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Estimation of the Thermo-Physical Properties of Foods using Substances Contents in the Temperature Range of -40°C to +40°C

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Abstract

An easy way to calculate thermal conductivity, specific heat, density and thermal diffusivity for foods using the percentage contents by classes of substances (water, proteins, fats, carbohydrates, fibers and ash) using the MS-Excel program has been presented and a comparison has been made with the available method. The comparison shows that quadratic expressions of Choi and Okos (1986) method may be replaced with the developed models, which are using straight line equations. This work utilized the MS-Excel worksheet to develop models for the thermal properties of five food components (viz: fat; protein; carbohydrate; fiber; and ash), water and ice using Choi and Okos model to generate data. The results of correlation coefficients of the generated data using the developed models, show that: the values of R2 for: thermal conductivity ranges between 0.997 and 1; thermal diffusivity ranges between 0.991 and 1; specific heat ranges between 0.995 and 0.999; while that of density is 1. The R^2 value in the case of water and ice properties i.e., thermal conductivity, thermal diffusivity, specific heat and density are in the range of 0.918-1 and 0.981-1. This shows that the developed models may be used in the temperature ranges from -40°C to 40°C.

INTRODUCTION

Thermal properties of food and beverage items are one of the most important considerations in the design of storage and refrigeration equipment. Thermal properties help in estimating process time for refrigerating, freezing, heating, or drying of food and beverages. It is a known fact that thermal properties of foods and beverages strongly depend on chemical composition and storage temperature of the food items and there are so many food items that it is nearly impossible to experimentally determine and tabulate the thermal properties of all food and beverages for all possible conditions and compositions. However, some food and beverage composition data can be obtained from the literature (Holland et al., 1991).

It has been pointed out that the thermo-physical properties of food and beverages that are often required for heat transfer calculations include: density; specific heat; enthalpy; thermal conductivity; and thermal diffusivity. Constituents commonly found in food items include: water, proteins, fats, carbohydrates, fiber, and ash. In 1986, Choi and Okos (1986) developed mathematical quadratic expression (except for density and certain properties of ice) models for prediction of thermal properties of these food components as well as thermal properties of ice and water, as functions of temperature in the range of -40^0C to 150^0C. changes during ripening of fruit is also the most important attribute because in addition to defining the quality of the fruit for consumption. Although data are available for numerous foods and beverages components (Fikiin, 1996; Acre and Sweat, 1980), models for prediction of these food components are not readily available. This study therefore proposed a simpler linear model compared to those of Choi and Okos (1986) for the prediction of food components at temperature ranges between -40^0C to +40^0C.

MODEL DEVELOPMENT

The models presented by Choi and Okos (1986) were used to generate data between temperature ranges from -400C to +400C in MS-Excel. The generated data were used to develop new linear expressions for the prediction of thermo-physical properties. The aim of this work is to present a simpler model which can be easily remembered and used. Hence the linear forms of models are considered as shown in equation (1).

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Table 1: Summary of Models and Statistic Analyses

Choi and Okos Models	Present Models	R^2
Thermal Conductivities (W/(m.K))		
k-pro=0.17881+1.1958*10^{-3}T-2.7178*10^{-6}*T^2	0.002*T+0.177	0.999
k-fat=0.18071-2.7604*10^{-3}T-1.7749*10^{-7}*T^2	-0.00278*T+0.180	1
k-carb=0.20141+1.3874*10^{-3}T-4.3312*10^{-6}*T^2	0.00122*T+0.199	0.997
k-fib=0.18331+1.2497*10^{-3}T-3.1683*10^{-6}*T^2	0.0012*T+0.181	0.997
k-ash=0.17881+1.1958*10^{-3}T-2.7178*10^{-6}*T^2	0.001*T+0.323	0.998
Thermal diffusivity (m^2/s)		
α- pro=10^{-8}*(6.8714+4.7578*10^{-2}T-1.4646*10^{-4}*T^2)	10^{-8}(0.047*T+6.791)	0.995
α- fat=10^{-8}*(9.8777-1.2569*10^{-2}T-3.8286*10^{-6}*T^2)	10^{-8}(-0.012*T+9.875)	1
α- carb=10^{-8}*(8.0842+5.3052*10^{-2}T-2.3218*10^{-4}*T^2)	10^{-8}(0.053*T+7.957)	0.991
α- fib=10^{-8}*(7.3976+5.1902*10^{-2}T-2.2202*10^{-4}*T^2)	10^{-8}(0.051*T+7.276)	0.992
α- ash=10^{-8}*(12.461+3.7321*10^{-2}T-1.2244*10^{-4}*T^2)	10^{-8}(0.037*T+12.39)	0.995
Density (kg/m^3)		
ρ-pro=1329.9-0.5184T	1329.9-0.518*T	1
ρ-fat=925.59-0.41757T	925.5-0.417*T	1
ρ-carbo=1599.1-0.31046*T	1599-0.31*T	1
ρ-fib=1311.5-0.36589*T	1306-0.365*T	1
ρ-ash=2423.8-0.28063*T	2423-0.28*T	1
Specific heat (kJ/kg-K)		
cp-pro=2.0082+1.2089*10^{-3}T-1.3129*10^{-6}*T^2	0.001*T+2.007	0.999
cp-fat=1.9842+1.4733*10^{-3}T-4.8008*10^{-6}*T^2	0.001*T+1.981	0.995
cp-carbo=1.5488+1.9265*10^{-3}T-5.9399*10^{-6}*T^2	0.001*T+1.545	0.995
cp-fib=1.8459+1.8306*10^{-3}T-4.6509*10^{-6}*T^2	0.001*T+1.843	0.997
cp-ash=1.0926+1.8896*10^{-3}T-3.6817*10^{-6}*T^2	0.001*T+1.090	0.998
Ice		
k=2.2196-0.0062489*T+0.00010154*T^2	-0.01*T+2.193	0.989
cp=2.062+6.0769*10^{-3}*T	0.006*T+2.062	1
α = 10^{-6}*(1.1756-0.0060833*T+0.000095037*T^2)	10^{-6}(-0.009*T+1.150)	0.989
ρ= 916.89-0.13071*T	-0.13*T+916.8	1
Water		
k=0.57109-0.0017625*T+0.0000067036*T^2	0.001*T+0.567	0.998
α = 10^{-7}*(1.3168+0.0062477*T-0.000024022*T^2)	10^{-7}*(0.006*T+1.303)	0.993
ρ=997.18+3.1439*10^{-3}*T-3.7574*10^{-3}*T^2	0.003*T+997.1	0.978
cp (0 to -40 C)=10^{-3}*(4081.7-5.3062*T+0.99516*T^2)	3.916-0.042*T	0.918
cp(T>0C)= 10^{-3}*(4176.2-0.090864*T+0.0054731*T^2)	4.179-9*10^{-5}*T	1

$$\Psi = a + b * T \quad (1)$$

where:

Ψ = the property in question (e.g. thermal conductivity etc)

a, b = constants to be determined using available data

T = the temperature (^{0}C)

These data were statistically analyzed together with the data generated from Choi and Okos Models. The Choi and Okos Models, the developed models and their coefficient of correlations are shown in Table 1. The thermal conductivity values as predicted by Choi and Okos model is presented in Fig. 1a, while thermal conductivity values as predicted by proposed model is shown in Fig. 1b. Similarly other properties may be graphed in MS-Excel.

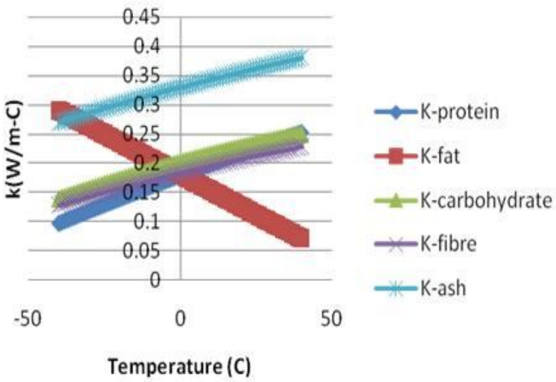

Fig. 1a Thermal conductivity values as predicted by Choi and Okos (1986)

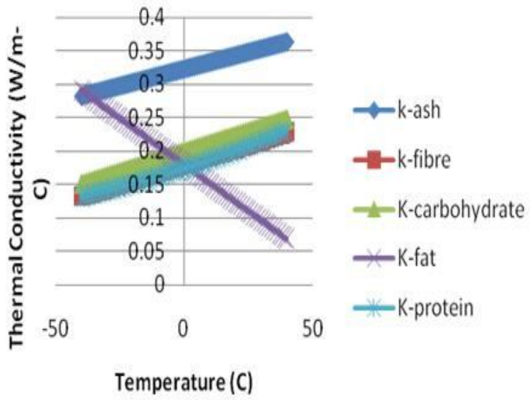

Fig. 1b Thermal conductivity values as predicted by present model

RESULTS & DISCUSSION

The errors associated with the present proposed model are shown in tabular form in Table 2. In the case of thermal conductivity maximum variation is found in the case of ash with error % varying in between 4.72765 to -5.23382 % and carbohydrates also show some more errors with error percentages varying in between 1.789582 to -8.06993 %, while the lowest error has been found in the case of fat with error % varying in between 1.728347 to -0.12309 %. In the case of thermal diffusivity, maximum error % is found for fibre content which is varying in between 1.643776 to -5.43086. while the lowest variation was found in the case of fat with error % varying in between 0.186366 to -0.2795. In specific heat case maximum error % variation was found in the case of ash with error % varying in between 2.778411 to -3.8447 and lowest variation was found in the case of protein with 0.362887 to -0.47282. In the case of prediction of density, highest variation was found for fat with error % varying from 0.011971 to 0.007394 ad lowest variation was found for carbohydrates with error % varying in between 0.07347 to 0.005143.

Similarly, in the case of ice maximum variation was found for thermal diffusivity with variation ranging from -0.25095 to -3.88234 %, while lowest variation was found for density where its variation was from -0.0982 to -0.01284. In the case of water maximum variation was found for specific heat [T<0 C] with variation ranging in-between 3.830449 to -4.93024, while the lowest variation was found for specific heat [T>0 C].

Table 2. Errors in percentage associated with the developed model

Thermal conductivity

Property	k-protein	k-fat	k-carbohydrate	k-fibre	k-ash
Max. Error (%)	1.24103	1.728347	1.789582	1.308477	4.72765
Min. Error (%)	-1.66882	-0.12309	-8.06993	-3.7015	-5.23382

Thermal diffusivity

Property	α-protein	α-fat	α-carbohydrate	α-fibre	α-ash
Max. Error (%)	1.170067	0.186366	1.581605	1.643776	0.569778
Min. Error (%)	-3.74014	-0.2795	-4.4068	-5.43086	-1.27869

Specific heat

Property	CP-protein	CP-fat	CP-carbohydrate	CP-fibre	CP-ash
Max. Error (%)	0.362887	0.705074	1.939929	1.500383	2.778411
Min. Error (%)	-0.47282	-1.22626	-2.92455	-2.1394	-3.8447

Density

Property	ρ-protein	ρ -fat	ρ -carbohydrate	ρ -fibre	ρ -ash
Max. Error (%)	0.001185	0.011971	0.007347	0.000341	0.033889
Min. Error (%)	-0.00122	0.007394	0.005143	-0.00033	0.032115

Ice

Property	K (W/m-C)	α*10^6 (m^2/s)	CP(kJ/kg-C)	ρ (kg/m^3)
Max. Error (%)	0.339151	-0.25095	0.152593	-0.00982
Min. Error (%)	-1.48251	-3.88234	-0.01455	-0.01284

Water

Property	K (W/m-C)	α*10^6 (m^2/s)	CP(kJ/kg-C) [T<0 ^{0}C]	CP(kJ/kg-C) [T>0 ^{0}C]	ρ (kg/m^3)
Max. Error (%)	1.923672	3.358741	3.830449	0.076072	0.599126
Min. Error (%)	-0.86975	-1.07398	-4.93024	-0.05554	-0.00802

From above mentioned error % it is clear that in no case the variation is more than 10 %, and all the proposed equation show a good correlation with R2> 0.9 with Choi and Okos model. Hence the proposed models may be used for the prediction of thermo-physical properties of foods.

NOMENCLATURE

K : thermal conductivity
α : thermal diffusivity
CP: specific heat capacity
ρ : density

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