Phenomenological Characterization of Chilling of Pork Carcasses

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ABSTRACT

Carcass chilling is an important step in pork meat processing. The chilling air velocity at the surface of a carcass is not uniform, mainly because of its geometry, this may results in different values for the local heat transfer coefficient and consequently, affecting surface and interior temperatures. This may have important implications in weight loss and safety. Experimental measurements and computational modeling were carried out to estimate heat transfer coefficient variation. Pork carcasses were stored at cool temperatures and then exposed to room temperatures using forced convection. The change of temperature in the pork carcass surfaces was monitored using an infrared camera, and interior temperatures were measured with thermocouples. The experimental results were used to fit a computational model of heat and mass transfer, based on finite elements to estimates of the local heat transfer coefficients. With a velocity of approximation of 10.5 m/s, the heat transfer coefficient varies between 33 to 9 W/m\textsuperscript{2}K depending on the location and side (inner/outer) of the carcass. This result enables a better understanding of heat transfer and weight loss during the chilling of pork carcasses.

Keywords: Refrigeration; Convection; Modeling.

INTRODUCTION

During the processing of pork carcasses a series of steps are required, including the reduction of the temperature from 37 °C to -1/-2 °C (or pork carcass chilling). In this process, the pork carcasses are suspended vertically and exposed to an up-down flow of cooling air [1], figure 1. This process is designed to achieve the following objectives:

- Cooling rate should be sufficient to slow microbial growth and to prevent food spoilage.
- The process should minimize weight and volume losses.
- The product should not freeze at any time (not even locally) during the process.
- The process should minimize associated operation costs, mainly from electrical consumption.

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{chiller.png}
\caption{Industrial setup for the chilling of pork carcasses.}
\end{figure}
The design of commercial systems for the chilling of pork carcasses consists of sub-steps at different temperatures, where the cooling air temperatures vary between 0 to -15 °C. Varying the residence time in each sub-step allows flexibility to achieve the above objectives: slowing microbial growth; preventing spoilage; minimizing weight and volume losses; avoiding freezing; and minimizing operation costs. Carcass weight loss is an important objective [2], and it can be estimated through heat and mass transfer equations in which the respective transfer coefficients are to be known. Considering the shape of pork carcasses and the flow patterns that can evolve, it is expected that the heat transfer coefficients will show spatial variability. Figure 2 presents pork carcass geometry, including cross-sectional views.

![Figure 2. Cross-sectional areas of a pork carcass](image-url)

The main objective of this study is to implement a method for estimating the local convective heat transfer coefficients (inner outer surfaces of the cross-sectional areas in figure 1).

**MATERIALS & METHODS**

A phenomenological model is being implemented for heat and mass transfer analysis during pork chilling. This model considers the system carcass/air. In the case presented here it is assumed that the transport in the vertical direction — along the airflow — is negligible compared with the lateral directions. This allows the expression of the heat and mass transfer equations as follows [3,4]

\[
\rho \cdot C_p \frac{\partial T}{\partial t} = k \frac{\partial^2 T}{\partial x^2} + k \frac{\partial^2 T}{\partial y^2}, \quad (1)
\]

\[
\frac{\partial M}{\partial t} = D_M \frac{\partial^2 M}{\partial x^2} + D_M \frac{\partial^2 M}{\partial y^2}, \quad (2)
\]

where \(\rho\) corresponds to density, \(C_p\) specific heat, \(k\) thermal conductivity, and \(D_M\) moisture diffusivity through the pork carcass; \(T\) and \(M\) correspond to the temperature and moisture fields in the pork carcass. The system solution requires boundary conditions for equations (1) and (2) as follows:
\(-k \left( \frac{\partial T}{\partial x} \hat{i} + \frac{\partial T}{\partial y} \hat{j} \right) = \left( h_f (T - T_{\text{ambiente}}) + L_v * h_m (P_A - P_{\text{air}}) \right) \tilde{\alpha}, \) (3)

\(-D_m \left( \frac{\partial M}{\partial x} \hat{i} + \frac{\partial M}{\partial y} \hat{j} \right) = \frac{h_m (P_A - P_{\text{ambiente}})}{\rho S} \tilde{\alpha}. \) (4)

where \(L_v\) is the water vaporization heat; \(P_A\) and \(P_{\text{air}}\) are water partial pressure at the carcass surface and air, respectively; and \(h_f\) and \(h_m\) are heat and mass transfer coefficients, respectively. The solution of the coupled equations (1) and (2) allows for temperature and moisture evolution as a function of time and position. The relationship between moisture content and water partial pressure was analyzed using the following expression for the water activity \(a_w\) as a function of temperature [5]:

\[ \left( a-w \right)(T) = d \cdot \text{EXP} \left[ a \cdot e^{-b M} \cdot \left( \frac{1}{T} - c \right) \right], \] (5)

The parameters \(a\), \(b\), \(c\) and \(d\) in (5) are determined using experimental data for pork carcasses, considering meat and skin separately. The relationship between heat/mass transfer coefficients has been modeled using the following relationship [3]:

\[ h_m = \frac{h_f}{L_v \cdot 64.7 [Pa/K]}, \] (6)

The previous equations are solved numerically for each cross-sectional area using finite element and the commercial software, PdEase-2D.

The experimental setup is developed considering the same process shown in figure 1. Since the specific objective is the analysis of the local heat transfer coefficient, a pork carcass, stored at 8 °C, is warmed with air at a velocity of approximately 10.5 m/s. The local air velocity was measured using a hot wire anemometer. The temperature at the surface of the carcass is recorded using an IR camera, AVIO TVS 100. Temperatures inside the carcass are measured using inserted thermocouples. Two experiments are performed using the same procedure.

The measured temperatures are used to estimate the local heat transfer coefficients. The heat transfer coefficients, considered as variables, are estimated by minimizing the deviation between the experimental and calculated values:

\[ \text{MIN} \left\{ f(h_{T,local}) = \sqrt{\frac{\sum_{i=1}^{n} (T_{\text{experimental}} - T_{\text{simulada}})^2}{n}} \right\}. \]

The heat transfer coefficients are determined for each cross-section, and different values are estimated for the outer (skin covered) and inner (not covered by skin) sides of the pork carcass.

**RESULTS & DISCUSSION**

Figure 3 presents the variation of the local velocity across the geometry. This variation supports the fact that local heat transfer coefficients along the carcass surface should be used.
The temperatures measured on the surface and inside the carcass are presented in figure 4.

The following values in Table 1 were obtained for the local heat transfer coefficients.

<table>
<thead>
<tr>
<th>Section</th>
<th>Outer side</th>
<th>Inner side</th>
</tr>
</thead>
<tbody>
<tr>
<td>AA'</td>
<td>33</td>
<td>33</td>
</tr>
<tr>
<td>BB'</td>
<td>24</td>
<td>20</td>
</tr>
<tr>
<td>CC'</td>
<td>20</td>
<td>9</td>
</tr>
<tr>
<td>DD'</td>
<td>20</td>
<td>18</td>
</tr>
</tbody>
</table>

The results of the model for temperature evolution using optimized values for local heat transfer coefficients are presented in figure 5.
A good representation of the surface temperature evolutions has been obtained through use of the proposed model (Figure 5). The optimized values for the local heat transfer coefficients show variation with position, in agreement with the local velocities. The observed changes in the heat transfer coefficient values are consistent with the differences in temperature evolution for the surfaces and the insides of the pork carcasses. The inside of section AA’ shows a slower temperature rise. This is consistent with the recommendation of measuring the temperature at this location during the chilling processes.

The inner side of sections BB’ and CC’ presents the lower values for the local velocities and consequently lower values for the heat transfer coefficients. Section AA’ show a better agreement, between the model and the experimental results. A more complete approach could include the modeling of the full 3-D structure to account for axial heat transfer.
In addition, the mass transfer coefficients can be evaluated through equation (6) and the known values of local heat transfer coefficients. This allows the estimation of weight losses during the chilling process.

Knowledge of temperature and moisture at the carcass surface allows for the estimation of microbiological contamination. Thus this model could be used in combination with those for microbial growth, and used to identify the more favorable conditions for the development of pathogens for certain process conditions.

**CONCLUSION**

The heat transfer coefficients were identified for different locations, both on the skin side and inside of the pork carcasses. The local mass transfer coefficient could be readily estimated once the local heat transfer coefficients were known.

There is an observed difference in the heat transfer rate along the pork carcass during processing. The estimated heat transfer coefficients indicate that there is a strong spatial variation of heat transfer coefficients.

**REFERENCES**


