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CFD study of airflow and temperature heterogeneity within a pallet of heat generating products: application to cheeses.

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ABSTRACT

The objective of this numerical study is to characterize temperature and airflow within a ventilated pallet of heat-generating products. Thus, it takes into account the resulting effect of forced and natural convection. An original Computational Fluid Dynamics (CFD) hybrid approach was developed. It combines porous medium approach for the container and direct CFD method for the external cardboard wall, including vent characteristics.

The computational domain is limited to one pallet level. The simulations are performed on steady state. The model was validated by comparison with experimental results related to velocity profiles and product temperature. When compared to direct CFD model, the hybrid approach shows also a good accuracy and allows reducing the mesh size and computational time. The model will be extended to an unsteady state to predict the cooling and heating kinetics of heat-generating products.

Keywords: Heat-generating products, direct CFD, porous medium, hybrid approach, mixed convection.

1. INTRODUCTION

Cheese is associated with significant heat generation induced by its respiration activity. Hence, the control of the product temperature is a major issue to preserve their gustative quality, thus reducing product loss. Its temperature must be controlled and maintained below a recommended value of 6 °C all along the cold chain facilities (Pham et al., 2021). Products heat generation can promote natural convection and thus affects temperature levels and their heterogeneity. Some studies on forced air cooling of food products have taken into account the heat respiration without including its effect on natural convection (Sajadiye and Zolfaghari, 2017). The assumption of neglecting the heat respiration of the products and the resulting natural convection is often stated (Berry et al., 2017; Defraeye et al., 2015). This hypothesis is hard to verify, especially in the case of a long precooling process (Nasser Eddine et al., 2022) or low air velocity, such as during storage, where the forced convection is weak and may be predominated by natural convection (Page et al., 2009). Moreover, Pham et al. (2021) showed that natural convection has a positive effect on heat transfer, with a product temperature lower under mixed convection than in forced convection alone.

Experimental studies are usually conducted to understand the cooling behaviour of product stacks, but remain limited because of costs and time manipulation (Zou et al., 2006a). To reduce the complexity of the experiments, two principal CFD approaches are therefore used. Direct CFD approach reproduces explicitly the geometry of boxes and products with good accuracy but is limited to small domains since it involves a high computational time (Wu et al., 2019). For larger-scale modelling, the porous medium approach is used

(Hoang et al., 2015). However, this method lacks sensitivity in modelling local airflow and temperature characteristics within boxes or stacks (Zou et al., 2006b).

To overcome these limitations, this study aims to develop an original hybrid approach based on CFD method, which combines the porous media method for the container of cheese boxes, and direct CFD approach to model explicitly the ventilated cardboard including vent design and characteristics. The model takes into account natural convection induced by heat generation associated with the respiration of cheese.

2. MATERIAL AND METHOD

2.1. Hybrid approach

As illustrated in Fig. 1b, the hybrid approach is based on modelling the inside of the boxes (cheese and air) in a porous medium and the cardboards including its vents dimension and positions using direct CFD approach. In order to simplify the geometry and reduce the calculation time, the thickness of the cardboards walls was not taken into account in the modelling domain. However, the corresponding thermal resistance effect of cardboards thickness on the convective heat transfer between the product and the ambience was considered.

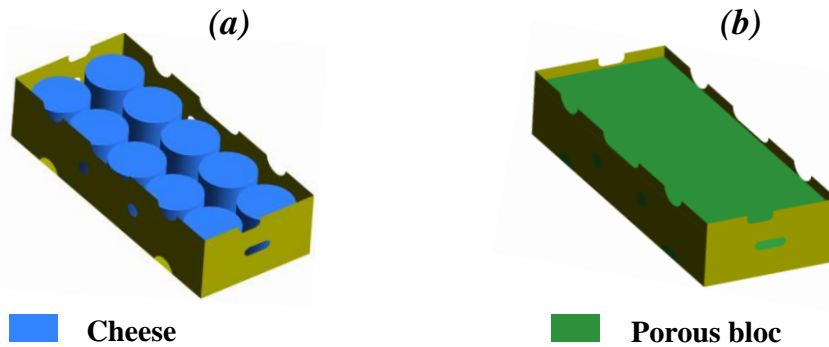


Figure 1: Schematics of the geometry modelled on direct CFD approach (a) and hybrid approach (b).

2.2. Computational model

The device is composed of one pallet with industrial size ($800\text{ mm} \times 1200\text{ mm} \times 1455\text{ mm}$) placed in a cold room ($5100\text{ mm} \times 3200\text{ mm} \times 2860\text{ mm}$) with a control of ambience parameters, velocity, and temperature. The pallet contains nine levels with six cardboards each. Every cardboard box is filled with thirty camemberts (Pham et al., 2019). Each 250 g of the products generates heat flux Q .

A three-dimensional (3D) CFD model is developed and conducted on a steady state. It is limited to one level of pallet (Fig. 2). Thus, the bottom vents of the cardboards were not taken into account since there is no interaction with the other pallet levels. The 3D geometry includes the space of 1 cm in between cardboards of the pallet level.

The thermophysical parameters of the different materials are obtained from Pham et al. (2021). Since cheese is supposed to be wrapped in a primary packaging (carton box), the equivalent thermal conductivity of the porous zone is considered anisotropic and includes the thermal conductivity of the cheese, the carton box and the stagnant air in between (On longitudinal and transversal directions $\lambda_x = \lambda_z = 0.32\text{ W} \cdot \text{m}^{-1}\text{K}^{-1}$; on vertical direction $\lambda_y = 0.30\text{ W} \cdot \text{m}^{-1}\text{K}^{-1}$).

2.3. Numerical modelling

Some simplifications and assumptions were made in order to reduce the computational cost while providing a good representation of the system. The flow is incompressible and turbulent. The source term $q = Q/V_{PM}$

is considered uniform in the porous zone and the natural convection is taken into account. Darcy-Forchheimer coefficients were calculated numerically and the Local Thermal Equilibrium (LTE) is assumed.

The steady heat transfer and incompressible flow are solved using Reynolds Averaged Naviers Stokes (RANS) equations. In this study, Boussinesq approximation is assumed and the RANS equations are combined with a standard $k - \varepsilon$ and standard wall function turbulence model. This model provides a good accuracy related to velocity and temperature behavior and was used by Tegenaw et al. (2019).

Since the numerical results of this study will be compared to Pham et al. (2021) results, identical boundary and initial conditions are imposed. Air inlet velocity $u_{air,in} = 0.31 \text{ m.s}^{-1}$, atmospheric pressure at the outlet, and adiabatic walls on each side.

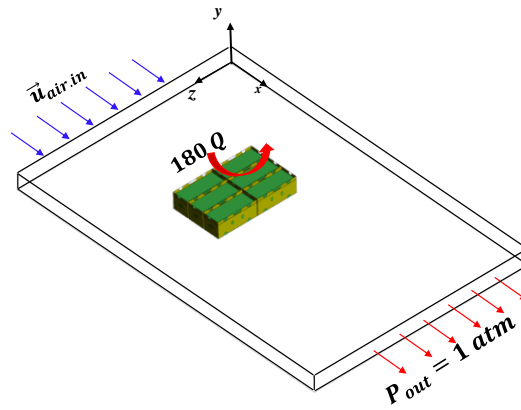


Figure 2: Schematic of the computational domain including the initial and boundary conditions.

2.4. Simulation set-up

After the conception of hybrid approach geometry, a tetrahedral mesh was developed. It was refined in the openings. The geometry is discretized on 741 420 cells. The simulations are performed using ANSYS Fluent-2021 on a 64-bit Windows 10 computer, Intel® Xeon® W-2133CPU @3.60GHZ with 256 GB RAM (12 cores). The solving algorithm and discretization schemes are the same as Pham et al. (2021). The computational time of each simulation is four hours.

3. RESULTS AND DISCUSSION

3.1. Airflow validation

Fig. 3c, Fig.3d and Fig.3e show the dimensionless air velocities ($u_x/u_{air,in}$) obtained using hybrid approach compared to numerical and experimental results of Pham et al. (2021). Experimental measurements were obtained using LDV (Laser Doppler Velocimetry).The results are extracted at mid-height of the air gap between the porous zone and the top of the cardboards C_1 , C_2 .and C_3 (See Fig. 3a).

$$u_{air.in} = 0.31 \text{ m.s}^{-1} ; Q = 0.05 \text{ W}$$

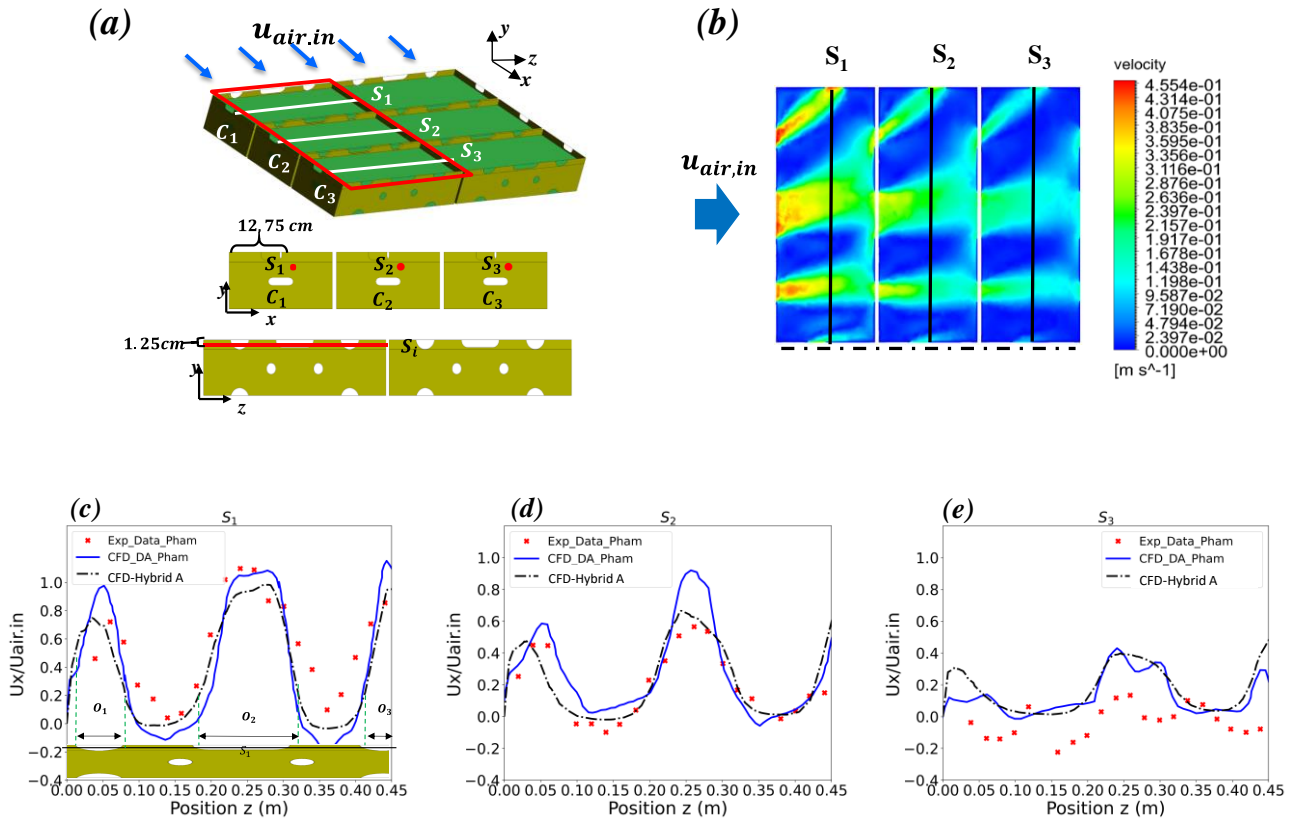


Figure 3: Schematic of velocity measurements positions (a), mid-high air gap velocity magnitude contour (b), comparison of dimensionless velocity profiles on S_1 (c), S_2 (d) and S_3 (e).

According to the dimensionless velocity profiles showed in Fig. 3c, Fig. 3d and Fig. 3e, the results of the hybrid approach are in agreement with experimental measurements. The upper peaks are related to the airflow entering through the upper vents of the cardboards O_1 , O_2 , and O_3 . These peaks of velocity on S_1 located on upstream of the ventilation are in the same order as the inlet velocity. Based on the velocity contour in Fig. 3b, the airflow passing through vents O_1 is mainly deviated and exits the boxes from the side vents.

The flow tends to slow down while crossing the cheese boxes from upstream to downstream. Concerning the results on box C_3 and comparing to experimental measurements, both direct CFD and hybrid approach results overestimate the velocity. These experimental results can be related to the roughness of the primary packaging of the cheese, to the imperfections of arrangements and to the presence of resistance cables inside the cardboards between cheeses. All these aspects increase pressure losses of the airflow within the air gap, which results in decreasing air velocities.

3.2. Temperature validation

Fig. 4b and Fig. 4c show a distribution of differential temperature ($T_x - T_{air.in}$) over the three cheese cardboards for one velocity inlet $u_{air.in} = 0.31 \text{ m.s}^{-1}$ and generated heat flux 0.05 W . The values of temperature are taken at 45 mm depth of the porous bloc (see Fig. 4a). The numerical results are compared to experimental temperatures. T-type thermocouples ($\pm 0.2^\circ\text{C}$) are used for the experimental measurements.

$$u_{air.in} = 0.31 \text{ m.s}^{-1} ; Q = 0.05W$$

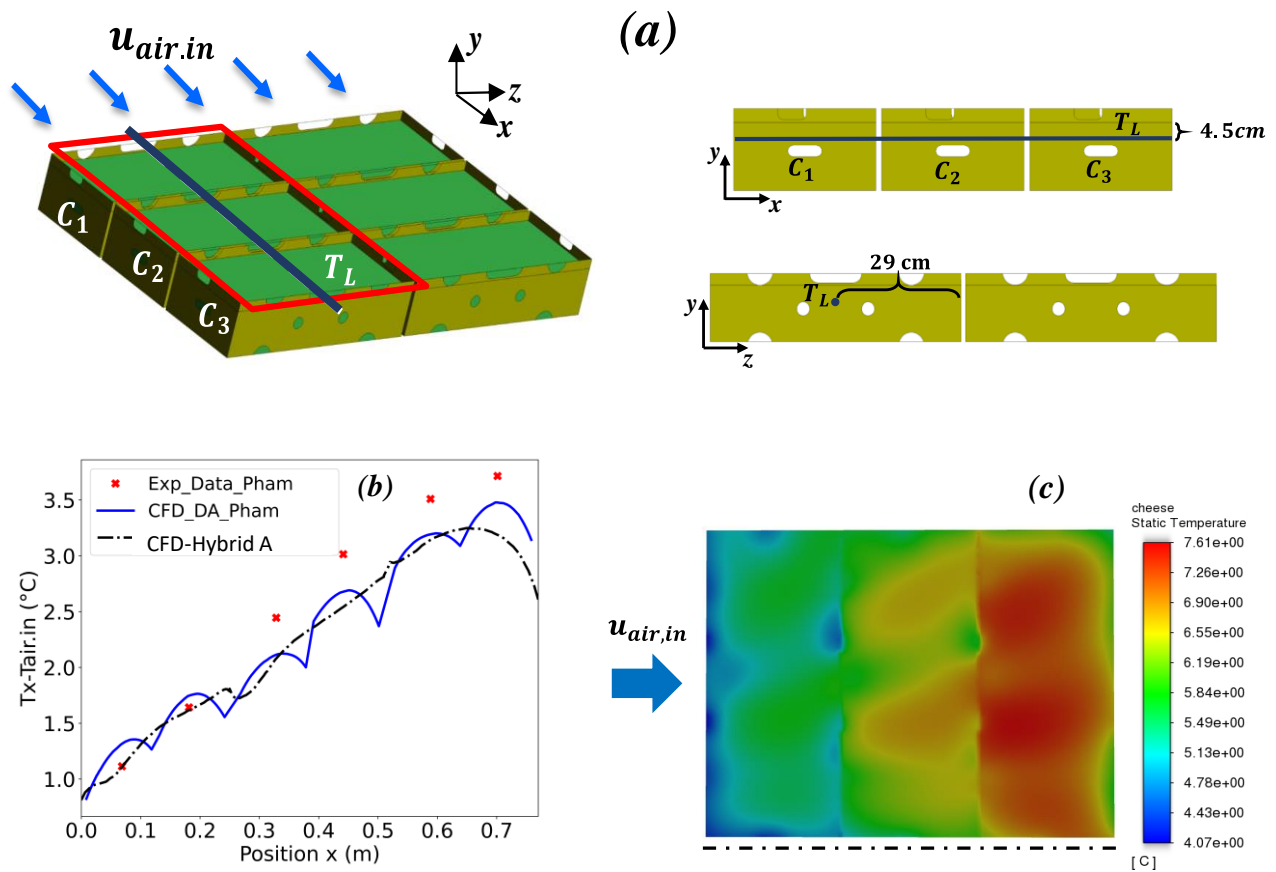


Figure 4: Schematic of temperature measurements positions (a), Differential temperature comparison plot (b), Temperature contour (c).

The difference in appearance between the two plots of direct CFD and hybrid approach shown in Fig. 4b is attributed to the geometry representation of the two modelling methods. The hybrid approach defines the geometry as a homogeneous parallelepiped porous bloc and tends to uniform the temperature curves. The direct CFD method, meanwhile, is a juxtaposition between cheese and air, so the temperature is higher in the center of cylindrical cheeses and lower around the borders (See Fig. 1).

Fig. 4b shows that the hybrid approach results are in good agreement with the experimental measurements. The relative error (RE) and Root Mean Square Error (RMSE) are 8.64% and 0.27°C, respectively for 0.05W.

According to the results of differential temperature distribution, its heterogeneity is related to the position of the products and to the heat flux they generate. The temperature of the products upstream of ventilation is lower than those downstream. This behaviour is in agreement with the airflow velocity results discussed above in section 3.1. The air velocity decreases in the ventilation direction and its temperature increases as the heat of the products is extracted. Thus, the products located in the upstream part of the pallet are better cooled than those in the rear.

4. CONCLUSIONS

In this numerical study, an original CFD hybrid approach is developed on one level of a pallet of heat generating cheese and performed at steady state. The model showed a good agreement with experimental results related to air velocity and product temperature.

Besides the simplification of the geometry provided by this method and the reduction of computational time to four hours compared to forty-eight hours using direct CFD, it also allows, through the discrete modelling

of the cardboards, a good description of the preferential path of the airflow with an accurate prediction of temperature evolution within the boxes.

The model will be improved by assuming local thermal non-equilibrium assumption and adding local convective heat transfer coefficients. To investigate the cooling and heating kinetics of heat generating products, further studies will be conducted using this method on a transient state on one level and an entire pallet.

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NOMENCLATURE

u	Airflow velocity ($m \times s^{-1}$)		$RMSE$	Root Mean Square Error ($^{\circ}C$)
T	Temperature ($^{\circ}C$)		RE	Relative Error (%)
Q	Heat generated by 250g of cheese (W)		air. in	Airflow in the inlet
λ	Thermal conductivity ($W \times m^{-1} \times K^{-1}$)		out	outlet
q	Source term ($W \times m^{-3}$)		x	Longitudinal direction
V_{PM}	Total volume of the porous media (m^3)		z	Vertical direction
p	Pressure (atm)		y	Transversal direction

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