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Analysis of the effect of perforation on the permeability of biodegradable non-barrier films

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Abstract

Perforated plastic films are used in Equilibrium Modified Atmosphere Packaging (EMAP) of fresh produce such as fruits and vegetables. The most common material used in such applications is the oriented polypropylene (OPP), which has low permeability with respect to relevant gases, namely water vapor (WV), CO_2, and O_2. Therefore, the synthesis of the in-package atmosphere is regulated only by the size and number of perforated holes. The replacement of the OPP films with biodegradable ones made of polylactic acid (PLA) or starch based polymers for environmental reasons results into difficulties with respect to designing the EMAP system, since these films are more permeable to the relevant gases and in particular to WV. As a result, the effect of micro-perforation is influenced by the permeability of the film. In the present work, the dependence of the gas flux through perforation on the permeability of the film for the same gas was investigated by experimental and numerical methods. It was shown that the effect of perforation decreases as the permeability of the film increases. The diffusive gas flux through perforation becomes independent of the film permeability, if it is about 100 times smaller than the diffusivity of the studied gas in air.

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Keywords: EMAP; biodegradable packaging; micro-perforation

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1. Introduction

The development of thin transparent barrier films offered new possibilities to the food packaging industry. Packing food in a Modified Atmosphere Packaging (MAP) of low concentration of oxygen retards or prevents the oxidation process, which is responsible for the deterioration of the taste and flavor [1]. However, such packaging techniques cannot be applied to fresh produce, since fruits and vegetables are living objects interacting with the surrounding atmosphere through respiration and transpiration. Equilibrium Modified Atmosphere Packaging (EMAP) is a method for prolonging the shelf life of fresh

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produce (i.e. fruits and vegetables) by optimizing the in-package equilibrium atmosphere [1]. This is achieved by modifying the permeability of the packaging film using micro-perforation, in order to optimally regulate the equilibrium concentrations of O_2 and CO_2. The in-package relative humidity (RH) should also be regulated, since it is responsible either for the excessive weight loss or for incidences of fungal spoilage.

Several attempts have been made to model gas transfer through a perforated film for optimizing EMAP. These models focus on the gas transfer through the perforation holes, while the film itself is considered impermeable (barrier film) [2, 3]. Such modeling approaches are based on Fick's law of diffusion [2] or Stefan–Maxwell law [4].The simplest model assumes Fick's diffusion in a cylindrical pore filled with stagnant air simulating the hole. However, an end correction term for the diffusive path length must be introduced to compensate for end effects at the hole mouths [2]. Such phenomenological corrections are not needed when 3D computer simulations are applied for modeling diffusion through a hole. For this reason, a 3D numerical approach was used in the present work.

Environmental concerns recently press towards a change in food packaging materials from conventional oil-based plastics to biodegradable polymers made of sustainable recourses. Various bio-based polymers, such as PLA, or starch based plastics have been tested as packaging materials despite their current high cost. Such new materials have different gas permeability properties than conventional plastics [5]. In particular, their water vapor transmission rate (WVTR) is much higher than the conventional packaging films made of oriented polypropylene (OPP) [5]. When such non-barrier films are used in Equilibrium Modified Atmosphere Packaging (EMAP), the effect of perforation is influenced by the permeability of the film.

The present work is aiming at estimating the excess WVTR due to perforation as a function of the water vapor permeability of the film. The combined effect of perforation and permeability of the film on the synthesis of the EMA is also investigated.

2. Material & Methods

The diffusion of a gas is described by Fick's law which relates the diffusive flux to the concentration field:

$$J = D \ \nabla c \qquad (1)$$

Where J (mol m^{-2} s^{-1}) is the flux density (i.e. gas diffusion) through the film, D (m^2 s^{-1}) is the diffusion coefficient (or diffusivity), and ∇c (□mol□ m^{-4}) is the gas concentration gradient, c being the concentration for ideal mixtures (mol m^{-3}) [6].

In the case of diffusion through a permeable material, its permeability P (g m^{-1} s^{-1}) is defined as:

$$F = P \cdot A \cdot \nabla p \qquad (2)$$

where F (g s^{-1}) is the mass flux, □ ∇p is the mass fraction gradient (percent), and A (m^2) is the area of the film. The mass fraction gradient can also be expressed by the partial pressure difference of the gas (Pa). As a result, permeability is also reported in g m^{-1} s^{-1} Pa^{-1}. Alternatively, if volume flux is considered instead of the mass flux, permeability, P (m^2 s^{-1} Pa^{-1}), refers to the amount of gas, by volume, which penetrates unit thickness and area of the material per unit time, under constant temperature and unit partial pressure difference when permeation is stable [7]. If partial pressure difference is given as mass fraction difference, permeability is expressed in the same units as diffusivity (m^2 s^{-1}).

When a thin film is considered, its gas transfer characteristics are described by the permeance, PR (g m^{-2} s^{-1}) or (g m^{-2} s^{-1} Pa^{-1}):

$$F = PR \cdot A \cdot \Delta p \qquad (3)$$