Original article

Thermal conductivity of South African sauces in a shear flow field

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Summary The objectives of this work were to determine the thermal conductivity of sauces obtained from a South African supermarket in a shear flow field and to develop theoretical models to predict their thermal conductivities under these conditions. A coaxial cylinder apparatus with a rotating outer cylinder was used to measure the thermal conductivity. The thermal conductivities of the substances were determined as a function of temperature (20–50 °C) and shear rates (0–1 000 s^{-1}). The fluids were observed to be shear thinning and their thermal conductivity values increased with both temperature and shearing rate. The thermal conductivity was also observed to increase asymptotically with time of shear to a constant value. Temperature and shear rate-dependent models, which correlate the observed thermal conductivity data fairly well, were proposed and tested for the materials.

Keywords Sauces, shear flow field, shear rates, temperature, thermal conductivity.

Introduction

Thermophysical and transport properties of food are important in engineering analysis and design of production systems and product quality evaluation. The transfer of heat to and from product is one transport property that is of significant interest in product quality control during processing of most food substances. The successful management of heat transfer processes depends on the availability of thermophysical data such as thermal conductivity. The thermal properties of food substances are used in quantitative analysis for various thermal processes, such as heating, cooking, sterilisation, drying and extrusion cooking (Drouzas & Saravacos, 1988). The processing of sauces involves some of these thermal processes.

Non-Newtonian liquid and semi-solid food substances have varying viscosity under a shearing environment. It is therefore reasonable to suggest that there will be changes in the thermal conductivities when these substances are subjected to a shearing field. There is significant information on the effect of temperature, moisture content and composition on thermal conductivity of food substances in literature (Sweat & Parmelee, 1978; Renaud *et al.*, 1992; Wang & Brennan, 1992; Reddy & Datta, 1994; Rahman, 1995; Tavman & Tavman, 1999). However, not much data are available on the effect of shear stress–shear rate on the thermal conductivity of foods. This is because available data (values) for most liquid foods have been measured under static conditions. If a shear rate effect exists on the thermal conductivity such as is the case with apparent viscosity, then measurements must be made over a range of shear rates when the fluid is in motion with respect to a static boundary.

The effects of shear rate on thermal conductivity of viscoelastic polymer fluids have been fairly reported in literature. Cocci & Picot (1973) reported that the thermal conductivity of Dow 200 fluids increases with increases in shear rate in the region of ($0 \le \dot{\gamma} \le 300s^{-1}$). In addition, Chitrangad & Picot (1981) and Picot *et al.* (1982) reported that at low shear rates of ($\dot{\gamma} \le 200s^{-1}$), the thermal conductivity of DOW 200 fluids and polyethylene melts increased with increasing shear rate, reached a maximum point and then decreased with increasing shear rate ($200 \le \dot{\gamma} \le 400s^{-1}$). Lee & Irvine (1997) observed for non-Newtonian fluids such as aqueous CMC and Separan solutions, that there were as much as 70 and 50% increases in thermal conductivities for CMC and Separan, respectively, depending on the shear rate, polymer concentration and temperature. Their results showed a linear relationship between shear rate and thermal conductivity. Shin & Lee (2000) carried out thermal conductivity measurements of polymer suspensions under rotating couette flow conditions with a varying rotational speed of the outer cylinder. The

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thermal conductivity of the test suspensions in shear flow increased with shear rate and displayed asymptotic plateau values at high shear rates. Furthermore, the shear rate-dependent conductivity was strongly affected by both particle size and volume concentration in shear flow field. Qi Lin *et al.* (2003) and Ikhu-Omoregbe & Chen (2005) used similar flow conditions to measure the thermal conductivity of fruit juices and sauces obtained from a supermarket in Auckland, New Zealand, respectively, observed trends as those for polymer materials. Thermal conductivity increases linearly as shear rate increases.

The objectives of this investigation were to: (1) determine the thermal conductivity of sauces of different consistency and viscosity in rotating couette flow conditions at different temperatures and shear rate; (2) investigate effect of time of shear on thermal conductivity and (3) propose empirical models to demonstrate the effect of shear rate on thermal conductivity.

Theoretical background

Models for thermal conductivity of food substances

A number of models have been reported in literature (Rahman, 1995; Hsu & Heldman, 2004) to predict the thermal conductivity of two-phase systems. These models were based on the geometry of the components in the two phases. Furthermore, some have been extended to predict multi-component systems. Maroulis *et al.* (1991) applied some of these models to predict the thermal conductivity of gelatinised starch at varying temperature and composition. The models proposed by Shin & Lee (2000) are not applicable here as theirs were for suspensions made up of particles whose diameters were specified.

Two types of thermal conductivity prediction models can be identified in literature (Rahman, 1995; Hsu & Heldman, 2004). The first relates temperature to thermal conductivity, whereas the second, structural models relate composition to thermal conductivity. These reported models, however, are applicable to non-shearing cases. The effects of share rates on thermal conductivity can be predicted using empirical models based on experimental results obtained.

The thermal conductivities of most of the substances are known to be the functions of temperature (Rahman, 1995) and are of the form:

$$k = a + bT + cT^2 \tag{1}$$

where *a, b,* and *c* are constants and *T* is temperature in degree Centigrade. In this paper, an empirical models of the form

$$k = a + bT + cT^2 + f(\dot{\gamma}) \tag{2}$$

will be proposed, where $\dot{\gamma}$ is shear rate.

In order to estimate the accuracy of the proposed empirical models, the correlation coefficients between the thermal conductivity values predicted by the models and the experimental values will be expressed as standard errors and standard percentage errors as described by Choi (1985) as:

$$\text{Standard error (SE)} = \sqrt{\frac{\sum (X_{\text{mod}} - X_{\text{exp}})^2}{N}} \tag{3}$$

where X_{mod} is the predicted value of thermal conductivity, X_{exp} is the experimental value of thermal conductivity and N the number of samples.

Standard percentage (%), (SP) error is defined as the ratio of standard error to the average experimental value expressed as a percentage.

$$\text{SP} = \frac{SE}{\sum X_{\text{exp}}/N} \times 100 \tag{4}$$

Materials and methods

Materials

Three commercial fruit sauces were obtained from a supermarket in Durban, South Africa. The compositions of the sauces as obtained from the labels on the containers are as follows:

1. Mustard sauce (Tiger Food Brands Ltd, Sandton, Johannesburg, South Africa): Water, modified starch, vinegar, mustard, salt, spices; preservatives: potassium sorbate, sodium benzoate, colourants and stabilizers. The solid content was found to be 36.22%, using an air-drying oven and a specific gravity of 1.23 was obtained for the sauce.
2. Veri-peri sauce (ALL-JOY Foods Ltd, Crown Mines, Johannesburg, South Africa): Water, sunflower oil, vinegar, acidifying agent (E260), lemon juice, salt, chillies, mustard powder, herbs, species, thickening agent (E415); Preservatives: Sodium Benzoate (E211), potassium sorbate (E202), SO_2 (220). The solid content was found to be 22.60% and the specific gravity of the sauce was 1.03
3. Garlic chilli sauce (S.A.D. Holdings Ltd, Wellington, South Africa): Tomatoes, saltanas, vinegar, sugar, garlic, onions, chillies, corn starch, salt, spices; Preservatives: SO_2, sodium benzoate. The solid content was found to be 25.71% and its specific gravity was 1.2.

Thermal conductivity measurement

The equipment and procedure adopted in this work are similar to those described in detail by Qi Lin *et al.* (2003) and Ikhu-Omoregbe & Chen (2005). The equipment consists of two concentric cylinders, in which the inner cylinder is stationary and the outer one can be rotated. Both cylinders are made of materials such as copper with high thermal conductivities, so that the temperature drop across each is negligible compared with that across the test fluid. The test fluid is contained in the annular space between the two cylinders. One of the advantages of couette method is the non-existence of Taylor vortices especially if the gap is narrow (Steffe, 1996; Mezger, 2006) and the annular space of r_o/r_i of 1.074 satisfies the elementary requirement of ISO 3219 for narrow gap. The rest of the system consists of a constant temperature bath, a main heater, a guard heater, thermocouple to measure the inner cylinder and bath temperatures, and Pico data acquisition system. To commence the run, the speed of rotation is set and the system allowed to reach a steady state which takes about 10–15 min. Then the temperatures, voltage and current are recorded every 10 s for 10 min through the data acquisition system; the speed of rotation of the outer cylinder was also recorded. The speed was varied as to give a shear rate of between 0 and 1 000 s^{-1}. The mean value of these readings at a set shear rate was taken as one experimental point. All thermal conductivity measurements were in triplicates and showed a variation of ± 5%. The effect of time of shear on thermal conductivity was examined at shear rates of 151, 403 and 860 s^{-1} and at 30 °C temperature.

If we assume that Fourier's law of conduction is applicable, the shear rate variation across the gap (annulus) is negligible, the thermal conductivity of the liquid (test fluid) in the narrow gap is considered to be independent of temperature; at steady state, the following equation can be written for thermal conductivity, k:

$$k = \frac{Q \ln(d_o/d_i)}{2\pi l \Delta T} \tag{5}$$

where Q = heat input calculated from current and voltage measurements [Q = current (A) × voltage (V)], d_o = inner diameter of outer rotating cylinder, d_i = diameter of inner stationary cylinder, l = length of the testing section, ΔT = temperature difference across the testing fluid.

For a narrow gap, ≈1.5 mm between the cylinders, regardless of fluid type, the velocity profile can be assumed to be linear over this distance. The shear rate ($\dot{\gamma}$) within the gap can thus be considered to be uniform and can be calculated as:

$$\dot{\gamma} = \frac{\pi n(d_o + d_i)}{60(d_o - d_i)} \tag{6}$$

where n is rotational speed, (r.p.m.); d_o and d_i are as defined above.

The rheological measurements (shear stress – shear rate and viscosity) of the three fruit sauces were made using an Anton Paar MC51 rheometer (Anton Paar GmbH, Ostfilden, Germany). The measurement system used for this work consists of a measuring cup of radius 21 mm and bob of radius 19.5 mm. The gap length was 60 mm and cone angle of the measuring bob was 120°. A constant temperature circulator (Viscotherm VT2, Anton Paar GmbH) with a temperature range of −20 and 180 °C (± 0.1 °C) was used to control measurement temperature. The rheological measurements were at various shear rates from 1 to 1 000 s^{-1} and at a temperature of 30 °C. The rheological measurements were made to demonstrate that the fluids used in this work are non-Newtonian fluids. However, the effect of time of shear on viscosity and shear stress was measured at a constant shear rate of 151 s^{-1} and 30 °C temperature to show if there is any qualitative relationship between viscosity and thermal conductivity trends.

Results and discussion

Prior to measuring the thermal conductivities of the commercial sauces, a series of runs were made using deionised water in order to ascertain the following:

1 That the apparatus could be used to measure thermal conductivity of water under different shear rates.
2 To establish to what extent of shear rate a secondary flow could start to affect the measurement. Usually, as viscosity of the fluid is decreased (say by raising the temperature), the secondary flow would start at a lower shear rate).

Figure 1 shows the thermal conductivity of deionised water at 20, 30, 40 and 50 °C. Analysis of the results showed that a critical shear rate of 400 s^{-1} was obtained for water using this system. From Fig. 1, it can be observed that beyond this shear rate value that the thermal conductivity starts to increase. The results show

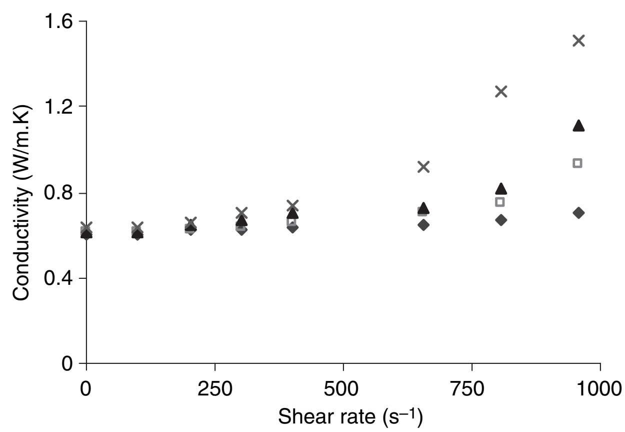

Figure 1 Thermal conductivity of deionised water at different temperature. 20 °C (♦), 30 °C (■), 40 °C (▲), 50 °C (×).

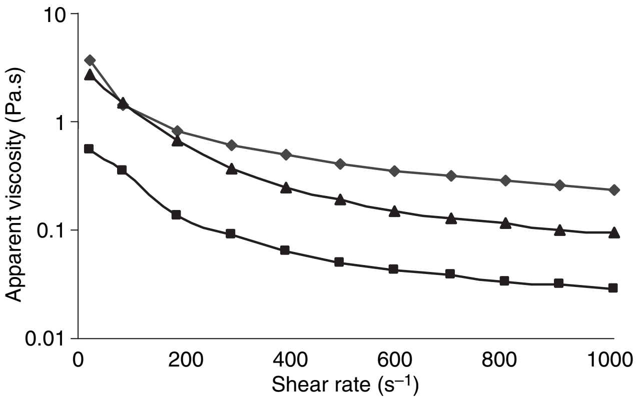

Figure 2 Viscosity – shear rate curves for the three materials at 30 °C. Mustard sauce (♦), veri-peri sauce (■), garlic sauce (▲).

agreement with literature (Qi Lin *et al.*, 2003) of constant thermal conductivity values up till a shear rate of > 500 s^{-1}, after which it starts to increase. It is believed that beyond this critical shear rate that flow instabilities and secondary (convective) flow because of occurrence of turbulence in the gap start to have effect. This has the effect of increasing the observed thermal conductivity as convective heat transfer through the annulus becomes significant. This is because of the fact that as the rotational speed of the outer cylinder increases (shear rate increases) the velocity gradient across the annulus will no longer remain constant as a result of the convective flow.

Figure 2 shows that the fluids are non-Newtonian, apparent viscosity decreases with increasing shear rate and hence are shear thinning fluids. The results indicate that the mustard sauce is the most viscous of the three materials. The apparent viscosity of the mustard sauce varied from 3.73 Pa s at low shear rate to 0.24 Pa s at high shear at a temperature of 30 °C. Similarly the values for the garlic sauce varied from 2.71 to 0.094 Pa s at low and high shear rates, respectively, while that of the veri-peri sauce varied between 0.555 and 0.029 Pa s at high and low shear rates, respectively, at the temperature of 30 °C. Table 1 shows the values of consistency index, *K* and flow behaviour index, *n* for the three materials obtained by applying the power law models to the obtained data. The results show a correlation coefficient, R^2 > 95% showing good fit. The values are compared with those obtained by Alvarez *et al.* (2004) for mustard and ketchup sauces at 30 °C. The results show that theses values are comparable to those obtained by the above authors. The slight differences could be attributed to the slight differences in solids contents in the sauces.

Figures 3–5 show the values of thermal conductivity with shear rate for the mustard sauce, veri-peri sauce and garlic sauce, respectively, at the different temperatures of 20, 30, 40 and 50 °C. The results indicate that for a given fluid and shear rate the thermal conductivity values increase with temperature. Similarly, thermal conductivity for all the fluids increases with increasing shear rate for a given temperature and fluid. It can be observed that the thermal conductivity values for the mustard sauce varied from 0.24 W m^{-1} K^{-1} at zero shear rate and 20 °C temperature, to 1.00 W m^{-1} K^{-1} at a shear rate of 960 s^{-1} and at 50 °C temperature. Similar values for the veri-peri sauce varied from 0.44 W m^{-1} K^{-1} at zero shear rate and 20 °C to 1.22 W m^{-1} K^{-1} at a temperature of 50 °C and shear rate of 960 s^{-1}. In addition, the conductivity values for the garlic sauce varied from 0.25 W m^{-1} K^{-1} at zero shear rates and 20 °C temperature to 1.13 W m^{-1} K^{-1} at 950 s^{-1} and 50 °C. The results tend to suggest that the more viscous material has the lowest

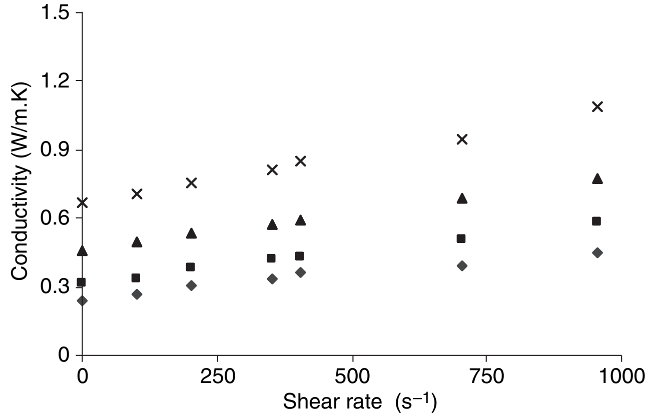

Figure 3 Thermal conductivity vs. shear rate at different temperatures for mustard sauce. 20 °C (♦), 30 °C (■), 40 °C (▲), 50 °C (×).

Table 1 Values of the power law model for the sauces

Material (sauce)	Solid content (%)	Flow behaviour index (*n*)	Consistency coefficient (*K*)	R^2
Mustard	36.22	0.284	31.88	0.999
Garlic	25.71	0.172	141.11	0.958
Veri-peri	22.60	0.158	10.18	0.971
Mustard (Alvarez *et al.*, 2004)	44.8	0.312	12.005	
Ketchup (Alvarez *et al.*, 2004)	33.0	0.359	14.180	

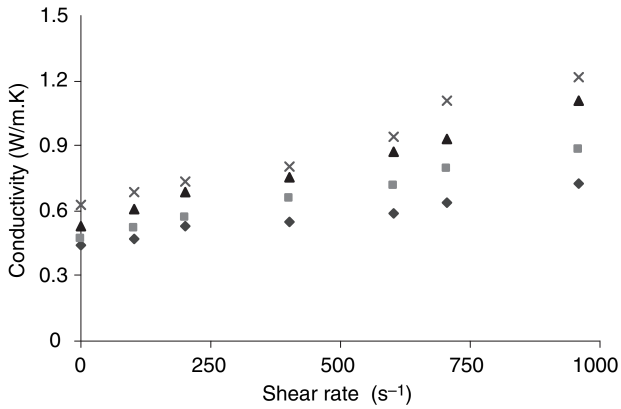

Figure 4 Thermal conductivity vs. shear rate at different temperatures for veri-peri sauce. 20 °C (♦), 30 °C (■), 40 °C (▲), 50 °C (×).

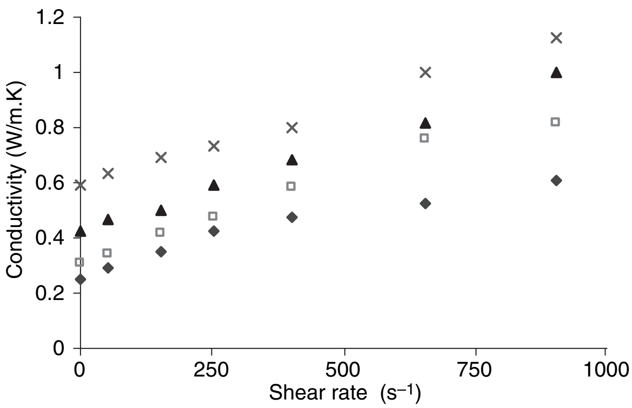

Figure 5 Thermal conductivity vs. shear rate at different temperatures for garlic sauce. 20 °C (♦), 30 °C (■), 40 °C (▲), 50 °C (×).

thermal conductivity. This is not very conclusive as the constituents of the substances used for this work are not the same and in composition.

Based on a critical Reynolds number of 1 000 after which instabilities and turbulence in the gap start to significantly affect the results, critical shear rates were determined for the three fluids and the system used. The critical shear rates obtained were 1 090 s^{-1} for the veri-peri sauce, 3 020 s^{-1} for the garlic sauce and 7 500 s^{-1} for the more viscous mustard sauce. As the respective critical shear rates were not exceeded for each material, it is expected that instabilities because of turbulence would not have had any significant effect on the results. Furthermore, the maximum Reynolds number experienced during the experiments was 890 for the least viscous material.

Correlation analysis suggests that there is strong linear correlation between thermal conductivity and shear rate ($R^2 > 0.95$ for the three liquids) on one hand and between thermal conductivity and temperature ($R^2 > 0.95$ for the three liquids). The analysis of the results also show that thermal conductivity for all the fluids increases significantly with increasing shear rate for a given temperature. These observations are in agreement with literature (Cocci & Picot, 1973; Lee & Irvine, 1997; Qi Lin *et al.*, 2003) that thermal conductivity of non-Newtonian fluids increase with shear rate. A number of reasons have been given for the effect of shear rate on thermal conductivity.

Cocci & Picot (1973) explained it to be as a result of either preferred orientation or cluster rotation of the polymer molecules. Shin & Lee (2000) suggested that the shear rate-dependent conductivity was strongly affected by both particle size and volume concentration in shear flow field. Qi Lin *et al.* (2003) suggested that the higher thermal conductivity at higher shear rates is because of the fluid structure becoming more aligned along the streamlines and hence becoming ordered. This was apparent because one of the fluids (mango concentrate) contained some fibres. Ikhu-Omoregbe & Chen (2005) suggested that the effect of shear stress on conductivity could be because of a realignment of the polymer structure as a result of shearing forces. It is also possible that the polymer structure could have become 'stretched' resulting in increased rate of heat transfer across the material.

A common phenomenon when a material is continuously being sheared is the occurrence of viscous dissipation resulting in local heating and temperature distribution and consequently affecting the thermal properties obtained. The contribution of viscous energy can be determined by estimating the Brinkman number and viscous heat production rate. Analysis of the system and results gave a Brinkman number less than 0.01 and viscous heat contribution of 3.76% for the most viscous material and highest shear rate of 1 000 s^{-1}. The implication of this is that viscous dissipation did not significantly affect the result obtained.

Figures 6–8 show that thermal conductivities for the three sauces increase asymptotically with the time of shear to a near constant value. The thermal conductivity increases from zero time until about between 10 and 15 mins. This is a period of unsteady state with reference to thermal conductivity when the shearing action is commenced. The increase in thermal conductivity values ranged from 10% at low shearing rate to as high as 30% for high shearing rate. However, this observed variation is more pronounced with the more viscous mustard sauce. These increases could not be attributed solely to the effect of viscous dissipation as its contribution energy flow was found to be less than 4.0%.

The effect of time on viscosity at constant shear rate is illustrated in Fig. 9 for a shear rate of 151 s^{-1} and 30 °C temperature. The results show that the apparent viscosity

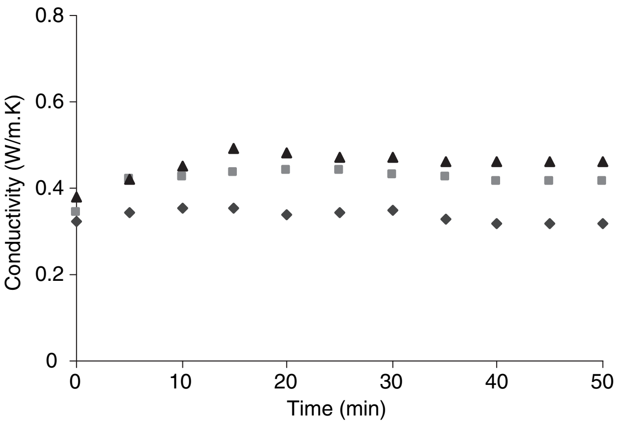

Figure 6 Thermal conductivity vs. time of shear for mustard sauce at different shear rates. 151 s^{-1} (♦), 403 s^{-1} (■), 860 s^{-1} (▲).

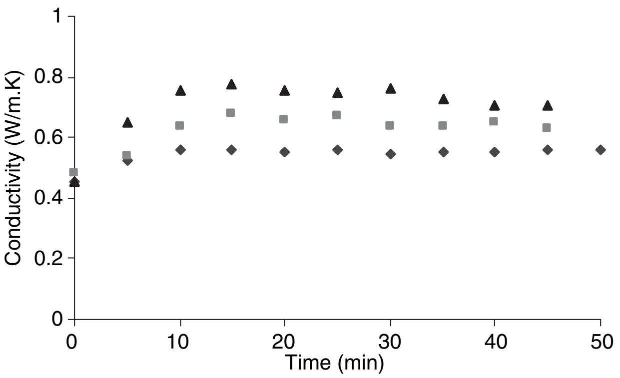

Figure 7 Thermal conductivity vs. time of shear for veri-peri sauce at different shear rates. 151 s^{-1} (♦), 403 s^{-1} (■), 860 s^{-1} (▲).

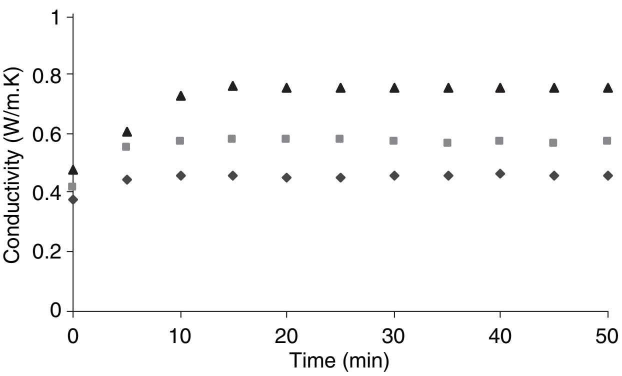

Figure 8 Thermal conductivity vs. time of shear for garlic sauce at different shear rates. 151 s^{-1} (♦), 403 s^{-1} (■), 860 s^{-1} (▲).

decreases with time of shear within the first 10 mins and remains rather constant thereafter. It is interesting to observe that in the region in which the apparent

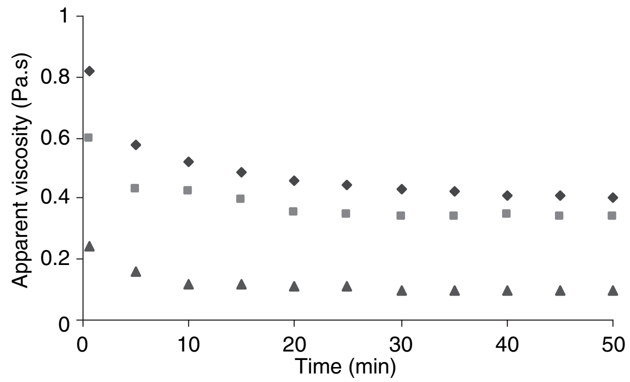

Figure 9 Effect of time of shear on viscosity at constant shear rate of 151 s^{-1} and 30 °C temperature. Mustard sauce (♦), garlic sauce (■), veri-peri sauce (▲).

viscosity is decreasing, the thermal conductivity was observed to be increasing. This suggests that as the bond forces are being stretched (sheared), the ability of the materials to conduct heat is enhanced agreeing with the observation of Ikhu-Omoregbe & Chen (2005). The effect of time of shear stress followed the same pattern as the viscosity–time curves: shear stress decreases initially with time of shear and then remains rather constant after about 10 min. Similar shear decay curves with time were obtained for mustard suspensions (Choi & Yoo, 2004), chickpea flour dispersion (Ravi & Bhattacharya, 2006) and mango pulp (Bhattacharya, 1999). However, the effect was less pronounced for the least non-Newtonian fluid, veri-peri sauce.

Thermal conductivity models

A number of models have been proposed in literature (Rahman, 1995; Hsu & Heldman, 2004) to predict the thermal conductivity of two-phase systems. These models were based on the geometry and composition of the components in the two phases. Furthermore, some have been extended to predict multi-component systems in a non-shearing field. In this paper, empirical models are proposed to account for the effect of shear rate/shear stress on the thermal conductivity of a food material. The thermal conductivity of most materials is known to be a function of temperature and is of the form of eqn 1.

From Figs 3–5, and from the correlation analysis, the relationship between thermal conductivity and shear rate can be assumed to be linear. Hence, it is possible to deduce empirical models of the form of eqn 2, which incorporate the effects of the rates of shear to correlate the data. From the results, the following three model forms can be deduced to relate conductivity, temperature and shear rate for these materials.

1. Mustard sauce

A. $k = 0.277 - 8.2T \times 10^{-3} + 3.2T^2 \times 10^{-4} + s\dot{\gamma}$

B. $k = 0.277 - 8.2T \times 10^{-3} + 3.2T^2 \times 10^{-4} + \dot{\gamma}T^{-2.37}$

C. $k = 0.277 - 8.2T \times 10^{-3} + 3.2T^2 \times 10^{-4} + 0.849\dot{\gamma}T \times 10^{-5}$

2. Veri-peri sauce

A. $k = 0.494 - 6.05 \times T^{-3} + 1.75T^2 \times 10^{-4} + s\dot{\gamma}$

B. $k = 0.494 - 6.05 \times T^{-3} + 1.75T^2 \times 10^{-4} + \dot{\gamma}T^{-2.25}$

C. $k = 0.494 - 6.05 \times T^{-3} + 1.75T^2 \times 10^{-4} + 0.129\,\dot{\gamma}\,T \times 10^{-4}$

3. Garlic sauce

A. $k = 0.287 - 7.43T \times 10^{-2} + 2.7T^2 \times 10^{-4} + s\dot{\gamma}$

B. $k = 0.287 - 7.43T \times 10^{-2} + 2.7T^2 \times 10^{-4} + \dot{\gamma}T^{-2.51}$

C. $k = 0.287 - 7.43T \times 10^{-2} + 2.7T^2 \times 10^{-4} + 0.156\dot{\gamma}T \times 10^{-5}$

where in the above equations, k = thermal conductivity, W m^{-1} K^{-1}, s = slope of the conductivity/shear rate curve (regressed), $\dot{\gamma}$ = shearrate, s^{-1}, T = temperature, °C.

Figures 10–12 show the thermal conductivity values obtained using the empirical shear rate-dependent models for mustard sauce at 40 °C, veri-peri sauce at 50 °C and garlic sauce at 20 °C, respectively. From the results, it can be observed that model A best correlates the data followed by model C, and model B did not fairly correlate the data. The models correlate the data better at low shear rates than at the higher shear rates. The performance of these models suggests that the relationship between thermal conductivity and shear rate is rather linear and not exponential. This justifies the earlier assumption of a linear relationship between thermal conductivity and shear rate.

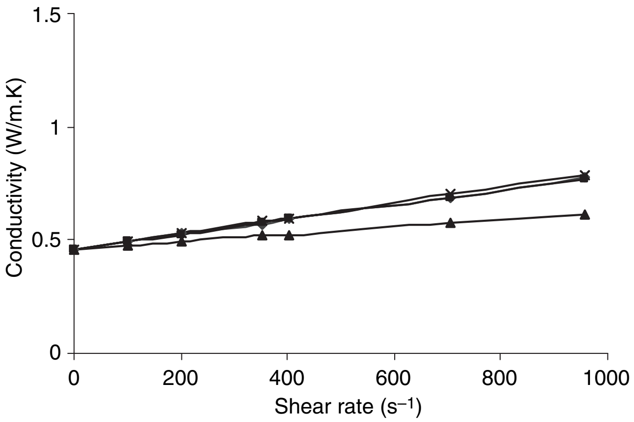

Figure 10 Predicted thermal conductivity values for mustard sauce at 40 °C. Experimental values (♦), model A values (■), model B values (▲), model C values (×).

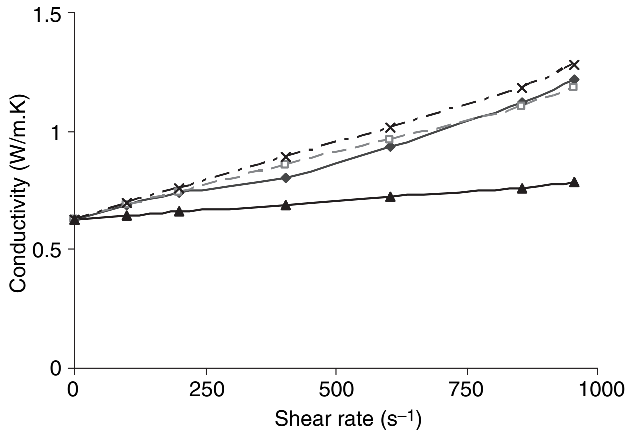

Figure 11 Predicted thermal conductivity values for veri-peri sauce at 50 °C. Experimental values (♦), model A values (■), model B values (▲), model C values (×).

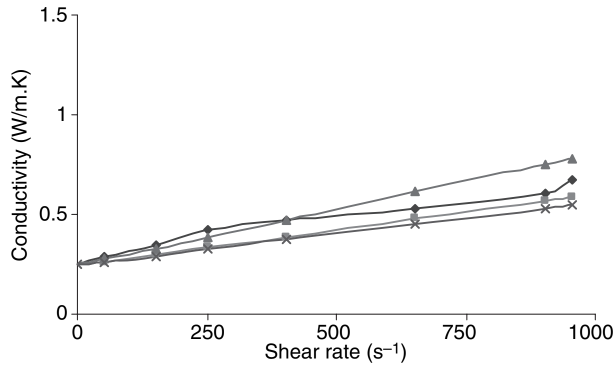

Figure 12 Predicted thermal conductivity values for garlic sauce at 20 °C. Experimental values (♦), model A values (■), model B values (▲), model C values (×).

Table 2 shows the standard errors and standard % error between experimental and predicted values for thermal conductivity for the three materials. It is clear from these results that model A gave the lowest standard error for all temperatures and materials. For example, model A gave a standard error of 0.0043 and standard % error of 7.25 at 20 °C for the mustard sauce. Model B gave the highest standard error for all temperatures and materials. For example, this model gave a standard error estimate of 0.82 and standard % error of 101.27 at 20 °C for the mustard sauce. Thus the predicted values for thermal conductivity values

Table 2 Comparison of standard errors and standard percentage errors (%) between experimental thermal conductivities and thermal conductivities predicted by the models

	Temp. °C	Standard error A	Standard error B	Standard error C	Standard % error A	Standard % error B	Standard % error C
Mustard sauce	20	0.004	0.823	0.007	7.25	101.27	9.09
	30	0.007	0.023	0.010	1.71	5.49	2.45
	40	0.005	0.083	0.008	0.83	14.11	1.36
	50	0.015	0.138	0.021	1.84	16.99	2.62
Veri-peri sauce	20	0.013	0.495	0.016	2.34	87.61	2.792
	30	0.018	0.033	0.025	2.70	5.06	3.77
	40	0.042	0.162	0.033	5.50	20.99	4.25
	50	0.025	0.236	0.056	2.83	26.94	6.42
Garlic sauce	20	0.043	0.101	0.071	9.49	22.36	15.75
	30	0.028	0.252	0.094	4.77	42.57	15.78
	40	0.035	0.319	0.012	4.88	45.22	1.71
	50	0.051	0.316	0.125	6.02	36.98	14.66

were in closer agreement with experimental values using model A for the three materials studied in this work. The performance of model A again suggests a rather linear relation between shear rate and thermal conductivity as this model is based on a linear relationship between thermal conductivity and shear rate.

It can also be observed that the models predict more closely the thermal conductivities of the mustard sauce and worst for the garlic sauce. Again model A gave a better performance for mustard sauce and least for the garlic sauce. This is true for all temperatures and shear rates. The thermal conductivity of these materials could not be related to their components as this could not be accurately ascertained because they are not only complex materials but the labels were not contents specific as well. It should be stated that as the models are empirical, the specific model parameters may not be applicable to other materials, but its form could be suitable for predicting the thermal conductivity for similar food materials.

Conclusion

The thermal conductivities of three commercial sauces have been measured in a shearing environment using a coaxial cylinder apparatus with a rotating outer cylinder. The three materials were found to be shear thinning and their thermal conductivity values increased rather linearly with increasing rate of shear. The thermal conductivities of the materials were also observed to increase asymptotically to a constant value with time of shear. This effect was more pronounced with the more viscous (mustard sauce) fluid. It is interesting to observe that in the region where the apparent viscosity was decreasing, the thermal conductivity was observed to be increasing with time of shear. The results were not significantly affected by viscous dissipation contribution. Three temperature and shear rate-dependent empirical models for the conductivities have been proposed and tested. The models were based on the assumption that the relationship between thermal conductivity and shear rate is linear. Two of these models were found to fit the data fairly well with correlation coefficient, $R^2 > 0.95$ for the three materials and at the temperatures investigated.

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