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CFD modeling of industrial cooling of large beef carcasses

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ABSTRACT

A computational fluid dynamics (CFD) model was developed to predict the changes in temperature and pH distribution of a beef carcass during chilling. The model was solved using the 3D geometry of the carcass side obtained by digital scanning and including post-mortem reaction kinetics. Carcass temperatures at various depths and sections were measured during a chilling experiment of a single carcass in commercial chiller conditions for model validation. The temperature predictions agreed with the measured temperature profiles at different positions inside the carcass, with excellent prediction in deep positions of the hind-quarter as compared to near surface positions. The simulations unveiled large difference in cooling rates and pH evolution between different parts of the carcass that could lead to differences in meat quality by heat shortening. The model can be used to study the effect of relevant cooling parameters on the rate and uniformity of cooling and meat quality.

Modélisation par la mécanique numérique des fluides du refroidissement industriel de grandes carcasses de bœuf

Mots clés : Mécanique numérique des fluides ; Refroidissement ; Taux de production de chaleur ; Scan au laser ; Coefficient de transfert convectif ; Modélisation

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Nomenclature

ATP	adenosine triphosphate
a_w	surface water activity
BC	buffering capacity [mol m^{-3} pH$_{unit}$ $^{-1}$]
$c_{p,m}$	heat capacity of meat [J kg^{-1} K^{-1}]
$c_{p,a}$	heat capacity of air [J kg^{-1} K^{-1}]
C	moisture concentration of the meat [kg m^{-3}]
$C_{v,s}$	moisture concentration on carcass surface [kg m^{-3}]
$C_{v,\infty}$	moisture concentration in the approach flow [kg m^{-3}]
CFD	computational fluid dynamics
CHTC	convective heat transfer coefficient [W m^{-2} K^{-1}]
CMTC	convective mass transfer coefficient [m s^{-1}]
CTCs	convective transfer coefficients
D_m	moisture diffusivity in meat [m^2 s^{-1}]
D_a	moisture diffusivity in air [m^2 s^{-1}]
E_a	energy of activation [J mol^{-1}]
[G]	glucose concentration [mol m^{-3}]
Δ	difference operator
∇	gradient operator
ΔH_{ATP}	enthalpy change during ATP hydrolysis [J mol^{-1} P$_i$$^{-1}$]
K_a	acid dissociation constant
k_f	thermal conductivity of fluid [W m^{-1} K^{-1}]
K_m	Michaelis–Menten constant [mol m^{-3}]
k_m	thermal conductivity of meat [W m^{-1} K^{-1}]
k_a	thermal conductivity of air [Wm^{-1} K^{-1}]
L	eddy length scale [m]
[La]	lactate concentration [mol m^{-3}]
Le	Lewis number
L_v	latent heat of evaporation of water [J kg^{-1}]
NRMSE	normalized root mean square error
$\boldsymbol{n}$	normal direction [m]
n	number of measured temperature values
P	parameter value
P_v	vapor pressure of water [Pa]
$P_{v,s}$	vapor pressure of water on surface [Pa]
P_w	saturated vapor pressure of water [Pa]
$P_{w,s}$	saturated vapor pressure of water on carcass surface [Pa]
$P_{w,\infty}$	saturated vapor pressure of water in air [Pa]
q	heat flux [W m^{-2}]
R	universal gas constant [J mol^{-1} K^{-1}]
R_v	specific gas constant for water vapor [J kg^{-1} K^{-1}]
RH	relative humidity
S	volumetric heat source [W m^{-3}]
$S_{t_{T\rightarrow 35^{\circ}C},v}$	the sensitivity of cooling time to cool deep leg temperature to 35 °C
U	air speed [m s^{-1}]
v	cooling parameter/variable
v_G	rate of glucose conversion [mol m^{-3} s^{-1}]
v_{La}	rate of lactate production [mol m^{-3} s^{-1}]
$V_{max,ref}$	maximum glycogen conversion rate at reference temperature [mol m^{-3} s^{-1}]
T	temperature [K]
T_a	air temperature [K]
T_{ref}	reference temperature [K]
T_i	initial temperature of carcass [K]
$T_{i,m}$	measured temperature value at a time point [K]
$T_{max,m}$	maximum measured temperature [K]
$T_{min,m}$	minimum measured temperature [K]
$T_{i,p}$	predicted temperature value at a time point [K]
T_{inlet}	inlet temperature [K]
T_{open}	temperature at opening boundary type [K]
T_s	surface temperature [K]
T_w	wall temperature [K]
TI	turbulence intensity [%]
t	time [s]

Greek symbols

ρ_a	density of air [kg m^{-3}]
ρ_m	density of meat [kg m^{-3}]
ε	emissivity
δ	Stefan–Boltzmann constant

Subscripts

conv	convection
evap	evaporation
rad	radiation

1. Introduction

Meat is usually cooled in industrial chillers at a carcass level, before further processing. Such chilling has to be performed soon after slaughter to inhibit the growth of microorganisms and to retard physiological and biochemical changes that are responsible for quality deterioration as well as to prevent excessive water loss (Daudin et al., 1996; Greer and Jones, 1997; Savell et al., 2005). Knowledge of heat and mass transfer through the carcass and removal from the surface by the cooling air is therefore critical to optimize control of chilling conditions and to ensure uniformity of carcass quality.

Chiller rooms are usually equipped with refrigeration and ventilation systems via which cooling air circulates inside the room over the carcasses. During cooling, heat is removed convectively from the carcasses until the desired temperature is reached. The convective heat and mass transfer at the carcass surface play an important role in determining the cooling rate of the carcasses. When modeling the heat transfer processes inside a beef carcass, the convective exchange processes at the air–carcass interface are usually accounted