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CFD Parametric Study of Thermal Performance of Different Fruit Packaging Box Designs

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Abstract. Air temperature and relative humidity values of cold storage conditions are the major factor affecting the perishability of fresh fruits. The sooner the field heat is extracted from the products and the proper temperature is maintained consistency throughout the cold chain, larger it will be shelf life of these products. Forced air cooling is the most commonly used technique to remove the field heat in post-harvest storage. Energy-efficient and quality-oriented cold storage mainly depends on the time to remove the heat. This time can be reduced by optimizing the configuration of the vent holes of the packaging box, namely it dimension (area), it shape, alignment and position. This paper shows the numerical predictions of air temperature and velocity by a CFD parametric study of eight different vent hole configurations. These configurations consider a packaging box with double wall. The vent holes of each wall have different dimension and shape. The vent holes of both walls can be also aligned or unaligned. The analysis of results aims to determine the best configurations that improve the cooling rate, the airflow and temperature uniformity. The numerical predictions of the air temperature show close values, but three configurations can be identified as predicting the lowest air temperature values with lowest standard deviation. These results may help on the development of new configuration for fruit boxes that promote the extension of the fruits shelf life.

INTRODUCTION

Peach fruit appearance, aroma, and juicy texture attract consumers around the globe. Since these fruits are perishable, convenient post-harvest management ensures to deliver a high-quality product to the end customers [1]. Most efficient packaging box keeps the fruits from the mechanical damage during transport and handling and must be also able to remove the field heat in the short duration and provide uniform cooling during storage [2]. Increasing the vent area of the packaging box reduces pressure across the container but it reduces the structural stability of the container. Several authors [3-4] show that aerodynamic airflow by modifying the vent area within the packaging box tends to reduce the overall energy consumption with uniform airflow. Vent opening area plays a major role in the packaging box where the position is considered more than the shape and if the total opening area is less than 25% it restricts the airflow with the lower cooling rate increasing the cooling cost [2]. Airflow pattern, temperature, and humidity levels are essential for the good shelf life of products in the ventilated packaging box [5]. Generally, the packaging design can be more reliable when comparing both numerical and experimental results. Since these transport phenomenon airflow, heat and mass transfer are complex, coupled process mathematical models are more reliable and used widely. The objective of this study is to develop 3D CFD transient model to predict the airflow and thermal behavior within eight different packaging boxes having a varying vent hole configurations.

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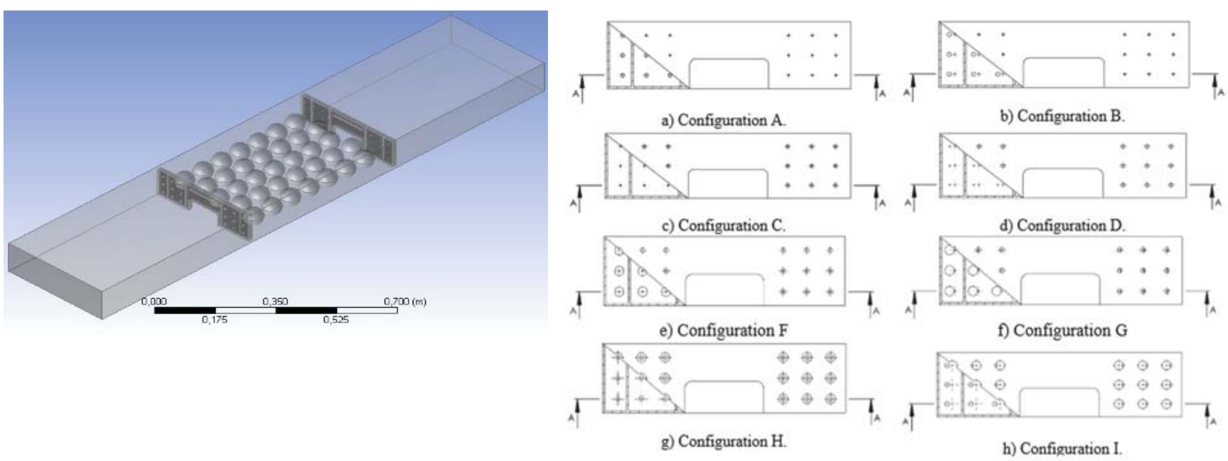
MATERIALS AND METHODS

Computational Methods

Recent advances in the numerical methods and computational tools are extensively used to analyse and modify the design of the horticulture storage [6]. The fluid flow, heat transfer during the transport and cold storage in the post-harvest of agricultural products are predicted by different mathematical models. The set of governing equations tends to predict mass, momentum and heat transfer by solving numerically the computational fluid dynamics (CFD) [10]. CFD model discretizes the complete domain into a set of control volumes and solves numerically in the constrained fluid domain. In the current study, the CFD model development and results analysis is performed using the commercial CFD software Ansys V16. The model needs to be discretized into pre-processing, solver and post-processing to perform the computational analysis.

Geometry Setup

3D model of the packaging box with fruits are modeled using the ANSYS Design Modeler. The box is modeled with 35 fruits per each box. To simplify the model, and considering that the airflow has the direction of the hand hole opening, the lateral and top walls were neglected, as boxes are aligned and stacked in a pallet. The lateral walls of the box are removed as the flow mainly depends on the axial vents facing front towards the flow and in a pallet other boxes are leaning against. To provide a simulation of the air flow inside the box without disturbance of the placement of the external boundary conditions of air flow inlet and pressure outlet, a long duct with dimensions of 1.8m×0.38m×0.11m as shown in Fig. 1 was defined. The peach storage box is modelled with vent and hand holes as shown in Fig. 2. For computational approximation, each peach is modelled as a sphere with a diameter of 62 mm. Six boxes having different vent hole configurations are tested to predict the airflow behavior inside the box. Ansys meshing tool was used to build the computational mesh. Quality checks were performed in the solver to identify the low-quality elements.

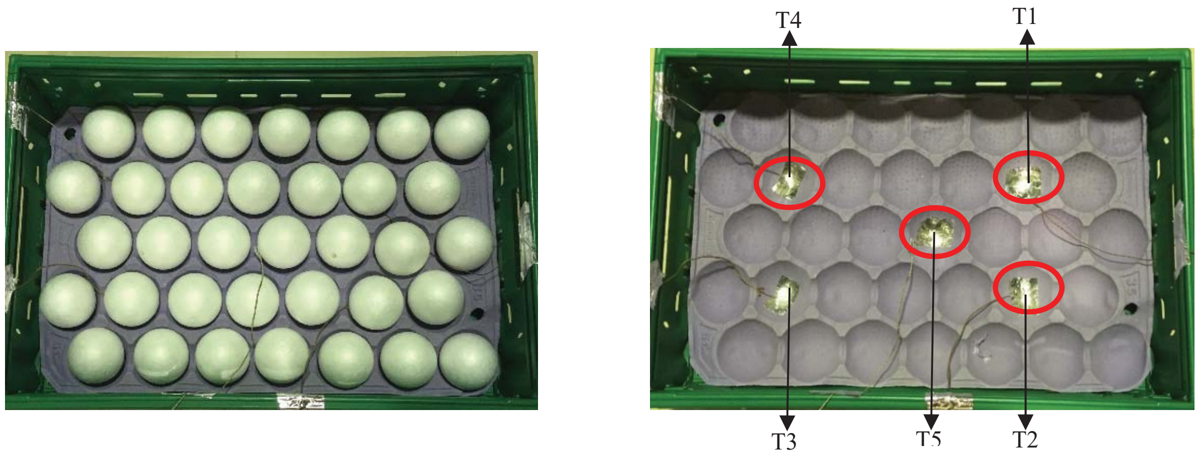


a) 3D model of packaging box with fruit model. b) Vent hole configuration.

FIGURE 1. 3D model of packaging box with fruit model

Numerical Model and Setup

The unsteady flow is solved using Reynold's-average Navier-Stokes equation. Governing equations for conservation of mass, conservation of momentum and conservation of energy are solved. Shear stress transport (SST) k-ω model is used in this study, as most of the previous cold storage applications [7] have successfully followed this model to predict the flow behavior. Spheres representing the peach fruits and detailed design of the box stored in duct were modelled. The outer diameter of fruit is considered as walls. At its external wall is set the ambient air temperature of T = 295 K. In the CFD model, the boundary condition must be defined at each surface on the fluid domain. The boundary conditions used in the model are air flow Inlet, air flow Outlet, and Wall. The air flow Inlet is set with constant velocity of U = 0.48 m/s with refrigerated airflow inlet temperature of Tinlet = 278 K. These values were obtained by experimental measurements of flow velocity and air temperature in pack of peach boxes in a refrigerated testing climatic chamber. A carton alveoli was placed inside each box. 35 polystyrene balls were placed in the carton alveoli as shown in Fig. 2 a). The alveoli was instrumented with 5 T-type thermocouples symmetrically distributed as shown in Fig. 2 b).



a) Carton alveoli with polystyrene balls inside the box. b) Carton alveoli instrumented with 5 T-type thermocouples.

FIGURE 2. Instrumented pack of boxes inside the refrigerated climatic chamber.

RESULTS AND DISCUSSION

Cooling rate and uniformity of the boxes were identified by the contour plots obtained from the analysis at the specific point and plane across the box. For reference, three section planes are introduced at the three different co-ordinates. These section planes were set to evaluate the details of airflow and thermal behavior of the box inside the duct. The temperature contours of Models A and B are shown in Fig. 3. The horizontal plane at each box allow to conclude that the field heat from the products is removed at a higher rate in the centre, when compared to the other regions inside the box. As less is the airflow resistance, higher is the temperature removal. Further, the vertical plane section along B and G configurations have better airflow near the lateral wall than the D and H configurations. Additionally, the fruit cooling rate (wall temperature) after the simulation shows that maximum temperature is removed from configuration A. Airflow within the packaging A is more even and with respect to time comparing all other boxes it has more thermal homogeneity and better thermal removal within the box. The converged values of average, minimum and maximum air temperature and its standard deviation in the plane sections describe above obtained after the solver process are shown in Table 1.

TABLE 1. Temperature prediction planes inside the different packaging boxes models.

Setup	T_{avg} [K]			T_{min} [K]			T_{max} [K]			Standard deviation [K]			T_{wall} [K]	
	Box	Mid	L	Box	Mid	L	Box	Mid	L	Box	Mid	L	Init.	Final
A	**279.0**	**278.9**	**278.9**	277.9	277.9	277.0	**290.1**	**290.1**	**290.1**	**1.62**	1.49	1.65	295	**284.0**
B	279.2	279.1	278.8	277.9	277.9	278.0	290.8	290.8	290.8	1.65	1.30	**1.61**	295	**284.1**
C	279.1	279.1	278.9	277.9	277.9	277.9	291.0	291.0	291.0	1.76	1.40	**1.61**	295	284.5
D	279.9	279.7	279.8	277.9	277.9	277.9	290.9	290.9	290.9	1.89	1.71	1.84	295	284.4
F	278.9	**278.8**	279.0	277.9	277.0	277.9	290.7	290.7	290.7	**1.64**	1.32	1.89	295	284.5
G	**279.0**	279.0	**278.9**	277.9	277.9	277.0	290.6	290.6	290.6	**1.68**	**1.28**	1.69	295	**284.4**
H	279.1	278.9	279.2	277.9	277.9	277.9	290.6	290.6	290.6	1.80	1.79	**1.52**	295	284.7
I	**279.0**	278.9	279.1	277.9	277.9	277.9	**290.1**	**290.1**	**290.1**	**1.74**	**1.29**	1.76	295	**284.3**

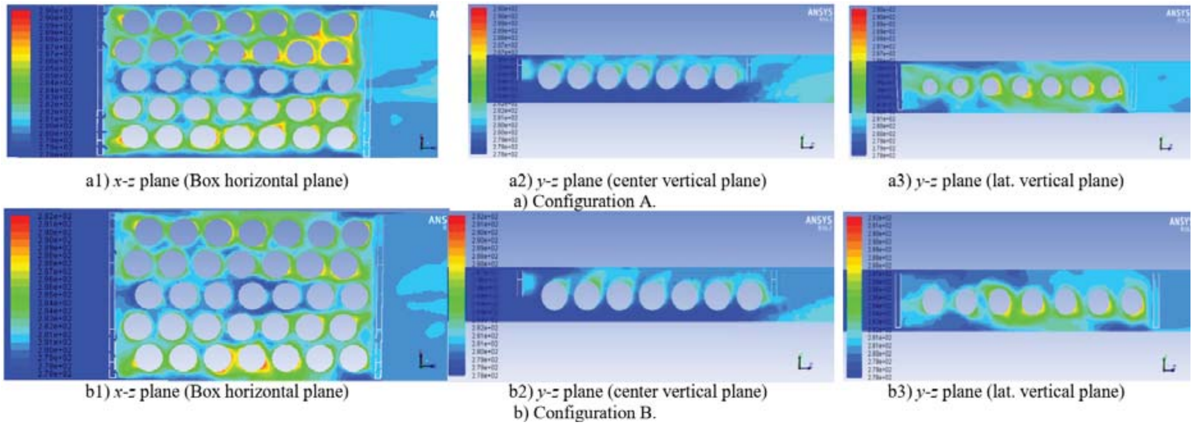


FIGURE 3. Temperature contour profiles along horizontal (*x-z*) and vertical (*y-z*) planes – Setup A and B.

CONCLUSIONS

This work established a 3D transient CFD model to predict the airflow and thermal behavior of peaches stored in a packaging box placed inside a duct using forced air cooling. The airflow pattern and thermal behavior were investigated, and results were gathered for eight different vent hole configurations. The numerical results predict that thermal distribution inside the box is heterogeneous and maximum thermal removal is obtained near the vent holes when compared to the other regions of the box. Difference in vent position and the dimensions shows contrast in the airflow behaviour from the results achieved from Table 1.

It clearly indicates that the thermal distribution is minimum in box with configuration A followed by G and I. The standard deviation values and the average, minimum and maximum temperature values are comparatively small when compared to other vent configuration. The future work aims to develop a complete flow behaviour with pallets placed in the chamber to enhance the time taken to remove the field heat from the products and thus reduces the energy taken in cooling chambers for post-harvest storage.

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REFERENCES

1. I.S. Minas et al. *Environmental and orchard bases of peach fruit quality*. Scientia Horticulturae **235**, 307–322. (2018), doi:10.1016/j.scienta.2018.01.028.
2. P.B. Pathare et al. *Design of packaging vents for cooling fresh horticultural produce*. Food and Bioprocess Technology **5**(6), 2031–2045 (2012), doi:10.1007/s11947-012-0883-9.
3. A. Ambaw et al. *The use of CFD to characterize and design post-harvest storage facilities: past, present and future*. Computers and Electronics in Agriculture **93**, 184–194 (2013), doi:10.1016/j.compag.2012.05.009.
4. J.L. O'Sullivan et al. *Forced-air cooling of polylined horticultural produce: optimal cooling conditions and package design*. Postharvest Biology and Technology **126**, 67–75 (2017), doi:10.1016/j.postharvbio.2016.11.019.
5. Q. Zou et al. *A CFD modeling system for airflow and heat transfer in ventilated packaging for fresh foods: I. Initial analysis and development of mathematical models*. Journal of Food Engineering **77**(4), 1037–1047 (2006), doi:10.1016/j.jfoodeng.2005.08.042.
6. J.-W. Han et al. *CFD simulation of airflow and heat transfer during forced-air precooling of apples*. Journal of Food Process Engineering **40**(2), e12390 (2016), doi:10.1111/jfpe.12390.
7. T.M. Berry et al. *A multi-parameter approach to vent hole design for cartons packed with internal packaging*. Acta Horticulturae **1194**, 1307–1314 (2018), doi:10.17660/actahortic.2018.1194.184.