Modeling of Thermal Properties of Food Components.

M.A. Akintunde, Ph.D.

Department of Mechanical Engineering, Federal University of Technology, Akure.
PMB 704 Ondo State, Nigeria.

*E-mail: ajyinka@yahoo.com

ABSTRACT

The most important requirement in the design of storage and refrigeration equipment for food and beverages is the thermal properties of the food items concerned. The thermal property will help in estimating process time for refrigerating, freezing, heating, or drying of food and beverages. Also it helps in the estimation of required refrigeration load for the design. Although, there are data for various thermal properties of food and beverages, a model for the prediction of the variation of these thermal properties are not so much available. Also, in storage design, the thermal properties of food components are very important. There are long lists of these in the literature, but there are no models for them. Models make the properties handy and the prediction easy.

This work utilized the least square methods together with other statistical tools to develop models for the thermal properties of five food components (viz: fat; protein; carbohydrate; fiber; and ash) using Choi and Okos model to generate data. A dimensionless number (Ak) was developed using four thermal properties (thermal conductivity; thermal diffusivity; density; and specific heat) used in this work. The results of correlation coefficients of the generated data using the two models, show that: the values of R for: thermal conductivity ranges between 0.9604 and 0.9831; thermal diffusivity ranges between 0.9691 and 0.9995; specific heat ranges between 0.9932 and 0.999; while that of density is 1. Comparing the R values calculated, using developed models with the tabulated values, at 95% and 99% confidence levels, the calculated values are greater than the tabulated values. This shows that the models are applicable up to 99 % confidence level in the temperature ranges from -40^{0}C to 40^{0}C considered in this work.

(Keywords: refrigeration, thermal conductivity, thermal diffusivity, density, specific heat)

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. According to ASHRAE (2002), thermal properties of foods and beverages strongly depend on chemical composition and storage temperature of the food item. ASHRAE reveals further that 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 such as, Holland et al. (1991) and ASHRAE (2002).

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. In addition, if a food item is a living organism, such as fresh fruits or vegetables, it generates heat via respiration and losses moisture via transpiration, Becker and Frick (1996). Both of these processes must be included in heat transfer calculation (Choi and Okos, 1986). These factors strongly affect the refrigeration load for the design (Akintunde, 2005). The refrigeration load is also influenced by the constituency of the food items.

Constituents commonly found in food items include: water, proteins, fats, carbohydrates, fiber, and ash. In 1986, Choi and Okos developed mathematical models for prediction of thermal properties of these food components as functions of temperature in the range of -40^{0}C to 150^{0}C. They also develop models for predicting the thermal properties of water and ice.

Karacam *et al.* (2002), studied the effects of thermal properties on shelf-life and quality of anchovies-brine at different conditions and stored both in refrigeration and at ambient temperature conditions. In their studies, total solids, ash, and fat contents of some food components were determined according to Association of Official Analytical Chemists (AOAC) standard methods. Meng and Ching-Yung (2002), characterized globulin from *Phaseolus anagularis* (red beans). Both studies mentioned above concluded that the issue of thermal properties can not be set-aside when the food quality as regard to storage and shelf-life is concerned.

Although data are available for numerous foods and beverages components (Fikiin, 1996; Akintunde, 2006; ASHRAE, 2002; Acre and Sweat, 1980), models for prediction of these food components are not readily available. This study therefore proposed a simpler models compared to those of Choi and Okos (1986) for the prediction of food components at various temperatures ranges between – 40^0C to $+40^0$C.

MODEL DEVELOPMENT

The models presented by Choi and Okos (1986) were used to generate data between temperature ranges from -40^0C to $+40^0$C. The generated data were used to plot Figures 1a to 4a. (The corresponding b-figures were plotted using the developed models in this work). The aim of this work is to present a simpler model which can be easily remembered and used. Hence the following forms of models were considered (Equations (1) to (4)).

$$\psi = a\ell^{bt} \qquad \textbf{(1)}$$

$$\psi = a\log_e t \qquad \textbf{(2)}$$

$$\psi = a + bt \qquad \textbf{(3)}$$

$$\psi = a + bt^2 \qquad \textbf{(4)}$$

where:

Ψ = the property in question (e.g. density etc)
a, b = constants to be determined using available data
t = the temperature (^{0}C)

All these equations were fixed into the data generated from Choi and Okos models, using least square method. For instance Equation (1), restated below, was analyzed as follows:

$$\psi = a\ell^{bt} \qquad \textbf{(1)}$$

Take natural logarithm of both sides of Equation (1) we have Equation (5):

$$\ln\psi = \ln a + bt \qquad \textbf{(5)}$$

Equation (5) can be written in linear form as shown in Equation (6):

$$y = a_0 + bt \qquad \textbf{(6)}$$

where:

$$a_0 = \ln a$$
$$y = \ln\psi$$

The difference of ordinates (λ) using Equation (6) is given by Equation (7) and the summation of λ^2 at any given point, say (y_i, t_i) is given in Equation (8).

$$\lambda = y_i - a_0 - bt_i \qquad \textbf{(7)}$$

$$\varepsilon = \left(\sum\lambda\right)^2 = \sum_{i=1}^{n}\left[y_i - a_0 - bt_i\right]^2 \qquad \textbf{(8)}$$

Equation (8) was then differentiated with respect to a_0 and b to obtain Equations (9) and (10), respectively.

$$\sum_{i=1}^{n} y_i - b\sum_{i=1}^{n} t_i - na_0 = 0 \qquad \textbf{(9)}$$

$$\sum_{i=1}^{n} y_i t_i - b\sum_{i=1}^{n}(t_i)^2 - a_0\sum_{i=1}^{n} t_i = 0 \qquad \textbf{(10)}$$

Equations generated from Equations (1) to (4) such as Equations (9) and (10) were used together with generated data to determine the values of "a_o" b and the value of "a" from $a_0 = \ln a$. Where the equation was applied to data generated for fat (using Equation (1)) Equation (11) was obtained:

$$k - fat = ae^{bt} \quad \textbf{(11)}$$

where:

$\psi = k - fat$ (Thermal conductivity for fat)

a = 0.1647 and b = -0.0171

Hence Equation (11) can be written as:

$$\begin{aligned} k - fat &= 0.1647ae^{-0.0171t} \\ OR & \quad \textbf{(12)} \\ k - fat &= 0.1647\exp(-0.0171t) \end{aligned}$$

Similar equations were obtained for the rest properties and components.

The equations, such as Equation (12) were used to generate data. These data were statistically analyzed together with the data generated from Choi and Okos Models. The coefficients of regression obtained while comparing models from Equations (2) to (4) were not reliable hence they were dropped. However model developed from Equation (3) shows a significant correlation when the thermal conductivity of ash was considered. Hence a linear model was retained for k-ash. The Choi and Okos Models, the developed models and their coefficient of correlations are shown in Table 1.

From the units of the four properties {thermal conductivity (k = W/m.K); thermal diffusivity (α = m^2/s); density (ρ = kg/m^2) and specific heat (c_p = J/kg.K)} considered in this work, it was observed that a dimensionless number (Ak) can be formed as shown in Equation (13).

$$Ak = \frac{k}{\alpha.\rho.c_p} \quad \textbf{(13)}$$

Data for Ak, using Equation (12) for all the food components (ash, fat, fiber, and carbohydrate) considered in this work at various temperatures were obtained using Choi and Okos models. The data generated from this models are shown is Figure 5a. Equations (1) to (4) were then used as before to generate a new model for Ak base on temperature variations. A good model was obtained for ash with equation (3) while equation (1) yielded good models for the rest components base on statiscal analysis. The developed models are shown in Table 1.

RESULTS AND DISCUSSIONS

Figures (1b) to (4b) show the plot of data generated at various temperatures using the developed models. Figure 5b, shows the plot of data generated from Ak models. The a-Figures and b-Figures were not plotted together to avoid clumsiness. Judging from the R-values, one can could observed that those curves are very close one to another.

The present models and the Choi and Okos models were used to generated data. The correlation coefficients of these data were obtained using Equation (14) (Lipson and Sheth, 2002).

$$R = \frac{\sum_{i=1}^{n}\left(x_i - \bar{x}\right)\left(y_i - \bar{y}\right)}{\left[\sum\left(x_i - \bar{x}\right)^2 \sum\left(y_i - \bar{y}\right)^2\right]^{1/2}} \quad \textbf{(14)}$$

where:

x	generated data from developed models
y	generated data fro Choi and Okos` models
$\bar{x}, \bar{y}$	means of generated data.

The calculated values of R are shown in Table 1.

In order to obtain the significant levels the calculated values of R, the results were compared with values from statistical tables (Lipson and Sheth, 2002).

From the table with the degree of freedom $v = n - p = 7$ [in this work, nine data points were considered, viz: -40^{0}C to 40^{0}C in step of 10^{0}C, and two variables, x & y, were correlated, hence p = 2, and the degree of freedom v = 7].

At 95 % and 99 % confidence levels, the tabulated values of R are 0.666 and 0.798 respectively. All the calculated values (as shown in Table1) are greater than these two values. It can be concluded that the new models can be used in place on the old models.

Table 1: Summary of Models and Statistic Analyses.

Choi and Okos Models♣	Present Models	(R^2)
Thermal Conductivities (W/(m.K))		
$k-pro = 1.7881 \times 10^{-1} + 1.1958 \times 10^{-3} t - 2.7178 \times 10^{-6} t^2$	$k-pro = 0.1742 \exp(0.0069t)$	0.9831
$k-fat = 1.8071 \times 10^{-1} - 2.7604 \times 10^{-3} t - 1.7749 \times 10^{-7} t^2$	$k-fat = 0.1647 \exp(-0.0171t)$	0.9604
$k-cabo = 2.0141 \times 10^{-1} + 1.3874 \times 10^{-3} t - 4.3312 \times 10^{-6} t^2$	$k-cabo = 0.1951 \exp(0.0072t)$	0.977
$k-fib = 1.8331 \times 10^{-1} + 1.2497 \times 10^{-3} t - 3.1683 \times 10^{-6} t^2$	$k-fib = 0.1782 \exp(0.0071t)$	0.9811
$k-ash = 3.2962 \times 10^{-1} + 1.4011 \times 10^{-3} t - 2.9069 \times 10^{-6} t^2$	$k-ash = 0.04t + 0.3277$	1.000
Thermal Diffusivity (m^2/s)		
$\alpha - pro = 6.8714 \times 10^{-8} + 4.7578 \times 10^{-10} t - 1.4646 \times 10^{-12} t^2$	$\alpha - pro = 7 \times 10^{-8} \exp(0.0073t)$	0.9771
$\alpha - fat = 9.8777 \times 10^{-8} - 1.2569 \times 10^{-10} t - 3.8286 \times 10^{-14} t^2$	$\alpha - fat = 1 \times 10^{-7} \exp(-0.0013t)$	0.9995
$\alpha - cabo = 8.0842 \times 10^{-8} + 5.3052 \times 10^{-10} t - 2.3218 \times 10^{-12} t^2$	$\alpha - cabo = 8 \times 10^{-8} \exp(0.0069t)$	0.9691
$\alpha - fib = 7.3976 \times 10^{-8} + 5.1902 \times 10^{-10} t - 2.2202 \times 10^{-12} t^2$	$\alpha - fib = 7 \times 10^{-8} \exp(0.0074t)$	0.9883
$\alpha - ash = 1.2461 \times 10^{-7} + 3.7321 \times 10^{-10} t - 1.2244 \times 10^{-12} t^2$	$\alpha - ash = 1 \times 10^{-7} \exp(0.003t)$	0.9883
Density (kg/m^3)		
$\rho - pro = 1.3299 \times 10^{3} - 5.1840 \times 10^{-1} t$	$\rho - pro = 1329.8 \exp(-0.0004t)$	1.000
$\rho - fat = 9.2559 \times 10^{2} - 4.1757 \times 10^{-1} t$	$\rho - fat = 925.53 \exp(-0.0005t)$	1.000
$\rho - cabo = 1.5991 \times 10^{3} - 3.1046 \times 10^{-1} t$	$\rho - cabo = 1599.1 \exp(-0.0002t)$	1.000
$\rho - fib = 1.3115 \times 10^{3} - 3.6589 \times 10^{-1} t$	$\rho - fib = 1311.5 \exp(-0.0003t)$	1.000
$\rho - ash = 2.4238 \times 10^{3} - 2.8063 \times 10^{-1} t$	$\rho - ash = 2423.8 \exp(-0.0001t)$	1.000
Specific Heat (kJ/kg.K)		
$cp - pro = 2.0082 + 1.2089 \times 10^{-3} t - 1.3129 \times 10^{-6} t^2$	$cp - pro = 2.0071 \exp(0.0006t)$	0.999
$cp - fat = 1.9842 + 1.4733 \times 10^{-3} t - 4.8008 \times 10^{-6} t^2$	$cp - fat = 1.98065 \exp(0.0007t)$	0.9933
$cp - cabo = 1.5488 + 1.9625 \times 10^{-3} t - 5.9399 \times 10^{-6} t^2$	$cp - cabo = 1.544 \exp(0.00013t)$	0.9932
$cp - fib = 1.8459 + 1.8306 \times 10^{-3} t - 4.6509 \times 10^{-6} t^2$	$cp - fib = 1.8422 \exp(-0.001t)$	0.9953
$cp - ash = 1.0926 + 1.8896 \times 10^{-3} t - 3.6817 \times 10^{-6} t^2$	$cp - ash = 1.089 \exp(0.0017t)$	0.9959
Dimensionless Number $Ak = \frac{k}{\rho.\alpha.c_p}$		
	$Ak - pro = 980.45 \exp(-0.0005t)$	0.8498
	$Ak - fat = 910.51 \exp(-0.0161t)$	0.9578
	$Ak - cabo = 1012.7 \exp(-0.0008t)$	0.9195
	$Ak - fib = 1036.3 \exp(-0.0011t)$	0.8523
	$Ak - ash = 39.27t + 877.59$	0.9885

♣ Choi and Okos Model (1986)

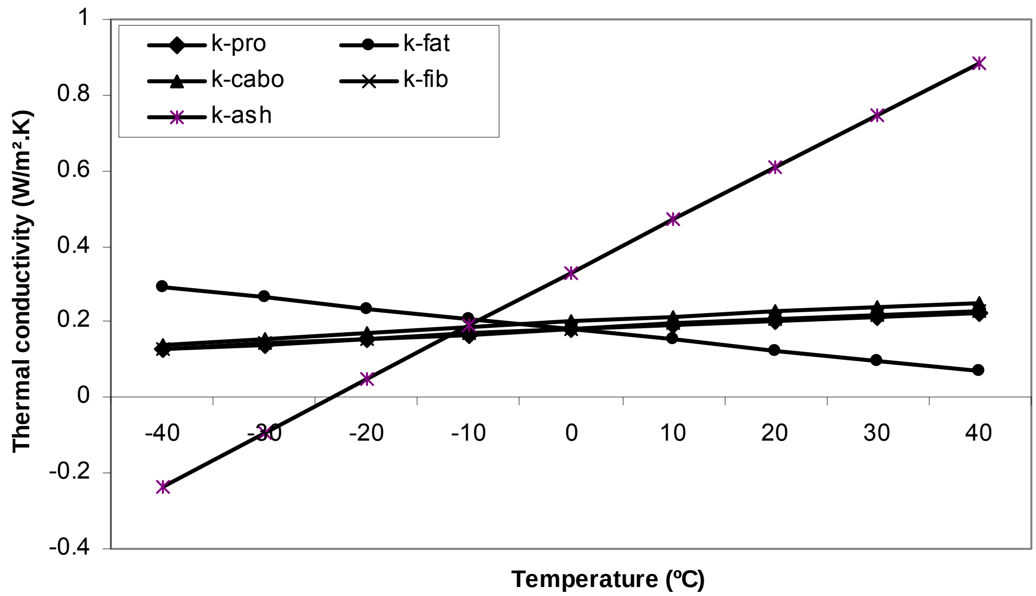

Fig. 1a Variation of Thermal Conductivities with Temperature

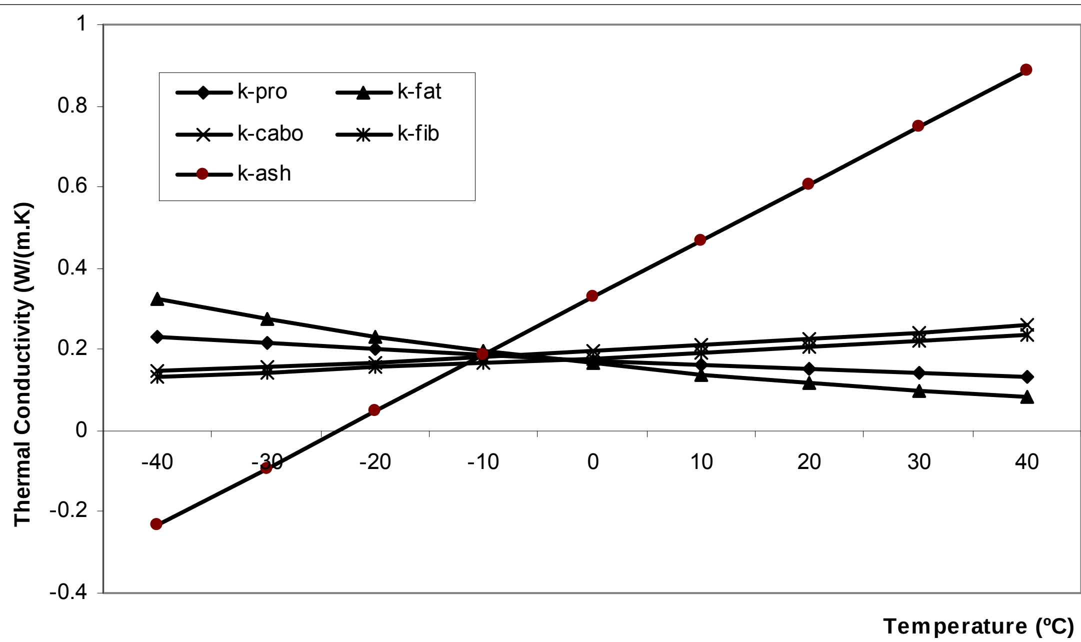

Fig. 1b Variation of Thermal Conductivity(Model) with Temperature

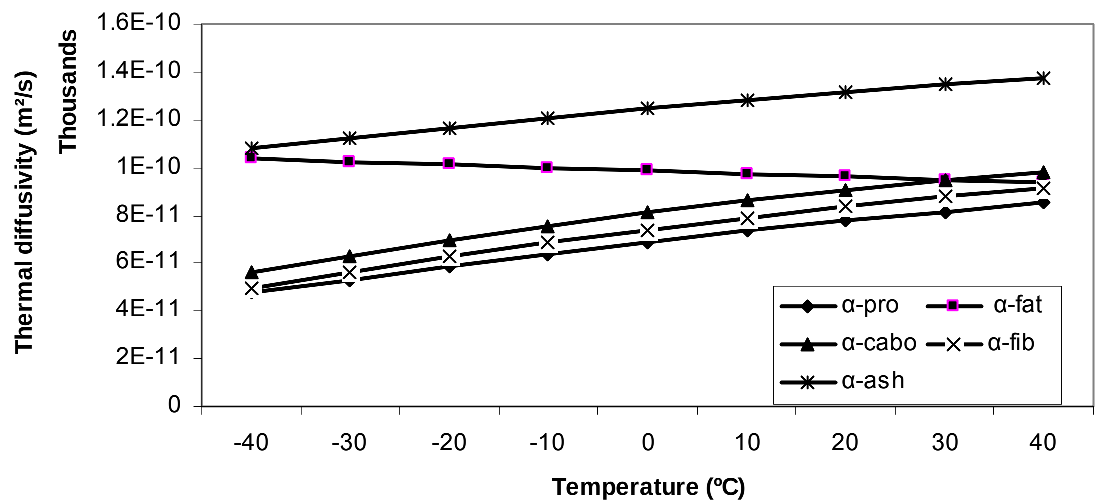

Fig. 2a Variation of thermal diffusivity with temperature

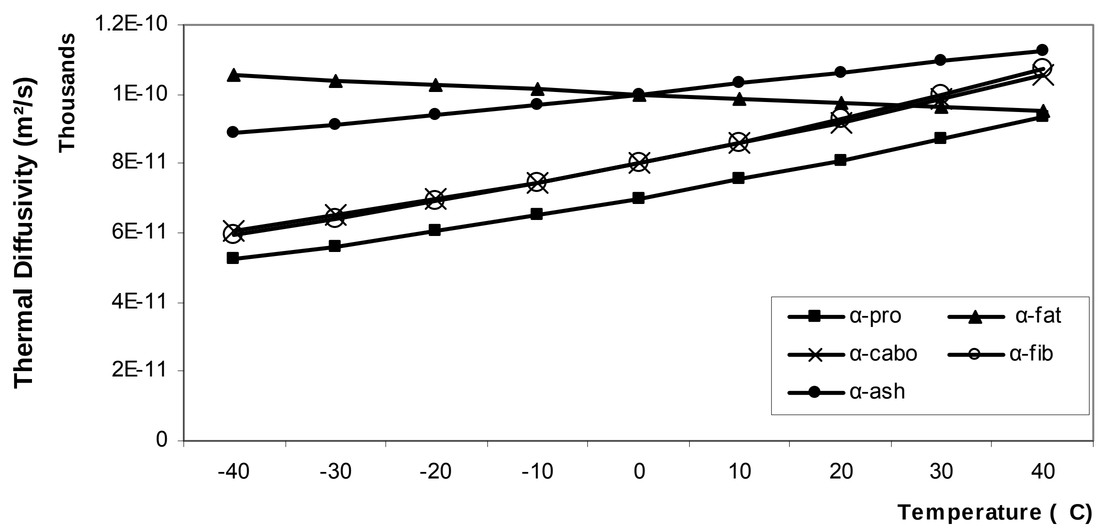

Fig. 2b Variation of Thermal Diffusivity(Model) with Temperature

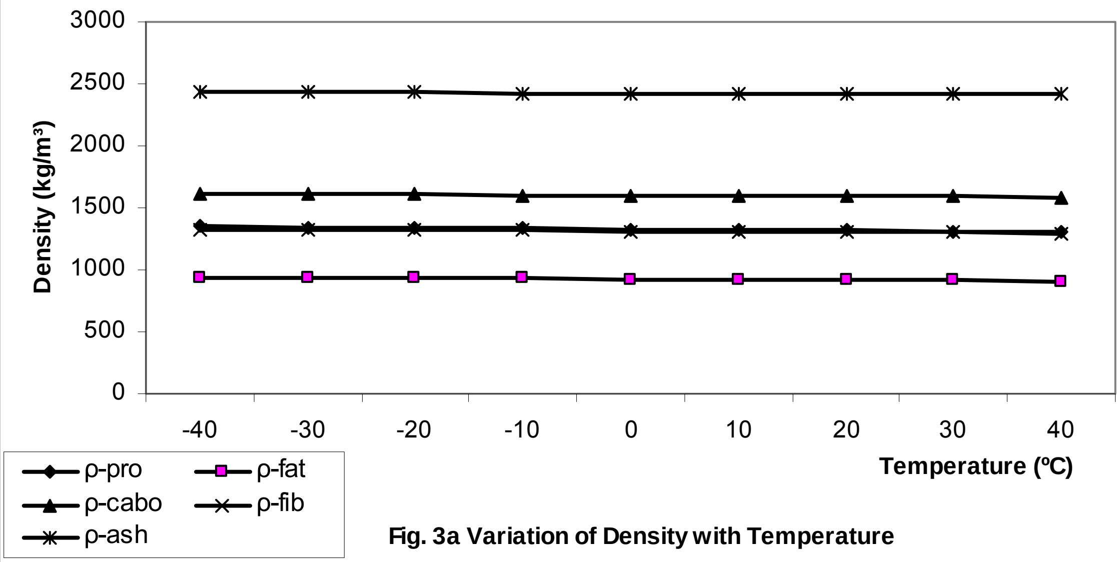

Fig. 3a Variation of Density with Temperature

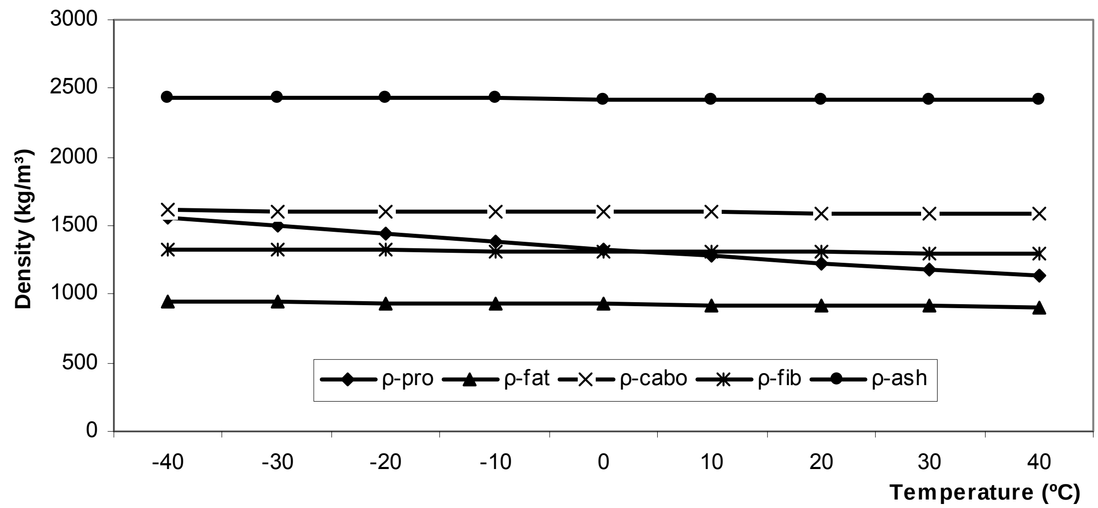

Fig. 3b Variation of Density(Model) with Temperature

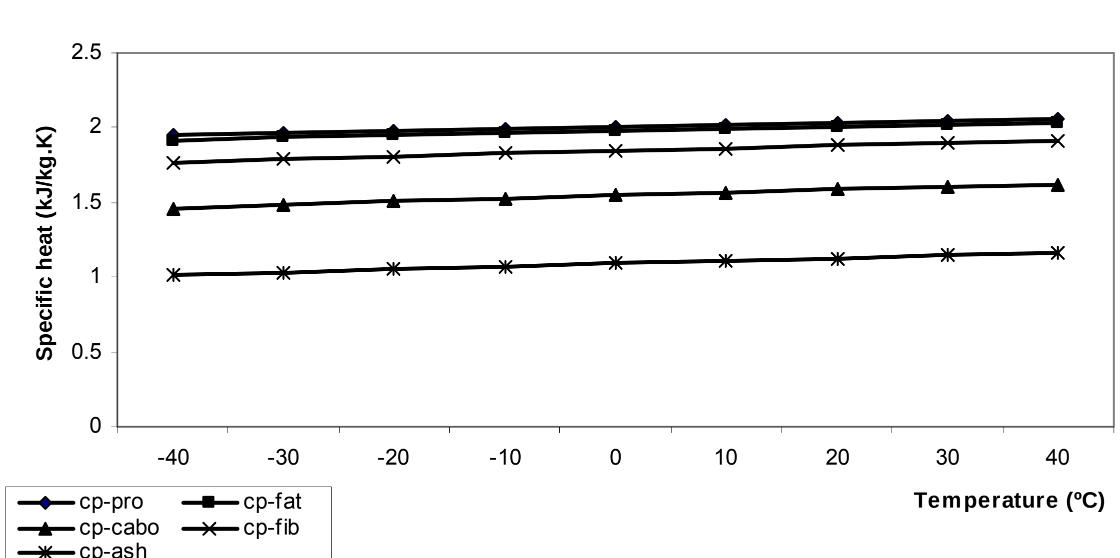

Fig. 4a Variation of Specific Heat with Temperature

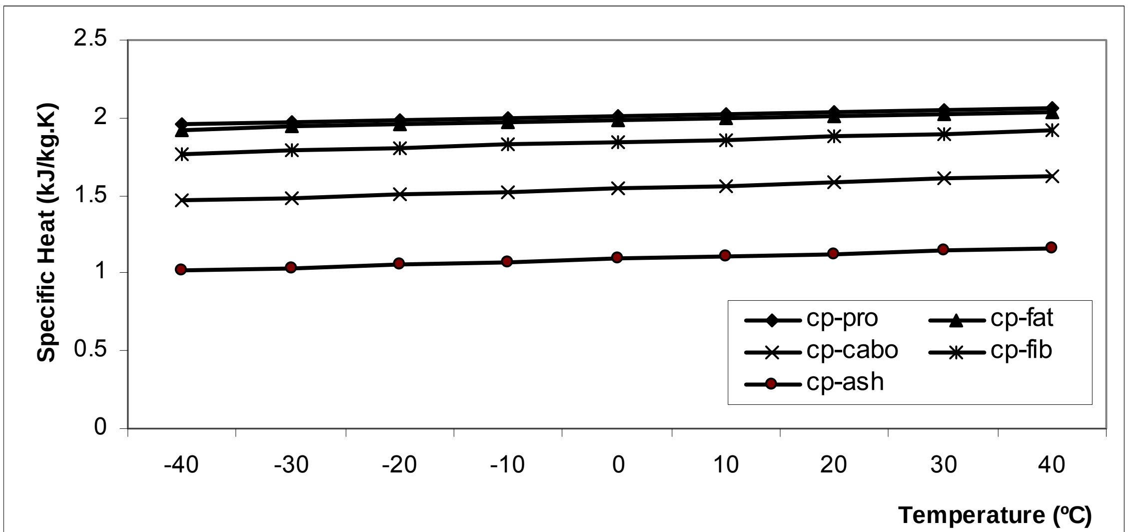

Fig. 4b Variation of Specific Heat (Model) with Temperature

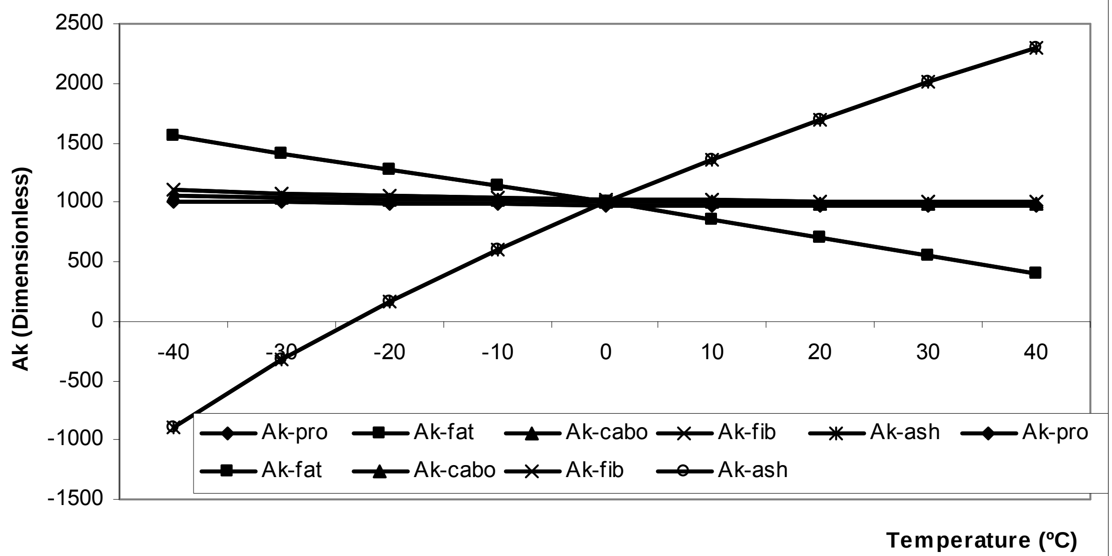

Fig. 5a Variation of Ma with temperature

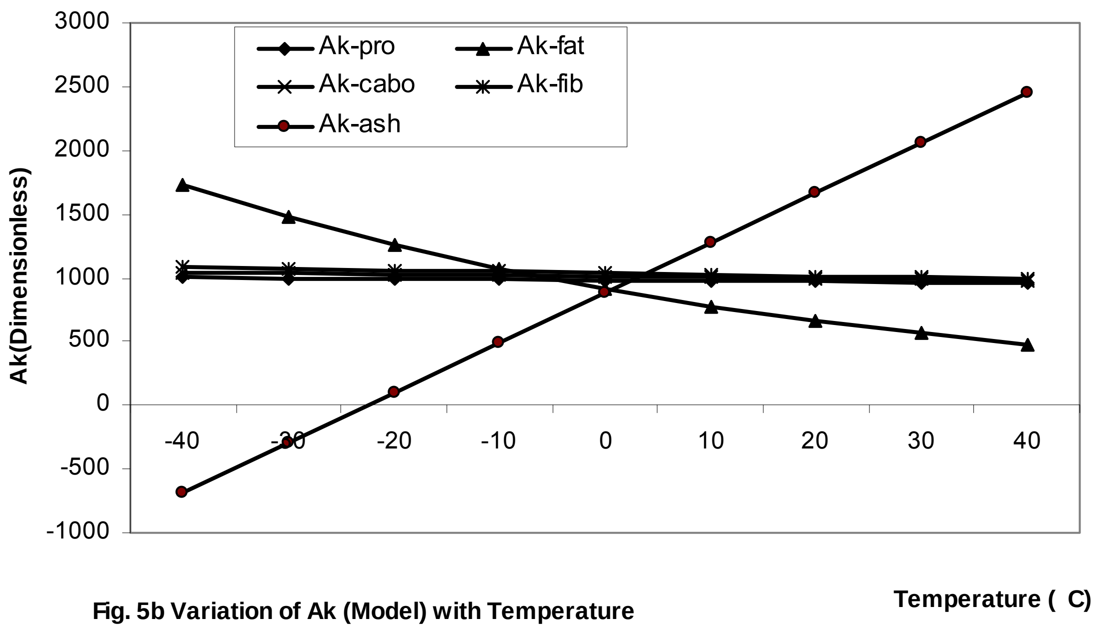

Fig. 5b Variation of Ak (Model) with Temperature

From Figures 5 a and b, it can be seen that the Ak values for ash varies almost linearly with temperature while that of fat varies exponentially.

As temperature increases, the Ak values for fat decreases while that of ash increases. The Ak values for other components (i.e., protein, carbohydrates, and fiber) are almost constant at an average value of 1000. Since this value (1000) satisfied both models (Figure 5) it can be used for those properties within the temperature limits considered in this work without jeopardizing the expected results.

CONCLUSION

In this work, simpler models were presented for predicting the variation of transport properties of food components such as fat, carbohydrates, ash, fiber, and protein. The models presented by Choi and Okos were used to generate data used in the development of these new models. The developed models, using the least square method, were compared statistically with those of Choi and Okos` models. The resulting correlation coefficients of the generated data using the two models, show that the values of R for thermal conductivity ranges between 0.9604 and 0.9831, thermal diffusivity ranges between 0.9691 and 0.9995, specific heat ranges between 0.9932 and 0.999, while that of density is 1.

A dimensionless number Ak was defined between the four parameters considered. Models for prediction of variation of the five food components with temperature were developed. The correlation coefficient between the data generated from the Choi and Okos models and the developed models for the dimensionless number indicated a ranges between 0.8498 and 0.9885. It was shown, as it was observed in the analysis, that it was the Ak values for both ash and fat that varies largely with temperature. While the values for ash increases almost linearly with temperature that of fat decreases exponentially. It was further observed that the Ak values for other components, remain almost constant at an average value of 1000.

Comparing the R values calculated, using developed models with the tabulated values, at 95% and 99% confidence levels, the calculated values are greater than the tabulated values. This shows that the models are applicable up to 99 % confidence level in the temperature ranges from -40^{0}C to +40^{0}C considered in this work. Also judging from this statistical analyses the value of 1000 (Ak) can be used for fiber, carbohydrates and proteins within the temperature range specified in this work. The presented models can be used to estimate more accurate values.

NOMENCLATURE

k =	thermal conductivity (W/m.K)
α =	thermal diffusivity (m2/s)
ρ =	density (kg/m3)
cp =	specific heat (kJ/kg.K)
Ak =	a dimensionless number
pro =	protein
fat =	fat
cabo =	carbohydrate
fib =	fiber
ash =	ash
R =	regression coefficient
t =	temperature (^{0}C)

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ABOUT THE AUTHOR

Dr. M.A. Akintunde, graduated from Obafemi Awolowo University, Ile-Ife in 1992 with first class honors in the Department of Mechanical Engineering. He studied Building Services Engineering at The Federal University of Technology, Akure (Nigeria). He completed his Master's degree in 1997 and Ph.D. in 2004. He is a Senior Lecturer in Mechanical Engineering at the Federal University of Technology, Akure Nigeria. His research interest includes refrigeration and air-conditioning, energy systems, thermodynamics, and mechanics.

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