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Effect of box materials on the distribution of 1-MCP gas during cold storage: A CFD study

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ABSTRACT

1-Methylcyclopropene (1-MCP) is a synthetic plant growth regulator used commercially to delay ripening of fruits. The substance is applied in gas form (as a fumigant) in the storage room. In long term postharvest cold storage, fruit are placed in boxes (usually plastic or wooden bins) and stacked in a specific pattern. The top of the boxes are frequently covered with a thin plastic sheet for the purpose of reducing fruit moisture loss. Wooden boxes, card linings and other plant based porous materials used in bins have 1-MCP adsorption capacity. Plastic covers affect the airflow and with that the 1-MCP transport. In this paper, the influence of box materials and plastic cover on the distribution of 1-MCP in cold storage was studied using validated CFD models. Reynolds Average Navier–Stokes equations with the SST k–ω turbulence model were used to calculate the airflow. Diffusion, convection and adsorption of 1MCP were modeled to obtain 3D spatial and temporal distributions of 1-MCP inside a storage container, boxes and fruit. Time dependent profiles of calculated 1-MCP concentrations in the air in the container agreed well with measurement data. The plastic cover imposed no effect on the adsorption of 1-MCP. Wooden boxes notably adsorbed 1-MCP from the treatment atmosphere and may reduce the efficacy and uniformity of the treatment.

1. Introduction

In commercial applications 1-MCP is released, as a gas, from a formulated cyclodextrin powder through aqueous dissolution. For apple fruit, responsiveness to 1-MCP differs between cultivars and the exact reason of this variation is not fully known (Watkins et al., 2000). Responses to treatment with 1-MCP are influenced by a number of factors including method of application, commodity type, concentration during treatment, duration of exposure, fruit maturity, treatment/storage temperature and the interval between harvest and treatment (Blankenship and Dole, 2003; Jayanty et al. 2004). For most commodities, treatment duration ranges from 12 to 24 h, which was sufficient to achieve a full response (Blankenship and Dole, 2003). The effective dose of 1-MCP for maximum efficacy of treatments is not yet clearly known. In fact, doses differ from country to country. In Canada and USA, the labeled treatment dosage for apple is 0.6 and 1.0 $\mu L\,L^{-1}$, respectively (Pest Management Regulatory Agency, 2004). In Europe, the minimum use rate is 0.545, and 1 $\mu L\,L^{-1}$ is prescribed as a critical use rate (European Food Safety Authority, 2005). Doses are given in volume of the active substance per empty room volume. Treatment can occur at any temperature between ambient temperature and the normal storage temperature recommended for each variety, including during the cooling of the fruit (SmartFresh™).

As a gas, 1-MCP has the potential to contact 'non-target' materials during treatment. Wooden boxes, card linings and other similar materials that usually coexist in the room have 1-MCP adsorption capacity (Ambaw et al., 2011; Vallejo and Beaudry, 2006). The losses of 1-MCP due to non-target materials directly affect the economic leverage of the treatment operation. Frequently, during storage, boxes containing apple are also covered with thin plastic sheets to reduce moisture loss and this may also affect the air flow distribution leading to a non-uniform distribution of the active substance in the treatment room.

In order to realistically investigate the above concerns, the spatial and temporal distribution of the gas and adsorption in fruit and materials are required. Here, computational fluid dynamics (CFD) is used to generate computer-based air flow and scalar transport simulations (Ambaw et al., 2013; Delele et al., 2008; Alvarez and Flick, 2007; Hoang et al., 2003, 2004; Nahor et al., 2005; Verboven

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Nomenclature

Roman symbols

C_a	concentration of 1-MCP in air (kg/m^3)
C_B	concentration of bounded 1-MCP in fruit (kg/m^3)
$C_{\max}$	1-MCP adsorption capacity of apple fruit (kg/m^3)
C_s	concentration of bounded 1-MCP in wood (kg/m^3)
D_a	kinematic diffusion coefficient of 1-MCP in air (m^2/s)
$D_{s,f}$	effective diffusion coefficient of 1-MCP inside fruits (m^2/s)
$D_{s,w}$	effective diffusion coefficient of 1-MCP in wood (m^2/s)
D_t	turbulent Diffusion coefficient (m^2/s)
$k_{a,f}$	adsorption rate constant per binding site in fruit (m^3 mol^{-1} s^{-1})
$k_{a,w}$	adsorption rate constant per binding site in wood (m^3 mol^{-1} s^{-1})
p	pressure (Pa)
r_s	rate of 1-MCP adsorption in apple fruit (kg m^{-3} s^{-1})
S_u	momentum source term (kg m^{-2} s^{-2})
t	time (s)
U	vector of velocity, $V_{x,y,z}$ (m/s)
u	velocity magnitude (m/s)

Greek symbols

μ	dynamic viscosity (kg m^{-1} s^{-1})
μ_t	turbulent eddy viscosity (kg m^{-1} s^{-1})
μ_{eff}	effective viscosity (=$\mu + \mu_t$) (kg m^{-1} s^{-1})
ρ_a	density of dry air (kg m^{-3})

Sub and super-scripts

a	air
max	maximum
s	solid
t	turbulent
T	the transform operator

et al., 2006). In the area of 1-MCP applications, we recently developed a combined discrete element (DE)-CFD model to study the effect of air flow on distribution of 1-MCP in a fruit storage container (Ambaw et al. 2012).

In the present study, the DE-CFD model is used to describe the fate of 1-MCP in the storage environment over the course of the treatment duration following a single pulse of 1-MCP. The main objective of this work is to investigate the effect of box materials and plastic cover on the 3D spatial and temporal distribution of 1-MCP in cool storages. Simulations are then performed to assess the possibility of dose reduction and obtain insight into the fate of the 1-MCP when fruit are stored in wooden boxes.

2. Materials and methods

2.1. Fruit supply

'Jonagold' apples (*Malus domestica* Borkh., cv. Jonagold) were purchased directly after harvest from a local grower in Belgium in September, 2010. All the fruits used for the test were free of visual defects. Fruit were stored at 1 °C in normal atmospheric air before and during the experiment that took place within a few days. The mean ± standard deviation ($n = 10$) of the mass and volume of fruits were 240 g ± 22 g and 300 mL ± 30 mL, respectively.

2.2. HDPE plastic boxes

Slotted high-density polyethylene (HDPE) plastic boxes (Euro Pool System International B.V., Rijswijk, The Netherlands) with dimension of 0.57 m × 0.37 m × 0.23 m were used to hold the fruits. The ventilating slots were spread over the five faces of the box with a vent-hole ratio of 20% at side faces and 3% at the bottom face of the box (Fig. 1a).

2.3. Wooden boxes

Slightly weathered wooden boxes constructed from oak wood with external dimensions of 0.55 m × 0.29 m × 0.35 m were used (Fig. 1b). The venting slots were horizontal gaps between the wooden slabs and spread over the five faces of the box as shown in Fig. 1b. The vent-hole ratio was 12% at side faces and 5% at the bottom face of the box.

2.4. Plastic cover

The effect of plastic cover on the gas distribution was assessed by setting up an experiment in which the top and portion of the sides of plastic boxes were covered as shown in Fig. 2. A thin polyethylene plastic sheet of 0.5 mm thickness is used. The top of the box was totally covered.

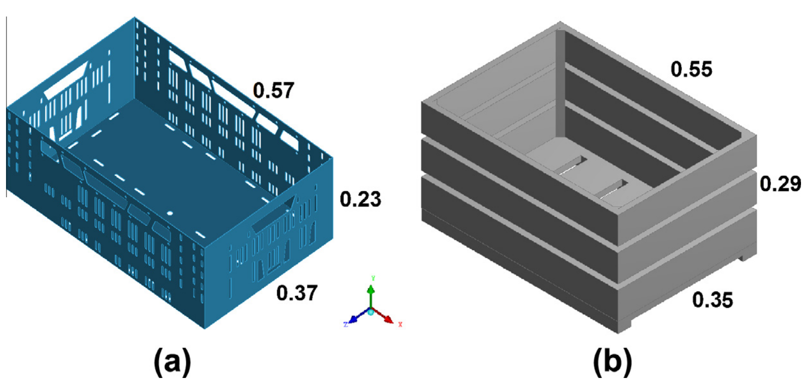

Fig. 1. The HDPE plastic box (a) and wooden box (b) used to contain apple fruits in the experiment. Dimensions are in m.