DEM-CFD of cooling of packed fruit using 3D shape models

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Abstract

Cooling of freshly harvested produce is crucial for maintaining a high product quality for a prolonged storage period and to reduce postharvest losses. Modelling the cooling process of packed horticultural produce provides a means for improving package designs and cooling operations. In this work, a methodology to more accurately model the cooling process of randomly stacked produce in packages is presented. First, a validated geometrical 3D shape model generator of apple fruit is used to create realistic CAD models. The generator also considers the biological variability of the produce shape to create a database of more than 100 representative fruits of each cultivar. A discrete element model (DEM) then randomly selects surface meshed bodies from the database to simulate the gravitational packing of produce in a designated box or bin. The resulting stacking pattern of the produce is used to generate a computational fluid dynamics (CFD) model. The CFD model solves the airflow, heat and mass transfer through the packages to evaluate the aerodynamic and cooling performance of packages under different conditions and configurations. The difference between using actual 3D fruit shapes and an approach using equivalent spheres is demonstrated in a simulation study of forced airflow cooling of apple fruit (cv. Braeburn) packed in a "Supervent" telescopic corrugated fibreboard package under typical precooling conditions. The results are analysed in terms of pressure drop characteristics, velocity profiles and distribution of cooling rates expressed by local surface heat transfer coefficients.

Keywords: Precooling, Apples, CAD models, packaging, randomised stacking, cooling efficiency

1. Introduction

Upon harvest, pome fruits such as apples and pears are collected in bins after which they are transported to cooling facilities where the field heat is removed rapidly. A fast removal of field heat is crucial in order to retain a high product quality (Thompson et al. 2008). Forced-air cooling (FAC) is the most commonly used technique to do this is. During FAC, a pressure gradient is applied over a stack of packages to force cold air through it (Brosnan and Sun 2001). Cooling rates and uniformity are influenced, amongst other factors, by air conditions (temperature, speed), package design, stacking arrangements of the fruits inside the package, but also by the fruits themselves (Berry et al. 2016). To improve the cooling process and the subsequent steps in the cold chain of freshly harvested produce, experiments can be conducted. This is, however, a time-consuming, costly endeavour and only reveals cooling trends that indicate certain phenomena (Gruyters et al. 2016). To obtain a more detailed insight in the overall cooling process, numerical models based on Computational Fluid Dynamics (CFD) can offer solace.

CFD has already been applied extensively to simulate the cooling process of produce. Often, the produce is assumed spherical and is either stacked in a specific pattern where all the spheres had the same diameter or at random with a constant or variable diameter (Delele et al. 2008; Defraeye et al. 2014; Tutar, et al. 2009). However, Ferrua and Singh (2011) could improve the FAC process of strawberries by taking the realistic shapes of strawberries into account and by developing a CFD model of the FAC process. This study clearly indicates the added value of using realistic shapes in combination with CFD. However, the development of the strawberry geometries was quite challenging and cumbersome.

The objective of the current study is to present a methodology to model the cooling process of randomly stacked produce in packages in a fast and accurate way. 3D shape models of apples (cv. Braeburn) are used in combination with a discrete element method (DEM) to develop a CFD model that allows investigating the cooling dynamics of apples randomly stacked in a Supervent box design in detail. A comparison between models that use either the actual shape of the apple fruit or a representative spherical geometry with the same hydraulic radius is made with a FAC simulation.

2. Materials and Methods

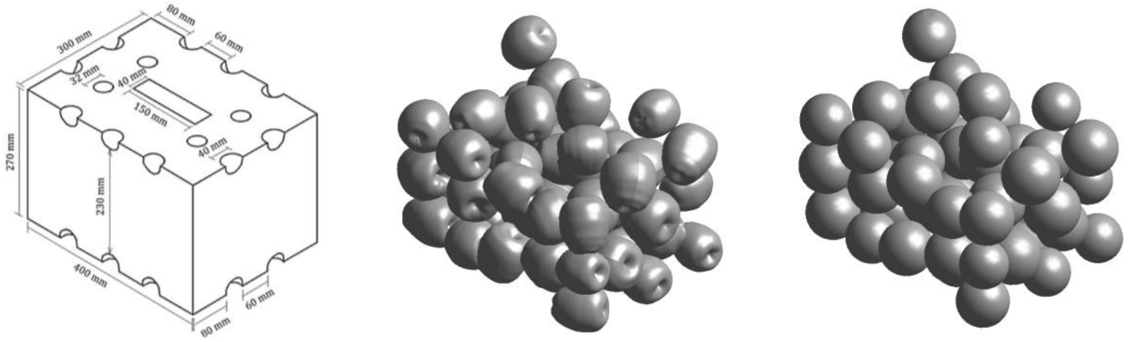
2.1. Geometry development

The box design used in this study is the 'Supervent', a telescopic corrugated fibreboard box design that has been shown to have beneficial airflow characteristics compared to other designs (Defraeye et al., 2013; 2014; 2016). The "Supervent" has as outer dimensions (400 mm × 270 mm × 300 mm) and is randomly filled with realistic apple geometries (Figure 1).

Realistic apple shapes are developed with a validated geometrical 3D shape model generator (Rogge et al. 2014; 2015). Based on non-destructive X-ray CT images of an apple (*Malus x domestica Borkh.* cv. Braeburn) and shape description techniques, the 3D contour of the apple is described with shape descriptors. By scanning a large batch of fruit, an extensive dataset of shape descriptors can be developed. Next, the covariance decomposition algorithm (Rubinstein 1981) is applied on the dataset of shape descriptors to create new sets of shape descriptors that can be transformed into new geometrical models. The end result is a database of more than 100 realistic apple geometries that takes into account the biological variability of the apple cultivar.

The discrete element method (DEM) is then applied to simulate the gravitational packing of 55 apples in the Supervent (Smeets et al. 2014; 2015). Each surface meshed body in the DEM simulation is randomly selected from the database. Subsequently, all forces acting on the colliding bodies in each time step are calculated after which Newton’s law of motion is integrated to obtain the position of the bodies at the next time step (Tijskens et al. 2003). The final result is a random stacking pattern of apples in the Supervent.

The stacking pattern of equivalent spheres is developed by calculating the Cartesian coordinates of the mass centre and hydraulic radius of each individual apple fruit. Then, the stacking pattern of the apples is reconstructed with regular spheres having an equivalent radius as the corresponding apple. The porosity (ε) of the fruits inside the box is kept the same for both stacking arrangements and is approximately 58.4%. The total surface area of the produce in the stacking pattern of the equivalent spheres is 6.3% lower than that of the apples. Figure 1 shows the model geometry of the Supervent and the stacking arrangement of the apples and spheres in the box



Supervent box design **Braeburn** **Equivalent spheres**

Figure 1. The geometry design of the Supervent (left); the stacking patterns of the Apples (middle); the stacking pattern of the equivalent spheres (right)

2.2. Model formulation

In the present work, forced airflow cooling of apple fruit (cv. Braeburn) packed in the Supervent box design is simulated by means of a resolved CFD model, meaning that transport phenomena in the airspaces between the fruit are explicitly resolved without applying averaging. Steady state airflow and heat transfer are considered with constant fruit surface temperature. Heat transfer inside the fruit can be solved as well to study the transient cooling dynamics, but was outside the scope of the present study. Rather, convective heat transfer coefficients at the fruit surfaces are calculated as a means for analysing heat transfer rate and uniformity. Figure 2 shows the configuration and the boundary conditions that are implemented in the steady-state heat transfer simulation of a single box filled with apple fruits and cooled by a horizontal airflow. The Supervent and the apples are modelled as a solid domain and the free-stream air as a fluid domain with properties such as specific heat capacity, density and thermal conductivity, obtained respectively from (Sweat 1974; Ho, et al. 2010; ASHRAE 2006). A uniform velocity inlet with medium turbulence (5%) is applied. Three different airflow rates are assessed, namely 1, 2, 3 l (kg produce)$^{-1}$ s^{-1} which are realistic values for FAC of apples (Brosnan and Sun 2001). The temperature of the apples is set to 20 °C, the air temperature to 0 °C. A zero static pressure boundary condition with mass conservation is selected at the outlet of the air domain. The sides along the computational domain are modelled as symmetry planes, thus representing multiple similar boxes in a stack. Reynolds-averaged Navier-Stokes (RANS) equations in combination with the shear stress transport k-ω turbulence model (SST k-ω model) are used (Launder and Spalding 1974; Menter 1994). The SST k-ω turbulence model applies standard wall functions to model scalar exchange at the surface of the produce with the environment (Defraeye et al. 2013). To accurately model the flow quantities in the boundary-layer region, a high grid resolution is required (i.e. small y+-values). The average y+-value for the realistic stacking pattern and the spherical representation is 9.47 and 12.75, respectively. It should be noted, however, that the requirements for properly using wall functions are y+-values that lie between 30 and 500 (Defraeye et al. 2012).

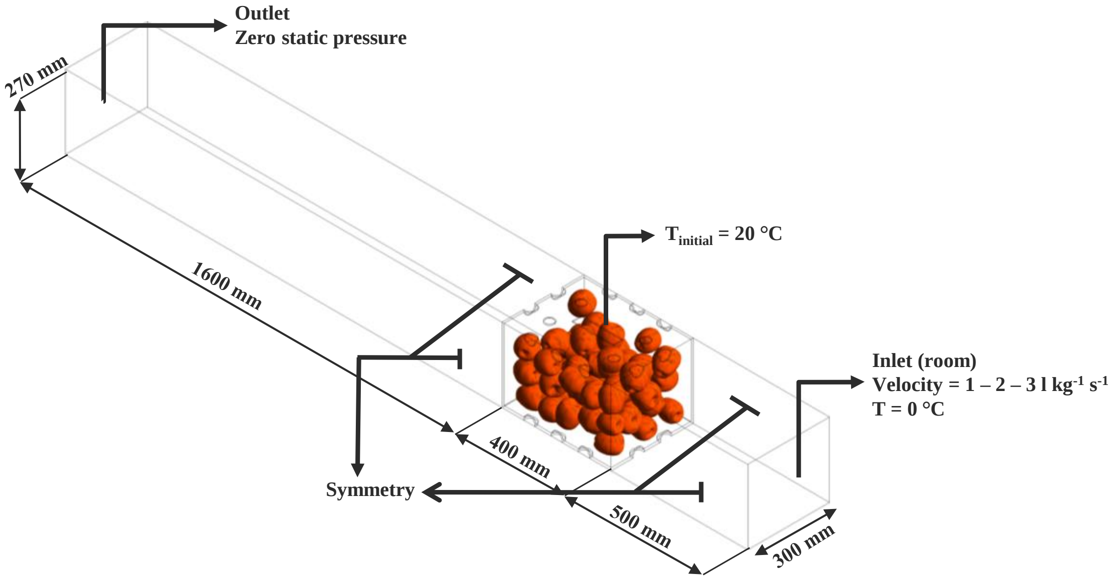


Figure 2. The schematic view of the simulation setup of the forced airflow cooling process of apples. The airflow enters the computational domain from the right hand side.

2.3. Solution procedure

The solutions of the simulations are obtained with the CFD code of ANSYS CFX 16.2 that uses the control volume method. All domains are discretised using hexahedral and tetrahedral mesh elements. A total of 3.89×10^6 and 3.99×10^6 cells are used in the simulations of the spheres and apples, respectively. Richardson extrapolation (Celik et al. 2008; Roache 1994) is used to estimate the average spatial discretisation error and is maximally 0.4% for the pressure drop over the Supervent and 1.7% for the heat flux from the apples. Iterative procedure is evaluated by monitoring the turbulent kinetic energy, mass imbalance, temperature and velocity on specific locations in the flow field and is stopped when the convergence criteria of 10^{-7} for each parameter is reached. The simulations are performed on a 64-bit Intel® Xeon® CPU E5-2630, 2.3 GHz, 128 GB RAM, Windows 7 PC.

3. Results and Discussion

Figure 3 shows the velocity contours of both stacking patterns at three different vertical cross sections of the Supervent with an inlet velocity set to 2 l (kg produce)$^{-1}$ s^{-1} or about 0.27 m s^{-1}. It can clearly be seen that there is a high degree of velocity heterogeneity inside the Supervent. The vent hole locations allow for the distribution of air along the top and bottom walls of the Supervent and thereby causing it to bypass the fruits located in the middle of box. In the middle of the stack, a zone of very low airflow velocities can be observed whereas the top and bottom regions are characterised by high airflow velocities. The velocity contours are similar for both stacking patterns.

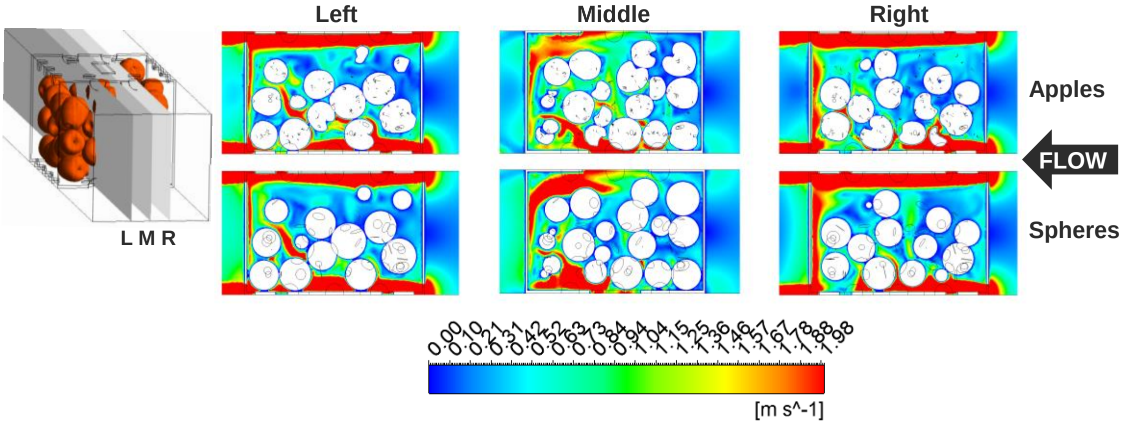


Figure 3. Velocity contours of three positions in the flow direction at 2 l (kg produce)$^{-1}$ s^{-1} or about 0.27 m s^{-1}. On the left hand side, a schematic overview of the different locations is presented.

Only a small difference (<2%) between the pressure drops over the Supervent filled with the different stacking geometries is noticed (Table 1). The reason for this observation is that the porosity inside the Supervent is kept the same for each stacking geometry. Furthermore, the major contributor to the pressure drop is the box design and not the stacked fruit inside the box. If the pressure drop over the stacked fruit inside the box is considered, much larger differences can be observed. The pressure drop over the simplified geometry is much larger (> 19.5%) than is the case for the realistic geometry. Further analysis is required to explain the observations.

The cooling heterogeneity is discussed with the convective heat transfer coefficient that is calculated by Eq. (1).

$$h = \frac{q_{c,w}}{T_w - T_{ref}} \tag{1}$$

where h is het convective heat transfer coefficient at the surface of the fruits (W m^{-2} K^{-1}), $q_{c,w}$ is the convective heat flux at the fruit-air interface (J s^{-1} m^{-2}), T_w is the temperature at the surface of the fruit (293.15 K) and T_{ref} is the reference temperature, equal to the incoming air temperature (273.15 K). Based on the local values of h, the heterogeneity in heat exchange inside the Supervent can be evaluated. Figure 3 shows the distribution of h on the surface of the simulated apples and spheres. The simplified representation of the stacking geometry with spheres shows a more uniform distribution but also much lower values of h in comparison to the realistic representation with the apples. The average h-value between both stacking geometries differs more than 25%. This indicates that the heat exchange and thus the cooling rate is severely underestimated when a simplified geometry is used to simulate the cooling process of produce. In general, high h-values are observed near the vent holes where there is a high air velocity and thus, high turbulence levels that aid in fast heat transfer. Low h-values are observed in the middle of the stacking geometry. Table 1 presents a summary of the simulations conducted with three different inlet velocities.

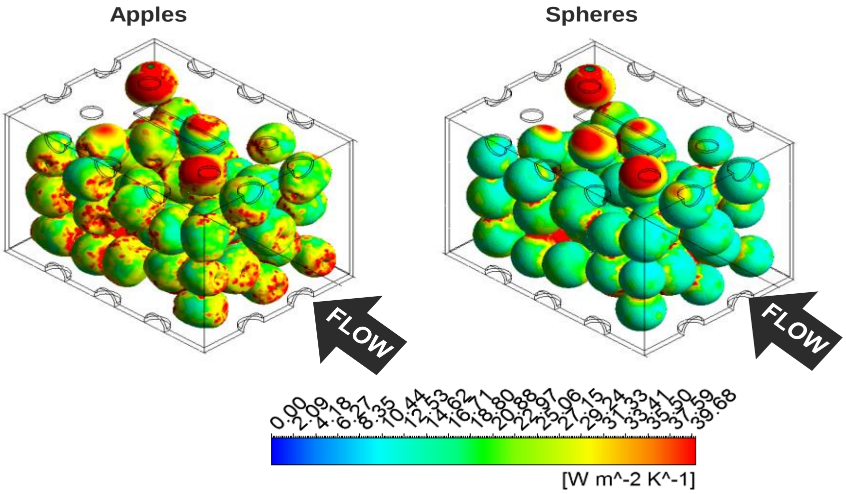


Figure 4. Contour plot of the wall heat transfer coefficient at the surface of the simulated apples and spheres at 2 l (kg produce) $^{-1}$ s^{-1} or about 0.27 m s^{-1}. The airflow enters the computational domain from the right hand side.

Table 1. Summary of the simulations

	1 l s-1 kg-1		2 l s-1 kg-1		3 l s-1 kg-1	
	Spheres	Braeburn	Spheres	Braeburn	Spheres	Braeburn
Pressure drop over Supervent (Pa)	35.9	35.2	143.3	141.2	323.9	318.8
Pressure drop over apples (Pa)	0.36	0.27	1.63	1.35	4.04	3.27
Average h (W m-2 K-1)	20.99	31.75	24.46	34.96	28.64	38.65
Difference in pressure drop over supervent (%)	1.99		1.49		1.60	
Difference in pressure drop over apples (%)	33		21		24	
Difference in average h (%)	34		30		26	

The cooling heterogeneity can also be discussed by analysing the relative frequency distribution of the normalised h value. This value is calculated by dividing the h-value of each computational cell on the surface of the fruits by the area average value of h over all the fruit surfaces. Fruits that show low values of this parameter exhibit a slower cooling process in comparison to the rest of the fruits in the Supervent. Figure 5 shows the relative frequency distribution of the normalised h-value for the two stacking geometries. The simplified geometry shows a rather sharp peak around the value of one and a small spread, indicating a rather uniform cooling process. Using more realistic produce shapes also shows a peak around one but has a larger spread. Therefore, a higher degree of cooling heterogeneity can be expected in this configuration. Ideally, the relative frequency distribution of the normalised *h* value should have a very sharp peak near 1 and a small spread.

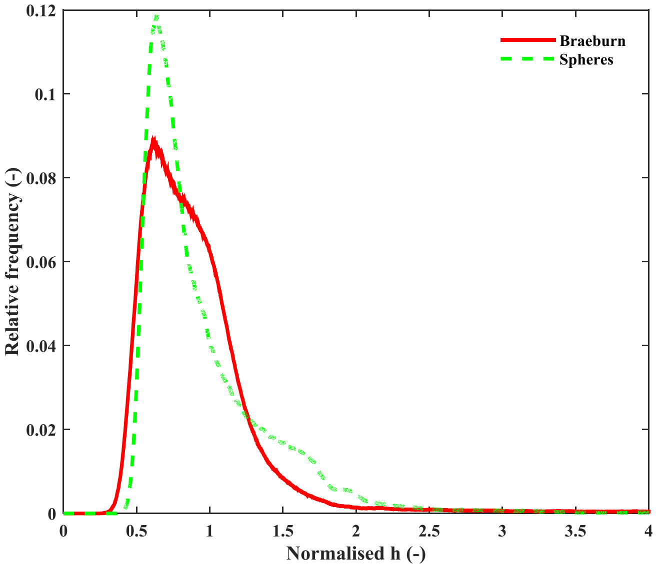


Figure 5. The relative frequency distribution of the normalized surface wall heat transfer coefficient of every computational cell on the surface of the stacking geometry of apples and spheres at 2 l (kg produce)$^{-1}$ s^{-1} or about 0.27 m s^{-1}.

In general, large differences between the two configurations in terms of *h*-values and the pressure drop over the stacked fruits are apparent. The low y+-value used in this study in combination with the standard wall functions could partially explain these observations. The *h*-values are calculated in the first computational cell at the surface of the produce. For the simplified geometry, a larger y+-value is used and thus, the *h*-values are calculated at a slightly larger distance from the surface of the produce. Furthermore, wall functions are used to calculate the scalar exchange at the surface of the produce. Since the y+-values are lower than is required for the wall functions, it could lead to inaccurate calculations. On the other hand, by decreasing the y+-values even more, low Reynolds number modelling (LRNM) can be applied. This technique allows to explicitly resolve the transport phenomena in the boundary layer and thus, to obtain very detailed information of the phenomena that occur at the boundary layer. Further investigation is, however, required.

4. Conclusions

A methodology is developed to model the cooling process of randomly organised and realistically shaped apple fruits in packages. While the pressure drop over the package was not affected by product shape to a large extent, the cooling behaviour of apples during FAC appeared to be underestimated by more than 25% when using a simplified geometry. This important finding will need to be verified by additional simulations with different stacking patterns, and an elaborate analysis of the turbulence simulations by means of low Reynolds number modelling.

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References

ASHRAE. 2006. *2006 ASHRAE Handbook: Refrigeration*. SI edition. Atlanta: American Society of Heating, Refrigerating & Air-Conditioning Engineers, Inc.

Berry, Tarl M., Thijs Defraeye, Bart M. Nicolaï, and Umezuruike Linus Opara. 2016. “Multiparameter Analysis of Cooling Efficiency of Ventilated Fruit Cartons Using CFD: Impact of Vent Hole Design and Internal Packaging.” *Food and Bioprocess Technology*. doi:10.1007/s11947-016-1733-y.

Brosnan, Tadhg, and Da-wen Sun. 2001. “Precooling Techniques and Applications for Horticultural Products - a Review.” *International Journal of Refrigeration* 24: 154–70.

Celik, Ismail B., Urmila Ghia, Patrick J. Roache, and Christopher J. Freitas. 2008. “Procedure for Estimation and Reporting of Uncertainty due to Discretization in CFD Applications.” *Journal of Fluids Engineering*.

Defraeye, Thijs, Els Herremans, Pieter Verboven, Jan Carmeliet, and Bart Nicolai. 2012. “Convective Heat and Mass Exchange at Surfaces of Horticultural Products: A Microscale CFD Modelling Approach.” *Agricultural and Forest Meteorology* 162-163 (September). Elsevier B.V.: 71–84. doi:10.1016/j.agrformet.2012.04.010.

Defraeye, Thijs, Rutger Lambrecht, Mulugeta A. Delele, Alemayehu Ambaw Tsige, Umezuruike Linus Opara, Paul Cronjé, Pieter Verboven, and Bart Nicolai. 2014. “Forced-Convective Cooling of Citrus Fruit: Cooling Conditions and Energy Consumption in Relation to Package Design.” *Journal of Food Engineering* 121 (January). Elsevier Ltd: 118–27. doi:10.1016/j.jfoodeng.2013.08.021.

Defraeye, Thijs, Rutger Lambrecht, Alemayehu Ambaw Tsige, Mulugeta A. Delele, Umezuruike Linus Opara, Paul Cronjé, Pieter Verboven, and Bart Nicolai. 2013. “Forced-Convective Cooling of Citrus Fruit: Package Design.” *Journal of Food Engineering* 118 (1). Elsevier Ltd: 8–18. doi:10.1016/j.jfoodeng.2013.03.026.

Defraeye, Thijs, Bart Nicolai, Wayne Kirkman, Sean Moore, Sonnica van Niekerk, Pieter Verboven, and Paul Cronj?? 2016. “Integral Performance Evaluation of the Fresh-Produce Cold Chain: A Case Study for Ambient Loading of Citrus in Refrigerated Containers.” *Postharvest Biology and Technology* 112. Elsevier B.V.: 1–13. doi:10.1016/j.postharvbio.2015.09.033.

Defraeye, Thijs, Pieter Verboven, and Bart Nicolai. 2013. “CFD Modelling of Flow and Scalar Exchange of Spherical Food Products: Turbulence and Boundary-Layer Modelling.” *Journal of Food Engineering* 114 (4). Elsevier Ltd: 495–504. doi:10.1016/j.jfoodeng.2012.09.003.

Delele, Mulugeta A., E. Tijskens, Y.T. Atalay, Q.T. Ho, H. Ramon, Bart M. Nicolaï, and Pieter Verboven. 2008. “Combined Discrete Element and CFD Modelling of Airflow through Random Stacking of Horticultural Products in Vented Boxes.” *Journal of Food Engineering* 89 (1): 33–41. doi:10.1016/j.jfoodeng.2008.03.026.

Ferrua, M. J., and R. P. Singh. 2011. “Improved Airflow Method and Packaging System for Forced-Air Cooling of Strawberries.” *International Journal of Refrigeration* 34 (4). Elsevier Ltd and IIR: 1162–73. doi:10.1016/j.ijrefrig.2011.01.018.

Gruyters, Willem, Alemayehu Ambaw, Ann Schenk, S. G. Gwanpua, A. Geeraerd, Pieter Verboven, and Bart Nicolai. 2016. “A CFD Study of Adapting on-off Cooling Cylces in Apple Cold Stores for Energy Saving.” In *4th IIR Conference on Sustainability & the Cold Chain*, 1–8. Auckland, New Zealand.

Ho, S. H., M. M. Rahman, and A. K. Sunol. 2010. “Modelling of the Thermal Response of a Multi-Tray Food Self-Heating Unit” 68: 123–34. doi:10.2495/HT100111.

Launder, B.E., and D.B. Spalding. 1974. “The Numerical Computation of Turbulent Flows.” *Computer Methods in Applied Mechanics and Engineering* 3 (2): 269–89. doi:10.1016/0045-7825(74)90029-2.

Menter, F. R. 1994. “Two-Equation Eddy-Viscosity Turbulence Models for Engineering Applications.” *AIAA Journal* 32 (8): 1598–1605.

Roache, Patrick J. 1994. “Perspective: A Method for Uniform Reporting of Grid Refinement Studies.” *Journal of Fluids Engineering* 116: 405–13.

Rogge, Seppe, Shiferaw D. Beyene, Els Herremans, Maarten L. Hertog, Thijs Defraeye, Pieter Verboven, and Bart Nicolai. 2014. “A Geometrical Model Generator for Quasi-Axisymmetric Biological Products.” *Food and Bioprocess Technology* 7: 1783–92.

Rogge, Seppe, Thijs Defraeye, Els Herremans, Pieter Verboven, and Bart M. Nicolaï. 2015. “A 3D Contour Based Geometrical Model Generator for Complex-Shaped Horticultural Products.” *Journal of Food Engineering* 157. Elsevier Ltd: 24–32. doi:10.1016/j.jfoodeng.2015.02.006.

Rubinstein, Reuven Y. 1981. *Simulation and the Monte Carlo Method*. New York, USA: John Wiley and Sons.

Smeets, Bart, Tim Odenthal, Janos Keresztes, Simon Vanmaercke, Paul Van Liedekerke, Engelbert Tijskens, Wouter Saeys, Hans Van Oosterwyck, and Herman Ramon. 2014. “Modeling Contact Interactions between Triangulated Rounded Bodies for the Discrete Element Method.” *Computer Methods in Applied Mechanics and Engineering* 277 (August). Elsevier B.V.: 219–38. doi:10.1016/j.cma.2014.04.017.

Smeets, Bart, Tim Odenthal, Simon Vanmaercke, and Herman Ramon. 2015. “Polygon-Based Contact Description for Modeling Arbitrary Polyhedra in the Discrete Element Method.” *Computer Methods in Applied Mechanics and Engineering* 290. Elsevier B.V.: 277–89. doi:10.1016/j.cma.2015.03.004.

Sweat, F. E. 1974. “Experimental Values of Thermal Conductivity of Selected Fruits and Vegetables.” *Journal of Food Science* 39 (6): 1080–83.

Thompson, J. F., F. Gordon Mitchell, Tom R. Rumsey, Robert F. Kasmire, and Carlos H. Crisosto. 2008. *Commercial Cooling of Fruits, Vegetables, and Flowers*. California: University of California.

Tijskens, E., H. Ramon, and J. De Baerdemaeker. 2003. “Discrete Element Modelling for Process Simulation in Agriculture.” *Journal of Sound and Vibration* 266: 493–514. doi:10.1016/S0022-460X(03)00581-9.

Tutar, Mustafa, Ferruh Erdogdu, and Burak Toka. 2009. “Computational Modeling of Airflow Patterns and Heat Transfer Prediction through Stacked Layers’ Products in a Vented Box during Cooling.” *International Journal of Refrigeration* 32 (2): 295–306. doi:10.1016/j.ijrefrig.2008.05.003.