Journal of Food Engineering 119 (2013) 370–376

Contents lists available at SciVerse ScienceDirect

Journal of Food Engineering

journal homepage: www.elsevier.com/locate/jfoodeng

# Engineering packaging design accounting for transpiration rate: Model development and validation with strawberries

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ARTICLE INFO

*Article history:*
Received 11 June 2012
Received in revised form 27 May 2013
Accepted 31 May 2013
Available online 15 June 2013

*Keywords:*
Packaging design
Water vapour transmission rate
Condensation
Moisture loss
Strawberry

ABSTRACT

Integrative mathematical modelling for Modified Atmosphere Packaging (MAP) has been used to determine the gas composition inside a package, but can also be used to determine the packaging needs of fresh produce in terms of permeability to gases and water vapour. Transpiration rate (TR) is an important physiological process that influences relative humidity (RH) and condensation inside the package, and ultimately quality and shelf life. Strawberries are an extremely valuable crop, but they are susceptible to grey mould rot, fungal decay, moisture loss and condensation. Quantification of strawberry transpiration rate TR would be required to estimate the packaging material water vapour transmission rate (WVTR) and therefore optimise engineering packaging design. This study investigated (i) the impact of temperature and RH on strawberry TR, (ii) developed a predictive model for quantifying TR, (iii) integrated transpiration rate model into the engineering packaging design and quantified the target WVTR for packaging of strawberry and (iv) validated packaging design by comparison to commercial packaging. Experiments were conducted following an experimental design, considering two factors at three levels ($3^2$), i.e. temperature (5, 10 and 15 °C) and RH (76%, 86% and 96%); TR was recorded during 5 days of storage. The results showed that both RH and temperature had a significant effect on TR. In a given temperature and RH range of study, it varied from 0.24 to 1.16 g/kg h. Mathematical model developed considering the effect of temperature and RH, was further validated at 12 °C and 76% RH, showing very good predictability ($R^2 > 0.997$). The TR model was found to be useful for describing the strawberry packaging requisites and for optimal engineering packaging design for strawberry. The target WVTR for achieving optimal RH of 90% at 5 °C was found to be 162 g/m$^2$ day. Packaging design validation showed that the package designed considering both gas and water vapour requisites of strawberry yielded favourable results for maintaining quality and shelf life of product.



## 1. Introduction

Modified Atmosphere Packaging (MAP) is a technique used to extend the shelf life of fresh produce by slowing down respiration, but it can lead to water accumulation at the product surface promoting microbial growth and sliminess, which impairs the objective of MAP (Song et al., 2001; Song et al., 2002). The low water vapour transmission rate (WVTR) of films commonly used for MAP of strawberries, combined with the strawberries transpiration, rapidly brings about saturation (~100% RH) of the package atmosphere. The saturated in-pack RH conditions along with temperature variation during supply chain can result in the condensation of water on the inside surface of the packaging film and on the contained produce, favouring microbial growth and discolouration. Commercial strawberry packages were found to be macro-perforated with 0.8 mm diameter hole (Mahajan et al., 2012) for free air circulation around the product thereby avoiding condensation inside the package. However, these macro-perforations cause no atmosphere modification, preventing MAP benefits.

Integrative mathematical modelling has been used to determine the gas composition packaging needs for fresh produce (Mahajan et al., 2007; Sousa-Gallagher and Mahajan, 2012,2013). Calculations have been based on $O_2$ consumption and $CO_2$ production rate, i.e. respiration rate of fresh produce. Rennie and Tavoularis (2009) presented a mass transport model in a cylindrical package with one perforation and found that the in-package convective transport was less that 4% by diffusion and the most important mass transport mechanisms were respiration and transpiration while $C0_2$ solubility was not significant for a steady state case. Recently, Xanthopoulos et al. (2012) developed a mathematical model to predict $O_2$, $CO_2$, $N_2$ and $H_2O$ in perforated-mediated polymer packages during cold storage of strawberries accounting for respiration and transpiration,

Strawberry is a highly perishable commodity due to its high respiration rate (Hertog et al., 1999) and it has a very short shelf life,

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http://dx.doi.org/10.1016/j.jfoodeng.2013.05.041

due in part to grey mould rot caused by *Botrytis cinerea*. Strawberries are typically packaged in the field and quickly transported to a cooling facility, where they are pre-cooled by forcing cold air through the vents of the packaging. Strawberries are very sensitive to humidity levels; they contain more than 90% of the weight at harvest is water and they lack a skin as a barrier to diffusion. Strawberries are highly suitable for packaging under modified atmospheres as high $CO_2$ can have an inhibiting effect on mould growth and, hence, mould attacks on strawberries can be delayed by MAP (Kader, 1992a). Moisture loss due to transpiration reduces the weight and quality of fresh produce during postharvest storage, and polymer film packaging can be used to modify package atmospheres and reduce moisture loss rate of strawberries.

Transpiration rate is the amount of water loss from the plant tissue per unit time and is influenced by product or commodity factors (morphological characteristics, surface to volume ratio, maturity stage, injuries) and environmental factors (storage temperature, relative humidity, air movement, and atmospheric pressure; Kader, 1992b). The most common method to measure transpiration rate has been to weigh fruit periodically while they are exposed to a given temperature and relative humidity. Shirazi and Cameron (1993) measured transpiration rates and corrected weight loss due to respiration exchange accounting for a correction of 0.5 $\mu g\ s^{-1}$ for a 25 g strawberry and 0.7 $\mu g\ s^{-1}$ for 140 g tomato. They found that an increase from 50% to 90% RH, led to 30% and 100% increase in apparent water vapour permeability coefficient ($P'_{H_2O}$) for strawberries and tomatoes, respectively, reporting that $P'_{H_2O}$ were similar to previously published values obtained in a conventional weight loss experiment. Burton and Noble (1993) found that weight losses from mushrooms stored in open punnets at either 5 °C (73% RH) or 18 °C (90% RH) were linear, at an average of 4% per day at 5 °C and 6% per day at 18 °C.

Several models for estimating transpiration rate have been proposed but their applicability to predict moisture loss is limited to cooling process and bulk storage, and may not be suitable for MAP applications (Song et al., 2002). Most models describe the moisture transfer through the skin as a function of the biophysical and thermo-physical properties such as surface cellular structure, skin thickness, pore fraction in the skin, geometry and thermal diffusivity of produce, which are not easily measured or determined. Song et al. (2001, 2002) developed a transpiration rate model for blueberry by applying simultaneous heat and mass transfer principles. The model was successfully verified for different types of packaging films in MAP with and without moisture absorber. Veraverbeke et al. (2003) estimated the actual diffusion coefficients of tissue, cutin and wax for apple cultivars using a finite element method. However, the model did not depict the effect of temperature and RH on water loss. Mahajan et al. (2008) developed a mathematical model for transpiration rate to understand the evolution of mushroom weight loss as a function of temperature and RH. Xanthopoulos et al. (2012), considered a transpiration model developed by Dincer (2003), driven by water vapour pressure deficit between the surface and its surroundings. The model predictions were tested against published experimental data of $O_2$ and $CO_2$ concentrations in MAP showing a satisfactory agreement, but to our knowledge no validation was performed for $H_2O$, Perhaps due to lack of transpiration rate data for strawberries.

Optimal engineering packaging design requires the measurement and modelling of transpiration rate of strawberry at different storage temperatures and RH, and integrate this data into the engineering design of modified atmosphere and humidity packaging (MAHP) (Fig. 1) in order to select the appropriate gases and water vapour packaging material barrier properties. The objectives of this study were to (i) measure transpiration rate of strawberries at different temperature and relative humidity, (ii) develop a mathematical model for predicting transpiration rate, and (iii) integrate the transpiration rate model into the engineering packaging design and validation for strawberries.

## 2. Materials and methods

### 2.1. Strawberries

Strawberry fruits (cv. Elsanta) grown in Glen Fruits, Waterford, Ireland were supplied by the local whole supplier (Southern Fruits, Cork, Ireland). Only strawberries without visible *Botrytis* infection were used for experiments. Strawberries with uniform size (19.6 ± 3 g) were used for transpiration rate measurement. Fruits were stored at each temperature of study for approximately 1 h to equilibrium to the temperature before experiments.

### 2.2. Transpiration rate measurement

To evaluate the transpiration rate, a weight loss technique as reported by Leonardi et al. (1999) was used. Two strawberries of approximately 20 g were placed separately in two petri-dishes and, weight loss was measured daily for 5 days using an electronic balance (Bosch SAE200, GmbH). Transpiration rate (TR) was calculated from the changes in weight of strawberry over time

$$TR = \frac{M_i - M}{t \times (M_i/1000)} \quad (1)$$

where TR is the transpiration rate in g/kg h, $M_i$ is the initial weight (g) and $M$ is the weight of strawberry (g) at time $t$ (h).

Experiments were performed according to a full factorial design, considering 2 factors at three levels ($3^2$), i.e., temperature (5, 10 and 15 °C) and equilibrium RH (76%, 86% and 96%). The experimental setup consisted of nine plastic containers placed in three refrigerating incubators each maintained at 5, 10 and 15 °C. Relative humidity within the plastic containers was independently controlled by using saturated salts solutions of sodium chloride, potassium chloride and potassium nitrate giving 76%, 86% and 96% RH, respectively (Patel et al., 1988). Salt solution was placed at the bottom of the container and supports were mounted above the solution level with large aluminium plates to hold the petri-dishes containing individual strawberry fruit. Temperature and RH inside the container was monitored continuously using a data logger (HMP50, Campbell Scientific, Inc., Utah). Experiments were replicated four times giving the total 36 number of data sets. An additional set of experiment was performed at 12 °C and 76% RH in order to validate the mathematical model for TR.

### 2.3. Development of transpiration rate model

The flow of water vapour through a fruit is proportional to the difference in water activity (RH/100) between the surface of a commodity and the surrounding air and can be related to Fick's law of diffusion (Ben-Yehoshua, 1987). It can be measured in terms of amount of water loss from the plant tissue per unit weight per unit time and is known as transpiration rate. Transpiration rate model Eq. (2) as a function temperature and RH was developed for mushrooms (Mahajan et al., 2008).

$$TR = K_i \times (a_{w_i} - a_w)(1 - e^{-aT}) \quad (2)$$

Eq. (1) was combined with Eq. (2) yielding

$$M = M_i - K_i \times (a_{w_i} - a_w) \times (1 - e^{-aT}) \times t \times \left(\frac{M_1}{1000}\right) \quad (3)$$

where $a_w$ is the water activity of the container (RH/100); $a_{wi}$ is the determined average water activity of the strawberry