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Finite element model for beef chilling using CFD-generated heat transfer coefficients

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ABSTRACT

A combined model of the beef chilling process is presented, in which computational fluid dynamics (CFD) was used to estimate the local heat and mass transfer coefficients, assuming uniform surface temperatures, and a set of 2-D finite element grids was used to solve the heat transfer equation in the product, which has an elongated shape. Another set of 1-D grids was used to solve the water transport equation near the surface of the meat. The surface transfer coefficients were calculated for various combinations of air orientations and speeds, and summarised in a set of regression equations. The model was verified by existing and new data on heat load, temperatures, weight loss and surface water activity.

Modèle à base d'éléments finis du refroidissement du bœuf utilisant des coefficients de transfert de chaleur générés à l'aide de la dynamique des fluides

Mots clés : Produit carné ; Viande ; Modélisation ; Refroidissement ; Dynamique numérique des fluides ; Transfert de chaleur ; Transfert de masse

1. Introduction

In industrial beef chilling, heat and moisture diffuse from the product and transfer to the air at the surface by convection. The rate of heat and mass transfer depends greatly on airflow conditions. Previous models (Earle and Fleming, 1967; James and Bailey, 1989) of these transfer processes assumed uniform heat and mass transfer coefficients over the product's surface, but in fact local variations in the heat and mass transfer coefficients are expected along the surface, producing local

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Nomenclature

c_s	specific heat of solid, $J\,kg^{-1}\,K$
D	diffusivity of water vapour in air, $m^2\,s^{-1}$
D_s	diffusivity of moisture in the solid, $m^2\,s^{-1}$
h	convective heat transfer coefficient, $W\,m^{-2}\,K^{-1}$
H_{fg}	latent heat of evaporation, $J\,kg^{-1}$
h_m	mass transfer coefficient, $m\,s^{-1}$
h_y	mass transfer coefficient based on Y gradient, $kg\,m^{-1}\,s^{-1}$
k	thermal conductivity of the air, $W\,m^{-1}\,K$
k_s	thermal conductivity of the solid, $W\,m^{-1}\,K$
L	carcass length, m
Nu	hL/k, Nusselt number
P8	site for measurement of fat thickness on the rump aligned with the crest of the third sacral vertebra in the AUSMEAT standard (http://www.ausmeat.com.au/Sales/pdf/BV-Lang-A4.pdf)
Pr	ν/α, Prandtl number
Re	$Lu\rho/\nu$, Reynolds number
s	distance from the (nearest) carcass surface (negative in the solid, positive in the air), m
Sc	ν/D, Schmidt number
Sh	$h_m L/D$, Sherwood number
Tu	$\overline{u}'^2/\overline{u}^2$, turbulence intensity
u	air velocity, $m\,s^{-1}$
u'	turbulent velocity, $m\,s^{-1}$
w	moisture content (dry basis), $kg\,kg^{-1}$
Y	air humidity dry basis, $kg\,kg^{-1}$
α	air thermal diffusivity, $m^2\,s^{-1}$
ν	air kinematic viscosity, $m^2\,s^{-1}$
ρ	air density, $kg\,m^{-3}$
ρ_{dm}	dry matter density, $kg\,m^{-3}$
ρ_s	solid density, $kg\,m^{-3}$

Subscripts

S	at the surface of the meat
∞	in the bulk of the air

differences in temperature and water activity. These variations are important because they may cause hot or moist spots where unacceptable microbial growth takes place. Thus, the measurement or prediction of local heat transfer coefficients is a major concern in modelling food processes (Kondjoyan, 2006).

Traditional computer models (Mallikarjunan and Mittal, 1994; Davey, 1998; Davey and Pham, 1997; Davey and Pham, 2000) have focused on solving the conduction equation in the meat, but the average heat (htc) and mass transfer (mtc) coefficients are calculated with empirical equations. In fact the mean heat and mass transfer coefficients are practically impossible to measure directly and data or regression formulae from a simpler situation such as a flat plate, cylinder or sphere must be used (Mallikarjunan and Mittal, 1994; Davey, 1998). Such an approach may lead to large errors in the heat transfer coefficients, but the effect might be masked by the fact that internal resistance is the dominant factor. In reality the heat and mass transfer coefficients vary from one spot to another, sometimes quite markedly if there is recirculation. The measurement of local heat transfer coefficients on a complex geometry such as animal carcass is difficult and has been rarely attempted, although there have been measurements on lamb (Harris et al., 2004), beef (Willix et al., 2006) and pork (Kondjoyan and Daudin, 1997). Turbulence as well as air velocity has a major influence on heat transfer coefficients in food processing (Kondjoyan, 2006). Nguyen and Pham (1999) used CFD to simulate the heat transfer process in beef carcass chilling, taking into account the conduction inside the meat and the convection in the air face, but they did not take into account the evaporation, radiation and mass transfer. Trujillo (2004) and Trujillo and Pham (2003, 2006) used the CFD software FLUENT to predict airflow and temperature fields around a beef side as well as temperature and moisture fields in the meat.

While CFD is a very powerful tool, its routine use is still impractical because of the computational load involved. A full simulation of a chilling test takes several days on the fastest computers presently available. To take advantage of CFD's predictive power while saving computation time, a compromise has to be made: CFD could be used to calculate the local surface heat and mass transfer coefficients, which then could be used in a program that performs calculations in the meat only, ignoring what goes on in the air. This is basically the approached presented in this paper.

2. Theory

2.1. Representation of beef carcass geometry

In this work, a beef side is represented by a series of cross-sections as shown in Fig. 1. The shapes and dimensions of

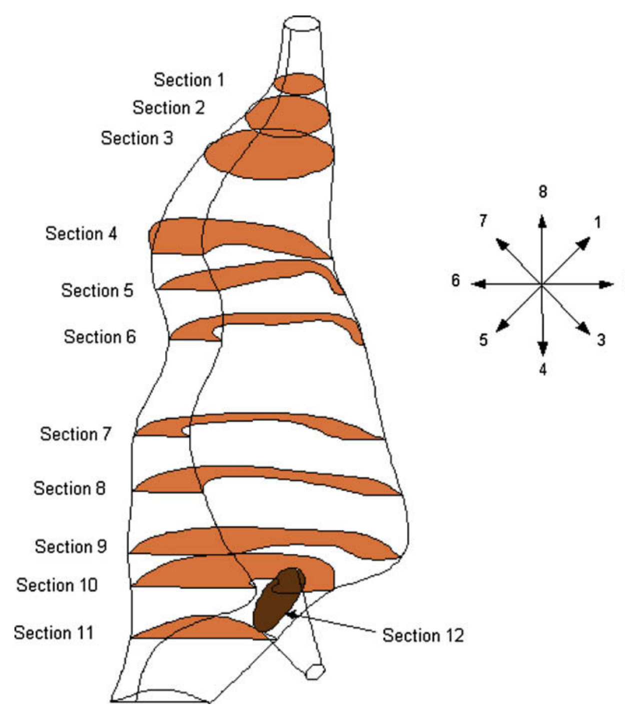

Fig. 1 – Cross-sections of a beef side and numbering of airflow directions. The air velocity is always in the front-to-back plane of the beef side.