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NUMERICAL MODELLING OF AIRFLOW AND HEAT TRANSFER WITHIN A MULTI-PACKAGING OF STRAWBERRIES

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KEYWORDS
Heat transfer, CFD, Multi-packaging, Cooling rate, Airtight clamshell.

ABSTRACT

Utilizing multi-layered packaging is crucial for highly perishable products, offering enhanced protection and preservation of their quality. However, the incorporation of various scales in packaging introduces complexities in heat transfer phenomena, necessitating improved ventilation around the package to optimize heat transfer.
This study aimed to develop a Computational Fluid Dynamics (CFD) model to predict the airflow behavior within a half layer of a strawberry pallet. The half layer comprised two trays, each containing 16 airtight clamshells (AC), representing modified atmosphere packaging. Within the ACs, the internal domain was modeled as an equivalent solid block, representing both the air and the strawberries. The primary focus is on understanding the thermal interaction between the airflow around airtight clamshells (AC) and the enclosed product. The numerical model showed a good agreement with experimental results. The proposed model can be potentially used as a design tool to improve the design of tray designs packages in order to improve the cooling efficiency.

INTRODUCTION

Precooling is the most efficient method for removing field heat from harvested horticultural product, ensuring the maintenance of product quality and preservation (Nasser Eddine et al. 2022). The pivotal factor influencing the precooling process, and consequently the cooling rate and uniformity of the products, is packaging (Pathare et al. 2012). Strawberries are commonly packaged in a multi-packaging system, with clamshells serving as primary packaging and trays as secondary packaging (Nasser eddine et al. 2023).
The design of each scale plays an important role in the airflow behavior inside the packages and thus the cooling of the products within it. Conducting experimental studies tends to be costly, time-consuming, and particularly challenging in the case of research involving biological materials (Delele et al. 2013). Different research studies have developed numerical models to overcome the limitation of the experiments in order to analyse the airflow and the heat transfer inside horticultural packages. Two CFD approaches are commonly employed Direct CFD approach (Ferrua and Singh 2009), or porous medium approach (Sajadiye et al. 2013).
In the case of the airtight clamshells such as the case of modified atmosphere packages, the thermal interaction between the air around the clamshells and the products within becomes challenging.
The objective of this paper is to create a simple CFD model to better understand the airflow dynamics within a tray filled with airtight clamshells (AC) and to evaluate the effect of that behavior on the cooling rate and heteregoneity.

NUMERICAL MODELS

Computational domain

The existing industry-standard arrangement for strawberry pallets comprises multiple layers, each containing four trays (Figure 1a). For the purpose of this study, and due to the symmetrical arrangement of the trays on a pallet layer, a half of a pallet layer was considered, equating to two trays.
A three-dimensional model was developed using SpaceClaim 2021.R1. The computational domain is composed of the free airflow fluid zone and the solid tray zones. The detail dimensions of the tray and AC used are presented in Figure 1c and d.
To simplify the problem and to reduce the number of mesh, several hypotheses were made:

- Only half of the trays are modelled, based on the assumption that the packaging system is symmetrical (Figure 1b), which reduced the computational time.
- There was no heat exchange between the different layers of the pallet in height direction.
- Each half tray was filled with 8 airtight clamshells.
- The modeling approach did not involve the direct representation of strawberries within the ACs. Instead, the interior of the ACs was simulated as a solid block with equivalent thermal characteristics. The attributes of this equivalent solid block were defined as follows: ρ=381 kg.m^{-3}; λ=0.12W.m^{-1}.K^{-1}; Cp=4094 J.kg^{-1}.K^{-1}.
- The numerical model incorporated heat transfer mechanisms, encompassing conduction, forced convection, and natural convection.

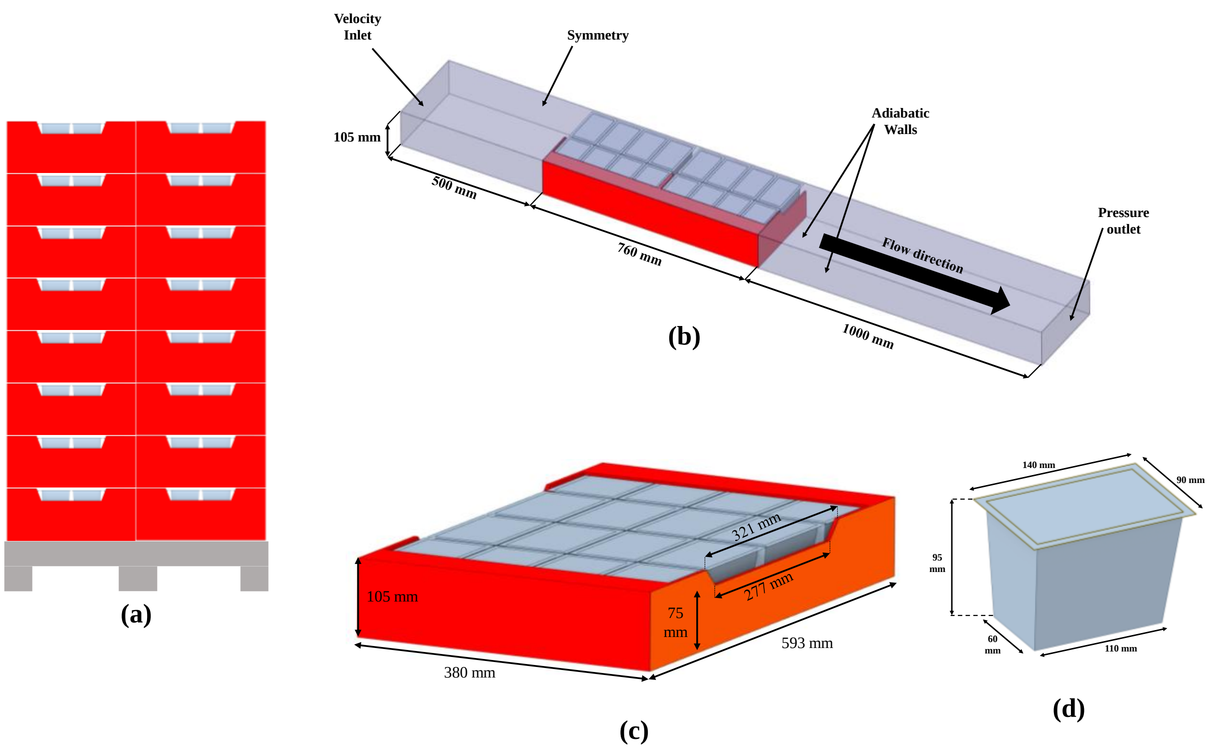

Figure 1: a) pallet, b) CFD model, c) tray dimensions, d) AC dimensions

Meshing

A hybrid mesh (tetrahedral and hexahedral cells) was created for the numerical study with 11 × 10^6 cells. The y+ values for the ACs and tray walls were found to be below 5, which is within the recommended range when utilizing enhanced wall treatment (y+<5).

Boundary conditions

At the domain's inlet, a uniform velocity was set equal to the one experimentally measured. The inlet temperature was set to 4 °C.
At the outlet, an atmospheric pressure was imposed.
The initial temperature of the ACs, trays and the equivalent solid bolcks was taken equal to 20 °C.
Two cases were applies: one that took account the natural convection and the other without natural convection.
The heat transfer and the airflow was solved by means of the Reynolds-averaged Navier- Stokes (RANS) equations. The RANS equations were combined with a standard $k - \varepsilon$ model, with wall functions using Enhanced Wall Treatment. In the case where the natural convection is included, the Boussinesq approximation was used in the model.
The "Coupled" algorithm with second-order upwind technique was applied to solve the pressure-velocity-temperature coupled equations.
The transient simulation operated with a time step of 120 s, with a maximum of 50 iterations per time step.
Simulations were run using a computer with a 2.4 GHz Intel® Xeon® Silver 4210 R CPU and 256 GB of RAM.

The validity of the model under the two cases was evaluated by comparing the HCT and SECT values obtained from models with the HCT and SECT calculated experimentally using the root-mean-square error (RMSE).

Experimental Study

Same experimental setup built by Nasser eddine et al. (2023) was used to conduct this study. The experimental setup was placed inside a controlled room.
However, in this study, the airtight clamshells were filled with 20 PVC strawberries each. These PVC strawberries were filled with carrageenan gel mixture. The thermal properties of this gel mixture closely approximate those of real strawberries (Table 1).

Table 1: Thermophysical properties of real strawberries and carrageenan gel

Property	Strawberries (Wang et al. 2019)	Carrageenan Gel (Agyeman et al. 2023)
λ(W.m^{-1}.K^{-1})	0.56	0.52
ρ(kg.m^{-3})	800	1013
Cp (J.kg^{-1}.k^{-1})	4000	4100

Five strawberries in each of the following ACs 1-2-7-8-9-10-15-16 (Figure 2) were instrumented with T type thermocouples to monitor the temperature during the cooling.

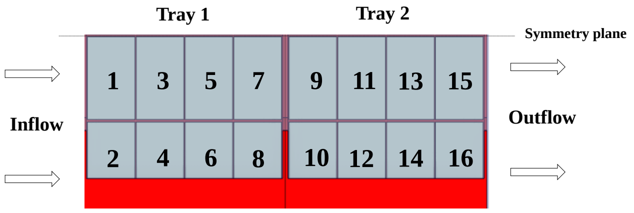

Figure 2: AC numbering; Central zone: ACs 1 ,3 ,5 ,7 ,9 ,11 ,13 ,15; Edge zone: ACs 2, 4 ,6 ,8 ,10 ,12 ,14 ,16

The cold room was first set to 20 °C to ensure uniform product temperatures. The entire experimental setup was then insulated with polystyrene foam, the fans were switched “off “ to prevent air circulation, and the cold room temperature was lowered to 4 °C. After a 30-minute phase of ambient temperature stabilization at 4 °C in the cold room, the polystyrene foam was removed from both the inlet and outlet of the experimental setup, and the fans were turned “on” to start the experiment.
Two cooling performance parameters were used to compare between the numerical and experimental results: Half cooling time (HCT) and seven eight cooling time (SECT).

RESULTS

Experimental validation

Table 2: Results for RMSE (hrs)

	Case-Natural convection included	**Case-Natural convection not included**
HCT (hrs)	0.44	0.42
SECT (hrs)	0.83	0.81

Table 2 presents a comparison of the Root Mean Square Error (RMSE) between experimental and numerical results, considering both cases with and without accounting for natural convection. The conclusion drawn is that, given the inlet velocity in consideration, natural convection can be deemed negligible.

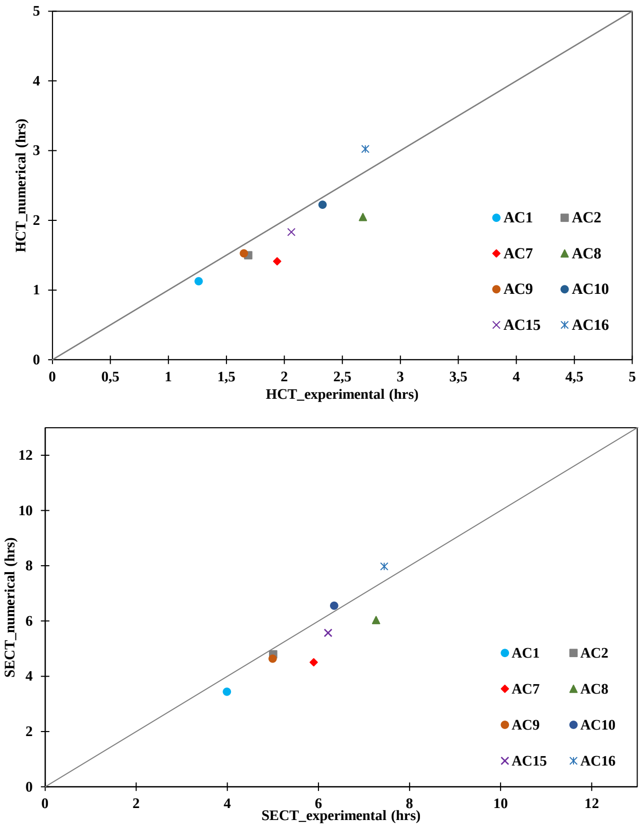

Figure 3: Comparison of the average HCT and SECT obtained from the experimental data and from the numerical model) for the ACs 1,2,7,8,9,10,15,16

Figure 3 compare the experimental HCT and SECT respectively with the predicted values from the numerical model. There is a consistency between the simulation results ad the experimental data. Most HCT and SECT are predicted within ± 20%. The discrepancies observed at some points can be explained by the various parameters governing the simulation and the experimental setup.

Airflow behavior

Figure 4 represents the simulated airflow on the symmetry plane of the two trays using arrows and contour plots for the velocity magnitude.
A portion of the air entering through the primary trapezoidal orifice is directed into the central air pathway along the symmetry plane. Within this pathway, the airflow splits into two distinct streams. The first stream gains horizontal acceleration at the inlet, separating from the top surface. Meanwhile, the second stream undergoes vertical diffusion before returning to a horizontal trajectory. These two streams eventually converge, experience acceleration, and exit through the central orifice. The same pattern is observed in the second tray, where the velocities of the airflow are notably higher.

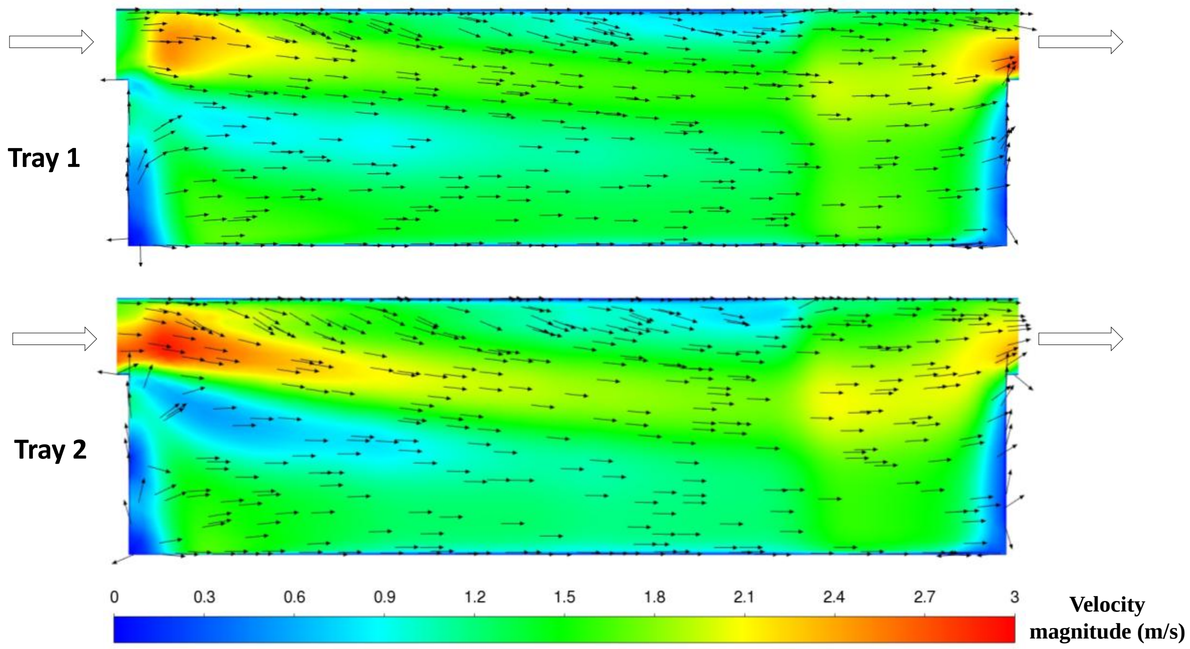

Figure 4: Simulated airflow profile within the vertical symmetry plane of the tray. Colored contours show the magnitude of air velocity, and arrows (vector) indicate the local direction of the airflow

As depicted in Figure 5, the airflow originating from the main orifice also diffuses into the two other pathways at the the edge of the tray, but with lower velocities. Notably, ACs numbered 1, 7, 9, and 15 experience higher ventilation compared to other ACs. This is attributed to their proximity to the orifices, where the airflow from the main orifices diffuses vertically, intensifying the ventilation effect on these specific ACs.

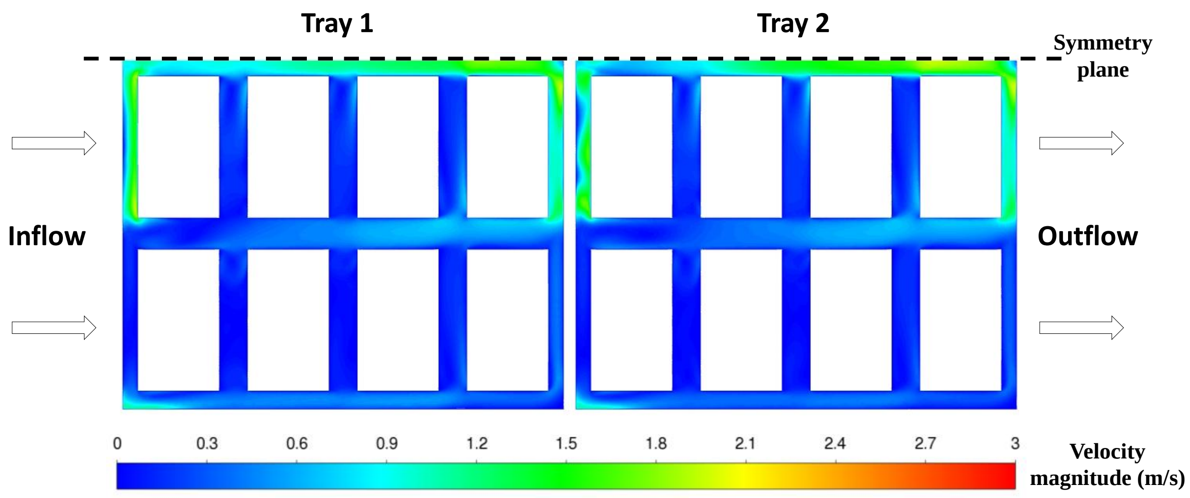

Figure 5: Velocity magnitude profile at the mid-height of the ACs

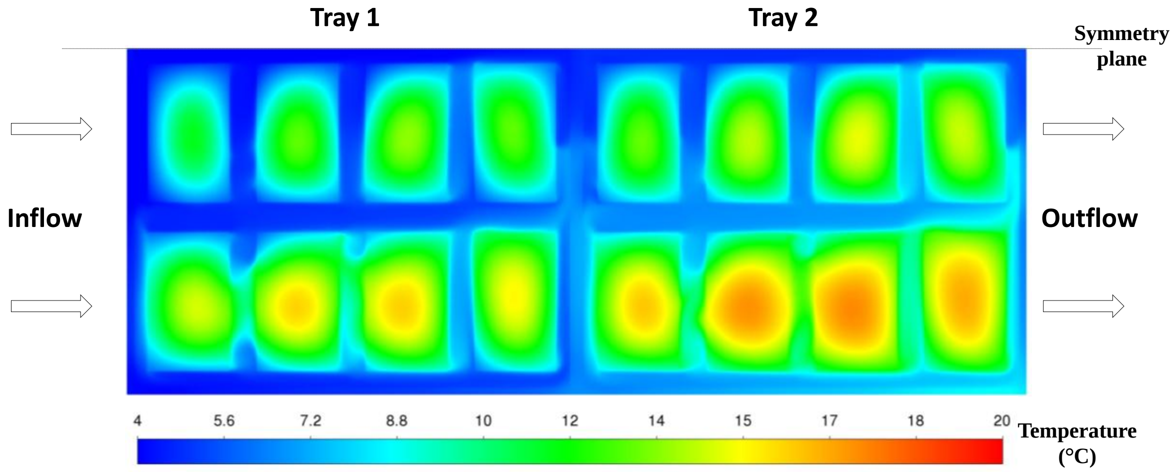

Figure 6: Solid bloc temperature contour after 120 mins of cooling

Cooling behavior

This airflow pattern, described in the preceding paragraphs, significantly influences the cooling rate and heterogeneities. Figure 6 displays the temperature contour in the horizontal plane at the mid-height of the ACs after 120 minutes of cooling for the case where natural convection is not considered. The temperature varied between 4 °C (air temperature in the pathways, green color) and 17.5 °C (temperature of the solid block within AC14, red color). A notable observation is the consistent increase in temperature for both the air and products within the trays along the direction of airflow. This trend is more pronounced at the edge of the tray, where ventilation is poor, as shown in Figure 5.
Additionally, the temperature heterogeneity across the width of the tray is more evident, influenced by the described airflow dynamics. Specifically, the ACs positioned at the center of the trays (ACs 1,3,5,7,9,11,13 and 15) experience more effective ventilation compared to those at the edge (ACs 2,4,6,8,10,12,14, and 16). This temperature heterogeneity is particularly pronounced in the second tray, where the impact of the ventilation and the warmer air through the pathways at the tray's edge becomes more significant.

CONCLUSIONS

A CFD model was developped to simulate heat transfer and airflow within a pallet of strawberries packed in airtight clamshells. The model concerned one layer of the pallet, treating the domain inside the clamshells (air and strawberries) as an equivalent solid block.
The results demonstrated good agreement between the experimental and numerical findings. The analysis revealed distinct airflow behavior within the tray, allowing for its classification into two zones: a well-ventilated central region and a poorly ventilated area at the edge of the tray. These airflow dynamics had a substantial impact on the cooling process of the products within the ACs. Two levels of temperature heterogeneities were identified along the airflow direction and across the width of the tray.
For a future work, different tray designs can be evaluated based on this model.

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