High Temperatures – High Pressures, 2001, volume 33, pages 693 – 697
15 ECTP Proceedings pages 1197 – 1201

DOI:10.1068/htwu492

Thermal conductivity of food materials at elevated temperatures

Walter E L Spieß, Elke Walz
Bundesforschungsanstalt für Ernährung, Institut für Verfahrenstechnik, Haid-und-Neu-Straße 9, D 76131 Karlsruhe, Germany; fax: +49 721 6625 303; email: walter.spiess@bfe.uni-karlsruhe.de

Paul Nesvadba
Robert Gordon University, Food Science and Technology Research Centre, School of Applied Science, St Andrew Str., Aberdeen AB25 1HG, Scotland, UK

Mike Morley
Collagen Research Group, Churchill Building, University of Bristol, Langford, Bristol BS40 5DU, UK

Izaäk A van Haneghem
Department of Agricultural Engineering and Physics, Agricultural University Wageningen, Bomenweg 4, NL 6703 HD Wageningen, The Netherlands

David R Salmon
National Physical Laboratory, Teddington, Middlesex, TW11 0LW, UK
Presented at the 15th European Conference on Thermophysical Properties, Würzburg, Germany, 5 – 9 September 1999

Abstract. In order to expand the available information on thermal conductivity of foods, within the framework of COST Action 93, a collaborative study was organised. In the first step, typical food components (apple pulp, meat, olive oil, sodium caseinate, starch, tomato paste) were used as standards for measurements, and in the second step, standardised glass beads were used for calibration experiments. The results have demonstrated that it is rather difficult to come up with reliable accurate information. Problems are to some extent related to the measuring procedures, in particular the variability in contact between heat source and test material and/or contact between test material and thermal sensors. Further problems arise for products which are not stable throughout the duration of the experiment.

1 Introduction

Modern food processing increasingly uses new types of thermal treatment with higher temperatures. For example, in ultrahigh temperature processing, the wall temperatures of heat exchangers are now approaching 150 °C instead of 130 °C as used in the past. Flash heating with high-temperature steam is another high-temperature application. At high processing temperatures, small differences in residence times may cause major differences, for example, in vitamin retention. Therefore, precise knowledge of the thermal diffusivity is extremely important for an accurate calculation of the required heat fluxes. Also, ohmic and microwave heating of increasingly complex and varied products and other applications require a very accurate time control of the process. Therefore, the equipment has to be designed by modelling the process conditions. The models require data on electrophysical and rheological properties, density, and also thermophysical properties such as thermal conductivity (λ), thermal diffusivity (a), heat capacity (c), and enthalpy (h). Those parameters determine the dimensionless Biot and Fourier numbers in the mathematical equations for the modelling procedures.

2 Available data

Previous and current EU Concerted Actions had the objective of producing reliable data on thermophysical properties (Jowitt et al 1983, 1987). However, these were mainly for ambient temperatures and temperatures around the freezing point of water. Only limited information is available for elevated temperatures. Above the boiling point of

Table 1. Heat capacity c, density ρ, thermal conductivity λ, and thermal diffusivity a at temperature t of food materials and materials used in food processing [data from Kessler (1976) and collected from literature in the framework of EU project FAIR-CT-1118, Osmotic Treatment of Food Material].

Material	$t/°C$	c/kJ kg^{-1} K^{-1}	ρ/kg m^{-3}	λ/W m^{-1} K^{-1}	$10^6 a$/m^2 s^{-1}
Water, liquid	0	4.218	999.8	0.569	0.134
	20	4.182	998.2	0.604	0.145
	40	4.178	992.2	0.632	0.152
	60	4.184	983.2	0.654	0.159
	80	4.196	971.8	0.669	0.165
	100	4.216	958.4	0.682	0.169
Water, solid	0	2.11	917	2.23	1.15
	−50	1.71	890	2.77	1.82
	−100	1.26	880	3.48	3.14
Water, vapour	100	2.14	0.578	0.0242	19.6
	200	1.93	0.452	0.0328	37.6
	300	2.01	0.372	0.0427	57.1
Fish	20	3.43	990	0.5	0.147
Meat, lean	20	3.2	990	0.4	0.126
Vegetable	20	3.2	1050	0.5	10.149
Potato	20	3.35	1050	0.55	0.156
Butter	20	2.5	925	0.2	0.086
Margarine	20	3.25	1000	0.2	0.062
Olive oil	20	1.6	920	0.17	0.155
Beer	20	3.77	1030	0.52	0.134
	70			0.64	0.169
Sugar	20	1.25	1000	0.25	0.2
Salt	20	0.92	2300	7	3.31
Ethyl alcohol	20	2.4	790	0.19	0.100
Glycerine	20	2.43	1260	0.28	0.092
Glass	20	0.75	2800	0.8	0.380
Porcelain	20	0.8	2400	1.5	0.781
PVC	20	1.1	1350	0.16	0.107
Steel, Cr–Ni	20	0.48	7800	13	3.47

water the data are extremely scarce. Table 1 gives an overview of some of the available data.

Water determines to a high degree the thermophysical properties of water-containing materials. In a first approximation, therefore, the thermophysical properties of water may always be used for modelling purposes. The thermophysical properties of real food products may, however, deviate from the properties of water quite considerably. The thermal conductivity of water-containing products such as fresh vegetables, fresh fruit, meat, or fish are usually 15%–20% lower than those of water. Fat-rich products such as butter, margarine, and oil have conductivities that are approximately one-third of that of water. Another observation is that the thermal conductivity of water-containing foods increases with temperature.

From the available data (Kostaropoulos 1971; Jowitt et al 1983, 1987) an extrapolation into the temperature range above 100 °C is possible to a certain degree, that means up to 110 °C or even 115 °C. However, above those temperatures an extrapolation has to be considered as a tentative approximation. It was, therefore, one of the objectives of the COST Action 93 to produce reliable data for the temperature ranges of technical interest up to the temperature of 140 °C.

3 Expansion of data on thermal conductivity

3.1 *First experiments with food materials*

In order to expand the available information on the thermal conductivity of foods, within the framework of COST Action 93, a collaborative study was organised. Typical food components were used as standards for measurements in the laboratories willing to cooperate. The materials listed in table 2 were bought from one source, sample divided, and shipped to the participants listed in table 3. The laboratories were asked to start the experimental work immediately after receipt of the material with their standard experimental devices (Kostaropoulos 1971).

Table 2. Range of results of thermal conductivity λ of model food products.

Product	λ/W m^{-1} K^{-1}		
	50 °C	100 °C	135 °C
Apple pulp	0.56 – 0.62	0.58 – 0.65	0.58 – 0.65
Meat	0.40 – 0.45	0.44 – 0.46	0.46 – 0.50
Nylon 66	0.32 – 0.33	0.30 – 0.32	0.29 – 0.30
Olive oil	0.15 – 0.17	0.15 – 0.17	0.15 – 0.17
Sodium caseinate solution (25%)	0.53 – 0.56	0.54 – 0.58	0.57 – 0.60
Starch solution (40%)	0.46 – 0.54	0.55 – 0.58	0.57 – 0.61
Tomato paste (triple)	0.50 – 0.56	0.51 – 0.60	0.55 – 0.62

Table 3. Laboratories participating in the collaborative study.

Country	Institution	Method applied
Belgium	Catholic University Leuven	line heat source
Germany	Federal Research Centre for Nutrition, Karlsruhe	(coordination)
Great Britain	Robert Gordon University, Aberdeen	thermal diffusivity method
	National Physical Laboratory, Teddington	line heat source
	University of Bristol, Langford, Bristol	line heat source
Ireland	University College, Cork	line heat source
Spain	Institute of Refrigeration, Madrid	line heat source
	University (UPV) of Valencia	thermal diffusivity method
The Netherlands	Agricultural University, Wageningen	line heat source

The experimental results obtained by the various groups varied considerably. They were only consistent in the way that the conductivity of all food materials in the experiments increased with temperature with the exception of olive oil, where no clear results were obtained. However, the conductivity values of Nylon 66 (used as a standard material for solid products), showed the opposite behaviour; they decreased in all cases with increasing temperature. This decrease was most pronounced at temperatures above 60 °C.

An analysis of reasons responsible for the deviations indicated that the various methods applied are obviously not delivering comparable results. Differences in the extent of convection and contact resistance cause irregularities in the heat flux across/along the probes. These irregularities make even results obtained with the same method difficult to compare. It was also observed that the different time frames which had to be applied for the experiments because of different experiment layouts caused different degrees of material decomposition/denaturation, possibly another source for deviating results. On the basis of the results obtained, the data given in table 2 have to be considered as very preliminary. As a general observation—which is supported independently of the experimental method—it can be said that over the temperature range 40 °C to 140 °C the conductivity values of all aqueous products increased by 10%. For olive oil a very pronounced scatter of experimental values was observed. One group of results showed a decrease of conductivity values with an increase of temperature; another group demonstrated just the opposite behaviour. In the absence of reliable information no statement on the temperature influence on the thermal conductivity of oils can be made.

3.2 *Food model system: glass bead dispersion*

Because the attempts to use food materials or organic materials like polyamides (Nylon) as standard/reference materials for thermal conductivity measurements failed, the groups cooperating in COST Action 93 agreed to use glass bead dispersions for calibration experiments and experiments to standardise equipment. Several groups cooperated in this effort. The glass beads were again bought at one source, sample divided, and distributed amongst the participating laboratories.

The beads were made from a soda-lime glass of specified composition, and the diameters of the beads were specified between 70 and 110 μm.

The density of the material was determined: $\rho_g = 2.48$ g ml^{-1} (21 °C). The thermal conductivity of the glass, calculated on the basis of the composition, had a value $\lambda_g = 1.18$ W m^{-1} K^{-1} (100 °C). The bulk density of the sample (beads dispersed in air) was $\rho_g = 1.54$ g ml^{-1} (1.55 g ml^{-1}). Experimental work for thermal conductivity measurements was carried out by the heated probe method. Despite a well coordinated work plan, the results obtained for beads in air at two laboratories again showed significant differences (table 4).

The differences of conductivity values obtained for the air dispersion sample may be explained by different contact situations in the sample. It is well known that after wetting the beads and drying them in a fixed bed, different contact situations amongst the individual spheres do arise depending on the method of drying.

In order to evaluate the data obtained, a model is required which would represent the structural arrangements of the beads in the fixed bed as closely as possible. Using a random array of closely packed spheres (Sangani and Acrivas 1983), one participant (University of Bristol) obtained theoretical results which did come close to one of the sets of results for air dispersion. Taking into account, however, all the results obtained in the study, the anticipated goal of recommending a precise and easy-to-follow procedure for conductivity measurements for foods at elevated temperature has not been reached, as the differences between laboratories are still amounting to 30%.

Table 4. Results of measurements of thermal conductivity of glass bead dispersions (2 series of 3–5 repeated measurements each; overall measurement error 3%).

Property	λ/W m^{-1} K^{-1}			
	50 °C	75 °C	100 °C	130 °C
Glass volume fraction in			0.618	
air			0.637	0.637
Experimental λ			0.218	
in air (Lab 1)			0.229	0.241
Experimental λ	0.195	0.220	0.255	0.305
in air (Lab 2)	0.170	0.178	0.191	0.203
Predicted λ in			0.234	
air			0.249	0.260
Glass volume fraction in			0.627	0.627
water			0.633	0.633
Experimental λ			0.909	0.958
in water (Lab 1)			0.932	0.944
Predicted λ in			0.977	0.985
water			0.980	0.988

4 Conclusion

The experimental work on the thermal conductivity of food materials and materials with conductivity values similar to those of foods has demonstrated that it is rather difficult to come up with reliable accurate information. Problems are to some extent related to the measuring procedures, in particular the variability in contact between heat source and test material and/or contact between test material and thermal sensors. Further problems arise for products which are not stable for the duration of the experiment. For a further development of standardised measurements, glass beads dispersed in water seem therefore a good choice for a model substance. Another possibility would be a hydrocolloid stable up to 150 °C. This is, however, not available for the time being. Building on the work of COST 93, the Department of Trade and Industry in the UK is supporting a project at the National Physical Laboratory, Teddington, and the Robert Gordon University, Aberdeen, to produce measurement standards for the food industry.

References

Jowitt R, Escher F, Hallström B, Meffert H Th, Spiess W E L, Vos G (Eds), 1983 *Physical Properties of Foods* (London: Applied Science)

Jowitt R, Escher F, Kent M, McKenna B, Roques M (Eds), 1987 *Physical Properties of Foods—2* (London: Elsevier Applied Science)

Kessler H G, 1976 *Lebensmittel-Verfahrenstechnik; Schwerpunkt Molkereitechnologie* (Freising: A Kessler)

Kostaropoulos A E, 1971 *Wärmeleitzahlen von Lebensmitteln und Methoden zu deren Bestimmung. Berichtsheft 16 der Fachgemeinschaft Lufttechnische und Trocknungs-Anlagen im VDMA* (Frankfurt/Main: Maschinenbau-Verlag GmbH)

Sangani A S, Acrivas A, 1983 *Proc. R. Soc. London A, Math. Phys. Sci.* **386** 263–275