Computational fluid dynamics (CFD) based analysis of the aerodynamic and thermodynamic performances of package designs during cooling of stacked pomegranates

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Abstract

The demand for pomegranate fruit is increasing due to the extensive knowledge acquired on the health benefits of pomegranate and the increased public awareness about functional food. Following this, there has been an increased interest in research to improve storability. A computational fluid dynamics (CFD) model was developed, validated and used to analyse the cooling characteristics of two different package designs used for the postharvest handling of pomegranate fruit. The model incorporated the geometries of the fruits, packaging box, tray and plastic liner. A thin layer of plastic material with conservative interface heat flux was used to model the liners. The accuracy of the model to predict the airflow and temperature distributions were validated against experimental data. The model predicted the airflow through the stacks and cooling rates within experimental error. The stack design markedly affected the airflow profile, rate and uniformity of cooling. The cooling rate of the two package designs differed by 30% and the plastic lining increased the average 7/8th cooling times significantly. The profile of the high and low temperature regions depended considerably on the packaging box design.

Keywords: heat-transfer, packaging, plastic liners, cold-chain, postharvest, loss reduction, energy-efficiency, simulation, precooling

INTRODUCTION

The demand for pomegranate fruit is increasing due to the extensive knowledge acquired on the health benefits of pomegranate and the increased public awareness about functional food. Due to this, in recent years, the global trade and consumption of pomegranate has increased dramatically. Following this, there has been an increased interest in research to improve the storability and shelf life to meet consumers' expectations of a consistent supply of quality fruit and to reduce the loss (Opara et al., 2015).

The temperature and relative humidity (RH) are the two crucial factors to control the respiratory activity, transpiration and the development of microbial pathogens as well as of certain physiological disorders during the storage of pomegranate fruit (Munhuweyi et al., 2016; Pareek et al., 2015). The recommended temperature for storage is within the range of 5-8°C and relative humidity (RH) should be 90-95% (Fawole and Opara, 2013). It is necessary to remove the field heat to bring the harvested produce to the storage temperature by employing a precooling process.

There are many factors to consider when precooling perishables for postharvest handling (Opara and Zou, 2007). Among them, the importance of package design and package arrangement on uniformity and rate of cooling have been highlighted by many researchers (Berry et al., 2015). The package design depends on the type of fruit to suit the

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contents, market expectations and supply chain logistics (Opara, 2011). The size, vent-hole proportion and vent-hole locations considerably affect the cooling of the packed produce (Berry et al., 2015, 2016). Plastic linings are commonly used to reduce moisture loss during storage and to control gas compositions (CO_2 and O_2) (Opara, 2011). On the other hand, plastic lining blocks the airflow path and reduces the rate of heat removal from the stacked produce. This inevitably increases the energy expenditure of the cooling process. Knowledge on the influence a package has on cooling helps to optimize the cold chain management of the fruit. While research on the health benefits and postharvest handling methods has been reported, little is known about the cooling performance of packaging systems used for handling pomegranate fruit in the cold chain (Opara et al., 2015). Direct extrapolation from studies on other fruit types is not appropriate since the thermal properties, package designs, package arrangement and precooling requirements are different. This necessitates a dedicated investigation of precooling of pomegranate.

The aim of the present work is to examine the aerodynamic and thermodynamic performances of two different corrugated fibreboard containers for 'Wonderful' pomegranate. To accomplish this, CFD models corresponding to each box design were developed and validated.

MATERIALS AND METHODS

Packages

Two corrugated packaging box designs (CT1 (Figure 1a) and CT2 (Figure 1b)) were examined in this study. Each carton was packed with 12 pomegranate fruit with an average fruit weight of 4.32±0.39 kg per carton. The precooling of palletized stack of boxes with fruits only or fruits as wrapped in a plastic lining were tested. The wrapping was done using a polyline bag. The fruit loaded boxes were stacked on a standard pallet of dimensions 1.2×1.0×0.1 m. The CT1 was stacked in 7 layers of 10 boxes and the CT2 in 8 layers of 12 boxes. The stack dimensions are shown in Figure 1.

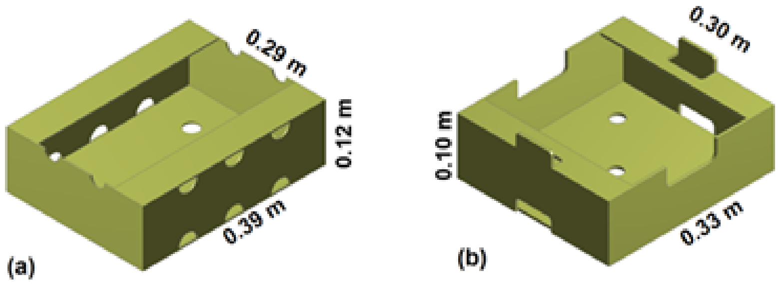

Figure 1. Schematics of the two package designs used for export handling of 'Wonderful' pomegranates. The top row shows the isometric view of the CT1 (a) and CT2 (b) boxes.

Precooling experiments

The stacks were equilibrated to an initial temperature of 17±3°C in ambient air. Then each stack was individually placed in a FAC system which was placed inside a cold storage room. The temperature and relative humidity (RH) of the cold store rooms were 7±1.2°C and 81.4±6.3%, respectively. The FAC system uses a centrifugal fan (Kruger KDD 10/10 750W 4P-1 3SY) to draw the cooling air through the stack. The pressure drops between the inlet and outlet of the FAC and air flow rate, leaving the FAC, were measured using the 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 with T-type thermocouple (Thermocouple products Ltd, Edenvale, South Africa, with operating range of -30 to 100°C and an accuracy of ±0.025%) inserted into the core of sample fruits. 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. This way pulp temperature data were collected every 300 s. The relative positions of the temperature sensors in the stack is shown in Figure 2. Sampling fruits were placed in layers 2, 4 and 6 of the stacks.

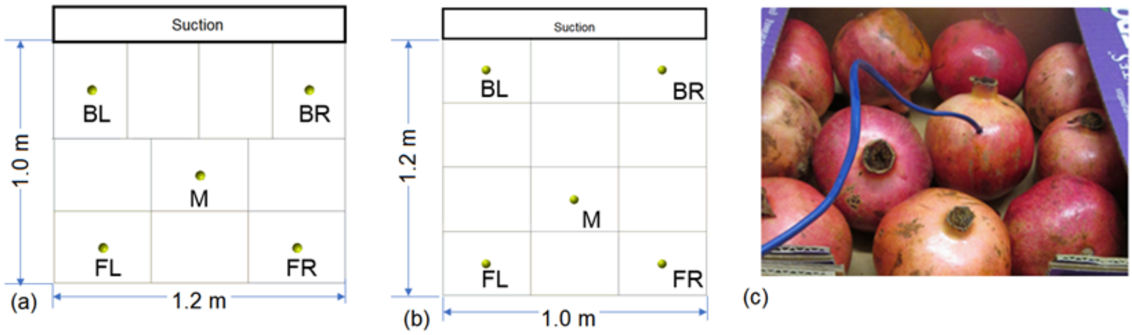

Figure 2. Schematics showing the package arrangement of CT1 (a) and CT2 (b) containers in a layer. Dots (BL = back left, BR = back right, M = middle, FL = front left and FR = front right) are the positions of temperature sampling fruits as illustrated in (c).

Governing equations

The prediction of the airflow was obtained by solving the Reynolds Averaged Navier Stokes (RANS) equations. The heat transfer process inside individual fruits were explicitly modelled using Equation 1:

$$\left(\rho_s C_{ps}\right)\left(\frac{\partial T_s}{\partial t}\right) = \nabla\left(k_s \nabla T_s\right) + Q_s \tag{1}$$

where ρ_s (kg m^{-3}) is the density of pomegranate fruit, C_{ps} (J kg^{-1} K^{-1}) is the heat capacity of pomegranate fruit, T_s (K) is the produce temperature, k_s (W m^{-1} K^{-1}) is the thermal conductivity of pomegranate fruit. Pomegranate is a nonclimacteric fruit and has a relatively low respiration rate that declines with time during storage after harvest (Fawole and Opara, 2013). Hence, the heat of respiration Q_s (W m^{-3}) in Equation 1 was assumed negligible in the model.

Geometry and boundary conditions

Figure 3 illustrates the model geometry and boundary conditions corresponding to the full stack as placed in front of the FAC system. The airflow distributions were modelled for the full stack containing fluid domain (the air) and two solid domains: fruits and packaging materials. Fruit surfaces, box surfaces and the guide to the centrifugal fan were set to wall, no-slip boundaries with respect to airflow and to conservative interface flux for heat transfer. The inlet of the domain was open to the atmosphere (at atmospheric pressure) and the outlet of the domain which corresponds to the inlet to the suction fan was at a specified suction pressure (negative gauge pressure). The initial produce temperature was 17°C. The cooling air temperature at inlet to the FAC was 7°C.

The transient heat transfer simulation was solved on a single layer taken from the stack. This was to reduce the high computational requirement of solving the transient problem on the full stack. The airflow profile as well as the pressure loss profile were first assessed to confirm the single layer assumption. The measured temperature data also supported the appropriateness of the single layer approximation.

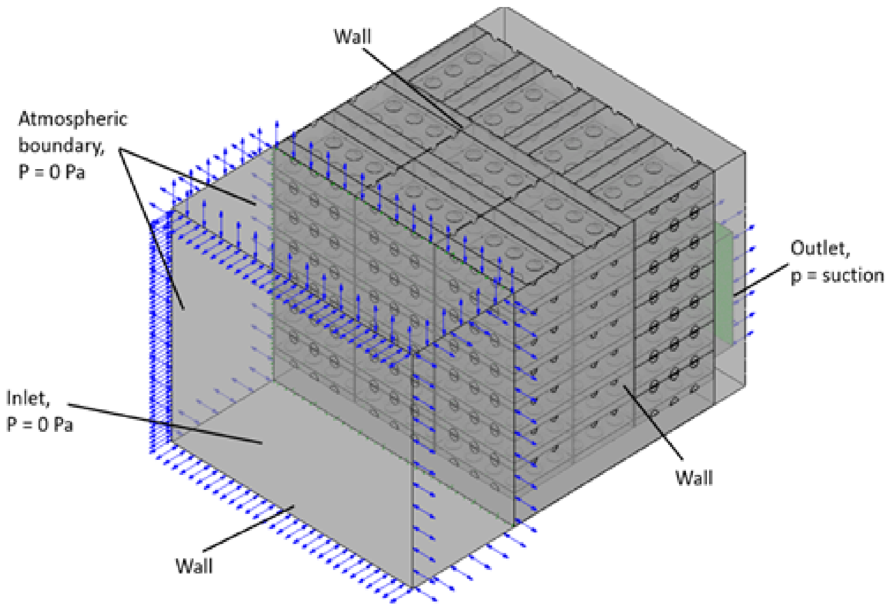

Figure 3. Schematics showing the computational domain and boundary conditions.

Simulation setup

The geometry creation, domain discretization and simulation were made with ANSYS® CFX™ Release 17.0 (ANSYS, Canonsburg, PA, USA). The mesh dependency was analysed based on the difference in values of air velocity in the full stack model for grid sizes of 4×10^6, 8×10^6 and 12×10^6 elements. For this purpose, air velocities through vent holes at the inlet side of the stack were compared. The actual simulations were finally undertaken using 10×10^6 elements which had an average discretization error in estimating air velocity of 2.6%. For the single layer model, a similar procedure, using fruit pulp temperature as criterion, gives a mesh elements of 2×10^6.

SIMPLE discretization scheme was used for pressure-velocity coupling and Second Order Upwind discretization was used for momentum, specific dissipation rate and energy calculations. A number of time step sizes: 360, 180, 72, and 36 s were assessed. Based on the accuracy and computational time, the time step size of 180 s with maximum 10 iterations per time step, was used. Simulation were run on a 64-bit, Intel® Xeon® CPU E5-1660 v3, 3 GHz, 32 Gb RAM, Windows 7 PC.

RESULTS AND DISCUSSION

Pressure drop characteristics

The superficial air velocity depends on the permeability of the stack, the flowing fluid (air) properties and the pressure gradient applied for the air delivery. This relationship is captured using the Darcy-Forchheimer equation (Equation 2):

$$M_V = -\frac{\mu}{k}V - \frac{\rho}{k_1}|V|V \qquad (2)$$

where, V (m s^{-1}) is superficial velocity, defined as the volumetric flow rate divided by the cross sectional area of the stack perpendicular to the flow direction. The coefficient μ/k (Darcy term) accounts for friction losses that are characteristics of the fluid viscosity μ (Pa s) and the permeability of the stack k (m^2). The coefficient ρ/k_1 takes into account inertial losses associated with expansion, constriction, and bends in the pore channels where the additional term k_1 (m) is known as inertial permeability. The measured and simulated pressure drop vs. flow rate data of stacks of the CT1 and CT2 boxes are shown in Figure 4. As expected, the pressure loss is affected by the package design and the plastic linings. CT2 stack arranged with its width perpendicular to airflow (CT2_No lining) has the lowest pressure loss while CT2 box with liner (CT2_ With lining) has the highest loss. The CT1 stack shows intermediate pressure loss characteristics.

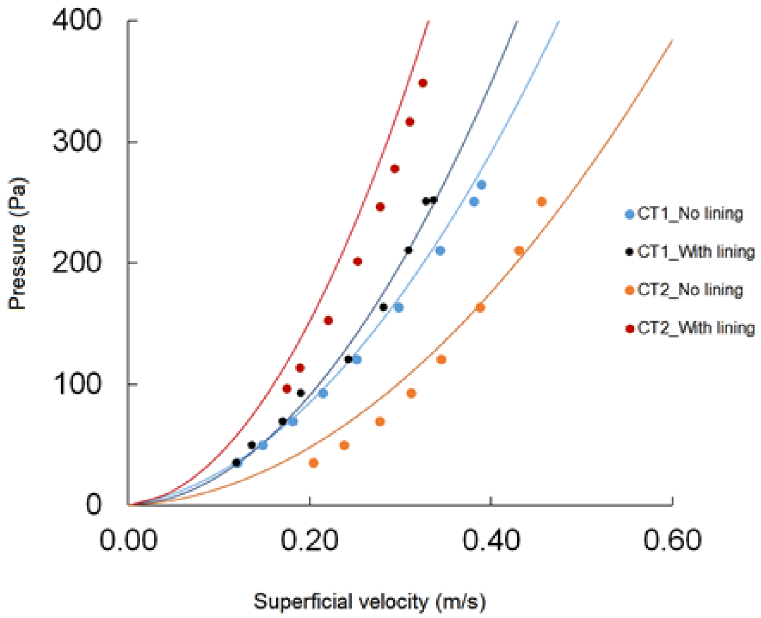

Figure 4. Measured (dots) and simulated (curves) pressure drop across the stacks as a function of superficial air velocity through the stack.

Plastic lining considerably increases the pressure loss, especially for the CT2 stack. For this box the use of plastic lining increased the pressure drop by 3 fold. For the CT1 stack, the influence of plastic lining was relatively small, it only increased the resistance by 20%. The vent holes of the CT1 container were many in number and were evenly distributed on the top and bottom rim of the sides. This leads to a reduced effect of plastic lining on the total airflow resistance. However, in the CT2 stack, the single and large vent hole on the top rim could be easily blocked by the plastic lining resulting in a huge increase in flow resistance.

The CFD model captured the pressure drop characteristics with an average overestimation error of 17% (curves in Figure 4). The boxes were ideally arranged in the model with gaps between boxes and between the stack and the stack covers completely neglected. In an actual case, such gaps are inevitable and air can leak through such gaps.

Cooling rates

To compare the cooling rate at equal ground a dimensionless parameter, as given by Equation 3 was used. This equation describes the cooling rate in terms of the fractional unaccomplished temperature change Y:

$$Y = \frac{T - T_a}{T_i - T_a} \qquad (3)$$

where T is the measure pulp temperature (°C), T_a is the cooling air temperature, which was taken equal to 7°C for all the experiments as well as in the simulation and T_i is the initial pulp temperature of the produce (°C). The result of the analysis showed that the time-temperature curve of the three layers were nearly identical. Hence, analysing a single layer was sufficient (Figure 5). In a layer, the magnitude of the cooling rates were ranked as FL>BL>FR>M>BR.

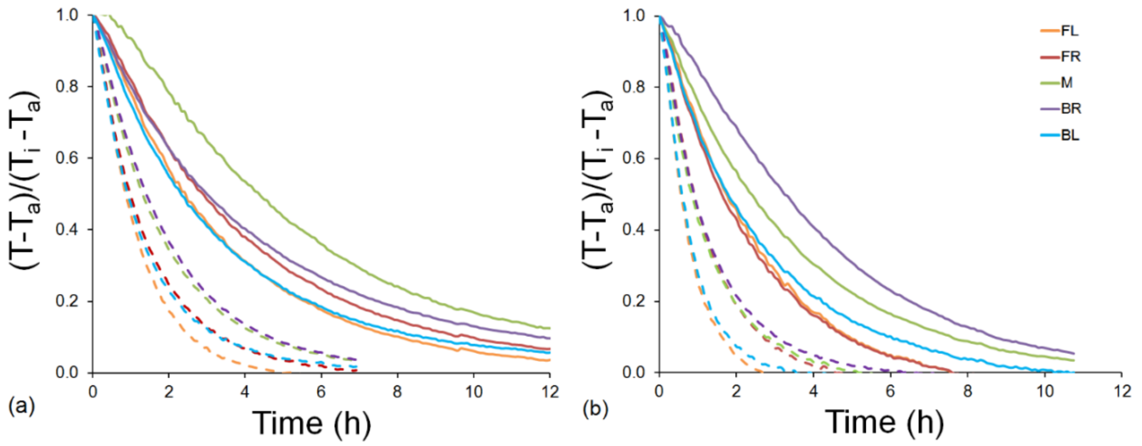

Figure 5. Measured average pulp temperature history showing the variation per position in CT1 (a) and CT2 (b) boxes, with lining (full curves) and without lining (broken curves).

Temperature distribution

The simulated contours of the temperature on the fruit surfaces are shown in Figure 6 for the CT1 and CT2 stacks. The two box designs show distinctly different temperature distributions. The CT1 stack is characterised by a wide variation of cooling rate between the rows. The 3rd row from the inlet side (fruit in the back boxes) was a high temperature region. Due to a change in the orientation of the package, the airflow path was partially blocked between the 2nd and 3rd row. Due to this, the 3rd row cools slower than the other rows. The airflow in the CT2 stack was channeled through the seriously connected large vent holes of the boxes. Fruits along the main flow path cool in a distinctly higher rate than fruits located at the left and right side of the airflow path.

A modification of the vent-hole design of the CT1 container has been investigated using the CFD model. The modifications to the vent-hole design were as illustrated in Figure 7. Clearly, the redesigning of the CT1 box from Figure 7a to 7b would result in a huge improvement on the uniformity of temperature distribution (Figure 8). The best container model will be manufactured by closing the old vent-holes and opening new ones manually in our lab. For the modified design, a FAC experiment will be conducted.

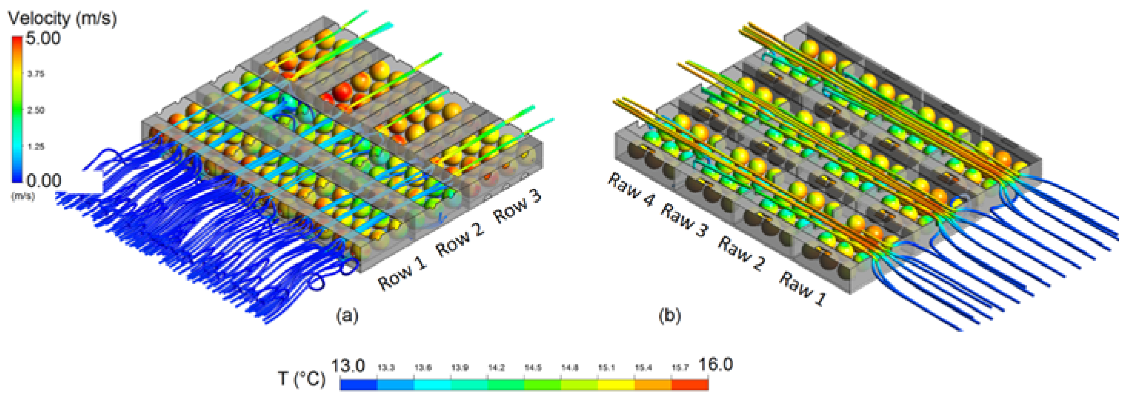

Figure 6. Simulated temperature contours and airflow stream lines in a layer of CT1 (a) and CT2 (b) stacks with no lining.

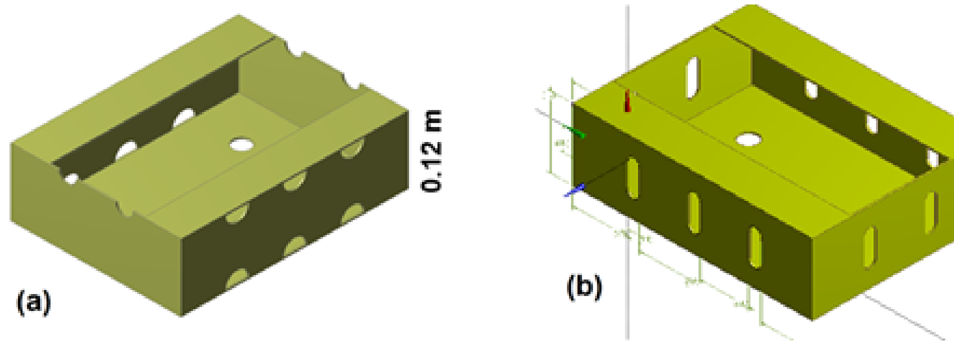

Figure 7. Modified design of the CT1 container. Old model (a) and modified (b).

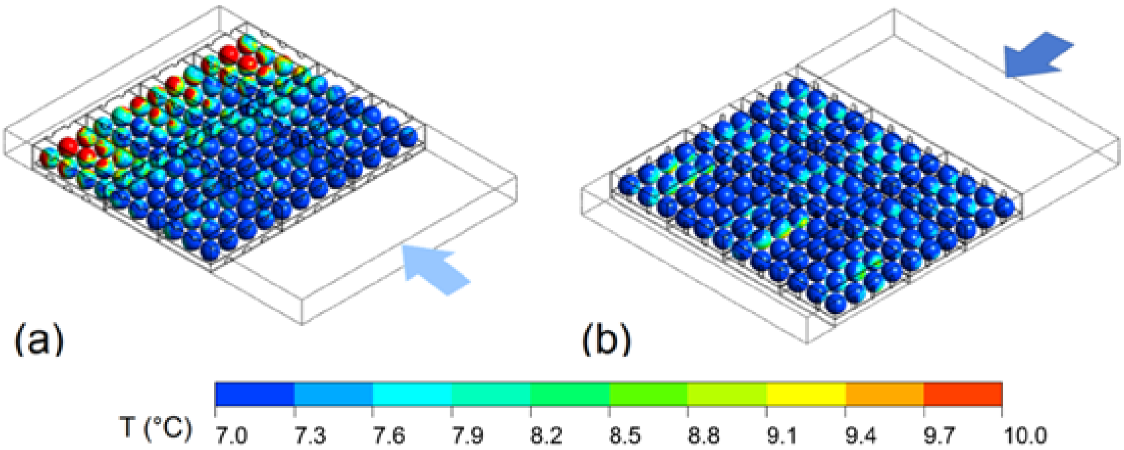

Figure 8. Comparison of the uniformity of horizontal airflow in a layer of stacked containers. Old model (a) and modified (b).

CONCLUSIONS

In this study, experiments and numerical simulations using the computational fluid dynamics code of ANSYS® CFX™ were carried out to characterize the pressure loss, airflow patterns, and temperature distributions during forced-air precooling of pomegranate fruit.

Experiments and simulations highlighted the importance of package design and added packaging material like plastic lining on the airflow and cooling performances. The study demonstrated the specific characteristics of the pomegranate packaging system compared to fruits like apple and oranges. The number of fruits box^{-1} was relatively low and they were loosely packed so that the pressure loss inside the box was minimum. Rather, pressure loss due to a sudden contraction, as air enters and leaves individual boxes in a stack, is dominant. Hence, in the FAC of pomegranate fruit, modification of package design had a significant influence on the aerodynamic and thermodynamic performances.

During the precooling of palletized pomegranate, the high and low temperature regions depend considerably on the package design. This is important information when designing a control system to manage the cooling operation. Especially during long storage of pomegranates or during long distance transportation, monitoring critical regions inside the stack would be very crucial for proper control of cooling process. As clearly demonstrated in this study the critical regions depend on the packaging design.

A liner is essential for the postharvest handling of pomegranates. It reduces the weight loss from fruit by acting as a barrier to moisture transport from fruit to the bulk air.

However, it increased airflow resistance and reduced convective heat transfer from produce, leading to increased cooling time and energy use. This study highlighted that the degree of flow resistance of liners in a package depend on package design (vent-hole size and location).

ACKNOWLEDGEMENTS

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