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Extension of soil thermal conductivity models to frozen meats with low and high fat content

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Abstract

Thermal conductivity models of frozen soils were analyzed and compared with similar models developed for frozen foods. In total, eight thermal conductivity models and 54 model versions were tested against experimental data of 13 meat products in the temperature range from 0 to −40 °C. The model by deVries, with water+ice (*wi*) as the continuous phase, showed overall the best predictions. The use of *wi* leads generally to improved predictions in comparison to *ice*; *water* as the continuous phase is beneficial only to deVries model, mostly from −1 to −20 °C; *fat* is advantageous only to meats with high fat content. The results of this work suggest that the more sophisticated way of estimating the thermal conductivity for a disperse phase in the deVries model might be more appropriate than the use of basic multi-phase models (geometric mean, parallel, and series). Overall, relatively small differences in predictions were observed between the best model versions by *deVries*, *Levy*, *Mascheroni*, *Maxwell* or *Gori* as applied to frozen meats with low content of fat. These differences could also be generated by uncertainty in meat composition, temperature dependence of thermal conductivity of ice, measurement errors, and limitation of predictive models.

Keywords: Frozen food; Modelling; Thermal conductivity; Experiment; Comparison; Soil

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Modèles de la conductivité thermique du sol appliqués aux viandes surgelées à faible et à forte teneur en matière grasse

Mots clés : Produit congelé ; Modélisation ; Conductivité thermique ; Expérimentation ; Comparaison ; Sol

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1. Introduction

Soils and foods are both heterogeneous porous media and share some similar features as well as a number of differences. Soils are mixtures of inorganic loose particles of

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Nomenclature

a, b, c	axes of ellipsoidal food components
a_0, a_1, a_2	constants in Eqs. (20) and (21)
F	alternative function for θ_d used in Levy's model
f	fat as continuous phase
f-d_{GMM}	fat as continuous phase; λ of dispersed phase (d) evaluated by GMM (Eq. (3a))
f-$d_{\parallel}$	fat as continuous phase; λ of dispersed phase (d) evaluated by $\parallel$ (Eq. (1))
f-$d_{\sum}$	fat as continuous phase; λ of dispersed phase (d) evaluated by $\sum$ (Eq. (2))
fib_{GMM}	λ_{fiber} (models by Mascheroni)–evaluated by GMM (Eq. (3a))
$fib_{\parallel}$	λ_{fiber} (models by Mascheroni)–evaluated by $\parallel$ (Eq. (1))
$fib_{\sum}$	λ_{fiber} (models by Mascheroni)–evaluated by $\sum$ (Eq. (2))
g	shape factor
k	weighting factor
i	ice as continuous phase
i-d_{GMM}	ice as continuous phase; λ of dispersed phase (d) evaluated by GMM (Eq. (3a))
i-$d_{\parallel}$	ice as continuous phase; λ of dispersed phase (d) evaluated by $\parallel$ (Eq. (1))
i-$d_{\sum}$	ice as continuous phase; λ of dispersed phase (d) evaluated by $\sum$ (Eq. (2))
M	mass fraction
N	the number of solid components
n	number of phases, data records, etc.
p	ellipsoid shape value (equatorial diameter/distance between ellipsoid poles)
RMSE	root mean square error
s_{GMM}	solids λ evaluated by GMM (Eq. (3a))
T	temperature (°C)
w	water as continuous phase
wi	water + ice as continuous phase
wi_{GMM}	water + ice = continuous phase; λ evaluated by GMM (Eq. (3a))
$wi_{\parallel}$	water + ice = continuous phase; λ evaluated by $\parallel$ model (Eq. (1))
$wi_{\sum}$	water + ice = continuous phase; λ evaluated by $\sum$ (Eq. (2))

Greek

β	variable in Eqs. (13) and (14)
θ	volume fraction
λ	thermal conductivity (W/m °C)
ρ	density
δ	λ_d/λ_{con}
σ	variable in Eqs. (7) and (8)
ξ	variable in Eqs. (15) and (16)

Subscripts

a	air
ash	ash/mineral
b	bulk
bw	bound water
car	carbohydrate
con	continuous phase
d	dispersed phase
exp	experimental
f	initial freezing point
fat	fat
fib	meat-fibre
GMM	geometric mean model
ice	ice
j	food component number
prot	proteins
s	solids
un	unfrozen water
w	water
wi	water + ice
$\parallel$	heat flow $\parallel$ to fibers of meat
$\perp$	heat flow $\perp$ to fibers of meat

various sizes and shapes, organic matter, water, and air. The total volume fraction of water and air is known as the soil porosity. Foods are heterogeneous capillary-porous colloidal materials composed of numerous solid constituents, such as carbohydrates, fats, proteins, vitamins and minerals, plus water; air voids can also be present. In the food literature, porosity generally refers to the air component only. Porosity of soils (relative volume of air plus water) typically varies from 30 to 60% while for foods moisture content generally varies from 15 to 90%. The water, containing dissolved substances, is a major component in both soils and foods and its transition from liquid into ice is the greatest factor influencing change in thermal properties with temperature (T). In soils, water exists in gravitational, capillary, and hygroscopic (bound) forms, while foods contain only capillary and bound water. Foods are generally saturated with water, while soils experience great variation of water content, from dryness to a field capacity (volumetric water content at saturation minus the gravitational water). A large part of the water, in both soils and foods, freezes rapidly between 0 and -5 °C, therefore, very sparse thermal conductivity (λ) data is available in this T range. Excluding water, ice and air, the thermal conductivity of other food components are similar, while in soils the thermal conductivity of quartz is large compared with other mineralogical constituents. Soil composition is usually given by volumetric fractions, while for foods mass fraction is most commonly employed.

Analysis, design and simulation of food freezing and