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Analysis of the effects of package design on the rate and uniformity of cooling of stacked pomegranates: Numerical and experimental studies

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ABSTRACT

Computational fluid dynamics (CFD) model was developed, validated and used to analyse cooling characteristics of two different package designs (CT1 and CT2) used for postharvest handling of pomegranate fruit. The model incorporated geometries of fruits, packaging box, tray and plastic liner. Thin layer of plastic material with conservative interface heat flux was used to model liners. The accuracy of the model to predict airflow and temperature distributions were validated against experimental data. The model predicted airflow through the stacks and cooling rates within experimental error. Stack design markedly affected the airflow profile, rate and uniformity of cooling. The cooling rate of the two package designs differed by 30% and plastic lining increased the average 7/8th cooling times from 4.0 and 2.5 h to 9.5 and 8.0 h for the CT1 and CT2 stacks, respectively. Profile of high and low temperature regions depended considerably on packaging box design.

1. Introduction

The demand for pomegranate fruit is increasing due to the extensive knowledge acquired on the health benefits of pomegranate and increased public awareness about functional food (Seeram et al., 2006). Following this, there has been increased interest in research to improve storability (Opara et al., 2015).

Temperature and relative humidity (RH) are important factors that control respiratory activity, physiological disorders and growth of microbial pathogens during storage of pomegranate fruit (Munhuweyi et al., 2016; Pareek et al., 2015). Optimum storage temperature varies by cultivar, production area, and postharvest treatment (Köksal, 1989; Onur et al., 1995). Normally, storage is recommended at temperatures between 5 °C and 8 °C (Artés et al., 1996; Fawole and Opara, 2013; Kader et al., 1984) and relative humidity (RH) between 90 and 95% (Artés et al., 1996; Mirdehghan et al., 2007). After harvest, produce normally contain heat from the field (field heat) and fruit temperature is higher than the recommendation. Hence, it is necessary to remove the field heat to bring the harvested produce to the storage temperature by employing a precooling process. After precooling, commodity should be maintained at its lowest safe temperature.

Precooling of pomegranate can be accomplished using room cooling. In this technique, stacked fruit are placed in an insulated room equipped with refrigeration units to chill the air. However, room cooling is a slow process. Forced-air cooling (FAC) system uses fan to drive cold air through stacked produce to increase the rate of convective heat transfer from the commodity to the cooling medium. Hence, FAC is the most commonly used technique in postharvest precooling of fruits and vegetables. FAC can be used in conjunction with cold storage room. Fresh harvest can be rapidly precooled to the required storage temperature and then transferred to cool store room. This helps to maintain the cool room environment constant.

There are many factors that affect the effectiveness of precooling of perishables (Opara and Zou, 2007; Zou et al., 2006a,b). Among these, the role of package design and package arrangement on uniformity and rate of cooling have been highlighted by many researchers (Berry et al., 2015, 2016; Defraeye et al., 2013; Delele et al., 2013; Ngcobo et al., 2012; Opara, 2011). Size, proportion and locations of vent-holes on top, bottom and side faces of a packaging box considerably affect cooling rate and uniformity (Berry et al., 2015, 2016). Plastic liner is commonly used to reduce moisture loss and to control gas compositions (CO2 and O2) during storage (Mangaraj et al., 2009; Opara, 2011). However, plastic liner also

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blocks airflow and reduces the rate of heat removal from the produce. Understanding the influence of package designs on the rate and uniformity of cooling helps to optimize the process.

Such knowledge can be acquired experimentally. Here, spatiotemporal temperature data can be processed to estimate cooling coefficients, 7/8th cooling time and cooling uniformities (Anderson et al., 2004; Gil et al., 2012; Akdemir and Arin, 2006). However, experimental approach alone is expensive, time taking and inconvenient to perform detailed analysis of airflow and temperature distributions. By combining experimental measurements with mathematical models, a more comprehensive analysis can be realised (Verboven et al., 2006; Zou et al., 2006a,b; Alvarez and Flick, 1999a,b; Ferrua and Singh, 2009). The powerful visualization capabilities and acceptable accuracy of the numerical predictions make computational fluid dynamics (CFD) the primary method of choice in modelling mass and heat transfer processes (Ambaw et al., 2013; Norton and Da-Wen, 2006; Smale et al., 2006).

While research on the health benefits (Mertens-Talcott et al., 2006; Viuda-Martos et al., 2010) and improved postharvest handling methods (Artés et al., 2000; Mirdehghan et al., 2006; Opara et al., 2015) has been reported, little is known about precooling of pomegranate fruit in the cold chain. Direct extrapolation from studies on other fruit types is not appropriate since thermal properties, package designs, package arrangement and precooling requirements are specific.

The aim of the present work is to examine the aerodynamic and thermodynamic performances of two different corrugated fibreboard containers to handle 'Wonderful' pomegranate fruit with or without plastic liner. To accomplish this, CFD models were developed and validated. Then, the validated model was used to analyse the airflow and temperature distributions with very high spatial resolution.

2. Materials and methods

2.1. Fruits

Pomegranate fruit (Punica granatum L., cv. Wonderful) was harvested at commercial maturity from Merwespont farm in Bonnievale, Western Cape, South Africa. Fruits were transported in an air-conditioned vehicle to Postharvest Technology Research Laboratory in Stellenbosch University. The average size of pomegranates were 8.00 ± 0.20 cm in diameter and 358 ± 10 g in mass. Before the start of the experiments fruits were equilibrated to ambient air temperature which was17 ± 3.0 °C.

2.2. Packaging boxes

Two corrugated packaging box designs (CT1 and CT2) were examined in this study. Each box design carry twelve pomegranate fruits (fruit only Fig. 1(a) and fruit enveloped in plastic liner Fig. 1 (b)). Table 1 summarizes the loading capacities and vent area characteristics of the boxes. Plastic wrapping was done by placing pomegranates in a single non-perforated 10 μm thick high density polyethylene (HDPE) plastic film (Fig. 1(b)). The dimensions and vent-hole locations of the two boxes are presented in Fig. 2.

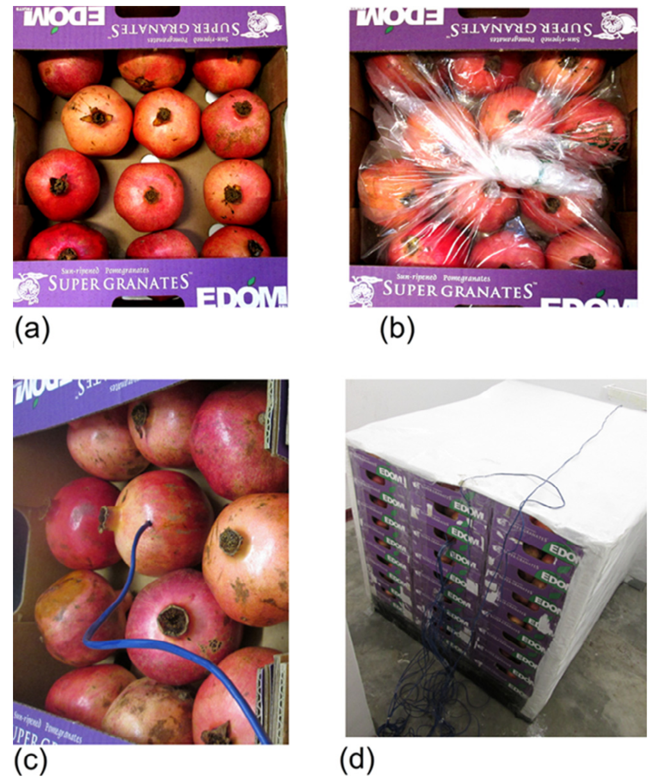

Fig. 1. Components of the experimental setup. Pomegranates in the CT2 packaging box, with no lining (a), with liner (b), thermocouple inserted to fruit centre to measure pulp temperature (c) and stack ready for the FAC test (d).

2.3. Precooling experiments

Boxes were stacked on a standard ISO industrial pallet (1.2 × 1.0 m × 0.1 m) (Fig. 2(e) and (f)). The CT1 stack holds 7 layers of 10 boxes while the CT2 stack holds 8 layers of 12 boxes. Then each stack was individually placed in front of the FAC system inside cold storage room. The top, left and right sides of the stack were carefully sealed with plastic sheet (Fig. 1(e)). The FAC system uses centrifugal fan (Kruger KDD 10/10 750W 4P-1 3SY) to draw cold air through the stack. Temperature and relative humidity (RH) of the cold store room were 7 ± 1.2 °C and 91.4 ± 6.3%, respectively. Pressure at inlet and outlet and air velocity at outlet of the FAC system were measured using differential pressure meter (Air Flow Meter Type A2G-25/air2guide, Wika, Lawrenceville GA 30043, USA with a long-term stability of ±1 Pa) with data controller (WCS-13A, Shinko Technos CO LTD, Osaka, Japan).

Fruit pulp temperatures were measured by inserting T-type thermocouple into the core of sample fruits (Fig. 1(c)). The thermocouple used has operating range of −30 to 100 °C and accuracy of ±0.025% (Thermocouple products Ltd, Edenvale, South Africa). The interference due to the physical presence of a thermocouple inside fruit (due to their heat capacity and density) was assumed negligible as the thermocouples were small in size compared to the fruit. The relative positions of the temperature sensors in a layer is

Table 1
Package dimensions, vent-hole ratios and loadings.

Models	Dimensions [m]	Vent hole ratio [%]			Loading	
		Short side	Long side	Bottom side	Number of fruits	Total weight [kg]
CT1	0.39 × 0.29 × 0.12	2.0	8.0	3.0	12	4.3
CT2	0.33 × 0.30 × 0.11	5.3[a]	10.20	3.8	12	4.3

[a] Not that during stacking this vent-hole would be blocked. In a stack, this side has practically no vent-hole.