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Modelling the effect of gas composition on the gas exchange rate in Perforation-Mediated Modified Atmosphere Packaging

Julio C. Montanez [a,1], Fernanda A.S. Rodríguez [a], Pramod V. Mahajan [a,*], Jesús M. Frías [b]

[a] Department of Process and Chemical Engineering, University College Cork, Ireland
[b] School of Food Science and Environmental Health, Dublin Institute of Technology, Dublin, Ireland

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ABSTRACT

Modified Atmosphere Packaging (MAP) relies on modification of the atmosphere inside a package, achieved by the natural interplay between the respiration of the product and the transfer of gases through the package. Polymeric films are the most usual packaging material but because of the increase in the consumption of fresh-cut products with a higher respiration rate and higher tolerance to CO_2, alternative materials are being investigated. The perforation-mediated package is one of those alternatives, where the regulation of the gas exchange is achieved by single or multiple tubes that perforate an otherwise impermeable packaging material. From an engineering point of view, the transport of gases through perforations is a complex phenomenon that involves diffusion gradients together with co-current transport of multiple species, with oxygen entering the package and carbon dioxide leaving it. The influence of one species transport in the other has not been studied so far. The objective of this work was to analyse the effect of initial concentration of CO_2 on the effective mass transfer coefficients of O_2 (K_{O_2}) and CO_2 (K_{CO_2}) in perforation-mediated MAP. K_{O_2} ranged from $(6.99 \pm 0.05) \times 10^{-8}$ ($m^3\ s^{-1}$) to $(28.50 \pm 0.01) \times 10^{-8}$ ($m^3\ s^{-1}$) and for K_{CO_2} from $(6.45 \pm 0.04) \times 10^{-8}$ ($m^3\ s^{-1}$) to $(28.32 \pm 0.01) \times 10^{-8}$ ($m^3\ s^{-1}$). On average K_{O_2} decreased by approximately 15% with an increase of CO_2 initial concentration from 25% to 100%. K_{CO_2} was insensitive to the composition of the gas mix. The permeability ratio (β) varied from 0.73 ± 0.01 to 1.34 ± 0.01. A mathematical model considering the co-current effect of CO_2 flux on the gas exchange rate for O_2 was developed. These results suggest that there is a significant drag effect in the gas exchange process that should be taken into consideration when designing perforation-mediated MAP.

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1. Introduction

Quality of fresh horticultural products can be preserved by different measures such as harvesting at optimum maturity, minimising mechanical injuries, proper sanitization and optimal storage conditions of temperature and gas composition of the environment in contact with the produce in terms of O_2, CO_2 and H_2O (Zagory and Kader, 1988). Today, the demand for fresh, convenient and nutritional fresh produce has led to extensive research on packaging design in order to arrive to the consumer preserving its fresh attributes. Modified Atmosphere Packaging (MAP) is a postharvest technology widely used to increase and preserve the shelf life of fresh products, improve the product image and reduce waste (Martinez-Ferrer et al., 2002). Modification of the internal atmosphere in packages containing respiring products can be achieved artificially (active modification) or passively owing to two simultaneous mechanisms, namely the respiration rate of the product (O_2 uptake and CO_2 production) and the permeability of the package film to gases due to gradients generated by the respiration between the internal atmosphere of the package and the storage environment (O_2 entering the package and CO_2 leaving).

The storage of fresh products in MAP aims to reach optimal recommended O_2 and CO_2 levels in the package in order to decrease the metabolic activity of the product, increasing therefore the shelf life (Talasila et al., 1995). However, some factors may affect the equilibrium gas composition in the package, among them (i) product-related characteristics such as respiration rate and (ii) package related properties such as barrier properties to O_2 and CO_2. Traditionally, the barrier being used to keep the balance between respiration and permeation through the package are permeable polymeric films, but these materials have some disadvantages because of their structure and permeation characteristics (Fonseca et al., 2000; Mahajan et al., 2008). Perforation-Mediated Modified Atmosphere Packaging (PM-MAP) is an alternative system to conventional MAP using polymeric films to control the gas exchange rates during the storage of fresh products (Emond and Chau, 1990; Mahajan et al., 2008; Fonseca et al., 2000; Lee and Renault,

* Corresponding author. Tel.: +353 21 490 2501; fax: +353 21 427 0249.
E-mail address: p.mahajan@ucc.ie (P.V. Mahajan).
[1] Present address: Department of Chemical Engineering, Autonomous University of Coahuila. Saltillo, Coahuila, Mexico.

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Nomenclature

a	parameter from the Eqs. 2, 3, 4, 7, and (8) ($m^3\ s^{-1}$)
b	parameter from the Eqs. 2, 3, 4, 7, and (8) (dimensionless)
c	parameter from the Eqs. 2, 3, 4, 7, and (8) (dimensionless)
D	tube diameter (m)
K	mass transfer coefficient ($m^3\ s^{-1}$)
L	tube length (m)
t	time (s)
V	package volume (m^3)
y	volumetric concentration (% v/v)
Greek symbols	
α	model constant (Eq. (5)) (m^3)
β	permeability ratio (dimensionless)
Superscripts	
e	surrounding volumetric concentration (% v/v)
exp	experimental volumetric concentration (% v/v)
i	initial volumetric concentration (% v/v)
pred	predicted volumetric concentration by the model (% v/v)
Subscripts	
p	permeability
O_2	oxygen
CO_2	carbon dioxide

1998; Riad et al., 2002). PM-MAP consists of macro perforations or tubes inserted in an otherwise impermeable rigid container and offers advantages for bulk packaging. It is also a good solution for packing high-respiring products, due to the high gas exchange rates and low permeability coefficients achieved.

PM-MAP has been applied for the storage of several products such as leeks (Baugerod, 1980), strawberries and broccoli (Emond et al., 1991), shipped mixed load of strawberry and snap beans (Silva, 1995), spinach (Chimphango, 1996), broccoli (Ramachandra, 1995), cauliflower (Ratti et al., 1998), cut onion (Lee and Renault, 1998), bananas (Williams et al., 2001; Stewart et al., 2005), shredded Galega kale (Fonseca et al., 1999), sweet corn (Riad et al., 2002). Until now, PM-MAP has been basically applied for whole fresh produce having high respiration rate, and studies assessing the application of this technology in the storage of minimally processed products are scarce. These studies demonstrated how to reach the optimal equilibrium gas composition recommended for the products, showing the applicability of this technology for the storage of products with high metabolic activity that cannot be packed in polymeric films. More research in order to assess the applicability of this technology in different minimally processed fruits and vegetables is needed due the increase on sales of these products and the limitations of the polymeric films to pack products with a high respiration rate (Fonseca et al., 2000). However, the implementation of PM-MAP packages is not straightforward and more studies on the impact of the variables involved in PM-MAP (storage temperature, internal gas composition, package configuration, package orientation, etc.) need to be developed. Several mathematical models have been used in PM-MAP to predict the gas exchange rate of O_2 and CO_2 during the storage of fresh produce (Emond and Chau, 1990; Silva, 1995; Lee and Renault, 1998; Ratti et al., 1998; Fonseca, 2001). The dynamics of gas composition depend on the number of tubes and the cross sectional area and length of each tube. Some models have been developed to quantify these effects on the gas exchange rate (Emond et al., 1991; Silva, 1995; Ratti et al., 1998; Fonseca et al., 2000; Paul and Clarke, 2002; Rennie and Tavoularis, 2009a,b). Emond et al. (1991), Silva (1995) and Fonseca et al. (2000) assumed that the gas exchange rate through the perforation between the environment and the package could be described according to a lumped-capacity model:

$$y_{O_2,CO_2} = y^e_{O_2,CO_2} + (y^i_{O_2,CO_2} - y^e_{O_2,CO_2}) \times e^{-\frac{K_{O_2,CO_2}}{V_p}t} \quad (1)$$

where y is the volumetric gas concentration (% v/v) of O_2 or CO_2 at time t (s), K is the mass transfer coefficient ($m^3\ s^{-1}$) of the gas being studied, V_p is the package volume (m^3) and the superscripts i and e refer to the initial and environmental gas composition, respectively.

Emond et al. (1991) developed an empirical model with 10 parameters that allows to predict the mass transfer coefficients for O_2 (K_{O_2}) and CO_2 (K_{CO_2}) as a function of tube dimensions (diameter and length) and storage temperature. Silva (1995) developed a similar mathematical model with a smaller number of parameters (8), but did not observe a significant temperature effect on K_{O_2} and K_{CO_2}. Ratti et al. (1998) developed a convection–diffusion approach to predict the effective length of the diffusion channel necessary to keep the optimal gas composition of O_2 and CO_2 inside the package during the storage of fresh cauliflower. Fonseca et al. (2000) developed a multiplicative model with three parameters to predict K_{O_2} and K_{CO_2} as a function of diameter and length of the tube. Later, this model was modified (Fonseca, 2001) to include the tube porosity with the objective of decreasing K_{O_2} and K_{CO_2} by designing perforations with a bed of particles. These results showed that PM-MAP systems are indeed a potential alternative for products that cannot be packed in films, but there is still much to be studied about these systems to ensure that adequate gas composition conditions are achieved and maintained throughout storage. One of the common practices in MAP is to "flush" the package with an gas whose composition is close to the optimal recommended atmosphere for the produce. No previous studies have been found to verify the effect of the initial gas composition on K_{O_2} and K_{CO_2}, and no considerations on the influence concurrent transport conditions have been made. Those factors can greatly influence the transport of gases and influence the efficiency of an optimal package design.

The objectives of this work were: (i) analyse the effect of the initial concentration of CO_2 on the effective mass transfer coefficients of O_2 (K_{O_2}) and CO_2 (K_{CO_2}) in PM-MAP, and (ii) develop a mathematical model relating the effect of initial concentration of CO_2 on the mass transfer coefficients K_{O_2} and K_{CO_2}.

2. Materials and methods

2.1. Experimental procedure

PVC tubes with different dimensions (Table 1) were inserted half inside half outside across tinplate twist-off lids fitted with stoppers for gas sampling and semi-rigid tubes to feed a gas mixture. Cylindrical glass jars (1.9 dm^3) having approximate height and diameter of 18.3 and 11.5 cm, respectively were flushed with different gas composition of CO_2 (Table 1) and were stored in a controlled temperature room. The temperature of the room was maintained within 1 °C of the set value (20 °C).

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