Mathematical modelling and computational analysis of mass transport in perforation-mediated modified atmosphere packaging of strawberries

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ABSTRACT
A space- and time dependent mathematical model was developed to predict O\textsubscript{2}, CO\textsubscript{2}, N\textsubscript{2} and H\textsubscript{2}O concentration in perforation-mediated polymeric packages during cold-storage of strawberries. The numerical solution of the corresponding mathematical model was obtained by applying the finite element method. The problem was solved in a domain comprising the headspace of a package augmented by the total void spaces of the contained bulk produce and for realistic boundary conditions. Transport of O\textsubscript{2}, CO\textsubscript{2}, N\textsubscript{2} and H\textsubscript{2}O was modelled based on Maxwell-Stefan equations for gas transport through packaging’s headspace and on Fick’s law for diffusion through micro-perforated packaging. The model predictions were tested against published experimental data of O\textsubscript{2}, CO\textsubscript{2}, N\textsubscript{2} and H\textsubscript{2}O concentrations during modified atmosphere packaging storage of strawberries. Further investigation showed that the tested micro-perforated polypropylene packaging and the adopted storage conditions were inadequate to achieve the recommended gases concentrations for strawberry storage. The theoretical findings are suggestive of improvements, in terms of material properties, regarding the selective film permeability.

Keywords: Modified atmosphere packaging (MAP); strawberries; mathematical modelling; finite element method; Maxwell-Stefan equations.

INTRODUCTION
Modified atmosphere packaging (MAP) is a technique of modifying the in-package atmosphere using polymeric films with or without perforations to reduce quality deterioration and improve shelf life of the packaged produce. In passive MAP, the in-package gas concentration is reached through respiratory activity of the packaged produce and in turn reduces the metabolic activity and water loss of the packaged produce, as well as microorganism growth [1]. The permeability of the MAP depends on the packaging type, its area and thickness. Commonly used MAP films are low density polyethylene (LDPE), polyvinyl chloride (PVC), polypropylene (PP), polystyrene (PS), saran (PVDC) and polyester (PET) [2]. The selectivity (the ratio of CO\textsubscript{2} and O\textsubscript{2} permeabilities) of this group of films is close to 3.0; this is inadequate to achieve the recommended O\textsubscript{2}/CO\textsubscript{2} concentrations when used with highly respired produce, unless micro-/macro-perforations are present [2, 3]. For the design of a MAP, produce mass/surface ratio and package dimensions and permeability should be considered. Significant design parameters are also the time required for reaching gas equilibrium, the in-package relative humidity and the storage conditions. Respiration is a metabolic process in which O\textsubscript{2} from the air is absorbed in the living tissues and with the existing organic molecules (mainly sugars) leads to the production of intermediate products, CO\textsubscript{2}, H\textsubscript{2}O and energy. Respiration modelling is complicated due to the large number of the involved variables such as storage temperature, availability and type of consumed substrates, gas concentrations and ripening stage. The gas concentration dependent respiration rate models are based on empirical equations, enzyme kinetics or adsorption theories [4]. Storage temperature strongly affects respiration and this dependence is described with Arrhenius type equations. Transpiration is the transport process of water vapor from the tissues to the surrounding air through skin cells, lentils and stomata [5]. Although Fick’s law can describe gas transport within the package and through packaging perforations, a more efficient model for multicomponent gas systems is Maxwell-Stefan equation. Heat transport through packaging can be assumed negligible in a single package stored in controlled air conditions. Moreover, temperature fluctuations during transportation and storage are ignored because they are small and temporary and, in addition, they would increase, if accounted for, the model complexity with negligible improvement of its predictive capability [3]. Renault et al. [6] developed a finite difference model for in-package gas prediction using Maxwell-Stefan equation and Fickian diffusion through micro-perforations, in which transport resistance at micro-perforations ends was neglected. Improving the previous
model, Lee and Renault [7] increased perforations length by 10% of its diameter. Paul and Clarke [8] calculated the theoretical length of a micro-perforation as the sum of its length augmented by the \(7/6\) of its diameter. Rennie and Tavoularis [9] presented a mass transport model in a cylindrical packaging with one perforation and found that the in-package convective mass transport was less than 4% of the diffusive and the most important mass transport mechanisms were respiration and transpiration. The main objective of the present work is the development of an efficient space-and-time dependent model for perforation-mediated MAP considering the most important mass transport mechanisms (respiration, transpiration and diffusive transport of \(O_2\), \(CO_2\), \(N_2\) and \(H_2O\)) in micro-perforated packages. The model consists of partial differential equations that are solved numerically with the finite element method and the results are compared with published experimental data [6]. Simulations are carried out at 5 °C and the mass transport mechanisms are analysed for different combinations of micro-perforations (in number and diameter) with the goal to achieve gas concentrations close to the recommended ones [6].

**MATHEMATICAL MODELLING AND COMPUTATIONAL ANALYSIS**

**Model assumptions**
- \(O_2\) consumption and \(CO_2\) production due to respiration depend on the \(O_2\) and \(CO_2\) partial pressures through a \textit{Michaëlis-Menten} type of model.
- \(CO_2\) production is a combined oxidative and fermentative process; the oxidative contribution is proportional to the \(O_2\) consumption and the fermentative follows a \textit{Michaëlis-Menten} type of model.
- \(O_2\) consumption and \(CO_2\) production are temperature dependent following an \textit{Arrhenius law}.
- \(O_2\), \(CO_2\), \(H_2O\) and \(N_2\) are exchanged between headspace and packaging surroundings through the packaging film and its micro-perforations.
- Packaged produce has uniform porosity and bulk density and consists of spherical elements of uniform diameter \(d_c\).
- Package walls are impermeable to \(O_2\), \(CO_2\), \(H_2O\) and \(N_2\).
- Packaged produce and the in-package gases are in thermal equilibrium.

**Respiration model**
The respiration model involves the partial pressures \(P_{O_2}\), \(P_{CO_2}\) (Pa) and the storage temperature \(T\) (K). The \(O_2\) consumption rate, \(RR_{O_2}\) (mol kg\(^{-1}\) h\(^{-1}\)), is calculated from an enzyme kinetics model with uncompetitive type \(CO_2\) inhibition; it is given by:

\[
RR_{O_2} = \frac{P_{O_2}}{Km_{O_2} + P_{O_2} \left(1 + P_{CO_2} / Km_{CO_2} \right)} \left[ Vm_{O_2,ref} \exp \left( - \frac{Ea_{VmO_2}}{R \left(1/T - 1/T_{ref} \right)} \right) \right] \tag{1}
\]

The maximum specific respiration rate of \(O_2\) is evaluated at a reference temperature \(T_{ref} = 283\) K and depends on \(T\) with an \textit{Arrhenius} type equation – cf. inside the brackets of Eq. 1 [10]. \(Km_{CO_2}\) and \(Km_{O_2}\) (kPa) are \textit{Michaëlis-Menten} constants, \(Vm_{O_2,ref}\) (mol kg\(^{-1}\) h\(^{-1}\)) is the maximum specific consumption rate of \(O_2\) at \(T_{ref}\), \(Ea_{VmO_2}\) (J mol\(^{-1}\)) is an activation energy and \(R\) (J mol\(^{-1}\) K\(^{-1}\)) is the ideal gas constant – cf. Table 1.

The \(CO_2\) production rate, \(RR_{CO_2}\) (mol kg\(^{-1}\) h\(^{-1}\)), is a combination of oxidative and fermentative processes and follows an \textit{Arrhenius law} in temperature dependence:

\[
RR_{CO_2} = RQ_{ox} RR_{O_2} + \frac{1}{1 + \frac{P_{O_2}}{Km_{O_2}(T)}} \left[ Vm_{CO_2,ref} \exp \left( - \frac{Ea_{VmCO_2}}{R \left(1/T - 1/T_{ref} \right)} \right) \right] \tag{2}
\]

where \(RQ_{ox}\) is the respiratory quotient (ratio of \(CO_2\) production and \(O_2\) consumption for oxidative respiration), \(Km_{O_2}(T)\) (kPa) is a \textit{Michaëlis-Menten} constant related to the inhibition of the fermentative metabolism due to the \(O_2\) presence, \(Vm_{CO_2,ref}\) (mol kg\(^{-1}\) h\(^{-1}\)) is the maximum specific production rate of \(CO_2\) at \(T_{ref}\) and \(Ea_{VmCO_2}\) (J mol\(^{-1}\)) is an activation energy.

The produce surface area \(A_c\) (m\(^2\)) is calculated assuming that the product is uniformly packed:

\[
A_c = \frac{6(\alpha \cdot \phi) \sqrt{\pi}}{\varepsilon} \tag{3}
\]

where \(V_p\) (m\(^3\)) and \(\varepsilon\) are the volume and porosity of the bulk produce, respectively. The quantities \(P_{O_2}\), \(P_{CO_2}\), \(RR_{CO_2}\) and \(RR_{O_2}\) in Eqs. 1 and 2 are calculated in every time step (see below) and the rest of the variables are taken from Table 1.
**Transpiration model**

Transpiration is driven by the water vapor deficit, VPD (Pa), between produce surface and its surroundings.

\[ VPD = (a_w - RH) \left( 0.047T^3 - 32.43T^2 + 8.567T - 757.07 \right) \]  

(4)

The water activity, \( a_w \), of the packaged produce is taken as 0.99 due to dissolved substrates [5]. Transpiration sets in when the water vapor pressure at the produce surface exceeds that in the headspace, i.e. when \( a_w \) is higher than the relative humidity (RH); otherwise it is taken zero. The water vapor flux \( \dot{m}_w \) (kg\(_{H_2O}\) m\(^{-2}\) h\(^{-1}\)), is given by

\[ \dot{m}_w = VPD \left( K_s + K_a \right)^{-1} \]  

(5)

where \( \left( K_s + K_a \right)^{-1} \) (kg m\(^{-2}\) s\(^{-1}\) Pa\(^{-1}\)) is the transpiration coefficient, \( K_s \) (kg m\(^{-2}\) s\(^{-1}\) Pa\(^{-1}\)) the skin mass transport coefficient [11,12] – cf. Table 1 and \( K_a \) (kg m\(^{-2}\) s\(^{-1}\) Pa\(^{-1}\)) the air-film mass transport coefficient, calculated from a Sherwood-Reynolds-Schmidt correlation [5]. Considering negligible flow around the packaged produce, \( K_a \) is estimated by

\[ K_a = 2D_v/R \]  

(6)

where \( M_{H_2O} \) (kg mol\(^{-1}\)) is the water molecular weight and \( D_v = 9.1 \times 10^{-5}T^{1/2}/T + 245.18 \) (m\(^2\) h\(^{-1}\)) the diffusion coefficient of water in air [5]. The quantities VPD and \( \dot{m}_w \) from Eqs. 4 and 5 are calculated in every time step and the rest of the variables are taken from Table 1.

**Modeling of O\(_2\), CO\(_2\), H\(_2\)O and N\(_2\) transport in the headspace**

The gas component mass fractions \( \omega_i \) (i = O\(_2\), CO\(_2\), N\(_2\) and H\(_2\)O) in the headspace are calculated by means of the Maxwell-Stefan diffusion formulation [13]. Only gas diffusion is considered, since inclusion of natural convection transport only marginally improves the theoretical prediction [9]. The governing transport equations read:

\[ \frac{\partial \omega_i}{\partial t} + \nabla \cdot \left[ -\rho \omega_i \sum_{j=1}^{n} D_{ij} \left( \nabla x_j + \left( x_j - \omega_j \right) \frac{\nabla P}{P} \right) \right] = 0 \]  

(7)

where \( \rho \) (kg m\(^{-3}\)) is the gas mixture (O\(_2\), CO\(_2\), N\(_2\) and H\(_2\)O) density, provided by:

\[ \rho = \frac{P}{RT} \sum_{j=1}^{4} x_j M_j \]  

(8)

In Eqs. 7 and 8, \( t \) (h) is the storage time, \( D_{ij} \) (m\(^2\) h\(^{-1}\)) is the multicomponent Fick diffusivity matrix, \( x_j \) is the mole fraction of component \( j = O_2, CO_2 \) and H\(_2\)O and \( P \) (Pa) is the total gas mixture pressure. The mass fraction of N\(_2\) is calculated from the balance of the gas components mass fractions, \( \omega_{N_2} = 1 - \omega_{O_2} - \omega_{CO_2} - \omega_{H_2O} \). In this study CO\(_2\) solubility is considered negligible. Estimation of the \( D_{ij} \) coefficients is based on Chapman-Enskog analysis [13]. \( M_i \) (kg mol\(^{-1}\)) is the molecular weight of the component \( i \). For the initial (\( t = 0 \)) in-package conditions, \( T = 10^\circ C, P = 1 \) atm and RH\(_0\) = 50%, the model is fed with the following initial values: \( \omega_{O_2} = 76.46\%, \omega_{CO_2} = 23.11\%, \omega_{CO_2} = 0.05\%, \omega_{H2O} = 0.38\%, D_{O2,CO2} = 13.69\times10^{-6} \text{ m}^2 \text{ s}^{-1}, D_{O2,H2O} = 18.82\times10^{-6} \text{ m}^2 \text{ s}^{-1}, D_{CO2,CO2} = 18.52\times10^{-6} \text{ m}^2 \text{ s}^{-1}, D_{CO2,H2O} = 13.25\times10^{-6} \text{ m}^2 \text{ s}^{-1}, D_{CO2,N2} = 13.68\times10^{-6} \text{ m}^2 \text{ s}^{-1} \) and \( D_{H2O,N2} = 18.48\times10^{-6} \text{ m}^2 \text{ s}^{-1} \). At every time step, the quantities \( \rho, \omega_i, D_{ij}, x_j, P, \) in Eqs. 7 and 8 are calculated.

**Boundary conditions**

The partial differential equations (Eqs. 7) are solved in the two-dimensional domain corresponding to a rectangular headspace of a MAP of width \( d_{pac} \) (m) and height \( h_{pac} \) \( = \left[ V_p - (1 - \varepsilon) m_b / \rho_b \right]/A_i \); \( A_i \) (m\(^2\)) is the area of the permeable film, \( m_b \) (kg) is the bulk produce mass, \( V_p \) (m\(^3\)) is the packaging volume and \( \rho_b \) (kg m\(^{-3}\)) is the bulk density of the bulk produce, all tabulated in Table 1. As already mentioned, the packaging walls are considered impermeable to gases. The bottom boundary conditions include the water vapor production flux, \( \dot{m}_w \) (cf. Eq. 5) and the gas component \( i = O_2, CO_2 \) consumption and production fluxes, \( \text{resp}_i \) (kg\(_{CO2}\) m\(^{-2}\) h\(^{-1}\)):

\[ \text{resp}_i = RR_i M_i \rho_b A_i \]  

(9)
where RR<sub>i</sub> is calculated from Eqs. 1, 2 and A<sub>c</sub> from Eq. 3. The top boundary conditions include the gas component i = O<sub>2</sub>, CO<sub>2</sub>, H<sub>2</sub>O transport through micro-perforated packaging film:

\[
m_{\text{total}} \left[ \frac{(K_i l)}{l} \right] \rho_i + \left( n \sum f_{\text{area}} \right) \left[ \frac{l_i A_f (R/M_i) T}{l} \right] \left[ \frac{x_{iA}}{P_a - \omega_i (R/M_i) \rho T} \right] \quad (10)
\]

\[
\rho_i = x_i \rho \left( \frac{M_i}{\sum x_i M_i} \right) \quad (11)
\]

where \( m_{\text{total}} \) (kg m<sup>-2</sup> h<sup>-1</sup>) is the total flux (from film and micro-perforations) of i = O<sub>2</sub>, CO<sub>2</sub>, H<sub>2</sub>O, \( K_i l \) (m m<sup>-1</sup> Pa<sup>-1</sup>) is the permeability of the packaging film in component i and \( l_i \) (m) is the thickness of the packaging film, cf. Table 1; \( \rho_i \) (kg m<sup>-3</sup>) is the density of component i, \( x_{iA} \) is the initial mole fraction of i = O<sub>2</sub>, CO<sub>2</sub>, N<sub>2</sub>, H<sub>2</sub>O gas component in the headspace; \( x_{o|O_2} = 0.21; x_{o|CO_2} = 0.00033; x_{o|N_2} = 0.78 \) and \( x_{o|H_2O} = 0.0061 \).

\( M_i \) (kg mol<sup>-1</sup>) is the molecular weight of the component i, \( n \) is the number of packaging micro-perforations, \( S_p \) (m<sup>2</sup>) is the area of a cylindrical micro-perforation of diameter \( d_p \) (m<sup>2</sup>) and \( l_f \) (m) is the thickness of the packaging film, – cf. Table 1; \( D_{\text{H}_2O/\text{air}} = 18.77 \times 10^{-6} \text{ m}^2 \text{s}^{-1}; D_{\text{O}_2/\text{air}} = 18.70 \times 10^{-6} \text{ m}^2 \text{s}^{-1}; D_{\text{CO}_2/\text{air}} = 13.80 \times 10^{-6} \text{ m}^2 \text{s}^{-1} \). The \( m_{\text{total}} \) is calculated from Eq. 10 at each time step, since the in-package partial pressure of component i = O<sub>2</sub>, CO<sub>2</sub>, H<sub>2</sub>O transport through micro-perforated packaging film:

Numerical solution procedure

The set of the governing equations along with their boundary and initial conditions was discretized numerically by the finite element method using Comsol Multiphysics v.3.4 [14]. The mesh was unstructured and composed of triangular elements and Lagrange quadratic shape functions were used. The resulting linearised equation system was solved by the generalized minimal residual method (GMRES) with the incomplete LU-factorization as preconditioner [15]. Mesh-independence of the solutions was established by solving in three different meshes composed of 60, 240 and 960 elements. The results reported here were obtained with a mesh of 240 elements. The selected maximum time step was 3,600s s.

RESULTS & DISCUSSION

The case studied here was so chosen as to enable comparison of model predictions with the experimental data in [6] for strawberries stored at 10 °C in a polypropylene MAP. The parameter values used in the model are summarized in Table1.

Table 1. Properties of packaged produce, package dimensions, and storage conditions used in the model

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>( d_p )</td>
<td>0.03 m</td>
<td>[9]</td>
</tr>
<tr>
<td>( d_f )</td>
<td>0.27 m</td>
<td>[9]</td>
</tr>
<tr>
<td>( K_{\text{H}_2O} )</td>
<td>48.96 × 10&lt;sup&gt;-6&lt;/sup&gt; m&lt;sup&gt;2&lt;/sup&gt; h&lt;sup&gt;-1&lt;/sup&gt; Pa&lt;sup&gt;-1&lt;/sup&gt;</td>
<td>[11]</td>
</tr>
<tr>
<td>( \rho_i )</td>
<td>200 kg m&lt;sup&gt;-3&lt;/sup&gt;</td>
<td>[9]</td>
</tr>
<tr>
<td>( x_{o</td>
<td>O_2} )</td>
<td>0.21</td>
</tr>
<tr>
<td>( x_{o</td>
<td>CO_2} )</td>
<td>0.00033</td>
</tr>
<tr>
<td>( x_{o</td>
<td>N_2} )</td>
<td>0.78</td>
</tr>
<tr>
<td>( x_{o</td>
<td>H_2O} )</td>
<td>0.0061</td>
</tr>
<tr>
<td>( A_f )</td>
<td>3.1 m&lt;sup&gt;2&lt;/sup&gt;</td>
<td>[6]</td>
</tr>
<tr>
<td>( l_f )</td>
<td>50 × 10&lt;sup&gt;-6&lt;/sup&gt; m</td>
<td>[6]</td>
</tr>
<tr>
<td>( K_{\text{H}_2O} )</td>
<td>4.5 × 10&lt;sup&gt;-10&lt;/sup&gt; m&lt;sup&gt;2&lt;/sup&gt; h&lt;sup&gt;-1&lt;/sup&gt; Pa&lt;sup&gt;-1&lt;/sup&gt;</td>
<td>Assumed</td>
</tr>
<tr>
<td>( V_p )</td>
<td>0.0015 m&lt;sup&gt;3&lt;/sup&gt;</td>
<td>[6]</td>
</tr>
<tr>
<td>( K_{\text{O}_2} )</td>
<td>8.5 × 10&lt;sup&gt;-10&lt;/sup&gt; m&lt;sup&gt;2&lt;/sup&gt; h&lt;sup&gt;-1&lt;/sup&gt; Pa&lt;sup&gt;-1&lt;/sup&gt;</td>
<td>[6]</td>
</tr>
<tr>
<td>( K_{\text{CO}_2} )</td>
<td>2.8 × 10&lt;sup&gt;-10&lt;/sup&gt; m&lt;sup&gt;2&lt;/sup&gt; h&lt;sup&gt;-1&lt;/sup&gt; Pa&lt;sup&gt;-1&lt;/sup&gt;</td>
<td>[6]</td>
</tr>
<tr>
<td>( V_a )</td>
<td>5.1 × 10&lt;sup&gt;-3&lt;/sup&gt; m&lt;sup&gt;3&lt;/sup&gt;</td>
<td>Assumed</td>
</tr>
<tr>
<td>( h_{\text{pack}} )</td>
<td>0.009 m</td>
<td>Assumed</td>
</tr>
</tbody>
</table>

\( d_p \) | 80 × 10<sup>4</sup> m | [6] |
| \( R_{\text{H}_2} \) | 0.5 | Assumed |
| \( E_{\text{A}_{\text{vin}, \text{CO}_2}} \) | 64 kJ mol<sup>-1</sup> | [10] |
| \( E_{\text{A}_{\text{vin}, \text{O}_2}} \) | 64 kJ mol<sup>-1</sup> | [10] |
| \( V_{\text{O}_2, \text{air}} \) | 242 nmol kg<sup>-1</sup> s<sup>-1</sup> | [10] |
| \( V_{\text{CO}_2, \text{air}} \) | 175 nmol kg<sup>-1</sup> s<sup>-1</sup> | [10] |
| \( T_{\text{ref}} \) | 10 °C | [10] |
| \( R_{\text{Q}_{\text{H}_2}} \) | 0.70 | [10] |
| \( K_{\text{O}_2} \) | 1.2 kPa | [10] |
| \( K_{\text{CO}_2} \) | 51 kPa | [10] |
| \( K_{\text{H}_2O} \) | 0.14 kPa | [10] |
| \( R \) | 0.314 J mol<sup>-1</sup> K<sup>-1</sup> | [13] |
| \( d_{\text{pack}} \) | 0.12 m | Assumed |

The estimated root mean square error between predictions and experimental data for CO<sub>2</sub> and O<sub>2</sub> mass ratio ranged between 1.0 - 2.2%. The selectivity of the non-perforated polypropylene MAP is 3.3 and CO<sub>2</sub> accumulation and O<sub>2</sub> exhaustion, shown in Fig. 1, occurred inducing anaerobiosis after 38 h of storage. The fermentative metabolism [10] increased CO<sub>2</sub> production (Fig. 1) before it reached an equilibrium value (1.0 × 10<sup>4</sup> - 1.2 × 10<sup>4</sup> kg m<sup>-2</sup> h<sup>-1</sup>) while the O<sub>2</sub> consumption became zero. Exama et al. [3] suggested the following MAP conditions for strawberries: 0-5 °C, 10% O<sub>2</sub> and 15-20% CO<sub>2</sub>. Based on these, simulations
were carried out at 5 °C, for two values of polypropylene thickness, namely 30 and 60 μm, for five values of micro-perforation diameter, 30, 40, 50, 60 and 70 μm and for various micro-perforation numbers ranging from 0 up to 10. It was found that the closest to the recommended by Exama et al. [3] O2 and CO2 combination was 8.5% and 9.8% respectively, and it was achieved with a packaging 30 μm thick, with 7 micro-perforations of 60 μm diameter each. The total micro-perforations area, assuming them as cylindrical, was 1.98×10⁻⁸ m² and the calculated selectivity values were Sf = 3.38 without micro-perforations and St = 0.74 with micro-perforations. The recommended O2 and CO2 concentrations could not be achieved with the previous packaging configuration. Exama et al. [3] mention that a packaging selectivity close to 1.1 is required for reaching the recommended O2 and CO2 concentrations, a value higher than the one estimated here (0.74). Based on Eq. 10, the O2 and CO2 contribution to the overall gas flux through the micro-perforated packaging was quantified using the previous MAP case.

![Figure 1](image1.png)

**Figure 1.** Respiratory (O2 and CO2) fluxes for 0, 5, 10 and 20 micro-perforations.

![Figure 2](image2.png)

**Figure 2.** Respiratory flux through micro-perforations and film (left) and the % mass flux (right).

In Figure 2 are shown the O2 influx (positive value) and CO2 efflux (negative value). It can be seen that the largest gas exchange is taking place through the packaging micro-perforations, as expected. In particular, for
O₂ exchange, 7.5% is taking place through the non-perforated part of the packaging and 92.5% through packaging micro-perforations. For CO₂, 20.6% through the non-perforated part and 79.4% through micro-perforations and for water, 3.2% through the non-perforated and 96.8% through micro-perforations. Among the three gas components, CO₂ transport through the non-perforated part of the packaging is comparable with the transport through the packaging micro-perforations (20.6% against 79.4%). This calls for further investigation with regard to the mechanical or chemical modification of the material properties so as to enhance accumulation of CO₂ in the packaging, which is desirable in most of the MAP cases.

**CONCLUSIONS**

A mathematical model was developed for the prediction of O₂, CO₂, H₂O (and N₂) transport in perforation-mediated polymeric packages during MAP of strawberries. The model equations were discretized and solved with the finite element method. The comparison of the model predictions with published experimental data is satisfactory – the discrepancy was between 1.0 and 2.2%. The computations showed that with the polypropylene micro-perforated packaging the recommended in the literature gas concentrations could not be reached, even at 5°C. The predictions suggest as most advantageous packaging choice the one with 30 μm thickness and 7 micro-perforations of 60 μm diameter each; the in-package atmosphere reached had 8.5% O₂ and 9.8% CO₂. In this particular case, the ratio of the exchanged CO₂ through the non-perforated part of the polymeric packaging and that exchanged through the packaging micro-perforations is approximately 1/4, while for the other gas components is about 1/9.

**REFERENCES**


