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Influence of cheese heat generation inside a ventilated pallet on cooling rate and heterogeneity

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ABSTRACT

Product temperature control during the cold chain is essential for the preservation of its quality and the reduction of food waste. For cheese like soft cheese, the metabolism of the microorganism generates heat. This study aims to investigate experimentally the influence of heat generation by cheese inside a ventilated pallet on cooling rate and heterogeneity.

An experimental device, consisting of a cheese pallet in a cold room, was used. The cheese was replaced by plaster cylinders equipped with electric resistances to represent the heat generation of the product.

The experiments were conducted under unsteady state at an upwind air velocity of 0.25m/s with and without heat generation (1.2W/kg). The results show that heat generation lowers the seven-eighths cooling time (SECT) of the product. The natural convection induced by heat generation helps to cool the product faster toward the equilibrium temperature, but this one is higher than the one of cooling air.

Keywords: Cold chain, heat-generating product, cooling rate, heterogeneity, natural convection, cheese.

1. INTRODUCTION

During the cold chain, it is crucial to maintain the temperature of soft cheese products below the regulatory temperature to preserve their safety, gustative quality and reduce their waste. However, this type of product generates heat associated to their microbiological activity (Pham et al., 2021), making the cooling process more complex. It is, therefore important to understand the impact of heat generation on product cooling.

Different parameters are studied in literature for their impact on cooling kinetics, such as box design (total opening area, orifice position, etc.) (Berry et al., 2021; Wang et al., 2019), stacking density (Jia et al., 2022), and ventilation conditions (Agyeman et al., 2023). In addition to these parameters, heat generation of products has an impact on temperature distribution and heterogeneity. Product heat generation is generally neglected during pre-cooling, where forced convection predominates natural convection. However, during storage (low air velocities), natural convection becomes non-negligible.

To the best knowledge of the authors, only Chourasia and Goswami, (2007) have studied the impact of heat generation on cooling rate of potatoes. No studies on pallet scale have investigated the impact of the heat generation and the resulting natural convection on the temperature distribution of products in both horizontal direction (from upstream to downstream) and vertical direction (from bottom to top) of pallet.

The aim of this study is to investigate, under unsteady-state conditions, the impact of heat generation on the temperature distribution along the different pallet rows, from upstream to downstream. Thus, two conditions were studied: without heat generation and with a flux of 0.3 W per product item (upstream air velocity was fixed at u_{air}=0.25 m/s).

2. MATERIALS AND METHODS

2.1. Experimental device

In this study, the experiences were conducted on one industrial-sized pallet of heat-generating cheese.

It contains:

- Nine levels of product
- Each level contains 6 vented boxes (face, lateral and bottom sides). Boxes on the same level are spaced 1 cm apart.
- Each box contains 30 soft cheeses (D = 11 cm, H = 4 cm each)
- Each product (250 g per product item) can generate a heat flux of Q=0.3 W

The pallet is placed within a cold room with controlled air temperature and velocity (Figure 1(a)). Cheese products are replaced by big blocks equivalent to 15 cheese items (see Figure 1(b)). In order to simulate the heat generation, the blocks were equipped with controllable electrical heat resistances.

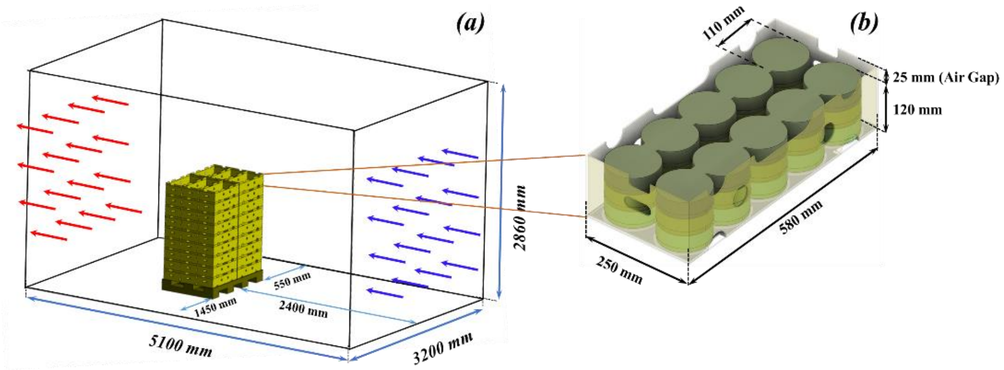

Figure 1: (a) Schematic of the pallet within a cold room; (b) Schematic and size of one vented cardboard.

In order to study the temperature heterogeneities inside this pallet, since there is a symmetry plane, a half pallet was considered for instrumentation. Thus, three rows (from upstream to downstream) of pallet (L_1, L_2 and L_3) were instrumented by calibrated thermocouples, K-type with an uncertainty of 0.2°C (Figure 2(b)). As shown in Figure 2(a-b), the coloured central product on boxes B_1, B_2 and B_3 were instrumented by thermocouples from first to seventh level (i=1 to i=7) and level nine (i=9). Additional thermocouples were added in the air gap of the boxes in level eight: $8B_1$, $8B_2$ and $8B_3$. BenchLink Data Logger software was used to record temperature measurements every 1 minute.

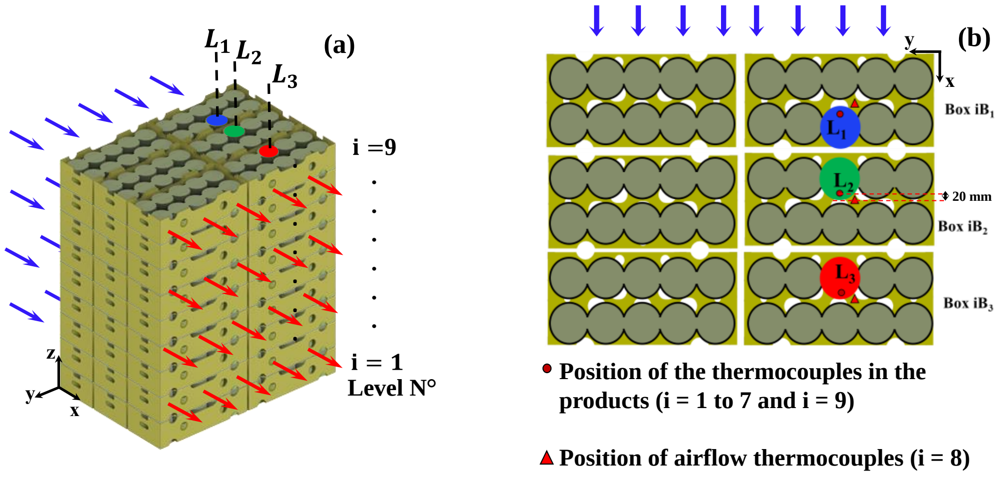

Figure 2:(a) Diagram of the position of the rows L_1, L_2 and L_3 within the pallet; (b) a top view of the pallet and thermocouples positions.

2.2. Experimental process

The experimental process is composed of three steps:

2.2.1. Step1: Pallet temperature equilibration

This step aims to reproduce the case where pallets are transferred between two cold chain facilities, and the temperature of products within a pallet has reached equilibrium in the first facility. For this step, the upstream air temperature is set at 20°C and the thermal resistances are activated until thermal equilibrium is reached. Therefore, at end of this step, the temperature is heterogeneous (for Q = 0.3W) in the pallet.

2.2.2. Step2: Isolation

Once step 1 has been completed, the set-point temperature of the room is reduced to 4°C. However, air temperature drop from 20°C to 4°C is gradual and takes about an hour. During this stage, the pallet is insulated with polystyrene panels and the heat resistances are turned off. This way, the product temperature remains almost constant.

2.2.3. Step3: Cooling process

Once step 2 is completed, the panels are removed, the heating resistances are activated and the cooling process is considered as started.

In order to evaluate the cooling rate of the products within the pallet, it's essential to estimate the dimensionless temperature θ. However, as shown by Pham et al., (2021) and Aguenihanai et al., (2023) under steady-state conditions, the final temperature of heat-generating products is different from position to another and different from the air temperature when $Q \neq 0W$. Thus, a new definition of θ is proposed

$$\theta(\mathrm{t}) = \frac{\mathrm{T(t)} - \mathrm{T_f}}{\mathrm{T_0} - \mathrm{T_f}}$$

where:

T_f is the equilibrium temperature (for upstream air temperature of 4°C) which is considered equal to the average temperature over the last 30 minutes.

T_0 is the initial temperature of the products (at beginning of step 3).

The cooling rate is assessed using the seven-eighths cooling time (SECT) estimation, which is defined as the time required for $\theta(\mathrm{SECT}) = 0.125$.

3. RESULTS AND DISCUSSION

3.1. Steady state

Figure 3 (a-b) show the distribution of products temperature (from level 1 to 7 and level 9) and the air temperature (level 8) along the row L_1, L_2 and L_3 at steady state.

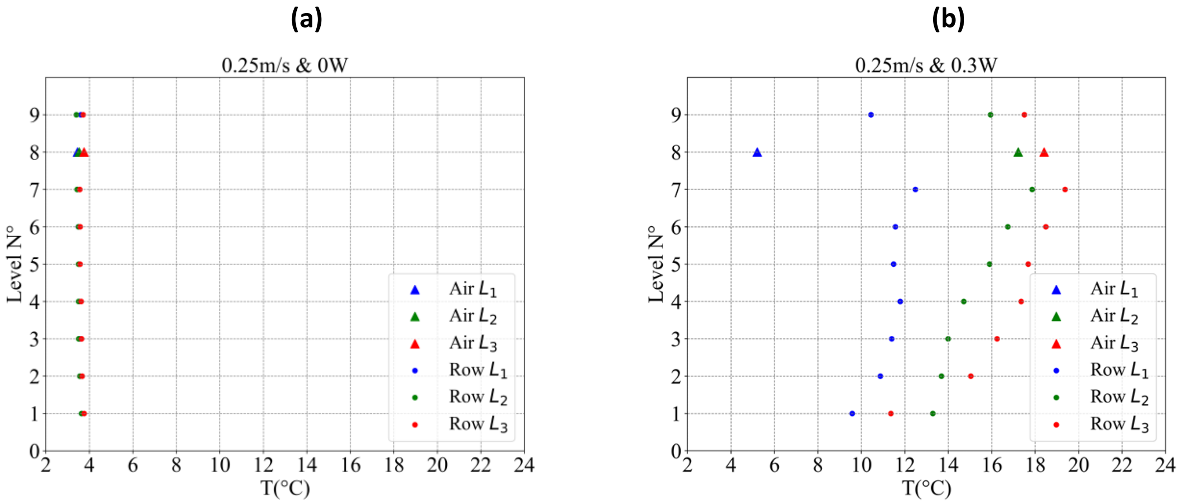

Figure 3: Product and air temperature distribution within different levels and rows of the pallet for u_{air} = 0.25m/s: (a) Q=0W; (b) Q=0.3W.

According to Figure 3(a), without heat generation (Q=0) a homogeneous distribution of the pallet temperature can be observed in both directions; horizontal (upstream to downstream) and vertical (bottom to top); with equilibrium temperatures equal to the upwind air temperature. However, as it can be seen in Figure 3(b), for Q=0.3W, the air and product temperature is heterogeneous in both directions (horizontal and vertical). Temperature increases from upstream to downstream. This is due, on one hand, to the increase in air temperature in the flow direction in contact with the warm products and, on the other hand, to the decrease in air velocity due to the air exiting through box lateral vents and spaces between the boxes B_1, B_2 and B_3 (Aguenihanai et al., 2023; Pham et al., 2021). However, at the 1st level of the pallet, it can be observed that the temperature of box B_3 (downstream part of pallet) is lower than the temperature of box B_2 (middle of pallet). This can be explained the presence of natural convection and the development of a thermal plume associated with the suction of surrounding cold air at the downstream part of the pallet. This phenomenon, therefore, cools the product in box B_3, unlike the box B_2, which receives air heated by products of the box B_1.

From the bottom to the top of pallet, it can also be observed that the temperature on row L_1 is generally homogeneous compared to the temperatures on rows L_2 and L_3 where a greater degree of heterogeneity can be seen. The temperature increases in the vertical direction of the pallet (from bottom to top) until the penultimate level. Temperatures at the last level are lower because of direct contact with the ambient air. As already explained, natural convection becomes predominant on the downstream rows of the pallet (L_2 and L_3), leading to a development of a vertical flow (thermal plume). The bottom of the boxes, as mentioned in section 2.1, includes vents allowing interaction between the different levels and the passage of the thermal plume evacuating the heat from the products in the vertical direction.

3.2. Unsteady state

Figure 4 (a, b, c and d) show the dimensional and dimensionless temperature evolution during the cooling process for both experimental conditions (u_{air}= 0.25m/s - Q=0W and u_{air}= 0.25m/s - Q=0.3W), along the different pallet rows: L_1, L_2 and L_3.

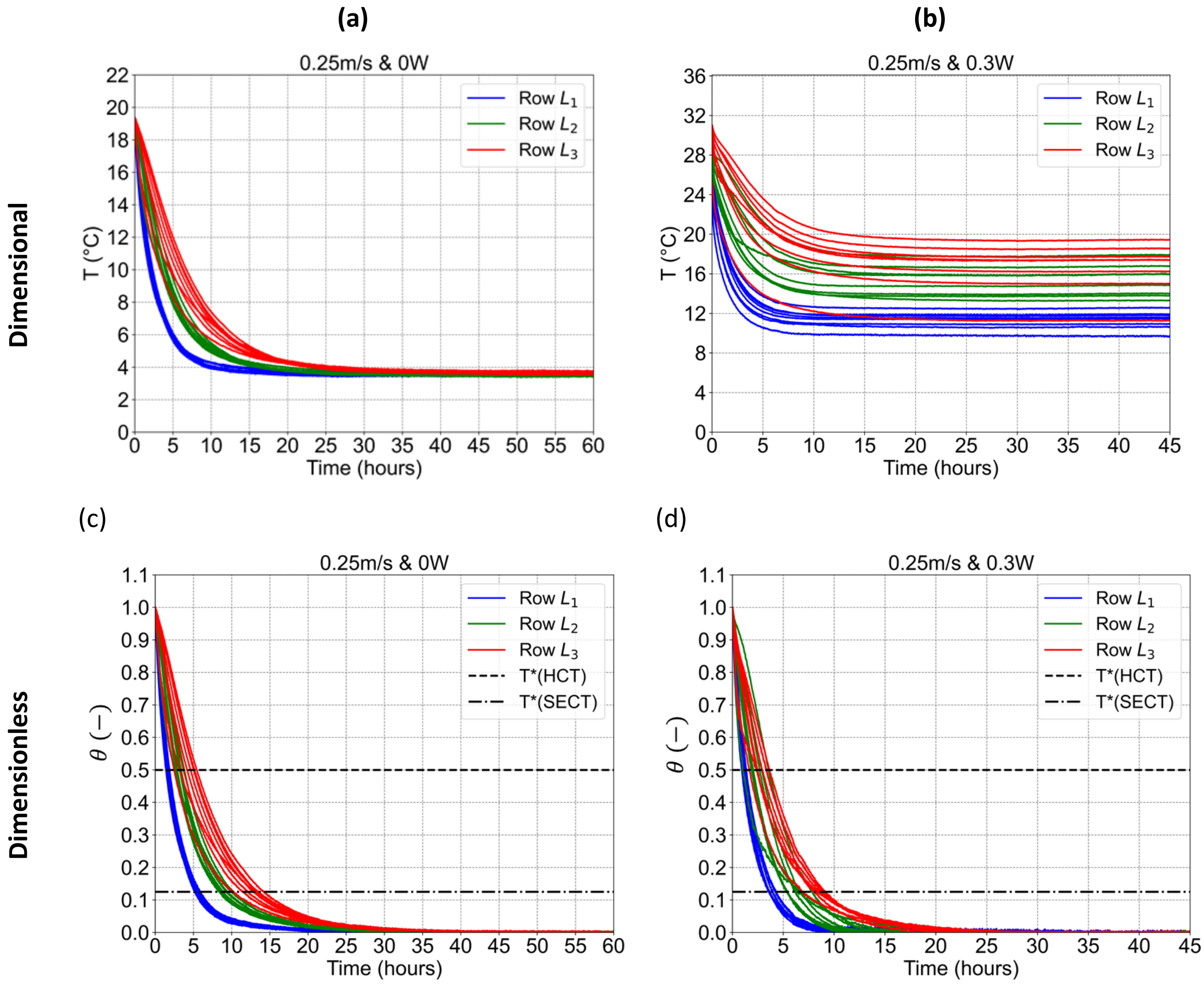

Figure 4: Rows L_1, L_2 and L_3 temperature evolution during cooling process for uair=0.25m/s: (a) Dimensional temperature Q=0W; (b) dimensional temperature for Q=0.3W; (c) dimensionless temperature for Q=0W; (d) dimensionless temperature for Q=0.3W.

It can be seen from Figure 4(a-b) that the final temperature of the products within the pallet are homogeneous for 0W while it is heterogeneous for Q = 0.3W.

According to Figure 4 and Table 1, products at upstream part of the pallet cool more quickly than those at the downstream part. This is partly due to the increase in air temperature from upstream to downstream on contact with warm products. Downstream product boxes receive warmed air and take more time to cool. On the other hand, as Aguenihanai et al., (2023); Pham et al., (2021) have demonstrated, air velocity decreases from upstream to downstream, which impacts the convective heat transfer coefficient and the cooling rate of the products.

Figure 4 compares the cooling kinetics of each pallet row for both heat fluxes (Q=0W and Q=0.3W). Although the temperature of the products is higher at heat flux Q=0.3W than at 0 W, the products that generate heat reach their equilibrium temperature more quickly than the products with no heat. As shown in Table 1, the SECT of products in rows L1, L2 and L3 decreases averagely by 29% when heat generation increases from 0 W to 0.3 W. These results are consistent with the findings of Chourasia and Goswami, (2007). They highlight the effect of the development of the thermal plume induced by natural convection (as explained in section 3.1), which helps the removal of heat from the products to reach their equilibrium temperature more quickly.

Table 1: Summary table of seven-eighths cooling time (SECT) for each pallet row L_1, L_2 and L_3 and each experimental condition (u_{air}=0.25m/s - Q=0W and u_{air}=0.25m/s-Q=0.3W).

Upwind air velocity (m/s)	0.25					
Heat generation per 250g of cheese Q (W)	0			0.3		
Rows	L_1	L_2	L_3	L_1	L_2	L_3
SECT (hrs)	5.50	9.21	12.58	3.86	6.23	8.38

4. CONCLUSIONS

This study investigates the impact of product heat generation on the temperature distribution and cooling rate of a ventilated pallet under both steady and unsteady state conditions.

The results demonstrate that under steady state conditions, a thermal plume is induced by natural convection at the downstream part of the pallet. In addition, under unsteady state, the cooling rate is higher with than without heat generation of the products. However, their equilibrium temperature is higher when heat is generated. The seven-eighths cooling time (SECT) of the different rows of the pallet decreases by 29% when the heat generation increases from 0W to 0.3W. This confirms that natural convection participates to heat dissipation from the products and cools them down more quickly.

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NOMENCLATURE

T	temperature (°C)	u_{air}	Upwind air velocity (m/s)
Q	Heat generation per 250g of product	SECT	Seven-Eighths Cooling Time (hrs)
T_0	Product initial temperature (°C)	θ	Dimensionless temperature
T_f	Product final temperature (°C)		

REFERENCES

Aguenihanai, D., Flick, D., Duret, S., Moureh, J., 2023. A Novel Hybrid Cfd Approach for Characterising Airflow and Temperature Distribution in a Ventilated Pallet of Heat-Generating Products: Application to Cheese.

Agyeman, E.K.K., Duret, S., Flick, D., Laguerre, O., Moureh, J., 2023. Computational Modelling of Airflow and Heat Transfer during Cooling of Stacked Tomatoes: Optimal Crate Design. Energies, 16(4), 2048.

Berry, T.M., Defraeye, T., Wu, W., Sibiya, M.G., North, J., Cronje, P.J.R., 2021. Cooling of ambient-loaded citrus in refrigerated containers: What impacts do packaging and loading temperature have? Biosystems Engineering, 201, 11–22.

Chourasia, M.K., Goswami, T.K., 2007. CFD simulation of effects of operating parameters and product on heat transfer and moisture loss in the stack of bagged potatoes. Journal of Food Engineering, 80(3), 947–960.

Jia, B., Yang, L., Zhang, L., Li, X., Liu, B., Chen, F., Zhang, Q., 2022. Energy consumption in relation to the number of stacked packages in forced air pre-cooling of apples. Journal of Food Process Engineering, 45(5), e14021.

Pham, A.T., Moureh, J., Belaidi, M., Flick, D., 2021. CFD modelling of a pallet of heat-generating product applied to a cheese product. International Journal of Refrigeration, 128, 163–176.

Wang, D., Lai, Y., Zhao, H., Jia, B., Wang, Q., Yang, X., 2019. Numerical and Experimental Investigation on Forced-Air Cooling of Commercial Packaged Strawberries. International Journal of Food Engineering, 15(7), 20180384.