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Experimental Characterization of Cooling Behavior Within a Multi-Package: Application on a Pallet of Strawberries

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ABSTRACT

The cooling behavior of horticultural products in multi-package systems is primarily affected by the airflow behavior, which in turn, is influenced by the design of primary and secondary packaging. An experimental study was conducted to characterize the cooling rate and its heterogeneity within a device representing a half layer of a pallet with two trays of airtight clamshells containing strawberries. The tray design's cooling efficiency was explored by comparing the existing design to two alternatives, investigating the impact of air headspace and vent hole area. Results revealed significant cooling heterogeneities between clamshells at the tray's center and those at the edge. This investigation highlighted the importance of having proper ventilation around the clamshells, which is mainly affected by the package design. The addition of vent holes to the commercialized design reduced half-cooling time, and enhance the cooling uniformity. However, both alternative designs exhibited higher ventilation energy consumption compared to the commercialized design.

Keywords: Cold Chain; Multi-package; Heat transfer; Cooling rate; Experiments.

1. INTRODUCTION

Post-harvest precooling is widely used for preserving horticultural products, especially with forced-air convection (Nasser Eddine et al. 2022) . However, this practice leads to uneven cooling in pallets due to airflow behavior, which is influenced by package design (Dehghannya et al. 2011).This underlines the importance of finding performant package designs to ensure rapid and homogeneous cooling (Pathare et al. 2012). Different studies have evaluate the impact of the package design on the cooling efficiency (Dehghannya et al. 2011, Berry et al. 2016, Han et al. 2017, Wu and Defraeye 2018).

Highly perishable products, such as strawberries, require enhanced protection through multiple layers of packaging. In practice, strawberries are packed in primary packaging, such as clamshells, which are then arranged within secondary packaging, such as open-top trays (Ferrua and Singh 2009a, Wang et al. 2019). (Ferrua and Singh 2009a, Ferrua and Singh 2009b, Ferrua and Singh 2009c) carried out both experimental and numerical studies to explore how clamshell and tray designs influence the efficiency of forced-air cooling. Their findings highlighted that cooling non-uniformity is primarily influenced by airflow behavior, which, in turn, is dictated by the design of the packaging (primary and secondary). In certain cases, the primary packaging can act as a barrier between the cold air and the product, which can have a significant impact on the cooling rate, as in the case of non-ventilated modified atmosphere packaging (MAP). According to our knowledge, no research has been conducted on the influence of secondary packaging design, the arrangement of MAP within the secondary packaging on the cooling rate and uniformity of product temperature. Considering these factors, it is crucial to understand the cooling dynamics among various MAP positions within a tray and the impact of the tray design on these dynamics.

Hence, the objective of this study is to examine the impact of different tray designs (secondary packaging) on the forced-air cooling of strawberries packed in a biodegradable airtight clamshell (AC), mimicking a

Modified Atmosphere Packaging (MAP). The investigation focuses on two factors, including vent holes, headspace above the AC, to analyze their effects on the strawberries cooling rate and uniformity.

2. MATERIALS AND METHODS

2.1. Experimental device

The experimental device used in this study is identical to that employed by Nasser eddine et al. (2023). The device represents half a layer of a pallet, given the symmetrical arrangement of the trays on a pallet layer (Fig. 1a and b). This device, resembling an air tunnel, comprises three sections: inlet section, outlet section, and a central section where trays are positioned. A honeycomb is placed at the tunnel inlet to ensure a uniform incoming airflow. At the outlet section, two fans are fixed to generate a differential pressure, allowing airflow through the trays. The tray shown in Fig. 1c illustrates the dimensions of the actual tray design commonly used in the industry, and is considered a reference case in this study.

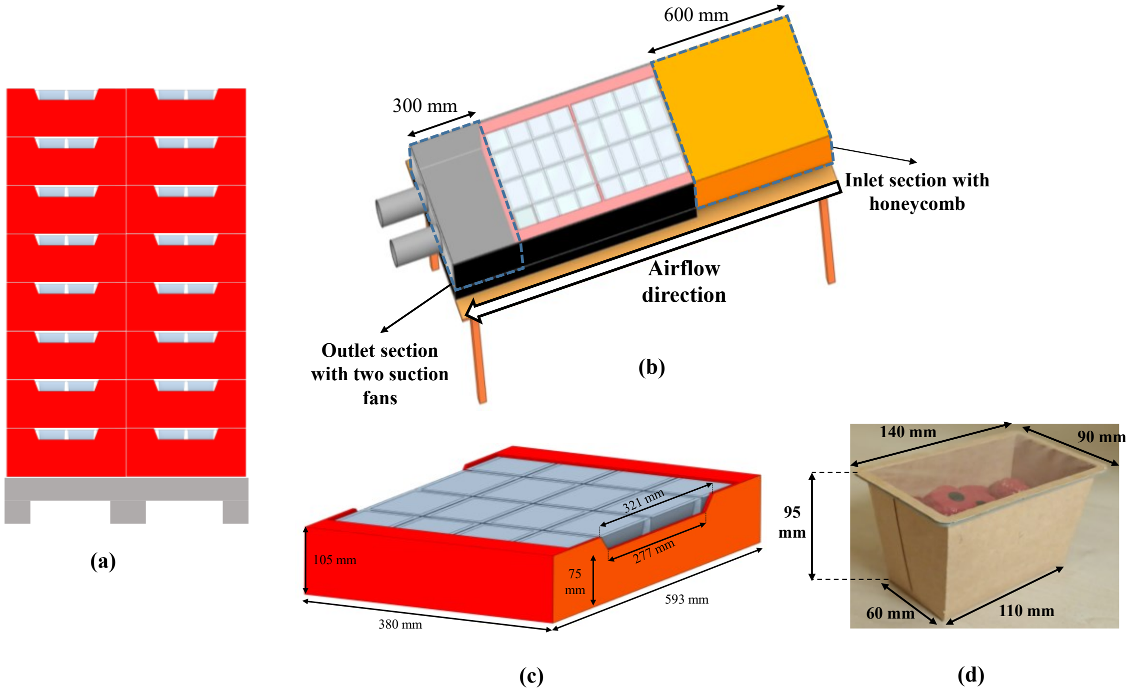


Figure 1: a) Pallet, b) Experimental setup, c) tray dimensions, d) airtight clamshell dimensions

The trays were loaded with Airtight Clamshells (AC), simulating the modified atmosphere package (MAP). Each AC contained 20 strawberries (Fig. 1d). Due to the high perishability of strawberries, they were substituted with PVC replicas and filled with a carrageenan gel possessing thermal properties akin to real strawberries. A comparison of the gel properties with those of strawberries is presented in the 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

2.2. Sensor positions

Temperature measurements were conducted solely on one half of the tray due to the symmetry of the ACs arrangement. Five strawberries in each of the specified ACs (1-2-7-8-9-10-15-16) were instrumented with type T calibrated thermocouples as illustrated in blue in Fig. 2a. The air temperature measurements were also undertaken at various positions within the trays, between the ACs (circular green points in Fig. 2b), and at the main trapezoidal vent holes (triangular green points in Fig. 2b).

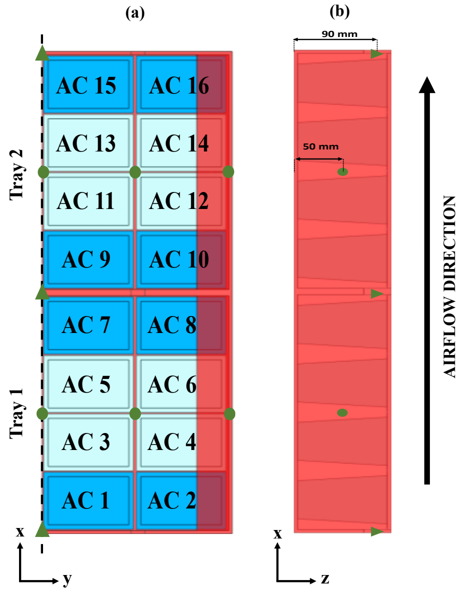


Figure 2: a) Top view of the device loaded with Airtight Clamshell (AC); instrumented AC in blue (5 instrumented strawberries), b) Thermocouple positions for air temperature measurements.

2.3. Description of the experiments

The performance of the currently used Open-tray design, called TD 1, is compared with alternative designs, namely TD 2 and TD 3, in order to assess the impact of additional vent holes and larger headspace above the ACs. The dimensions of each design are shown in Fig. 3.

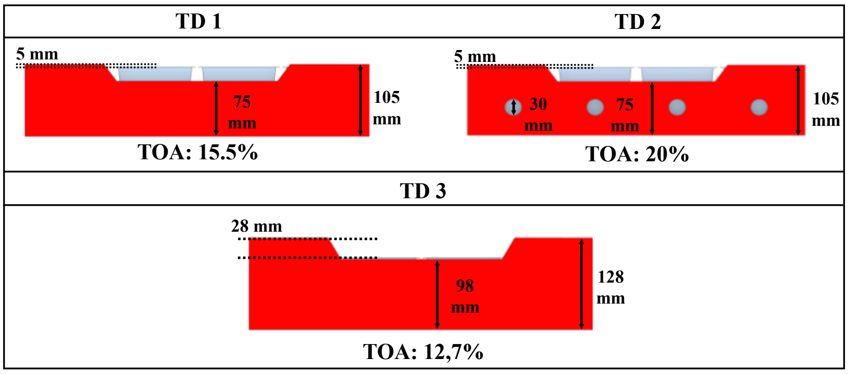


Figure 3: Dimensions and Total Opening Area (TOA) of three Tray Designs (TD 1, TD 2 and TD 3)

The cooling rate of strawberries in these different designs was compared under the same pressure drop (Δp) to ensure uniform operating conditions. The pressure drop measurements were taken using two pitot tubes fixed at the inlet and outlet sections of the experimental device. These tubes were connected to a Testo 400 device to record the measured values. The measured Δp (10.5 Pa) leads to airflow rates of 0.9, 1.3, and 2.0 $L.s^{-1}.kg^{-1}$ of product for TD 1, TD2 and TD 3, respectively. These airflow rates are representative for forced air precooling (Defraeye et al. 2013).

Regarding the experimental protocol, for each design, the cold room was first set at 20 °C to guarantee consistent initial product temperatures. Subsequently, the entire experimental setup was insulated using polystyrene foam, the fans were deactivated to prevent air circulation, and the cold room temperature was set at 4 °C. Following a 30-minutes period for ambient temperature stabilization at 4 °C in the cold room, the polystyrene foam covering both the inlet and outlet of the experimental setup was removed, and the fans were activated to start the cooling experiment. Temperature readings were consistently recorded every 10 seconds until uniform temperature stability was achieved across all products, indicating the attainment of a steady state.

Two cooling performance parameters were used to evaluate the cooling behavior within the trays and to compare the different proposed designs. These parameters are the following: Cooling times (half cooling time, HCT, and seven-eight cooling time, SECT) and Ventilation energy consumption (E).

HCT (h) and SECT (h) represent the time needed to reduce the product temperature to a value that is half (Y= 0.5) and seven-eighths (Y=0.125) of the initial temperature difference between produce and the cooling air (Brosnan and Sun 2001), where Y is the dimensionless temperature:

$$Y = \frac{T_s - T_a}{T_{s,0} - T_a} \qquad \text{Eq.(1)}$$

Where T_s is the temperature of strawberry in an AC at a given time of cooling, $T_{s,0}$ is the initial temperature of strawberry, and T_a is the set ambient temperature in the test room.

E (J) represent only the energy consumed by the ventilation system (fans) and is calculated as follows for a half layer of a pallet:

$$E = P \times SECT \qquad \text{Eq.(2)}$$

Where P is the power demand (W) and SECT is the highest value for each design (s).

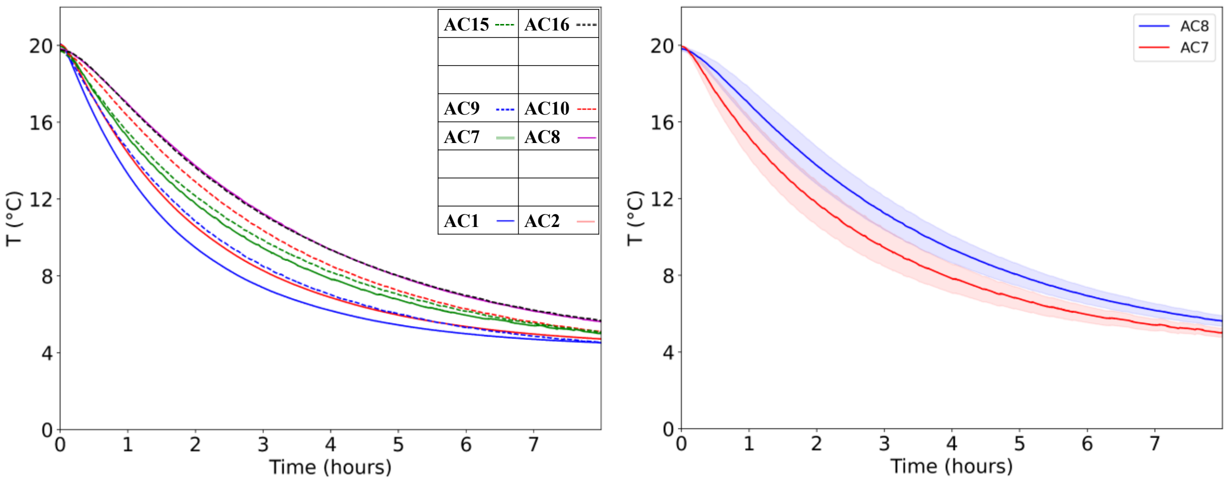
$$P = \Delta p \times G \qquad \text{Eq.(3)}$$

Where G is the flow rate across the pallet layer ($m^3.s^{-1}$) and Δp the pressure drop (Pa)

3. RESULTS

3.1. Reference case: TD 1

Fig. 4a illustrates the evolution of the average temperature of the five strawberries in each of the instrumented ACS during the cooling process from 20 °C to 4 °C for the TD 1 design. The curves reveals significant cooling heterogeneity among different AC positions, with AC1 the fastest cooling, AC16 and AC8 the slowest. Two types of temperature heterogeneities are observed, one along the airflow pathway and the other in the width of the tray. This behavior can be attributed to the airflow dynamics within the trays and the warming air.



(a) (b)

Figure 4: Evolution of strawberries average temperature inside different ACs (TD 1): ACs 1, 2, 7 and 8: solid blue, red, green and magenta lines, respectively; ACs 9, 10, 15 and 16: dashed blue, red, green and magenta lines, respectively, b) evolution of strawberries average temperature inside ACs 8 and 7 (continuous line) and standard deviation relative to the average of the five strawberries (clouds)

As noted by Nasser eddine et al. (2023), Tray 1 and Tray 2 exhibit similar average convective heat transfer coefficients (CHTC) on the sides of the ACs, indicating the same airflow behavior. However, Fig. 5a shows that the air temperature increases along the airflow pathway (4.5 °C temperature difference between the inlet orifice and the outlet orifice at 15 minutes from the beginning of the cooling) causing the first type of heterogeneity. The second type of heterogeneity is caused by the airflow behavior, where the center part of the tray is well ventilated by the main jet passing through the main orifice, and the ACs in the edge zone experience weaker ventilation due to the diffusion and entrainment mechanisms. These dynamics lead to heterogeneity of air temperature across the width of the tray, as shown in Fig. 5b. An air temperature difference of 6 °C can be observed in the first tray (positions 1 and 5), and of 7 °C in the second tray (positions 6 and 10) 15 minutes after the start of the cooling.

Nasser eddine et al. (2023) found that some ACs have high heterogeneity of convective heat transfer coefficient between the different sides. For example, AC7 exhibited 100% heterogeneity between the five sides (right, left, back, bottom and top sides) compared to AC8 which had lower side heterogeneity (35%). Therefore, Fig. 5b displays the evolution of the average temperature with the standard deviation of the five strawberries (shown by the clouds around the average). It is noteworthy that side heterogeneity of CHTC does not have an effect on the strawberries' cooling heterogeneity inside the ACs.

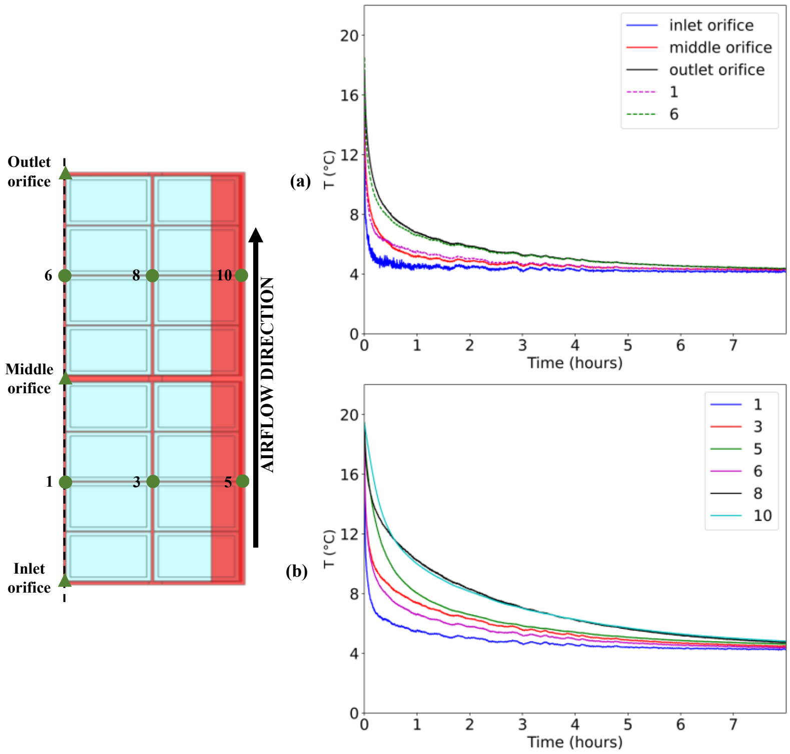


Figure 5: Evolution of air temperature within TD 1

3.2. Effect of tray design on cooling rate and energy requirements

Fig. 6 presents the average HCT and SECT of five strawberries within ACs1 ,2 ,7 ,9 ,10 ,15 ,16 for different tray designs (Δp=10.5 Pa). When working with the same pressure drop, the additional vent holes (TD 2), significantly improved HCT and SECT, especially for AC2 (25% reduction of HCT, 19% for SECT), AC8 (34% for HCT, 28% for SECT) and AC 10, (26% for HCT, 21% for SECT). This can be explained by higher airflow rate passing through TD 2 trays with additional circular vent holes, which improved ventilation of the vertical sides of the ACs.

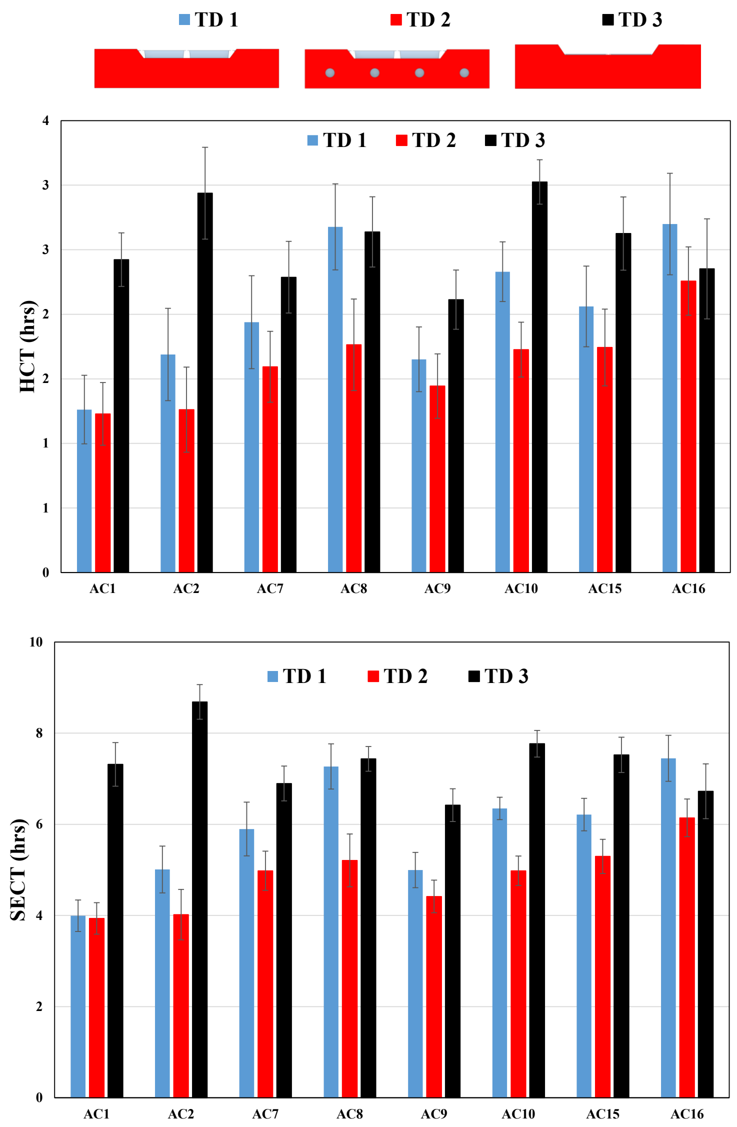


Figure 6: Experimental cooling time HCT and SECT (h) for different tray designs (Δp = 10.5 Pa), error bars present the standard deviation of the 5 strawberries

Conversely, increasing the headspace above the ACs (TD 3) while maintaining the same Δp (10.5 Pa), which led to a doubling of the airflow rate compared to TD 1, resulted in higher HCT and SECT. The maximum HCT reached 3.0 h (AC10), representing an 11% increase from the maximum HCT of TD 1 (AC16). The maximum SECT reached 8.7 h (AC2), which is 41 % more than the maximum SECT of TD 1 (AC16). The highest increase was recorded for AC1, with 92% and 83% for HCT and SECT, respectively. This can be explained by the fact that TD 3 allows the air bypass in the headspace above the ACs, reducing the ventilation of the vertical AC sides.

Table 2 outlines the effect of the three tray designs on ventilation energy consumption (for a half pallet layer). A comparison between the TD 3 and TD 1 designs at the same pressure drop favors the TD 1, as it exhibits lower energy requirements and cooling rates. TD 2 is better than the other designs in terms of achieving rapid and uniform cooling. However, concerning the ventilation energy consumption, 14% increase in energy is observed compared to TD 1 (Table 2), attributable to the higher airflow rate. Nonetheless, other criteria, such as product quality, may play a decisive role in selecting the optimal package design and should be considered for a comprehensive multi-criteria assessment.

Table 2. Energy consumption for the different cases studied

Tray design	Flowrate ($L.s^{-1}.kg^{-1}$)	Δp (Pa)	SECTmax (h)	E (W.h)
TD 1	0.9	10.5	7.4	0.7
TD 2	1.3	10.5	6.1	0.8
TD 3	2.0	10.5	8.7	1.8

4. CONCLUSIONS

Experiments were conducted to examine the cooling behavior of strawberries packed inside airtight clamshell, representing modified atmosphere packages (MAP), and to investigate the influence of the AC position within the tray on the cooling rate and heterogeneity. These experiments, carried out at laboratory scale, considered only half a layer of a pallet and simulated forced-air precooling. The performance of two alternative tray designs (TD 2 and TD 3) was evaluated and compared to the actual tray design (TD 1) in terms of cooling rate and energy ventilation consumption under the same pressure drop through the package.

Two levels of heterogeneity were observed between the different AC positions within the trays TD1. Heterogeneity was evident along the airflow and in the width of the tray and can be attributed to two factors. The first is the airflow dynamics within the tray that promote better ventilation in the central zone, and the second factor is the warming of air temperature. However, no significant heterogeneity was found among the strawberries inside each AC.

The assessment of various tray designs highlighted the significance of ensuring adequate ventilation of the ACs, particularly the vertical sides. This was evident in how adding vent holes to the existing tray design (TD 2) improved the cooling rate and uniformity, albeit at the expense of increased energy consumption for ventilation. In contrast, TD 3, which enhanced ventilation of the top sides, exhibited higher cooling times.

However, in terms of energy ventilation consumption, no improvement was achieved with the alternative designs; in both cases, the energy requirement by the fans increased, with a significant increase for TD 3.

Further research will focus on characterizing the heat and mass transfer within the clamshells to predict the evolution of the product (using real strawberries to account for different phenomena like transpiration and respiration) in terms of temperature, water content and quality along the cold chain.

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NOMENCLATURE

Y	dimensionless temperature	*G*	flow rate ($m^3.s$)
T	temperature (K)	*SECT*	seven-eight cooling time (h)
E	ventilation energy (W.h)	*HCT*	half cooling time (h)
P	power (W)	*p*	pressure (Pa)
ρ	thermal conductivity ($W.m^{-1}.K^{-1}$)	*λ*	density ($kg.m^{-3}$)
Cp	Heat capacity ($J.kg^{-1}.K^{-1}$)		

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