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Thermophysical properties of some species of Malaysian freshwater fish in unfrozen state

K. A. Abbas *, S. M. Abdulkarim and B. Jamilah
*Faculty of Food Science & Technology, Universiti Putra Malaysia (UPM), Serdang 43400, Selangor, Malaysia. *e-mail: ali_kassim@ hotmail. com*

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Abstract

Five widely consumed species of freshwater fish in Malaysia were investigated to determine their thermophysical properties due to their handling need for food industry sector from the viewpoint of the heat transfer calculations. These properties encompassed thermal conductivity, specific heat and thermal diffusivity. The species under study were black tilapia, red tilapia, catfish, yellowtail catfish and red pomphret. The major components (moisture, fat, protein, carbohydrate and ash contents) of the fish muscle were determined for each species in a fresh state. Mathematical formulae, which correlate between the components' values and the thermophysical properties were used to calculate these properties and their variation with temperature. The results were compared with the existing literature of other fish. Slight differences were noticed, however, the results were still within the common range of fish thermophysical values. The differences may be attributed to the different cultural and growing conditions. A logistic model correlated between the thermal diffusivity and temperature variation was developed in this work. It represents the basic requirement to the solution of heat transfer equation by which the thermal processing problems could be solved.

Key words: Freshwater, thermophysical properties, logistic model.

Introduction

The general transient heat conduction equation for a food object, subjected to heating or cooling process, may be written as:

$$\nabla(k\nabla T) = \rho C_P \frac{\partial T}{\partial t} \quad (1)$$

The above equation reveals that the temperature history at any position within the object is a function of time and thermal conductivity, and the thermal conductivity itself is slightly dependent on temperature variation. This equation could be simplified if k is considered constant and may be written in Cartesian coordinates as follows:

$$\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} = \frac{1}{\alpha}\frac{\partial T}{\partial t} \quad (2)$$

Therefore, the solution of this equation dictates the values of the thermophysical properties (k, Cp, ρ, α) and their variation with temperature. So knowledge of thermal properties is essential for efficient and economical design of all food processing operations involving heat transfer. Some of the common processes involving heat transfer are heating, cooling, freezing, thawing and frying. It is also of great importance in the development of thermal models for generating accurate numerical results. Therefore, several researchers [1-9] have emphasized the need for thermal properties of foods in general and seafood in particular. These properties greatly depend on the physical characteristics of food such as temperature, state (frozen or unfrozen), compositional constituents (moisture, fat, protein and ash content) and slightly on fiber orientation.

Thermal properties like thermal conductivity and thermal diffusivity can be measured by various steady state (guarded hot plate, concentric cylinder, concentric sphere) [10] and unsteady state methods (line source probe, thermal comparator, thermistor probe etc.). All these methods have several advantages and disadvantages. Researchers [11, 12] listed in details the sources of error in thermal property measurements of the various methods.

Steady state techniques pose two major problems for experiments with high moisture products, though they generally require simple mathematical relations to calculate thermophysical properties. Firstly, the time required for the temperature distribution to reach a steady state value takes a long time. Secondly, moisture diffusion can occur from high temperature regions to low temperature regions, altering the composition of the sample [13]. The moisture migration might be quite substantial because of the long tests. Transient techniques eliminate both these major problems as the test period mostly varies from a few seconds to a few minutes. Since thermal conductivity is greatly dependent on physical and chemical composition, which is most often considered as porosity, moisture content and fat content, hence, transient techniques are recommended for high moisture agricultural materials. Several researchers have also discussed

Notations: k thermal conductivity of product (W/mK), Cp specific heat (kJ/kg K), X mass fraction (decimal), v displaced volume (m^3), m samples mass (kg), α thermal diffusivity of sample (m^2/s), ρ mass density. Subscripts: a ash, c carbohydrate, f fat, p protein, w water.

the use of various thermal models developed from statistical analyses on experiments measuring chemical compositional parameters. Mohsenin [14] has discussed in detail several other methods used in specific heat measurements of agricultural materials. Mohsenin [14] and Sweat [15] suggested the differential scanning calorimeter as the best practical tool for these measurements on foods. However, this method is costly and complicated, therefore, many researchers still prefer the chemical composition correlation as a most accurate method. Therefore, many researchers developed some correlation between the major constituents and the thermophysical properties [5, 16-18]. The accuracy of the calculated thermophysical property can be improved if all the major constituents are taken into account and accurate values of the specific thermal property and mass fraction of each constituent are known.

An extensive literature search revealed that information of thermophysical properties concerned with freshwater fish in general and for Malaysian ones in particular is still lacking [8, 17]. It is appropriate to mention here that no study has been reported in the literature regarding the variation of the thermal diffusivity (the derived property that govern heat transfer phenomenon) with temperature of the fish under study. Therefore, the present research work has been justified due to the above-mentioned reasons and also based on the fact that these fishes are more likely to be of commercially value in the future [17].

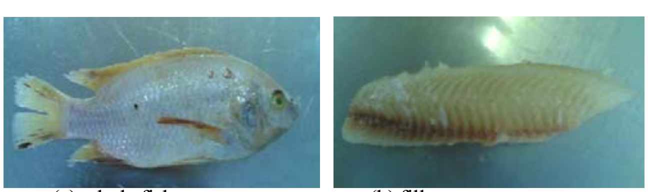
Material and Methods

Material and samples: The five species of freshwater fish used in this work are presented in Table 1. Fig. 1 shows red tilapia and its fillets prepared for subsequent tests, as an example of the sample prepared for the data collection.

Mass density measurement: The mass densities of the fish samples were determined by measuring the mass and volume of a sample. The mass of the fish sample was measured on an electronic balance (KERN PB) of the range of 4100 g, with a resolution of 0.01 g. The volume of the fish sample was measured indirectly by dipping it into a jar filled with water (Fig. 2) and the volume of the spilled water (determined by dividing the water weight read by the balance upon the water mass density) was calculated as the volume of the fish sample. The following equation was used to calculate the density of each species:

$$\rho = \frac{m}{v} \qquad (3)$$

Chemical composition analyses: The constituents, moisture, ash, fat and crude protein, were analused using the standard procedures [19-22]. The carbohydrate content could be determined by subtracting all the above constituents' values from 1.



(a) whole fish (b) fillets

Figure 1. Red tilapia.

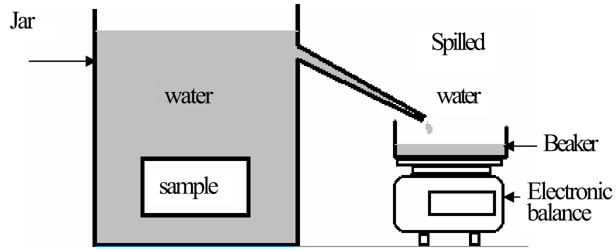


Figure 2. Set-up for measurement of the sample volume.

Thermophysical properties determination: Once the major constituents of the fish were known, the thermal conductivity and specific heat were computed empirically [15, 23, 24] by using the following equations respectively:

$$k = k_p X_p + k_f X_f + k_a X_a + k_w X_w + k_c X_c \qquad (4)$$

$$Cp = C_c X_c + C_p X_p + C_f X_f + C_a X_a + C_w X_w \qquad (5)$$

Rao and others [25] listed the thermal conductivities and specific heat variations of the major food component with temperature as shown in Table 2. The thermal diffusivity and its variation with temperature was determined by the following equation:

$$\alpha = \frac{k}{\rho Cp} \qquad (4)$$

Results and Discussion

Different chemical compositions of fresh fish were determined by the method as reported in previous section. The differences in the compositions were slightly noticeable. In general, the ash content among five species did not differ and ranged from an average of 0.89% (catfish) to 1.08% (yellowtail catfish). Meanwhile, moisture content ranged from 74.13% (catfish) to 79.02% (red tilapia) which showed dependence on whether the fish is fatty or lean. The fat content was higher for fatty fish rather than lean fish so it ranged from 1.24% (red tilapia) to 5.32% (catfish). Protein content ranged from 15.89% (tilapia) to 18.43% (red pomfret). The experimental results about the overall average chemical composition of fresh fish are shown in Table 3. Some of the values agreed well with the literature [26] values, but others showed slightly difference. These differences among and between species were due to different maturity, size, breeding and feeding condition, catch location, water quality, soil quality, season and climate.

The experimental results on the thermophysical properties above freezing point of fresh fish are displayed in Table 4. Overall thermophysical properties of the fish studied had no large differences. The specific heat capacity ranged from 3.5020 (catfish) to 3.6406 kJ/kg K (tilapia), while the thermal conductivity ranged from 0.4724 (catfish) to 0.4933 W/m K (tilapia). Thermal diffusivity ranged from 1.3300 x 10^{-7} m²/s (yellowtail catfish) to 1.3515 x 10^{-7} m²/s (tilapia). In general, it was found that the values of the thermal properties were quite similar when compared to those of the other species reported in the literature, although, some differences exist due to environmental, cultural and growing conditions which affect the composition of the fish it self.

The values of thermal diffusivities of all the species have been presented as functions of temperature as shown in Fig. 3. These

Table 1. Common and scientific name of fish species studied.

English name	Local (Malay) name	Scientific name	Average weight, (g)	Average length, (cm)
Black tilapia	Tilapia hitam	*Tilapia mossambica*	396.67 ± 5.77	26.67 ± 0.58
Red tilapia	Tilapia merah	*Tilapia* spp.	298.33 ± 2.89	22.67 ± 0.29
Catfish	Keli	*Clarias batrachus*	183.33 ± 5.77	28.83 ± 0.29
Yellowtail catfish	Patin	*Pangasius sutchi*	2800.0 ± 173.21	75.33 ± 1.15
Red pomphret	Bawal merah	*Piaractus brachyponus*	740.00 ± 17.32	34.33 ± 0.58

The value in the table represents the mean ± standard deviation. Each mean was taken from 3 fish.

Table 2. Thermal property models.

Major food constituents		
Thermal property	Major component	Group model Temperature function
K(W/m°C)	k_p	$k = 1.788X10^{-1}+1.195(10^{-3}T)-2.7178(10^{-6}T^2)$
	k_f	$k = 1.8071X10^{-1}-2.7604(10^{-3}T)-1.7749\ (10^{-6}T^2)$
	k_c	$k = 2.0141X10^{-1}+1.3874\ (10^{-3}T)-4.3312(10^{-6}T^2)$
	k_a	$k = 3.2962X10^{-1}+1.401\ (10^{-3}T)-2.9069(10^{-6}T^2)$
	k_w	$k = 0.57101+1.7621\ (10^{-3}T)-6.7036(10^{-6}T^2)$
C*p*	C_p	$C_p=2.0082+1.2089(10^{-3}T)-1.3129(10^{-6}T^2)$
	C_f	$C_f=1.9842+1.4732(10^{-3}T)-4.8008(10^{-6}T^2)$
	C_c	$C_c=1.5488+1.9625(10^{-3}T)-5.9399(10^{-6}T^2)$
	C_a	$C_a=1.0926+1.889(10^{-3}T)-3.6817(10^{-6}T^2)$
	C_w	$C_w=4.1762-0.0909(10^{-3}T)+5.4731(10^{-6}T^2)$

Table 3. Overall average chemical composition of fish species studied.

Fish	Constituents (%)			
	Ash	Moisture	Fat	Protein
Black tilapia	1.03 ± 0.06	79.45 ± 0.77	3.04 ± 0.05	15.89 ± 0.73
Red tilapia	0.99 ± 0.06	79.02 ± 0.06	1.24 ± 0.04	18.33 ± 0.10
Catfish	0.89 ± 0.02	74.13 ± 0.32	5.32 ± 0.30	17.39 ± 0.47
Yellowtail catfish	1.08 ± 0.02	76.72 ± 0.12	4.75 ± 0.11	16.85 ± 0.03
Red pomfret	0.98 ± 0.06	75.98 ± 0.40	3.28 ± 0.23	18.43 ± 0.16

The value in the table represents the mean ± standard deviation. Each mean was taken from 3 fish.

Table 4. Thermophysical properties of 5 fish species studied.

Fish	Specific heat,Cp (kJ/kg K)	Thermal conduvtivity, k (W/m K)	Thermal diffusivity, α (x $10^{-7}m^2/s$)
Tilapia	3.6406 ± 0.0203	0.4933 ± 0.0032	1.3515 ± 0.0017
Red tilapia	3.6276 ± 0.0015	0.4912 ± 0.0003	1.3515 ± 0.0002
Catfish	3.5020 ± 0.0090	0.4724 ± 0.0011	1.3426 ± 0.0022
Yellowtail catfish	3.5703 ± 0.0029	0.4817 ± 0.0004	1.3300 ± 0.0047
Red pomfret	3.5488 ± 0.0101	0.4792 ± 0.0016	1.3487 ± 0.0024

The value in the table represents the mean ± standard deviation. Each mean was taken from 3 fish.

Table 5. The constants of Equation 5 with some statistical comments of Equation 5.

Species	Constant			Standard error	Correlation coefficient
	a	b	c		
Yellow tail catfish	1.6667649	0.40264166	0.016361837	0.0029871	0.9997337
Catfish	1.6201025	0.38286114	0.018120934	0.0011637	0.9999591
Black tilapia	1.6906174	0.4049400	0.016113149	0.0037461	0.9995889
Red tilapia	1.6859186	0.41273992	0.016752402	0.0017182	0.9999187
Pomphret	1.6670519	0.40855175	0.016082978	0.0027371	0.9997762

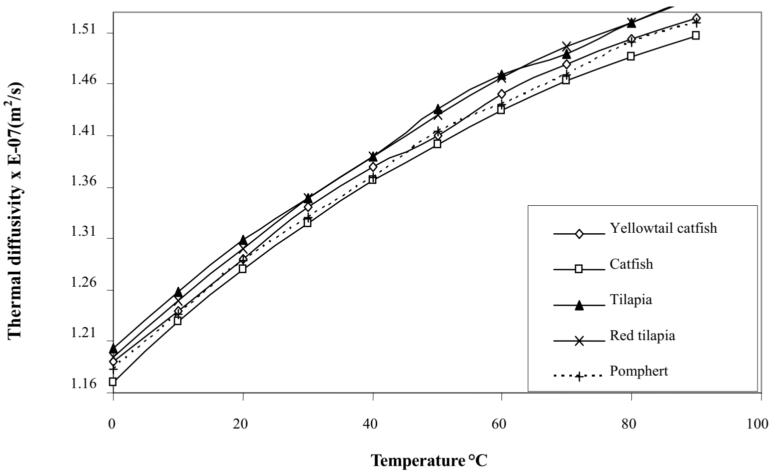


Figure 3. The variation of thermal diffusivities with temperature change for all the species.

functions are one of the basic requirements to solve Equation 1 or 2 by which the food technologists can predict the temperature profiles of the interior points of any food object subjected to any transient cooling or heating processes.

The logistic model listed was found to be the best fit to all the curves of the above graph. The constants a, b, c and some statistical details are listed in Table 5. Equation 5 is the most necessary requirement by which Equation 2 can be solved and the cooling or heating time could be determined.

$$\alpha = \frac{a}{1 + be^{-cT}} \qquad (5)$$

Conclusions

Chemical composition of five sweetwater fish species of Malaysian origin was analysed to determine their thermophysical properties. The main compositional differences between species were due to some of the fish were fatty while others were lean, as the fatty fish revealed less water content than the lean one. Meanwhile the difference with the existing literature was because of the different cultural and growing conditions. Thermophysical properties of all species were verified by comparing them with the literature. A database was developed through this study. This database provides the physical and chemical information about Malaysian freshwater fish, not found in literature. This information would be helpful in predicting the cooling and heating processing times by the food technologists and in designing the equipment by the engineers.

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