{2} limit under certain tube dimensional conditions. There were found to be the ranges of the tube diameter and length allowing the beneficial MA. The desired range of the tube dimension for spinach consisted of combinations of larger diameter and shorter length in the window of 0.3~2 cm diameter and 0.2~10 cm length. Similarly, that for king oyster mushroom was combinations of larger diameter and shorter length in the window of 0.9~2 cm diameter and 0.2~3 cm in length. Clear picture on generally affordable tube dimension range may be formulated by further study on a wide variety of commodity and pack conditions.

Keywords Modified atmosphere, Fresh produce, Sensor, Perforation, Control

Introduction

Modified atmosphere packaging (MAP) is a technique used for preserving the freshness of fresh produce and prolonging the shelf life by modifying the atmosphere surrounding the produce. The modified atmosphere (MA) in proper window is widely known and accepted to suppress the respiration, delay the ripening process and reducing the deterioration reaction, contributing to the quality preservation\textsuperscript{1,2}. The atmosphere modification inside the package is achieved by the interplay between two processes, the respiration of the produce and the transfer of gases through the packaging film, which leads to an atmosphere of reduced O\textsubscript{2} and increased CO\textsubscript{2} concentrations\textsuperscript{3,4}. While MA packages can attain the beneficial atmosphere relatively at lower cost compared to controlled atmosphere storage, their ability to create and maintain the optimum MA conditions is limited due to the limited range and characteristic of gas permeability of plastic packaging materials. As means to widen the applicability of MAP, high gas transfer devices such as micro-perforations or gas diffusion tubes have been tried for a variety of commodities\textsuperscript{5,6}. Recently, as a more effective way to create the beneficial MA in package or container of fresh produce, an MA container equipped with gas sensors and gas diffusion tube controllable in its opening/closing has been suggested and tested for maintaining a desired gas composition\textsuperscript{7}. It was reported that the gas composition of the properly designed container equipped with the diffusion tube could stay at the lower O\textsubscript{2} boundary or upper CO\textsubscript{2} limit of optimal MA helping the quality preservation. However, the ability to achieve the desired MA was reported to depend on tube dimension in a certain extent.

This study therefore aims to investigate the behavior of the container atmosphere depending on tube dimension variables to find their adequate ranges. The concept was tested at two typical commodities, spinach and king oyster mushroom for a commonly used temperature condition of 10°C. They were cho-
Mushrooms in the container were selected because of typically different respiration characteristics and optimal 
MA conditions (O\textsubscript{2} 7–10%/CO\textsubscript{2} 5–10% for spinach; O\textsubscript{2} 2–5%/CO\textsubscript{2} 10–15% for King Oyster 
mushroom), containing 0.35 kg of spinach or 0.9 kg of King Oyster 

Materials and Methods
1. Model MA container system
A fresh produce container with a diffusion tube that can be 
opened or closed with linkage to O\textsubscript{2} and/or CO\textsubscript{2} sensors as 
reported by Jo et al.\textsuperscript{7} was used as a model system for analysis. 
The container is equipped with O\textsubscript{2} and/or CO\textsubscript{2} gas sensors 
monitoring the gas concentrations on a real-time basis, and 
these concentrations are supplied to the control system as 
source information to regulate the opening/closing actuation 
of the diffusion tube. Mechanical mechanism such as solenoid 
valve may be used for the opening/closing of the tube. A typ-
ical container structure consists of a 2-mm thick polyprop-
ylene box with dimension of 32×23×18 cm \(=13\) L of vo-

2. Mathematical model for container atmosphere 
simulation
Based on the analysis of Kwon et al.\textsuperscript{10} a simplified dif-
fusion model on the perforated produce package was used to 
simulate the container atmosphere depending on the tube 
dimension:

\[
\frac{dn_{O_2}}{dt} = \frac{N D_{O_2} A (0.21 p_o - p_{O_2})}{L + \delta} \left( \frac{L}{RT} \right) + \frac{P_{O_2} S (0.21 p_o - p_{O_2})}{B} - WR_{O_2} 
\]

\[
\frac{dn_{CO_2}}{dt} = \frac{N D_{CO_2} A (0.00 - p_{CO_2})}{L + \delta} \left( \frac{L}{RT} \right) + \frac{P_{CO_2} S (0.00 - p_{CO_2})}{B} + WR_{CO_2} 
\]

\[
\frac{dn_{N_2}}{dt} = \frac{N D_{N_2} A (0.78 p_o - p_{N_2})}{L + \delta} \left( \frac{L}{RT} \right) + \frac{P_{N_2} S (0.78 p_o - p_{N_2})}{B} 
\]

where \(n_{O_2}, n_{CO_2}\) and \(n_{N_2}\) are the respective mole number of 
O\textsubscript{2}, CO\textsubscript{2} and N\textsubscript{2} gas in the container at time \(t\) (h); \(p_{O_2}, p_{CO_2}\) and \(p_{N_2}\) are the respective partial pressure of O\textsubscript{2}, CO\textsubscript{2} and N\textsubscript{2} 
gas in the container at time \(t\); \(D_{O_2}, D_{CO_2}\) and \(D_{N_2}\) are the 
respective diffusivities of O\textsubscript{2}, CO\textsubscript{2} and N\textsubscript{2} gas in air (m\textsuperscript{2} h\textsuperscript{-1}); \(N\) represents the state of the diffusion tube (1 when the tube is 
open and 0 when the tube is in close state), which has length 
(L), diameter \(d\) (m) and cross-sectional area \(A\) (m\textsuperscript{2}); \(d\) is a 
correction term for the gas diffusion resistance in the tube 
(1.1d); B and S are the thickness (mm) and surface area (m\textsuperscript{2}) 
of the plastic layer (wall and cover), respectively; \(P_{O_2}, P_{CO_2}\) and \(P_{N_2}\) are the gas permeabilities of the polypropylene layer 
against O\textsubscript{2}, CO\textsubscript{2} and N\textsubscript{2} (5.71×10\textsuperscript{-10}, 1.63×10\textsuperscript{-9} and 1.14×10\textsuperscript{-10} 
mm m\textsuperscript{-2} h\textsuperscript{-1} Pa\textsuperscript{-1} against O\textsubscript{2}, CO\textsubscript{2} and N\textsubscript{2}, respectively, at 
10\textdegree C); \(p_o\) is the normal atmospheric pressure (1.013×10\textsuperscript{5} 
Pa); \(R\) is the ideal gas constant (8.314 J K\textsuperscript{-1} mol\textsuperscript{-1}); \(T\) is the 
temperature (K); \(W\) is the produce weight (kg); \(R_{O_2}\) is the 
respiration rate of O\textsubscript{2} consumption (mol kg\textsuperscript{-1} h\textsuperscript{-1}); \(R_{CO_2}\) is the 
respiration rate of CO\textsubscript{2} production (mol kg\textsuperscript{-1} h\textsuperscript{-1}). The first terms on the 
right-hand sides of Eqs. (1)–(3) represent gas diffusion 
through the tube based on Fick’s law. The second terms on the 
right-hand sides of each equation describe the diffusive gas 
permeation through the plastic layer, and the last terms in Eqs. 
(1) and (2) describe the respiration.

In solving the Eqs. (1)–(3) for simulating the container atmo-
sphere, \(N\), the state of the diffusion tube is determined by the 
control logic for attaining the desirable MA\textsuperscript{7}. When oxygen 
concentration ([O\textsubscript{2}]) decreases up to its lower bound ([O\textsubscript{2}]) of 
optional MA window or carbon dioxide concentration ([CO\textsubscript{2}]) increases up to its higher limit ([CO\textsubscript{2}]) of optional MA 
window, the diffusion tube as a device to increase gas transfer is 
turned on to the open position (N=1) from initially closed state 
and also respond the same way later in the storage: whenever 
gas concentration reaches the borderline ([O\textsubscript{2}] or [CO\textsubscript{2}]), the 
control is made to open the valve for preventing it from enter-
ing the injurious zones (too low O\textsubscript{2} and/or too high CO\textsubscript{2} 
concentrations). While [O\textsubscript{2}] stays above [O\textsubscript{2}] and [CO\textsubscript{2}] is below 
[CO\textsubscript{2}], the tube may be controlled to simply close (N=0).

The respiration rate of the produce in Eqs. (1) and (2) was 
supplied as a function of the O\textsubscript{2} and CO\textsubscript{2} concentrations:

\[
R_{O_2} \text{ or } R_{CO_2} = \frac{V_{m p_{O_2}}}{K_m + (1 + p_{CO_2}/K_i) p_{O_2}} 
\]

where \(V_{m}, K_m\) and \(K_i\) are respiration model parameters. The 
respiration kinetic data for spinach and King Oyster 
mushrooms at 10\textdegree C were adopted from Jo et al.\textsuperscript{7}; \(V_{m}=1.911\) mmol 
kg\textsuperscript{-1} h\textsuperscript{-1}, \(K_m=3.58\) kPa and \(K_i=22.4\) kPa for the \(R_{CO_2}\) of spinach; 
\(V_{m}=1.516\) mmol kg\textsuperscript{-1} h\textsuperscript{-1}, \(K_m=3.32\) kPa and \(K_i=17.2\) 
kPa for the \(R_{CO_2}\) of spinach; \(V_{m}=5.717\) mmol kg\textsuperscript{-1} h\textsuperscript{-1}, \(K_m=5.92\) kPa and \(K_i=140.6\) kPa for the \(R_{CO_2}\) of king 
Oyster mushrooms; \(V_{m}=2.386\) mmol kg\textsuperscript{-1} h\textsuperscript{-1}, \(K_m=0.03\) kPa and \(K_i=85.0\) kPa for the \(R_{CO_2}\) of king 
Oyster mushrooms. With simple glance on the respiration parameters, king oyster mushroom is 
of higher respiration activity due to its higher values of \(V_{m}\).

Eqs. (1)–(3) were solved numerically by using Gear’s me-

thod to have partial pressures of $O_2$, $CO_2$ and $N_2$ ($p_{O_2}$, $p_{CO_2}$ and $p_{N_2}$) or to volumetric percentages under 1 atm converted from gas moles.

**Results and Discussion**

With adequate dimension of gas diffusion tube, the sensor-controlled container system was shown to produce a beneficial MA for spinach (Fig. 1A). The gas composition was equilibrated after 8 days for $[CO_2]$ and $[O_2]$ to stay at 10% ($[CO_2]_{0}$) and 8–9%, respectively. The atmosphere in the sensor-controlled produce container equipped with diffusion tube has been reported formerly to be determined by only one of lower $O_2$ boundary ($[O_2]_L$) or upper $CO_2$ limit ($[CO_2]_H$) depending on the characteristics of the commodity and the optimal MA. However, under certain condition of long and narrow tube (for example, 0.5 cm diameter and 6.0 cm length), $[CO_2]$ went beyond $[CO_2]_H$ and $[O_2]$ went eventually down below $[O_2]_L$, which might induce physiological injury due to too low $O_2$ and/or too high $CO_2$ concentrations (Fig. 1B). The control system of this dimension tube failed to locate the container atmosphere in the optimal MA region, because of too much activity of respiration to modify the atmosphere compared to gas transfer across the diffusion tube. The $O_2$ and $CO_2$ gas transfers through long and narrow tube were not enough to balance the spinach respiration. Simulations using Eqs. (1)–(3) were conducted for different combinations of tube diameter and length to figure out the container atmosphere depending on the tube dimension. The matrix of tube diameter and length could be divided into two regions: one to provide the desirable MA and the other to induce the too high $CO_2$ accumulation (Fig. 2). The adequate tube dimension was the combinations of larger diameter and shorter length in the range of 0.3–2 cm diameter and 0.2–10 cm length. Large diameter could afford long length, but small diameter could not afford too long length in the limited extent of analysis. Under the limitation of analysis boundary, the diameter size does matter but not the length of the tube: length can be anywhere in the range of 0.2–10 cm, but the diameter needs to be appropriate size depending on the tube length. As a simple approx-

![Fig. 1. Container atmosphere profiles of spinach container with tube dimension in (A) adequate range (diameter 1.0 cm/length 0.2 cm) and (B) inadequate range (diameter 0.5 cm/length 6.0 cm).](image)

![Fig. 2. Adequate range of tube dimension capable of maintaining beneficial MA close to the optimum ($O_2$ 7–10%/ $CO_2$ 5–10%) for spinach. Shaded area represents the adequate combination of tube diameter and length, while the other white one is non-adequate combination.](image)
length could make the desired MA condition.

Similarly to spinach container, adequate tube dimension could attain beneficial MA staying at \([O_2]\) of \(\approx 5\%\) and \([CO_2]\) of \(15\%\) after equilibration (Fig. 3A). As observed in spinach container (Fig. 1A), the \([CO_2]\) resided at the upper tolerable limit of \(CO_2\) concentration (\([CO_2]_H\)), which is \(15\%\) for king oyster mushroom. Before reaching the \([CO_2]\) equilibrium, \([O_2]\) stayed at the lower limit of \(2\%\) (\([O_2]_L\)) for some time. The sensor-based control could create and maintain the beneficial safe MA by playing on the borderline of \([O_2]_L\) or \([CO_2]_H\). The effective control like Fig. 3A was attained with several possible combinations of tube diameter and length, which were presented in Fig. 4. With different adequate tube dimensions there were slight variations in the equilibrium \([O_2]\) attained along with \([CO_2]\) at \([CO_2]_H\).

On the other hand, tube of narrow diameter and long length resulted in persistently increased \([CO_2]\) well above \([CO_2]_H\) without reaching equilibrium along with anaerobic condition of \([O_2]\) < \(1\%\) (Fig. 3B), which may be detrimental to the mushroom physiology. The larger gas diffusion resistance across the tube due to small perforation area and long length made the gas transfer not high enough to balance the mushroom respiration. The increased \([CO_2]\) level in the injurious range was higher with narrower diameter and longer length of the tube. Fig. 4 shows also non-tolerable range of tube dimension in terms of attainable gas composition. Adequate domain of tube dimension consisting of larger diameter and shorter length in the king oyster mushroom container was smaller in the analyzed boundary and disposed more in the direction of larger diameter and shorter length in comparison to that of spinach. As a rough and simple view, any tube dimension of \(1.3\sim2\ cm\) in diameter and \(0.2\sim1\ cm\) in length seems OK to attain a beneficial MA condition close to optimum \((O_2 2\sim5%/CO_2 10\sim15\%)\).

Even though the control regime of the sensor-controlled MA container system can maintain the desired MA condition inside the container, it is valid only under the adequate dimension of gas diffusion tube. Thus the domain for the adequate

<table>
<thead>
<tr>
<th>Diameter (cm)</th>
<th>0.1</th>
<th>0.2</th>
<th>0.3</th>
<th>0.5</th>
<th>0.7</th>
<th>0.9</th>
<th>1</th>
<th>1.3</th>
<th>1.5</th>
<th>1.7</th>
<th>2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length (cm)</td>
<td>0.2</td>
<td>0.5</td>
<td>0.7</td>
<td>0.9</td>
<td>1</td>
<td>3</td>
<td>4</td>
<td>5.5</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Fig. 4. Adequate range of tube dimension capable of maintaining beneficial MA close to the optimum \((O_2 2\sim5%/CO_2 10\sim15\%)\) for king oyster mushroom. Shaded area represents the adequate combination of tube diameter and length, while the other white one is non-adequate combination.
dimensions needs to be figured out for any specific system of commodity, fill weight and container volume. The approach used in this study may be applied to the different systems for effective container design. General picture on affordable tube dimension depending on the commodity and pack conditions may be constructed from further study applying many different variables. It also needs to be mentioned that this kind of control is more adoptable for large size container than for small package.

Conclusions

Even though the real-time control of opening/closing of the gas diffusion tube in response to the measured $O_2$ and $CO_2$ concentrations can create and maintain the desired MA in the produce container, achievement of the desired MA condition is found to be possible only under adequate ranges of the diffusion tube dimension. Adequate dimensions need to be determined in consideration of the produce respiration characteristics and container conditions.

Acknowledgements

This study was supported by the R&D Convergence Center Support Program of the Ministry of Agriculture, Food and Rural Affairs, Korea (Project #710003).

References