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SIMPLIFIED MODEL OF AIRFLOW AND HEAT TRANSFER IN A PALLET OF FOOD PRODUCT GENERATING HEAT

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ABSTRACT

During storage, pallets of food product generating heat (e.g. cheese, fruit, vegetable) are exposed to low velocity ventilation. In addition the boxes have often little perforation. Therefore airflow is weak inside the boxes located downstream of the pallet; and if the product generates heat, its temperature can rise above the recommended one. CFD modelling can predict these phenomena but needs an expertise of numerical fluid flow, a detailed description of product and packaging and leads to expensive computational costs. A simplified model is here developed based on a hydraulic network analogy. Given the vent holes areas of the boxes and the heat generation, it predicts the global air flow (flow through the box faces) and the product temperature. The predictions are in good agreement with experimental data. The software (Matlab executable) is easy to use and needs only some seconds to compute. It can be used to predict temperature evolution along a cold chain and to improve packaging and logistic operating conditions.

Keywords: Mathematical modeling, temperature distribution, heat generating product, zonal model

PRACTICAL APPLICATIONS

Based on a on a hydraulic network analogy, a simplified zonal model of airflow and heat transfer in a pallet of food generating heat is built with the Matlab software. It takes into account the vent holes areas of the boxes and the heat generation, and allows predicting the distribution of air fluxes through the box faces and the product temperature. The major advantage of this model is that it is easy to use and needs only some seconds to compute. Therefore, it can be easily used in industrial field.

1. INTRODUCTION

To study airflow and heat transfer in ventilated packages of fresh foods, the experimental approach is usually considered expensive, time-consuming and situation-specific (Zou et al. 2006). Moreover, it is difficult to generalize the problem and control the experimental conditions while dealing with biological products (Delele et al. 2013). Computational Fluid Dynamics (CFD) is a powerful alternative method. It allows studying different configurations of the system at low cost (Defraeye et al. 2015). But CFD requires a lot of computational resources and its use is limited since the user need to have a good knowledge of simulation in order to modify the model. Another alternative to overcome this limit is the zonal approach. Evidently, it cannot give detailed results as CFD. However, the calculation time can be reduced significantly. For example, the zonal model of a cold room developed by Laguerre et al. (2015) required only one second for the calculation, compared to that of the CFD model (8.10^5 cells) which needed more than 24 h for the same configuration

This study aimed to create a zonal model of one layer of a pallet of product generating heat. Taking into account that similar temperature distribution within the pallet for all layers are obtained experimentally (Pham et al. 2019) except for the upper one which is better ventilated, the modelled layer is considered of being representative of an intermediate layer of the pallet.

The model takes into account the geometry of the package (opening area) and the heat flux generated by the products. The airflow rates and the temperatures (air and product) are calculated in each zone. This model can be applied to different palletized products.

2. EXPERIMENTAL SET-UP

The experimental set-up includes a pallet of artificial products placed inside a cold room (Figure 1). Each artificial product is made of plaster instrumented with a heating resistance to simulate the heat generated by the product. The air temperature and velocity in the cold room (upstream of the pallet) can be controlled. More details of the experimental set-up can be found in our previous paper (Pham et al. 2019).

Figure 1 Experimental set-up

The air velocity at the center of the vents was measured by a hot wire anemometer TESTO 435-4 (precision 5% of the read value or ±0.03 m.s^{-1}). This allows estimating the airflow rates through the vents. The temperature was measured by using T-type thermocouples (with a precision of ±0.1 K after individual calibration between 273 and 293 K). The product temperature was measured on the axis of the cylindrical plaster blocks, 5 mm from the top.

3. MODEL

It has been shown (Pham et al. 2019) that inside a pallet, the temperature profile is almost the same for all the box layers except for the upper one which is better ventilated. Since the product quality issue is related to high temperature, the upper layer was not considered and the study was focused on an intermediate layer. This layer is constituted by several boxes, and each box is divided in some zones. It is assumed that the pallet is submitted to an external horizontal upstream airflow normal to one of it vertical face (called later upstream face). Generally, the pallet has a longitudinal symmetry plane so only half of a pallet has to be considered. Figure 1 presents an example of the division of a half pallet layer (dimension L_x L_y) into IxJ (here 3x6) zones. Δx and Δy are the width and the length of a zone. Δz is the eight of the layer (excluding the thickness of the bottom cardboard face of the box).

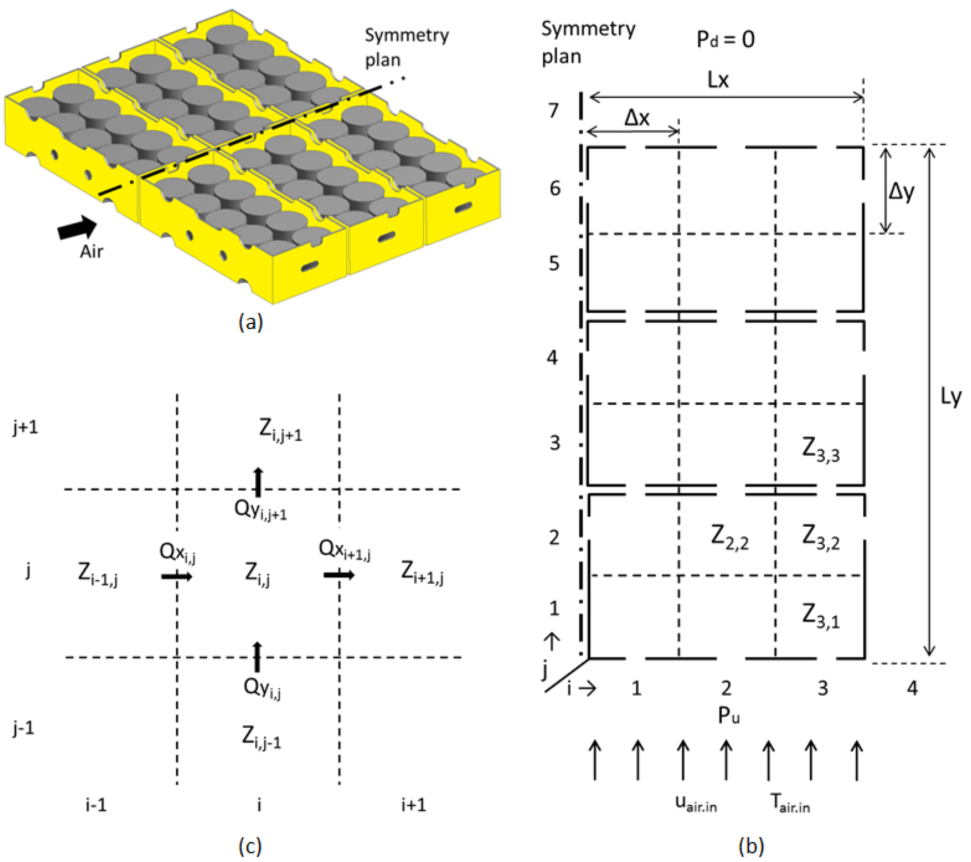


Figure 2: Pallet layer:(a) 3D view of the layer; (b) 2D zonal model; (c) zoom of zone $Z_{i,j}$

In this example, the zone $Z_{3,2}$ (i=3, j=2) is separated from $Z_{3,3}$ by two perforated cardboard faces (the vent holes being at same location); it is separated from the lateral free space by one perforated face. There is no separation between $Z_{3,2}$ and $Z_{2,2}$ or $Z_{3,1}$. The airflow rate (m^3s^{-1}) from $Z_{i-1,j}$ to $Z_{i,j}$ (in the x direction) is referred as $Qx_{i,j}$. In a similar way the vent hole area in the face separating $Z_{i-1,j}$ and $Z_{i,j}$ is called $Sx_{i,j}$. Likewise, the flow rate and the perforation area between $Z_{i,j-1}$ and $Z_{i,j}$ (in the y direction) are called $Qy_{i,j}$ and $Sy_{i,j}$.

The global fluid flow estimation is based on a hydraulic network analogy. The density ρ (kg m^{-3}) is assumed as constant. The centre of each zone is considered as a pressure node. The pressure drop between $Z_{i-1,j}$ and $Z_{i,j}$ is the sum of the singular pressure drop corresponding to the airflow through the vent holes and the linear pressure drop corresponding to the airflow through the gaps between and above the products along a distance Δx:

$$P_{i-1,j} - P_{i,j} = -\left[K \frac{\rho v_h^{\ 2}}{2} + \lambda_f \frac{\rho v_g^{\ 2}}{2} \frac{\Delta x}{D_h} \right] \quad (1)$$

The average velocity in a vent hole is equal to the flow rate divided by its area:

$$v_h = \frac{Qx_{i,j}}{Sx_{i,j}} \quad (2)$$

$Sx_{i,j}$ represents the area of the vent hole separating $Z_{i-1,j}$ and $Z_{i,j}$.

The value of the singular pressure drop coefficient K depends on the exact geometry of the perforation; it is typically comprised between 1 and 1.5. In addition, the air flows in different complicated channels between and above the products. This is like a very rough duct for which the friction factor λ_f can be assumed as constant. Often there is preferential air flow in the headspace (air gap between the top of the product and the bottom face of the upper box). Therefore the characteristic velocity can be calculated from the height of the air gap (Δz_g) and its width (Δy):

$$v_g = \frac{Qx_{i,j}}{\Delta z_g \Delta y} \tag{3}$$

The hydraulic diameter of this gap is equal to twice its height: $D_h = 2\Delta z_g$ .Finally, the pressure drop can be calculated by:

$$P_{i-1,j} - P_{i,j} = -\frac{\rho}{2}\left[KSx_{i,j}^{-2} + \frac{\lambda_f}{2}\Delta x \Delta y^{-2} \Delta z_y^{-3} \right] \left| Qx_{i,j} \right| Qx_{i,j} \tag{4}$$

For the outer zones, the length considered for the linear pressure drop (e.g. from $Z_{3.1}$ to lateral free space) is $\Delta x/2$ instead Δx.

The same procedure can be applied for flow and pressure drop calculation in the y direction.

In addition, the mass balance of zone $Z_{i,j}$ becomes:

$$Qx_{i,j} - Qx_{i+1,j} + Qy_{i,j} - Qy_{i,j+1} = 0 \tag{5}$$

The external pressure is assumed to be known all around the pallet. The difference between upstream and downstream pressure for the turbulent flow around an obstacle is of the order of the dynamic pressure: ½ $\rho u_{air.in}^2$ where $u_{air.in}$ is the upstream velocity (far from the pallet). Therefore the downstream pressure is set to zero:

$$\forall i : P_{i,J+1} = P_d = 0 \tag{6}$$

And the upstream pressure is assumed to be:

$$\forall i : P_{i,0} = P_u = a_u \frac{1}{2} \rho u_{air.in}^2 \qquad \text{where } a_u \text{ is close to 1} \tag{7}$$

The pressure in the lateral free space depends on the proximity of other pallets; it evolves between the upstream and downstream pressures. Linear variation with y position is assumed.

$$P_{I+1,j} = \left[b_u + \frac{y}{L_y}(b_d - b_u) \right] P_u = \left[b_u + \frac{j-0.5}{J}(b_d - b_u) \right] a_u \frac{\rho u_{air.in}{}^2}{2} \tag{8}$$

Where b_u et b_d are dimensionless parameters between 0 and 1. The software allows also imposing a given mean velocity in the vent holes of the upstream face u_m indeed it was observed that this mean velocity is close to the upstream one (Pham et al. 2019). Therefore, the problem is first solved with $P_u = \frac{1}{2} \rho u_m^2$ and the mean velocity in the upstream face is calculated for this boundary condition: u_m'. Then, all the flow rates and velocities calculated with the first boundary condition are multiplied by u_m/u_m' and the pressures by $(u_m/u_m')^2$. Indeed, since all the pressure drops are assumed proportional to the square of local flow rate, the ratio between two flow rates is independent of the upstream pressure.

The heat generation per unit area (q' in W m^{-2}) is assumed uniform in the box. It can be calculated from the heat generation per unit mass (q in W kg^{-1}), the weight of a product item (m in kg) and the number of items in a layer of a half pallet (n). Only convective fluxes are considered in the model. The heat balance of zone $Z_{i,j}$ is written by distinguishing the flows coming in and out. For example, $\max(0,Qx_{i-1,j})$ is the eventual inflow coming from $Z_{i-1,j}$. and $\max(0,-Qx_{i+1,j})$ is the eventual inflow coming from $Z_{i+1,j}$. The following equations allows the prediction of the air temperatures $T_{i,j}$ inside the pallet:

$$\max(0,Qx_{i,j})T_{i-1,j}+\max(0,-Qx_{i+1,j})T_{i+1,j}+\max(0,Qy_{i,j})T_{i,j-1}+\max(0,-Qy_{i,j+1})T_{i,j+1} \quad (9)$$
$$+q'\Delta x\Delta y/(\rho Cp_{air}) = (\max(0,-Qx_{i,j})+\max(0,Qx_{i+1,j})+\max(0,-Qy_{i,j})+\max(0,Qy_{i,j+1}))T_{i,j}$$

The air temperature around the pallet is assumed to be the upstream one

The local product temperature: T_p, is higher than the local air temperature T. The difference depends on the convective heat transfer coefficient: h ($Wm^{-2}K^{-1}$) and the area of product/air interface of a product item (S). This coefficient depends theoretically on product geometry, local velocity and turbulence intensity. Here a constant value is applied. This constant value was estimated by the experimental study (Pham et al. 2019). The product temperature in each zone can be calculated by:

$$Tp_{i,j} = T_{i,j} + \frac{mq}{hS} \quad (10)$$

Where m (kg) represents the mass of the product in the $Z_{i,j}$ zone.

This hypothesis leads to a constant difference between local air and product temperature. Experimental observations (Pham et al. 2019) confirmed that this is almost the case.

The fluid flow problem is nonlinear because of the quadratic influence of flow rate on pressure drop. Therefore a fixed point iterative method with under-relaxation was used to solve it. At a given iteration step, following approximation is used:

$$P_{i-1,j} - P_{i,j} = -\frac{\rho}{2}\left[KSx_{i,j}^{\ -2} + \frac{\lambda_f}{2}\Delta x \Delta y^{-2} \Delta z_g^{\ -3} \right] \left| Qx_{i,j} \right|_{old} Qx_{i,j} \tag{11}$$

Where $Qx_{i,jold}$ is the previous estimation of the flow rate. This way, the set of approximate equations becomes linear and is easily solved in a matrix form. The iterations are carried out until the relative variation of the flow rates become smaller than 0.1%. Once the flow rates are determined the linear set of air temperature equations are solved. Finally the product temperature is deduced. The model was numerically solved using MATLAB R2015b.

4. COMPARISON OF PREDICTED AND OBSERVED RESULTS

It was shown by a CFD model considering one pallet in the cold room that the lateral pressure around is close to the downstream one. Therefore, for a single pallet, it is assumed that b_u=b_d=0. The heat transfer coefficient was estimated in our previous study (Pham et al. 2019). This coefficient varied between 2.2 and 3.4 W.m^{-2}.K^{-1}. For the simulation, the heat transfer coefficient h was fixed at 3W.m^{-2}.K^{-1}. The value of the friction factor λ_f is difficult to estimate because it depends on the complex geometry of the air flow channels. In analogy with very rough tubes (roughness being around 10% of tube diameter) λ_f is around 0.2 (according to Nikuradzé' s correlation $\lambda_f = [\ 2\log_{10}(3.71D/\varepsilon)\ ]^{-2}$).

TABLE 1	K	λ_f	b_d	b_u	h	$u_m/u_{air.in}$
	1.5	0.2	0	0	3	1

Table 1: numerical values used for the simplified model

The chosen configuration represents half layer of a pallet of camembert (Figure 2). There are 30 products per box. Each box is divided into 6 zones in the model. The experimental conditions are presented in the TABLE 2

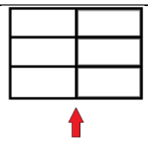
TABLE 2	$u_{air.in}$=0.31 m.s^{-1}	$u_{air.in}$ =0.73 m.s^{-1}	
Heat flux Q (per cheese item of 250g)	0.05W	0.05W	
	0.15W	0.15W	
	0.30W	0.30W	

Table 2: Experimental conditions used for the model validation

Figure 3 presents the predictions of the model for $u_{air.in}$=0.31 m.s^{-1}, $T_{air.in}$=4°C, Q=0.05W. It can be observed that a great part of the incoming airflow does not reach the rear part of the pallet but flows out through the lateral vent holes.

The air temperature progressively increases as it passes through the pallet. The highest product temperature is observed near the symmetry plane at the last row of the pallet. This conditions ($u_{air.in}$=0.31 m.s^{-1}, Q=0.05W) can be encountered in practice for camemberts in a cold room. In this case, the ripening of the warmest camembert (8.1°C) would be accelerated compared to the coldest one.

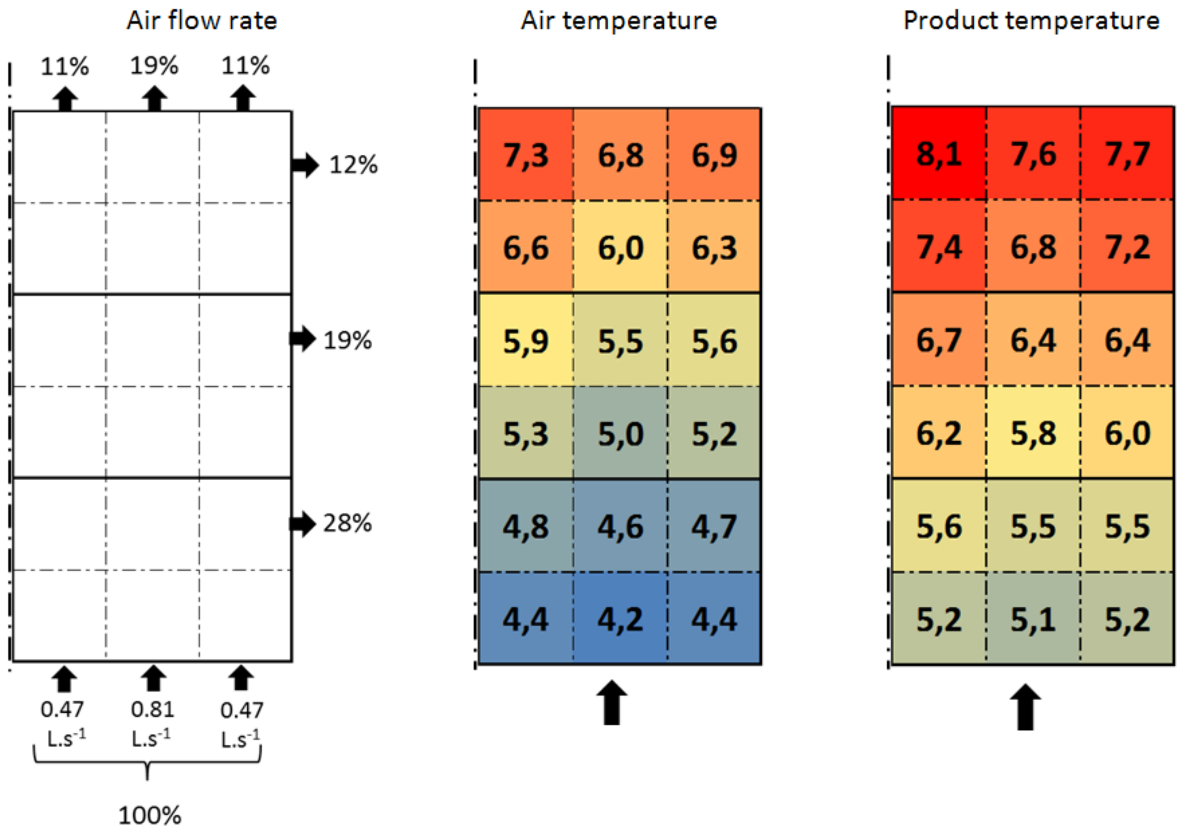


Figure 3: Numerical results for $u_{air.in}$=0.31 m.s^{-1}, $T_{air.in}$=4°C, Q=0.05W

The experimental flow rates at each face of the boxes were estimated by multiplying the air velocity measured in front of the vent holes by their surface. The figure 4 represents the simulation results in function of the experimental ones without heating products at two upwind velocities ($u_{air.in}$) 0.31 m.s^{-1} and 0.73 m.s^{-1}

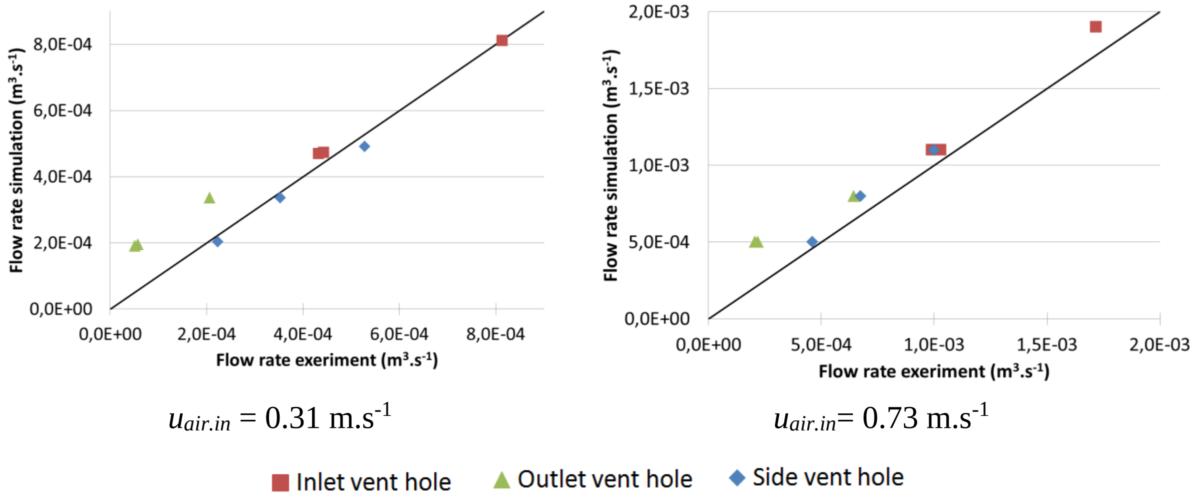


Figure 4: Comparison between the flow rates obtained by experiment and simulation

The model predicts well the flow rate at the inlet vent holes and the side vent holes. The differences between the model and the experiment concerning the outlet flow rate can be explained by the sensibility of the measurement. Air slows down as it passes through the pallet. Therefore, air velocity downstream of the pallet is very weak compared to the upstream one, becoming sometimes out of the precision range of the hot wire anemometer. Moreover, the sensor can disturb the flow and the flow is not necessary normal to the vent section.

Figure 5 compares the difference between the product temperature and the upstream air temperature $\Delta T=T_p\text{-}T_{air.in}$ for experiment and simulation. The center line of the half pallet was chosen for the thermal validation. This line of product corresponds to the position i=2 in the model (Figure 2b). The comparison was done for the 6 configuration presented in TABLE 2.

The model predicts well the tendency of the experimental result: the further the product in the main flow direction, the higher its temperature is. There is an exception when Q=0.30W and V_u=0.31m.s^{-1}. In this configuration, the final product temperature (position 6) is lower than the one just before it (position 5). This decrease in temperature was explained by the influence of the natural convection that allows cold air entering by the downstream vent holes (Pham et al. 2019). Since the buoyancy forces (free convection) are not considered in the present model, the maximal product temperature is slightly overestimate in this case.

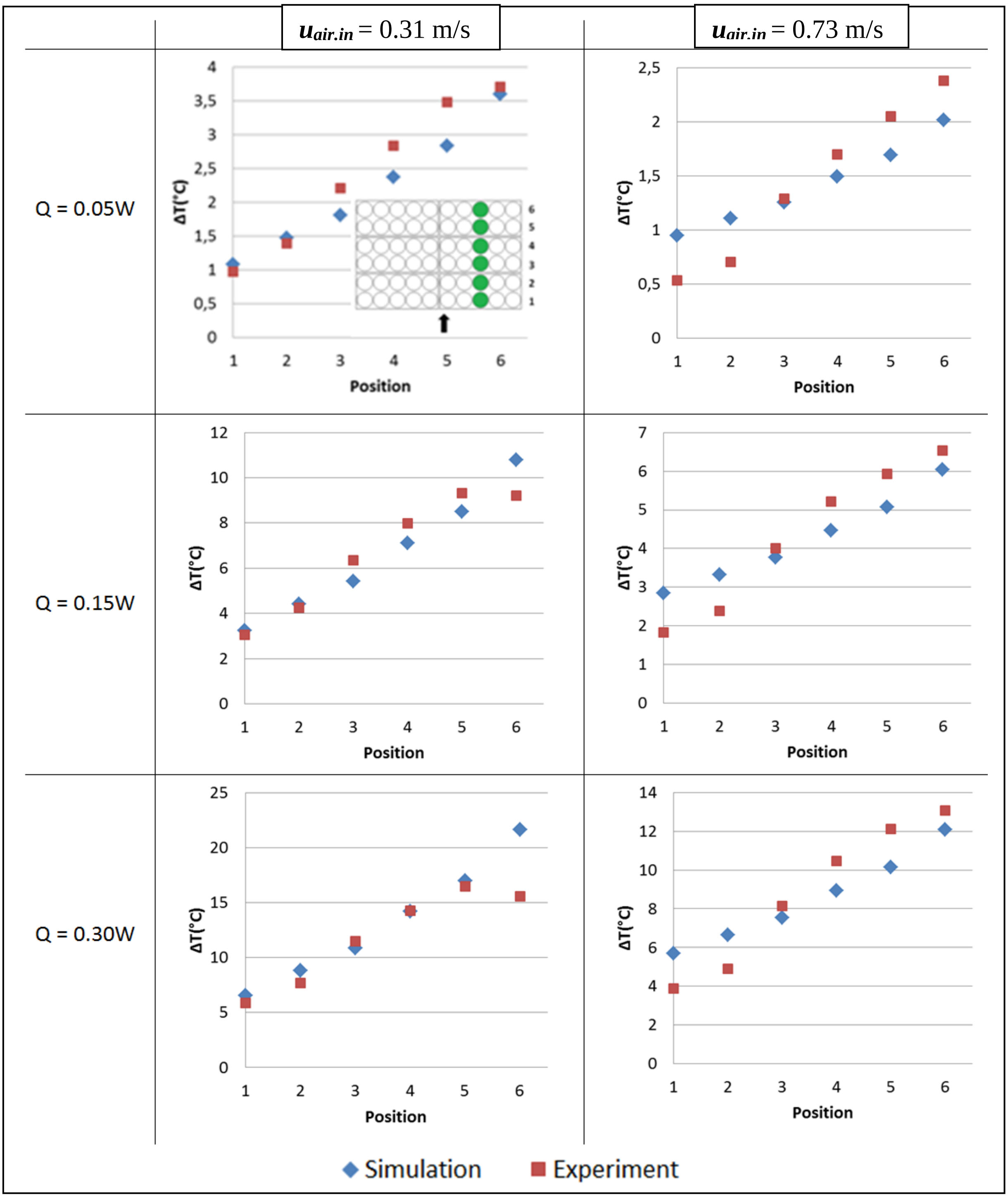


Figure 5 Comparison between experiment and simulation temperature profiles: $\Delta T = T_p - T_{air.in}$

The simulation results are in relatively good agreement with the experimental ones. The average difference between the experimental and calculated temperature is 0.8°C. This level of precision is satisfactory since the model was simplified compared to the experimental set-up. It allows predicting the product temperatures under different configurations in a short calculation time (2 seconds compared to 48h by CFD method)

5. CONCLUSION

A simplified model which represents airflow and heat transfer was developed for half a layer of a pallet of heat-generating products. This model allows obtaining the airflow rate as well as the air and product temperature at different zones in the pallet. The input parameters of the model are the upstream air velocity and temperature, the heat generation per mass unit, the dimensions of the product, boxes and the opening surface of the different faces of the boxes.

Even though several hypotheses were applied in order to simplify the model, a good agreement between the experimental and simulation results was found. The main advantage of this model is the computing time (only several seconds). Another advantage is that the user of the model does not need to have an expertise in modeling. Therefore, it can be applied for industrial use.

The model is a potential design tool that allows predicting the product temperatures in function of packaging and operating conditions. It can be extended to other palletised product stored in a cold room. The results here are for steady state, but the model can easily by extended to predict product temperature evolution along a cold chain with variable upstream air temperature and velocity

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