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Experimental Determination of Thermal Conductivity of Water−Agar Gel at Different Concentrations and Temperatures

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ABSTRACT: Thermal conductivities of water−agar gels were determined at concentrations with mass fractions between $w = 0.001$ and $w = 0.1$ and temperatures from (278.15 to 323.15) K by means of a specifically designed probe system based on the line heat source principle. The thermal conductivity probe was calibrated and validated using glycerin (with mass fraction $w = 0.99$), glycol (with mass fraction $w = 0.99$), and ultra pure water (with resistivity 18.4 $\text{M}\Omega\cdot\text{cm}$, electric conductivity 0.055 $\mu\text{S}\cdot\text{cm}^{-1}$). Their measured and recommended values of thermal conductivity were in good agreement. The experimental data of thermal conductivity values of water−agar gels were sensitive to both concentration and temperature. The thermal conductivity of water−agar gels decreased with increasing concentration, while it increased as temperature increased. Predictive regression models were proposed to give a good fit for thermal conductivity with concentration and temperature.

1. INTRODUCTION

Agar consists of unbranched polysaccharides obtained from the cell walls of many species of red seaweed (*Gelidiaceae* and *Gracilariaceae*).[1] In bio- and food-engineering research, agar gel has a number of practical applications. Agar gel acts as bacterial culture support and separation media in column chromatography and electrophoresis.[2] Agar gels have found use in medicine and pharmacy.[3] In the food industry, agar gels are commonly used as a thickening agent, a vegetarian gelatin substitute, or a clarifying agent in brewing.[2,3] Many kinds of dessert gel with agar have been used in traditional cooking.

Agar forms a thermo-reversible gel in aqueous solution, and the gel remains stable over a wide temperature range; agar gels have a gelling or setting temperature close to 313 K and a melting temperature near 363 K.[2,4] The solid matrix ensures the gels holding excellent mechanical properties, while the large water content makes the transport of diffusive ions possible. It has been widely reported that the physicochemical, mechanical, and rheological properties of agar gels.[2,5] However, to our knowledge, there exists no previous report on the thermal conductivity of water−agar gel with different concentrations at various temperatures. The thermal conductivity of water−agar gel is one of the important thermophysical properties used to estimate the rate of heat transfer during processes, such as preservation, transportation, and freezing.[6] It is also important to be aware of factors that may affect the properties of agar gels.

The overall objective of this work was to determine the thermal conductivities of water−agar gel with different concentrations at various temperatures. The specific objectives of this research were (1) to elaborate a designed probe system which is simple, fast, accurate, and convenient and has a low cost for determining the thermal conductivity of water−agar gel and (2) to develop prediction equations for the thermal conductivity of water−agar gel at different concentrations and various temperatures.

2. MATERIALS AND METHODS

2.1. Sample Preparation. Water−agar gels with different concentrations ($w_1 = 0.001$, $w_2 = 0.005$, $w_3 = 0.01$, $w_4 = 0.05$, $w_5 = 0.1$) were prepared by dissolving powdered agar (B1017, Westang Agar Bacteriological, Japan) in ultra-pure water (UPH-II, Millipore, USA). To obtain a better reproducibility, each solution was heated up to boiling over a hot plate in a Pyrex beaker and poured into and filled in three cylindrical glass containers with 50 mm in diameter and 60 mm in height. Each sample was allowed to solidify at room temperature. Before the measurement, the container filled with a sample was sealed and placed in a constant temperature apparatus (LHS-100CL, ± 0.5 K of accuracy, Shanghai Precision Instrument Co., Ltd., China) of temperatures of (278.15, 283.15, 293.15, 303.15, 313.15, and 323.15) K to ensure a constant and uniform initial temperature of sample.

2.2. Line Heat Source Theory. Theoretically, the line heat source technique is based on idealized nonsteady state transient heat conduction model composed by a zero radius linear heat source of infinite length, which is immersed in an infinite and homogeneous medium with constant thermophysical properties.[7,8] Under such conditions, energy balance and heat conduction in Fourier's law could be combined to give the temperature T of a given point of the medium, after time τ has elapsed since the origin of the thermal flux, into the following equation (eq 1):[9,10]

$$\frac{\partial T}{\partial \tau} = a\nabla^2 T \tag{1}$$

The determination equation of thermal conductivity using the line source technique is obtained in terms of the temperature rise

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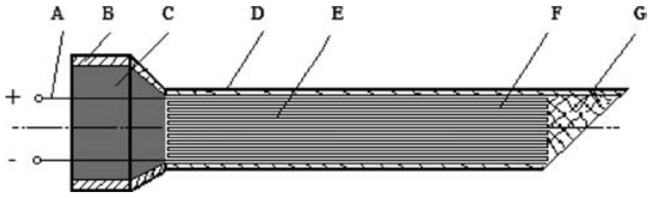

Figure 1. Schematic structure of thermal conductivity probe: A, leadout wire; B, electrically insulated end lid; C, electrically insulated gel; D, stainless steel tube; E, insulated copped wire; F, vacuum silicon oil; G, epoxy resin.

of any point located at a distance r from the linear source axis (eq 2):[11−13]

$$\Delta T = \frac{q}{4\pi k} \ln\left(\frac{4a\tau}{E_u r^2} + \frac{r^2}{4a\tau} + ...\right) \tag{2}$$

where ΔT is the transient temperature rise at a radial distance r in the medium. τ is the heat time. k and a are the thermal conductivity and thermal diffusivity of the medium, respectively. q is the heat input power per unit length, and E_u is the Euler's constant. Equation 2 describes the ideal model which cannot be employed directly to the practical instrument. Many of the analytical corrections were developed and imposed on eq 2 to eliminate the departure of a practical instrument from the ideal one.[14,15] The working equation of the method is as follows (eq 3):

$$k = \frac{q}{4\pi} / \frac{\partial(\Delta T)}{\partial \ln \tau} \tag{3}$$

Equation 3 is the formula which was used to calculate thermal conductivity from experimental data including the slope of a plot of temperature against the natural logarithm of heat time and the power input per unit length. The line heat source method is at present the most accurate technique for measuring the thermal conductivities of liquids.[16] It can be operated with a precision of 0.02 % and an accuracy of 0.2 %.[7] However, the very thin hot wire is apparently inconvenient to measure solid materials.

2.3. Experimental Apparatus. Depending on the line heat source theory, the thermal conductivity probe method was recommended for the measurement of thermal conductivity.[10,17] Advantages of this technique were the simplicity, speed, convenience, and small sample size requirement.[18−20] The conventional probe constructed as a line heat source was made of a metal tube and wire. Nichrome wire insulated with Teflon was fused at one end of the tube. A calibrated copper-constantan thermo couple wire was placed inside the tube with its tip positioned just outside the center of the tube.[10,21] The Nichrome wire was used as the heated element, and the copper−constantan thermo couple wire was used as the temperature measurement element.

In this work, a thermal conductivity probe measurement system with a different probe structure was designed and constructed based on the idealized nonsteady state transient heat conduction model as above.[22] The thermal conductivity probe shown in Figure 1 is a stainless needle with a 0.7 mm outer diameter, a 0.3 mm inner diameter, and a 32 mm exposed length. An insulated heating copper wire with a 0.02 mm diameter was enclosed in the needle. The copper wire worked as both a heating element and a resistance thermometer instead of the thermocouple wire.[23] For high moisture materials, the axial flow error was recommended a maximum relative error of 0.07 % when the length or diameter ratio of the thermal conductivity probe was more than 30.[15,24] The thermal conductivity probe was full of vacuum silica gel which had good heat conduction and electricity insulation. The front and back sides of the thermal conductivity probe were insulators to reduce axial heat transfer. Thus, the axial heat loss from the front and back sides was considered small enough to be neglected in the measurement of thermal conductivity.

The whole experimental apparatus is shown schematically in Figure 2. It was composed of a thermal conductivity probe, a direct current power supplier (HY1791-2S, Huian Yaguang Electron Co., Ltd., China), a data acquisition system (model 2700, Keithley Instruments, USA), a constant temperature apparatus (LHS-100CL, Shanghai Precision Instrument Co., Ltd., China), and electrical circuit system.

The sketch of electrical circuit of the measurement system is shown in Figure 3. The Wheatstone bridge was utilized to improve the sensitivity for voltage measurement.[25] The two arms R_{b1} and R_{b2} were equal to 10^4 Ω. The thermal conductivity probe formed the third arm with the electric resistance R_s. The fourth arm was the balance arm with a variable resistor R_t. A precision voltage source E = 2.52 V provided by a DC power supply was applied to the bridge.

At first, the thermal conductivity probe was inserted into sample that was filled in a cylindrical glass holder (50 mm in diameter, 1 mm in wall thickness, and 60 mm in height) keeping the thermal conductivity probe in the geometric center of the holder. The samples were equilibrated to the desired temperature by a constant temperature apparatus. The bridge was balanced through adjusting the variable resistor $R_t = R_s$. Then the thermal conductivity probe was heated while the circuit system was turned on. The heat flows in the radial direction outward through the heated probe to the test sample. According to the high correlation between the copper electric resistance value and the temperature, the electric resistance value R_s of the heated copper wire would change with the temperature change of the probe. An electric voltage signal ΔV would be produced from the controlled electric circuit, which would be amplified by the data acquisition system and imported by a computer; a linear relation equation of electric voltage against logarithmic time could be obtained.

The process of measurement was in the unsteady state. It could be described as one-dimensional radial heat flow in an infinite homogeneous medium. According to the linear heat source theory, the thermal conductivity of the sample (k) could be developed and obtained from the slope of output electric voltage of the electric circuit (ΔV) against natural logarithmic time ($\ln \tau$) and power input voltage (E), as given by the following equation (eq 4):[22]

$$k = \frac{E^3}{{R_s}^2} I_n / \frac{d(\Delta V)}{d(\ln \tau)} \tag{4}$$

where I_n, calculated from the defined formula $I_n = \alpha_0 R_0 / 64\pi L$, is the instrument constant of the probe, $\Omega \cdot m^{-1} \cdot K^{-1} \cdot s^{-1}$. It is only related with the probe material and length and had nothing with the heating power or testing temperature of the testing system.[26] ΔV is the output electric voltage of the electric circuit, V; τ is heating time (s). k is the thermal conductivity of sample, $W \cdot m^{-1} \cdot K^{-1}$. E is the electric voltage of power supply, V. R_s is the initial electric resistance value of probe, Ω. α_0 is the copper electric resistance's temperature coefficient at 273.15 K, K^{-1}. R_0

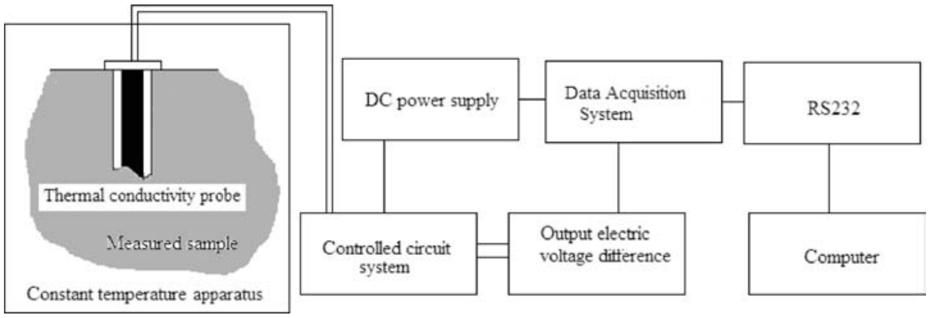

Figure 2. Schematic diagram of the measurement system.

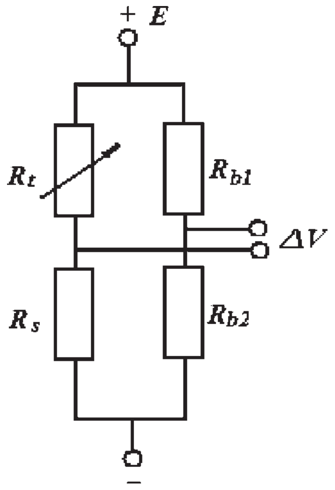

Figure 3. Sketch of electrical circuit: E, Wheatstone bridge voltage; R_t, variable resistor; R_s, probe resistance; R_{b1}, balance resistor 1; R_{b2}, balance resistor 2; ΔV, output voltage difference.

is the electric resistance value of the copper electric resistance at 273.15 K, Ω. L is the effective length of the probe, m.

The voltages and time were measured by the data acquisition system with accuracy of 10^{-4} mV and 0.1 s, respectively. The temperature rise of the probe was determined by the data acquisition system with an accuracy of 0.01 K. The power input to the heater was controlled by means of a booster, which allowed the adjustment of the voltage with a stability of 0.01 %.

2.4. Determination Procedure of Thermal Conductivity. First, the thermal conductivity probe should be calibrated to reduce experimental errors because the thermal conductivity probe used had a finite length of the line heat source, a finite radius of the line heat source, and thermal mass, which deviated from the theoretical line heat source model. The thermal conductivity probe was calibrated by measuring the thermal conductivity of glycerin (Shanghai Lingfeng Chemical Reagent Company, with mass fraction w = 0.99) to get the instrument constant of the thermal conductivity probe. The thermal conductivity probe was calibrated with a glycerin in the initial state at 293.15 K. Measured data of glycerin are shown in Table 1. The average of six replicates was 0.0314 $\Omega\cdot m^{-1}\cdot K^{-1}\cdot s^{-1}$ with a standard deviation of 0.000171 $\Omega\cdot m^{-1}\cdot K^{-1}\cdot s^{-1}$ and a relative deviation of 0.55 %.

During the test run, the heating time was no more than 20 s, and the temperature rise was below 1 K. According to the heat transfer theory, convection would occur as the result of the motion of the fluid due to density changes arising from the heating process. However, the convection condition would be judged by calculating the dimensionless group called Grashof number (G_r).[27]

Table 1. Experimental Parameters of Glycerin at 293.15 K Including the Electric Voltage of Power E, Initial Electric Resistance Value of Probe R_s, Test Time τ, Maximal Temperature Rise of the Probe ΔT, Instrument Constant of the Probe I_n, Average Relative Deviation ε, and Linear Correlation Degree R

	E	R_s	τ	ΔT	I_n	ε	
number	V	Ω	s	K	$\Omega\cdot m^{-1}\cdot K^{-1}\cdot s^{-1}$	%	R
1	2.521	54.5	19	0.99	0.0317	0.68	0.999961
2	2.52	54.5	20	0.97	0.0316	0.46	0.999989
3	2.52	54.5	19	0.94	0.0312	−0.89	0.999951
4	2.521	54.5	20	0.95	0.0314	0.00	0.999982
5	2.523	54.5	20	0.87	0.0312	−0.74	0.999987
6	2.524	54.5	19	0.86	0.0316	0.49	0.999964

$$G_r = \rho^2 g \beta x^3 \Delta T/\mu^2 \qquad (5)$$

where ρ is the density of fluid. g is the standard gravitational acceleration. β is the volume expansion coefficient. x is the characteristic dimension. ΔT is the temperature rise. μ is the viscosity of fluid.

The Grashof number would decrease with the decrease in the temperature rise in the same situation.[28] When the temperature rise is below 1 K, the Grashof number is less than $1.43\cdot 10^4$ according to eq 5, which has not yet achieved the laminar flow limit.[27] The error caused by the temperature rise is estimated under 0.4 %.[29,30]

Second, the measurement accuracy of the apparatus was validated by determining known thermal conductivities of glycol (with mass fraction w = 0.99) and ultra-pure water (Millipore, USA, resistivity 18.4 MΩ·cm, electric conductivity 0.055 $\mu S\cdot cm^{-1}$) in the initial state of the sample with temperatures ranging from (278.15 to 323.15) K. The experimental results are listed in Table 2 by comparing to the recommended values.[31,32] The results showed that a good linear agreement between the measured and the recommended thermal conductivity values of the glycol and ultra-pure water at (278.15, 283.15, 293.15, 303.15, 313.15, and 323.15) K. Mean relative error between the recommended and the measured thermal conductivity values were 1.10 % and 0.61 %, respectively. The repeatability was better than 1 %. The results suggested that the experimental system was reliable and experimental results were accurate for the evaluation of thermal conductivity.

Table 2. Relative Deviation ε of Measured Thermal Conductivity Values k Using Equation 4 and Reference Values from References 31 and 32 at Different Temperatures T

	glycol			ultra-pure water		
	$k/\mathrm{W \cdot m^{-1} \cdot K^{-1}}$			$k/\mathrm{W \cdot m^{-1} \cdot K^{-1}}$		
T/K	eq 4	ref 32	ε/%	eq 4	ref 31	ε/%
278.15	0.258	0.254	1.57	0.584	0.572	2.1
283.15	0.257	0.255	0.78	0.583	0.582	0.17
293.15	0.259	0.257	0.78	0.603	0.601	0.33
303.15	0.261	0.258	1.16	0.619	0.617	0.32
313.15	0.261	0.259	0.77	0.634	0.63	0.63
323.15	0.264	0.26	1.54	0.643	0.643	0

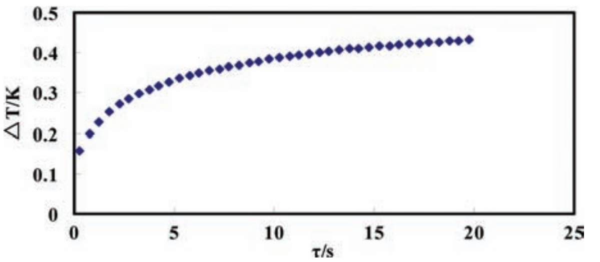

Figure 4. Changes of temperature rise (ΔT) of the probe with heat time (τ).

Third, the thermal conductivities of five concentrations of water—agar gels (w_1 = 0.001, w_2 = 0.005, w_3 = 0.01, w_4 = 0.05, w_5 = 0.1) were determined at six temperatures: (278.15, 283.15, 293.15, 303.15, 313.15, and 323.15) K, respectively. Three replicates of each sample were used for each run, and each run was repeated at least three times (nine replicates). After each run, it took more than 300 s for the whole system to restore a new equilibrium. The thermal conductivity values obtained were the averages of nine measurements under the same conditions. Each sample was equilibrated for 3600 s to a desired temperature, (278.15 to 323.15) K, prior to testing. The power lever was 1.5 $\mathrm{W \cdot m^{-1}}$, and the scanning rate was 2 reading/s with the help of a data acquisition unit in all experiments. The experimental results show that a linear regression line was fitted to the output electric voltage of the electric circuit versus natural logarithm of heated time data between 10 and 20 s by the least-squares method. The nonlinear regressed line for the first 10 s data was not used for the data fitting. The run was rejected if the coefficient of determination (R^2) was less than 0.999.

3. RESULTS AND DISCUSSION

Figures 4 and 5 show two typical courses of the output electric voltage difference of the electric circuit (ΔV) with heated time (τ) and natural logarithm of heated time ($\ln \tau$) during the thermal conductivity measurements, respectively. There is a strong linear dependence of the output electric voltage difference of the electric circuit (ΔV) on the natural logarithm of heated time ($\ln \tau$). The linear correlation degree of $\mathrm{d}(\Delta V)/\mathrm{d}(\ln \tau)$ curve is more than 0.999.

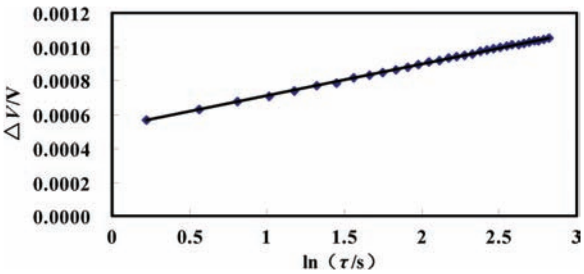

Figure 5. Changes of output voltage difference (ΔV) with the natural logarithm of heat time ($\ln \tau$).

The thermal conductivities of water—agar gels were measured and averaged in three samples with the same temperature and concentration. The thermal conductivity was determined to within about 5 % of the published data for agar.[33−35] The highest observed relative deviation values in triplicate for each measurement value were 0.95 % in one sample. The final experimental data and standard deviation for thermal conductivities of water—agar gels in the initial state of the sample with temperatures ranging from (278.15 to 323.15) K are shown in Table 3. The repeatability of the measured thermal conductivity is within 1 %. Because of the influence of precise concentration preparation of sample, the reproducibility is within 2 %. The average values of thermal conductivity of water—agar gels at five selected concentrations levels ranging from w = 0.001 to w = 0.1 at six selected temperatures levels ranging from (278.15 to 323.15) K were from 0.505 $\mathrm{W \cdot m^{-1} \cdot K^{-1}}$ to 0.653 $\mathrm{W \cdot m^{-1} \cdot K^{-1}}$, with the standard deviation in the range of 0.002 $\mathrm{W \cdot m^{-1} \cdot K^{-1}}$ and 0.011 $\mathrm{W \cdot m^{-1} \cdot K^{-1}}$. The statistical testing shows that concentration and temperature have a significant effect on thermal conductivity at a 99 % confidence level.

The effect of the two most significant variables on the thermal conductivity of water—agar gels is shown in Figures 6 and 7, respectively. There is a strong dependence of thermal conductivity on concentration and temperature. A noticeable decrease of the thermal conductivity of water—agar gels is observed with the increase of concentration in Figure 6. It is observed from Figure 7 that the thermal conductivity of water—agar gels increases linearly with temperature. There is a highly positive linear correlation between temperature and thermal conductivity of water—agar gel.

To obtain a better understanding of the effects of concentration and temperature on the thermal conductivities of water—agar gels, the experimental data are analyzed by the least-squares method. Efforts are made to establish the combined effect of concentration and temperature on the variation of thermal conductivity. The linear relationship of concentration and temperature with the thermal conductivity of the water—agar gels in not more than mass fraction w = 0.1 concentrations under the temperatures from (278.15 to 323.15) K can be represented by the following equation (eq 6):

$$k/\mathrm{W \cdot m^{-1} \cdot K^{-1}} = -8C/\mathrm{kg \cdot kg^{-1}} + 1.5 \cdot 10^{-3} T/\mathrm{K} + 1.63 \cdot 10^{-1} \quad (R^2 = 0.928) \qquad (6)$$

in which T is the temperature of the water—agar gel in K, C is the concentration of the water—agar gel in mass fraction, and k is the thermal conductivity of agar gel in $\mathrm{W \cdot m^{-1} \cdot K^{-1}}$. The negative sign of concentration indicates that thermal conductivity decreases with increasing concentration. The positive sign of temperature indicates that thermal conductivity increases with increasing temperature.

Table 3. Average Values of Measured Thermal Conductivity k and Standard Deviation S_d of Water−Agar Gels at Different Concentrations C and Temperatures T

T	C									
	$w_1 = 0.001$		$w_2 = 0.005$		$w_3 = 0.01$		$w_4 = 0.05$		$w_5 = 0.1$	
	k	S_d	k	S_d	k	S_d	k	S_d	k	S_d
K	$W \cdot m^{-1} \cdot K^{-1}$	$W \cdot m^{-1} \cdot K^{-1}$	$W \cdot m^{-1} \cdot K^{-1}$	$W \cdot m^{-1} \cdot K^{-1}$	$W \cdot m^{-1} \cdot K^{-1}$	$W \cdot m^{-1} \cdot K^{-1}$	$W \cdot m^{-1} \cdot K^{-1}$	$W \cdot m^{-1} \cdot K^{-1}$	$W \cdot m^{-1} \cdot K^{-1}$	$W \cdot m^{-1} \cdot K^{-1}$
278.15	0.585	0.006	0.570	0.005	0.551	0.002	0.526	0.003	0.505	0.004
283.15	0.590	0.005	0.579	0.006	0.558	0.005	0.537	0.004	0.508	0.002
293.15	0.616	0.005	0.588	0.005	0.566	0.004	0.543	0.004	0.523	0.004
303.15	0.629	0.009	0.608	0.011	0.588	0.004	0.564	0.006	0.539	0.005
313.15	0.638	0.009	0.625	0.005	0.616	0.005	0.575	0.004	0.552	0.005
323.15	0.653	0.004	0.633	0.003	0.623	0.004	0.580	0.007	0.563	0.005

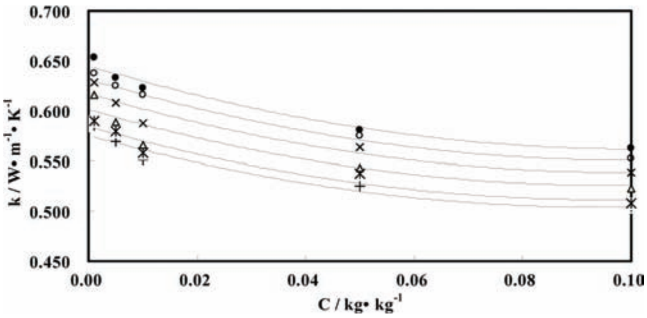

Figure 6. Change of thermal conductivities (k) of water−agar gel with concentration at different temperatures: +, T = 278.15 K; ∗, T = 283.15 K; △, T = 293.15 K; ×, T = 303.15 K; ○, T = 313.15 K; ●, T = 323.15 K.

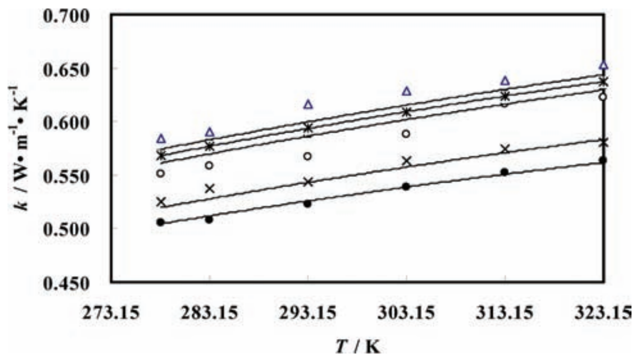

Figure 7. Change of thermal conductivities of water−agar gel with temperature at different concentrations: △, w = 0.001; ∗, w = 0.005; ○, w = 0.01; ×, w = 0.05; ●, w = 0.1.

Table 4. Relative Deviation ε of Predicted Thermal Conductivity Values k_1 Using Equation 6 and k_2 Using Equation 7 and Reference Values from Reference 31 of Pure Water at Different Temperatures T

T	ref 31	k_1	ε	k_2	ε
K	$W \cdot m^{-1} \cdot K^{-1}$	$W \cdot m^{-1} \cdot K^{-1}$	%	$W \cdot m^{-1} \cdot K^{-1}$	%
278.15	0.572	0.580	1.44	0.576	0.64
283.15	0.582	0.588	0.98	0.584	0.42
293.15	0.601	0.603	0.29	0.601	0.04
303.15	0.617	0.618	0.12	0.617	−0.01
313.15	0.630	0.633	0.43	0.632	0.26
323.15	0.643	0.648	0.73	0.645	0.36

Considering the nonlinear relationship between thermal conductivity and concentration at low concentrations of water−agar gels as shown in Figure 6, an improved model of thermal conductivity as a function of concentration and temperature are developed by the quadratic equation (eq 7):

$$k/\mathrm{W \cdot m^{-1} \cdot K^{-1}} = -7.58C/\mathrm{kg \cdot kg^{-1}} + 4.68 \cdot 10^{-3}T/\mathrm{K} + 8.14 \cdot 10^{-1}C^2 - 5.21 \cdot 10^{-6}T^2 - 2.76 \cdot 10^{-2}CT - 3.23 \cdot 10^{-1} \quad (R^2 = 0.964) \tag{7}$$

for 278.15 K $\leq T \leq$ 323.15 K and $0 \leq C \leq (w = 0.1)$ where k is the thermal conductivity of agar gel, $W \cdot m^{-1} \cdot K^{-1}$; C is the concentration of the water−agar gel, mass fraction; and T is the temperature of the water−agar gel, K. The regressive combined model performed well in reflecting the relationship between thermal conductivity and concentration and the temperature of the water−agar gel according to the experimental data. The mean relative deviation value between the calculated and the measured thermal conductivity is 0.92 %. The fitted functions have $R^2 > 0.96$, and the residual analysis shows the adequacy of the model.

In the limit $C \to 0$ eqs 6 and 7 represent the pure water characteristics. The comparison of recommended and predicted thermal conductivity values of pure water by eqs 6 and 7 are listed in Table 4. It is observed that eq 6 results in an average deviation of 0.67 % and a maximum deviation of 1.44 % from the recommended values for the thermal conductivity of pure water,[31] while eq 7 results in an average deviation of 0.29 % and a maximum deviation of 0.64 % from the recommended values for the thermal conductivity of pure water.[31] So, through the models the thermal conductivity of agar gels in not more than mass fraction $w = 0.1$ concentrations under temperatures from (278.15 to 323.15) K could be predicted perfectly.

4. CONCLUSIONS

Data on thermal conductivity of water−agar gels were generated using a thermal conductivity probe apparatus. The advantages of this method are rapidity, simplicity, accuracy, and a small sample requirement.The experimental setup worked satisfactorily in terms of reliable and accurate determination of the thermal conductivity. It was shown that the thermal conductivity of water—agar gels decreased with an increase in concentration between 0 and mass fraction $w = 0.1$, while it increased with an increase in temperature from (278.15 to 323.15) K. The regressive combined model for the thermal conductivity of water—agar gels as a function of concentration and temperature was obtained and could be used as predictive equations for practical purposes.

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