PREDICTION OF THERMAL CONDUCTIVITY OF MEATS AND OTHER ANIMAL PRODUCTS FROM COMPOSITION DATA

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ABSTRACT

Existing data on the thermal conductivity for meat, fish and other animal products show a great deal of scatter. The data were critically examined with regards to adequacy of measuring method, agreement with general trends, availability of product composition data and other stringent criteria. About 200 datapoints from 11 datasets were selected for further consideration.

Seven physical models and one set of empirical equations were compared to the screened data. Levy's model was found to be the most accurate. The EMT model performed slightly worse but had somewhat better physical justifications. Two popular models, the parallel model and the Maxwell-Eucken model, performed less well than Levy's model and the EMT model. Uncertainties in the values of physical parameters had negligible effects on the accuracy of the models.

NOTATION

k Thermal conductivity, W/m K
T Temperature, °C
v volume fraction
x Mass fraction
ρ Density, kg/m³

Subscripts
b bound water
c continuous phase
d dispersed phase
f at initial freezing temperature (-0.9°C)
i ice
j j-th component

INTRODUCTION

Several methods have been proposed to calculate the thermal conductivity of meat and other biological products and foodstuffs. These methods can be divided into two classes:

1. Purely empirical relationships found by curve-fitting the data. For meat, the best known are those by Spells [1] and Sweat [2].

2. Equations derived from physical models, the best known of which are the parallel model [3-7] and the Maxwell-Eucken model [8-10]. Other well-known models are those of Kopelman [11], Hill et al. [12] and van Beek [13]. Almost without exception, the parameters used must still be found by curve-fitting to ensure good agreement with data. The exception is Levy's [14] modified Maxwell-Eucken equation, which Pham and Willis [15] applied successfully to their data using independently-obtained parameter values.

This paper extends Pham and Willis's [15] investigation to other datasets on meat and other animal materials. The main problem to be resolved is the very large scatter of reported data [2] which tends to mask any trend; a large amount of effort was therefore spent in eliminating doubtful data.

THEORY

Equations and models

Seven physical models will be considered: 1: The parallel model, 2: The series model, 3: The Maxwell-Eucken model [8], 4: Levy's model [14], 5: Kopelman's model [8], 6: Hill et al.'s model [12], 7: The effective medium theory (EMT) model [16-17]. The first six models have been summarized in [15]. In the EMT model, the mixture conductivity k is given by

\[ \sum \left( v_j \cdot \frac{k_j}{2k + k_j} \right) = 0 \]  (1)

The following empirical equations by Spells [1] and Sweat [2] will also be considered:

\[ k = 0.080 + 0.52 \cdot x_w, \quad 0 < T < 60°C \]  (2)

\[ k = -0.28 + 1.9 \cdot x_w \cdot 0.0092 \cdot T, \quad -40°C < T < -5°C \]  (3)

To use the physical models, the thermal conductivities and densities of the components must be known. Table 1 summarizes their values [6]. For water [15] and ice [7]...
\[ k_w = 0.560 + 0.00165 T \]
\[ k_f = 2.2196 \cdot 0.0062489 T + 0.00010154 T^2 \]

\[
\begin{align*}
\text{TABLE 1} \\
\text{Properties of meat components.} \\
\hline
\text{Component} & k_j & x_j \\
\hline
\text{Fat} & 0.18 & 930 \\
\text{Protein} & 0.20 & 1380 \\
\text{Water} & \text{Eq.(4)} & 1000 \\
\text{Ice} & \text{Eq.(5)} & 917 \\
\text{Mineral} & 0.26 & 2165 \\
\hline
\end{align*}
\]

Ice fraction

To calculate the ice fraction below freezing, the model of Schwartzberg [18] is used. Schwartzberg divides the water into a bound fraction and a freezable fraction, the latter behaving as an ideal solution, so that the ice fraction is calculated from

\[ x_i = (x_w - x_b) (1 - T_f/T) \quad T < T_f \]

(6)

where the bound water fraction is related to protein fraction by [19]

\[ x_b = 0.4 x_p \]

(7)

A reasonably accurate value of the initial freezing point \( T_f \) must be known for eq. (6). Pham [19] found by curve-fitting calorimetric data that the initial freezing point for non-dehydrated meats and fish is in the range \(-0.7\) to \(-1.0^\circ\text{C}\), with mean \(-0.85^\circ\text{C}\). This last value was used for all species.

Continuous and dispersed phases

Models 3 (Maxwell-Eucken), 5 (Kopelman) and 6 (Hill et al.) require a continuous phase and a dispersed phase to be deﬁned. For these models, the continuous phase was considered to be the one with the highest volume fraction, be it liquid water, ice or fat. All the other components were lumped into the dispersed phase. Levy’s equation was applied consecutively to all the components. No matter what order was used in introducing the components, the k-value of the final mixture did not change by more than 1%.

Inﬂuence of product form and heat flow direction

Pham and Willix's [15] results indicated that ﬁbrous (muscle) tissues with ﬁbres parallel to heat ﬂow, ground tissue and whole tissues without ﬁbres have similar thermal conductivity values. Muscle tissue with ﬁbres perpendicular to heat ﬂow, on the other hand, have frozen k-values lower than the above by 8% [2, 15]. Therefore, to enable data for this case to be lumped with the rest, predicted “perpendicular” values below freezing were divided by 1.08. Predicted “perpendicular” values above freezing were kept unchanged.

Compositional data

Most previous workers gave only the water content and not the fat, protein and ash contents. Ash is always only a minor component (of the order of 1%) and unlikely to affect results. Fat and protein have very similar thermal conductivities (0.18-0.20 W/mK) and so, again, ignorance of their relative contents is unlikely to affect results above freezing. A complication arises, however, below freezing, since the actual protein content affects the bound water content, which in turn inﬂuences the ice content, according to eqs. (6) and (7). In the calculations, when data was not available, an ash content of 1% and a fat content equal to half the protein content were assumed, based on typical values for meat [15].

DATA SELECTION

Past critical reviews [20, 2] showed that thermal conductivity data reported for foodstuffs are of extremely variable quality, ranging from very good to absurd. A comparison of experimental results on standardized materials showed that even when similar methods are used, wide differences can still result [21]. Therefore it is essential that some rigorous screening of data is carried out to avoid random errors masking the real trends. The following criteria were used to select the datasets to be considered:

1. Product composition, or at least the water content, must have been measured or otherwise accurately established.
2. From each dataset, at most two datapoints below freezing and two above freezing were used, at the extremes of the frozen and unfrozen ranges, with no two datapoints less than 5°C from each other except when the phases are different.
3. There should be no obviously unusual trend which contradicts the majority of other data (e.g. k-values higher than that of water, k-values constant or decreasing with temperature below freezing).
4. No data between -4°C and the freezing point were used. It is virtually impossible to measure accurately the thermal conductivity in this temperature range due to the strong dependence of k on temperature.
5. No data above 40°C, and preferably not above 30°C. It is difﬁcult to avoid moisture loss from the sample during measurement at high temperatures, so the reported value of moisture content may not be reliable.
6. The measuring equipment must have been checked or calibrated against a material with a known k-value.
7. Data for product that had become porous due to drying or cooking were discarded.
8. Data obtained at similar temperatures on closely similar products, e.g. meat emulsions with water contents differing by less than 2%, were averaged and treated as a single datapoint. This is to avoid giving too much weight to any one class of product.

The reviews by Kostaropoulos [22], Morley [23], Qashou et al. [20] and Sanz et al. [24] were used as starting points for data collection. The original papers referred to were then examined to see if all the above criteria were fulfilled. No data were used if the original paper was not accessible to the author. Each k-T curve was represented by at most four points. Thus, although the number of datapoints was slightly less than that used by Sneath [2], it is believed that the present review is at least as comprehensive.

A total of 203 datapoints from 11 datasets [1, 3, 4, 6, 9, 10, 12, 15, 25-28] was selected. Water contents varied from 0.0 to 91.5% and fat content from 0.1 to 100%. Products included beef, veal, pork, lamb, poultry, fish, offals, fats, intermediate- or low-moisture meat products, eggs, blood and plasma. Tabulated data are available on request from the author.

RESULTS

The error statistics show that Levy's model was clearly the most accurate on all criteria: mean error, standard deviation and error range (Table 2). Next, but far behind, are the EMT model, the Maxwell-Eucken model and Kopelman's model. When the data are split into frozen and unfrozen ranges, Levy's model was still the best in each range (Table 2). All other models tended to have much larger errors in the frozen range than in the unfrozen range, due to the large differences between the thermal conductivities of ice and of the other components.

### TABLE 2

<table>
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<tr>
<th>Model</th>
<th>% error statistics all data</th>
<th>Unfrozen</th>
<th>Frozen</th>
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<td>19</td>
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<td>8.1</td>
<td>23</td>
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<td>9.4</td>
<td>29</td>
</tr>
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<td>Kopelman</td>
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<td>9.5</td>
<td>34</td>
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<td>146</td>
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<th>Product configuration</th>
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<th>Levy s.d.</th>
<th>EMT Mean</th>
<th>EMT s.d.</th>
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<td>6.4</td>
<td>+1.9</td>
<td>9.9</td>
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</table>

* Other: randomly oriented ungrown non-fibrous tissues

The effect of product composition on the Levy and EMT models was examined in more detail. The errors in Levy's model were not affected by moisture or fat content (Fig. 1), whereas the errors in the EMT model tended to be sensitive to both (Fig. 2).

Figure 1. Errors in Levy's model vs moisture and fat contents.
established and unlikely to cause significant errors in the predictions. The ratio $\frac{x_L}{x_p}$ would also have to be changed to quite unrealistic values before the accuracy is substantially affected. Pham [19] found that this ratio varies from 0.3 to 0.5. Using an extreme value instead of 0.4 leaves the accuracy of the models almost unchanged (Table 5).

### Table 5

<table>
<thead>
<tr>
<th>Model</th>
<th>$x_L/x_p = 0.3$</th>
<th>$T_f = -1.0\degree C$</th>
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<td>Mean s.d.</td>
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<td>EMT</td>
<td>5.5 10.0</td>
<td>8.0 10.7</td>
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<td>13.1 12.1</td>
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<td>Kopelman</td>
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<td>19.1 10.2</td>
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<td>Hill et al.</td>
<td>20.2 12.0</td>
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<td>Series</td>
<td>-47.4 11.8</td>
<td>-46.7 11.6</td>
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</table>

The uncertainty in the freezing point is about 0.15\degree C. At -5\degree C or below this would lead to an uncertainty of at most 3% in the ice content of frozen products, and a smaller uncertainty in the thermal conductivity. Thus, Table 5 also shows that using an extreme value of $T_f$ hardly changes the accuracy of the models. (In this table only frozen product values are considered since changing $x_L/x_p$ and $T_f$ will not affect unfrozen product values.)

For those products where full compositional data were not available, a protein-to-fat ratio of 2.0 was assumed. Changing this ratio was found to have negligible effect on the models' accuracy. The mean error in Levy's model changed by only 0.4% when the ratio was changed to 1.0.

### Conclusions

Several physical models and one set of empirical equations have been compared to the most reliable data for meat, fish and other animal products. Levy's model was found to be by far the most accurate. Its accuracy is probably sufficient for most engineering computations. Furthermore, this model seems equally valid for all types of products, with the possible exception of poultry meats, over a wide range of composition and temperatures. The EMT model performs slightly worse than Levy's model but has somewhat better physical justification. Two popular models, the parallel model and the Maxwell-Eucken model, performed less well than Levy's model and the EMT model. Uncertainties in the values of physical parameters have negligible effects on this paper's conclusions. Levy's model has been incorporated in thermal computation software developed at the author's institute [29].
REFERENCES


### APPENDIX

**SUMMARY OF PUBLISHED THERMAL CONDUCTIVITY DATA**

Composition: * means not given.


<table>
<thead>
<tr>
<th>T</th>
<th>k</th>
<th>Composition (%)</th>
<th>Form</th>
<th>Type</th>
<th>Method</th>
<th>Ref.</th>
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References for temperature and conductivity data include Hill et al. (1967), Lentz (1961), Pham and Willix (1989), Sweat (1985), Baghe-Khandan et al. (1982), Baghe-Khandan and Okos (1981), Sweat et al. (1973), Spells (1960), Poppendiek et al. (1966), Perez and Calvelo (1984), and Timbers et al. (1982).
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