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Heat transfer characteristics within a multiscale packaging: application on a pallet of strawberries

Ahmad Nasser eddine^{*(a)}, Steven Duret^(a), Denis Flick^(b), Jean Moureh^(a),

^(a) Université Paris-Saclay, INRAE, FRISE, 92761 Antony, France

^(b) Université Paris-Saclay, INRAE, AgroParisTech, UMR SayFood, 91120 Palaiseau, France

*Corresponding author: ahmad.nasser-eddine@inrae.fr

ABSTRACT

Packaging design is an essential factor to be considered when evaluating the cooling efficiency all along the cold chain. A heat transfer study is crucial to understand better the effect of different package designs on the cooling rate. This experimental study was conducted to characterize the impact of tray design on the local convective heat transfer coefficient (CHTC) within trays representing a half pallet level during cooling. These trays were filled with empty airtight clamshells (AC) representing Modified Atmosphere Packages (MAP). These measurements were performed on two tray designs (existing and optimized designs). The experimental results showed different levels of heterogeneity: along the airflow direction, in the width positions, and between the different sides of the AC. By comparing the performance of different designs, it was found that adding vent holes to the trays improves the uniformity of the average CHTC within the tray but increases the heterogeneity between the different sides of one AC.

Keywords: Cold Chain, multi-layer of package, convective heat transfer coefficient, modified atmosphere packaging, vent hole

1. INTRODUCTION

Strawberries are perishable fruits and are subject to mechanical damage and quality deterioration. Therefore, multi-scale packaging is commonly used to both for protection and preservation. Plastic clamshells are the most used individual packages to pack strawberries. These clamshells are placed inside open-top trays. Ferrua and Singh (2009a,b,c) conducted an experimental and numerical study to investigate the effect of the clamshells and tray designs on the cooling efficiency of the forced air cooling. They reported that the cooling heterogeneity is affected mainly by the behaviour of the airflow and, thus by the package design. A new solution proposed by Ferrua and Singh (2011) consists of splitting the air between the two trays in series, which improved the time and the uniformity of cooling.

Modified Atmosphere Packaging (MAP) is considered a promising technology to increase the shelf life of strawberries throughout the post-harvest chain by reducing the heat of respiration and maintaining an appropriate low temperature. However, using the MAP, there is no direct contact between the refrigerated airflow and the products inside the package. Therefore, it is crucial to ensure high-level ventilation around packages associated to a uniform heat transfer between the different packages sides of the MAP with respect to their localization in a ventilated pallet.

Nasser Eddine et al. (2022) stated that no studies were carried out to analyse in depth the airflow and heat transfer inside a tray full of MAP. Mainly the study of MAP focuses on the effect of the environment conditions on the quality of strawberries (Joshi et al., 2019, Jalali et al., 2021).

The objective of this study is to measure the local convective heat transfer coefficient (CHTC) on the different sides of an airtight clamshell within a tray of a ventilated pallet. Two tray designs were examined to evaluate

their cooling performance in terms of CHTC levels and heterogeneity. The results of this study are complementary to a study of airflow inside the trays. This will allow a better understanding of the coupling between the airflow behaviour and the heat transfer.

2. MATERIALS AND METHODS

An experimental setup was built inside a room where the temperature can be controlled (Fig. 1a). The setup consists of a rectangular duct (Tunnel) with, successively, an inlet section, a section containing two trays, an outlet section and two suction fans. Two trays with 583 mm x 370 mm x 100 mm as internal dimensions and 593 mm x 380 mm x 105 mm as external dimensions (Fig. 1b) were placed in series inside the tunnel. Each tray was filled with 16 empty airtight clamshells (AC) representing the MAP. Fig. 1c represents the external dimensions of the AC used. The two fans create a differential pressure between the inlet and the outlet to let the air flow through the packages. The system was sealed to ensure no infiltrations. A honeycomb was placed at the inlet of the tunnel to homogenize the airflow entering.

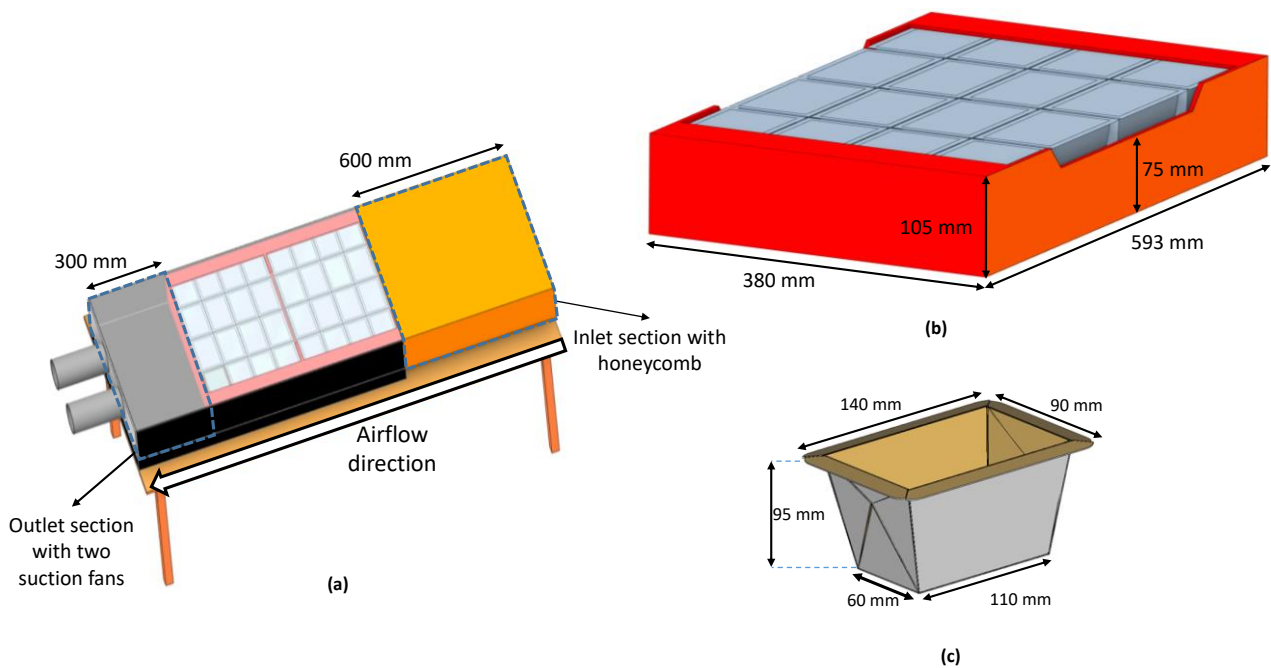


Figure 1: (a) Experimental setup (top view), (b) dimensions of the existing tray, (c) dimensions of the AC

The method used to measure the local CHTC on the surfaces of the AC is similar to that used in previous studies (Willix et al., 2006, Merai et al., 2019). A circular (30 mm diameter) copper-surface heat flux sensor (Captec-France) with a heating resistor bonded to the surface of the flux-meter was used. The calibrated accuracy of the flux-meter is assured by the manufacturer to 3% of the read value. A specific value obtained for each heat flux sensor makes it possible to convert the output signal from μV into $W \cdot m^{-2}$. Five sides of one instrumented AC were equipped with heat flux sensors and thermocouples (Fig. 2a). The CHTC for each side is calculated using the measured heat flux and the recorded temperature difference between the surface of the flux-meter and the surrounding air according to Newton's law: $q/A = h(T_s - T_{air})$.

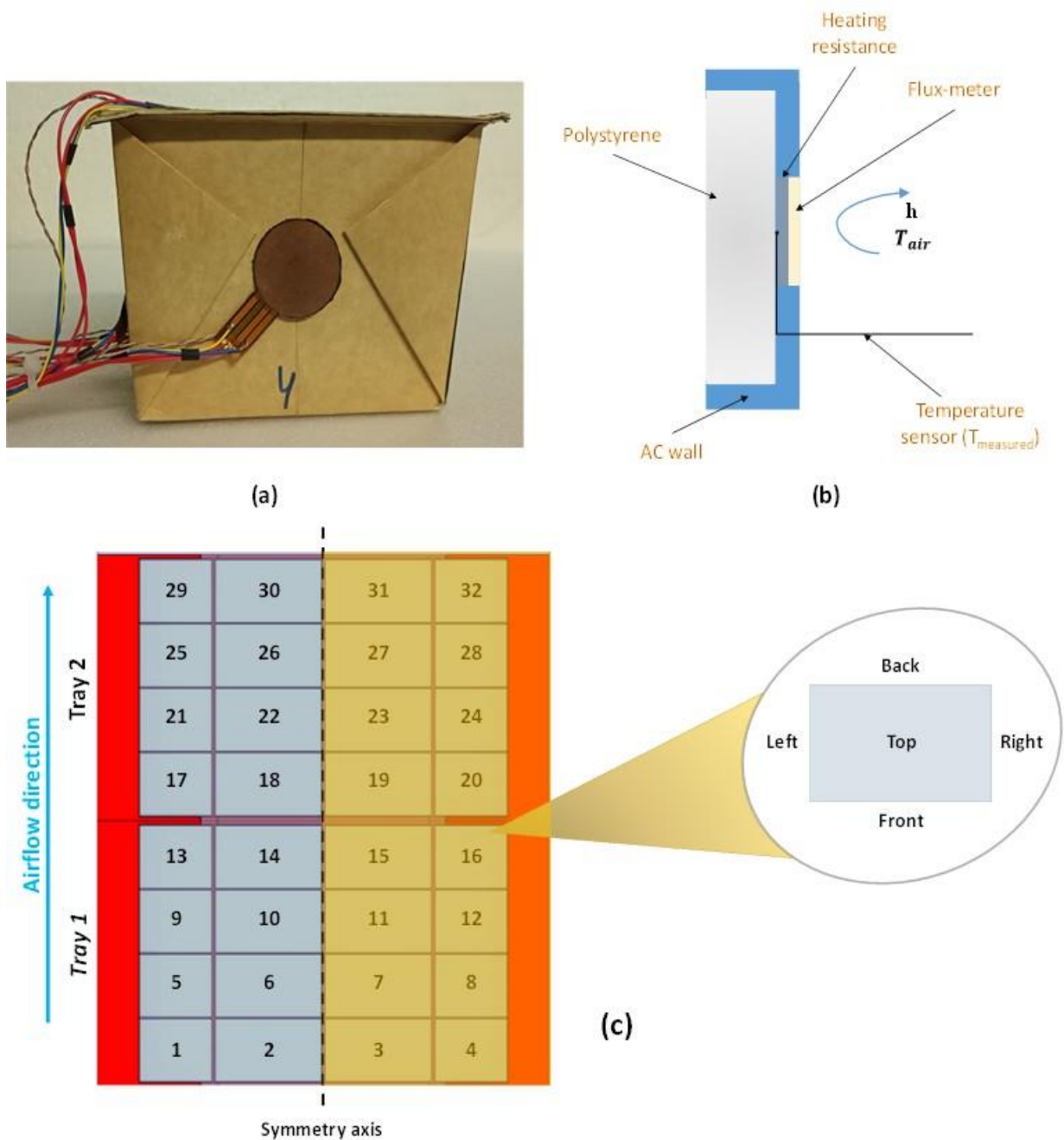


Figure 2: (a) instrumented AC with flux-meters and thermocouples, (b) schematic of a section cutting the flux-meter, (c) AC numbering and side names

Air temperature and AC surface temperature were measured using T-type thermal sensors (with a precision of ± 0.1 K after individual calibration). Five thermocouples were bonded between the AC surface and the heating resistor to measure the interior surface temperature ($T_{measured}$), as shown in Fig. 2b. Then, the temperature of the surface of the flux-meter (Surface exposed to airflow, T_s) was calculated by taking into account the heat transfer resistance by conduction through the flux-meter and the heating resistor. The air temperature was measured in the tunnel before the trays (inlet section).

Considering the symmetry of the package system, the measurements were conducted on half of the tray (highlighted in yellow in the Fig. 2c). The instrumented AC was displaced at different positions into the tray in order to characterize the corresponding CHTC. Fig. 2c shows the numbering of the AC positions inside the two trays and the names of the different sides.

Temperature and flux-meter output signal acquisitions were performed every 10 s using a data-logger (Keysight DAQ970A) and acquisition software (Keysight BenchVue). Each experiment consisted in heating continuously the resistors until a steady state was reached. The time to reach a constant temperature depended on the face and the position of the AC.

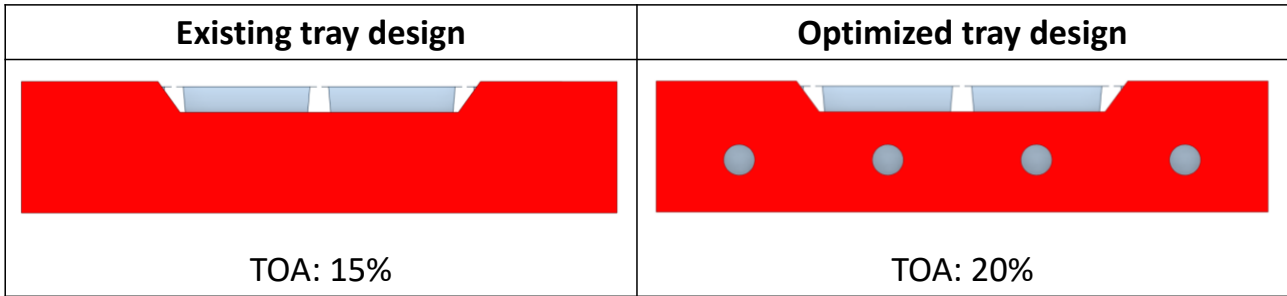


Figure 3: Different tray designs (TOA: Total opening area)

In this study, the performance of an open-top corrugated tray design is compared to a new solution. The proposed design has additional circular vent holes with a diameter of 30 mm added to the longitudinal face of the tray (Fig. 3). The total opening area (TOA) increased from 15% for the existing design to 20% for the optimized one. The experiments were conducted at the same airflow for the different AC positions and different tray designs. The airflow rate per unit of fruit mass across the palletized row was computed as $1.1 \text{ L}\cdot\text{s}^{-1}\cdot\text{kg}^{-1}$.

3. RESULTS

Fig. 4 summarizes the measured local CHTC throughout the trays in both studied configurations. The measured values are presented in the form of: the average of the CHTCs of the five sides (CHTC_{avg}), the CHTC of the top side (CHTC_{Top}), the average of the CHTC of the vertical sides (right, left, back and front sides) ($\text{CHTC}_{\text{avg,vertical sides}}$), and the relative variation of CHTC between the different sides of each position ($\frac{\text{CHTC}_{\text{max}} - \text{CHTC}_{\text{min}}}{\text{CHTC}_{\text{avg}}}$).

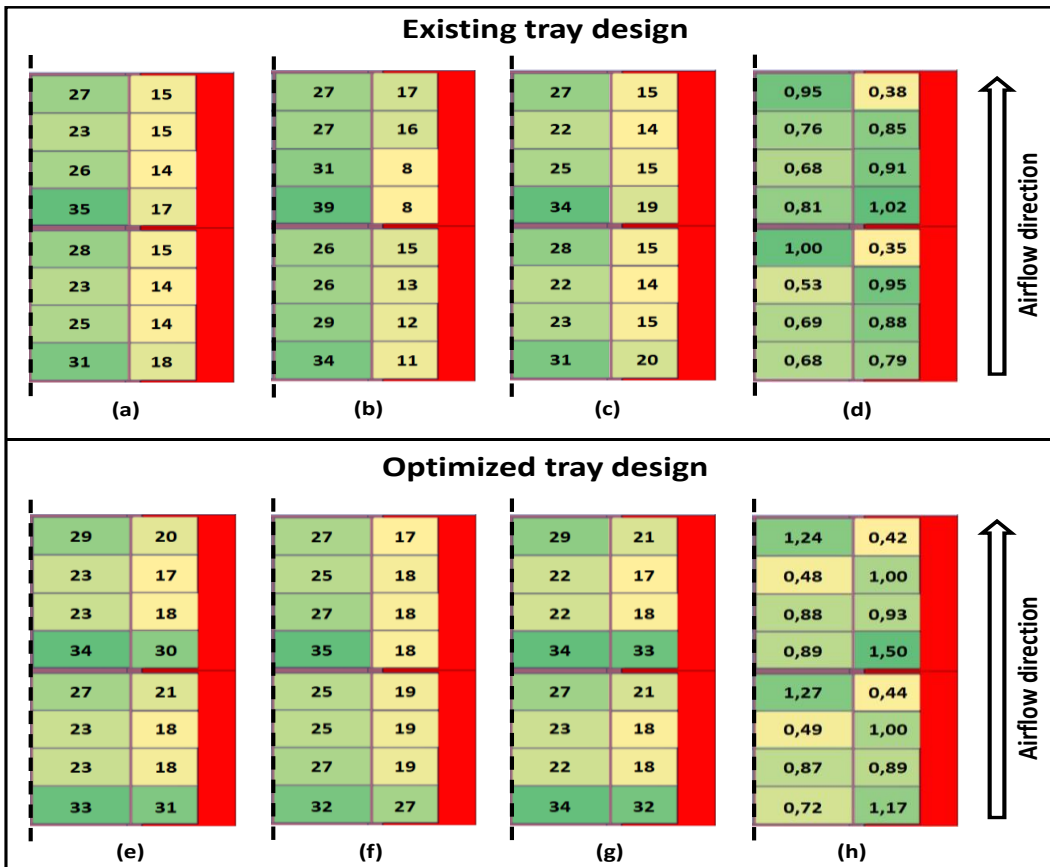


Figure 4: (a) and (e) $CHTC_{avg}$, (b) and (f) $CHTC_{Top}$, (c) and (g) $CHTC_{avg,vertical sides}$, (d) and (h) $\frac{CHTC_{max} - CHTC_{min}}{CHTC_{avg}}$

For the existing tray design, the most important heterogeneity is found in the width positions (transversal direction) for the two trays, mainly between the ACs placed in the middle and those at the border. A difference of 21 $W.m^{-2}.K^{-1}$ is observed between the maximum and minimum of the average CHTC. The variations of the CHCT are mainly related to the characteristics of the airflow. Therefore, the heterogeneity can be explained by the fact that the ACs positioned at the border are less ventilated as the most airflow with high velocity passes in the middle of the tray through the main vent hole between and above the ACs.

Fig. 4b and c provide a better understanding of the effect of the airflow behaviour on the heat transfer of different sides. Comparing the CHTC of the top wall between the ACs placed in the middle and the ones placed at the border, a maximal difference of 31 $W.m^{-2}.K^{-1}$ can be observed between the AC 19 and 20 (Fig. 4b). This difference can be explained by the fact that AC 19 is located in the core air jet flowing through the main hole of the tray while AC 20 is located in a supposed recirculated weak ventilated area induced by the same jet. In this configuration, there is a primary airflow represented by an air-jet issuing the main hole that develops in the air gap above the AC placed in the middle of the tray. The secondary airflow passing between the AC induced to the same effect, a significant heterogeneity between the $CHTC_{avg,vertical sides}$ of the ACs positioned in the middle and those placed at the border where a maximum difference of 15 $W.m^{-2}.K^{-1}$ can be observed between the AC 19 and 20.

A second heterogeneity can be noticed between the different sides of each AC especially for positions 15 and 20 as the relative difference between the maximum and minimum CHTC reaches about 100% (1.00 for position 15 and 1.02 for position 20). The thermal behaviour of the AC 15 can be explained that it is placed near the outlet of the first tray, the flow is accelerating towards the longitudinal vent hole. Therefore, the right, left, back, and top side are subjected to higher velocities compared to the back side where it is facing a relatively dead zone, which has resulted in a higher CHTC on different sides except the back side.

A small heterogeneity is found along the flow direction: The CHTC is higher near the inlet and outlet sections of the trays where the airflow accelerates when passing through the opening.

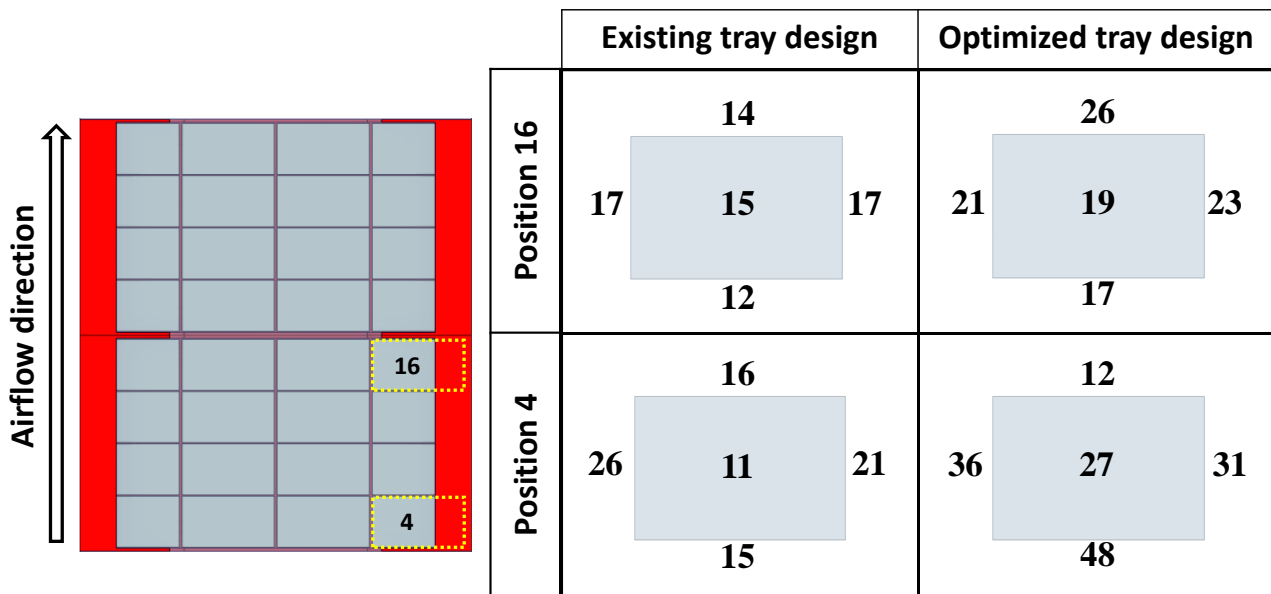


Figure 5: Local CHTC of the different sides for positions 16 and 4

Comparing the two designs, the overall averaged CHTC is increased from $21.2 \text{ W.m}^{-2}.\text{K}^{-1}$ for the existing design to $23.2 \text{ W.m}^{-2}.\text{K}^{-1}$ for the optimized tray design. The main improvements of the average CHTC are obtained for the AC positioned near the added vent holes (3-4-15-16-19-20-31-32).

To illustrate the variations in CHTC on different sides between the two configurations studied, Fig. 5 compares the measured CHTC for two positions (4 and 16) that have the greatest improvement in terms of average CHCT. The average CHTC increased by $13 \text{ W.m}^{-2}.\text{K}^{-1}$ for AC 4 and $6 \text{ W.m}^{-2}.\text{K}^{-1}$ for AC 16. The circular vent hole is placed in front of the front side of the AC 4, for that the CHTC of this side increased from 15 to $48 \text{ W.m}^{-2}.\text{K}^{-1}$; improvements can be seen also in the other sides except for the back side which is facing a dead zone. In case of the AC 16, the airflow is accelerating at the outlet of the first tray to exit from the vent holes, therefore, CHTC improvement can be remarked mainly on the back side of the AC 16.

While the homogeneity of the average CHTC improved with the use of the new design with circular vent holes, it should be noted that the heterogeneity between the different sides of each AC increased. The relative difference between the maximum and minimum CHTC for AC 20 increased from 1.02 to 1.5 (Fig. 4 d and h). This can be explained by the fact that the CHTC of the front side significantly increased due to its position in front of the added vent hole (outlet of tray 1 and inlet of tray 2) contrary to the CHTC of back side.

4. CONCLUSIONS

Experiments were conducted to measure the local convective heat transfer coefficient (CHTC) inside a corrugated tray filled with empty and airtight clamshells (AC) representing modified atmosphere packages. A steady state method was used to measure the CHTC of each side of an instrumented AC.

Three levels of heterogeneity were found within the tray. The most important difference is within the width of the tray and is due to the airflow behaviour where the main jet passes through the middle part of the tray. A second level of heterogeneity is found between the different sides of each AC and that is related to the side orientation versus the airflow. There is also a small variation along the airflow because air accelerates to flow through the vents.

It was noted that the new tray design provides an enhancement in the average CHTC but the heterogeneity between the different sides increased, which is not necessarily the best for fruit quality as chilling injury can occur during cooling.

Further investigations will focus on two key aspects. Firstly, air velocity measurement around the AC will provide a better understanding the interaction between airflow and heat transfer phenomena. Secondly, experimental and numerical characterization of the heat and mass transfer at the scale of a clamshell to predict the evolution of the product (strawberries) in terms of temperature, water content and quality along the cold chain where the knowledge of the CHTC on the different wall sides is essential, especially, for weight loss and condensation issues.

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NOMENCLATURE

A	Surface area (m ²)	min	minimum
q	Heat flux (W)	max	maximum
T	Temperature (K)	avg	average
h	Convective heat transfer coefficient - CHTC (W.m ⁻² .K ⁻¹)	s	surface
		a	air

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