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Experimental Analysis of Thermal Conductivity of Carboxymethylcellulose Sodium Salt Aqueous Solutions in Coaxial Cylinder System

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Abstract

In the present paper the results of the experimental studies directed on the correlation of non-Newtonian fluids rheological behavior and thermal conductivity taking into account the shear rate effect, have been presented. The liquids tested were water, glycerol and petrol, as Newtonian fluids, and carboxymethylcellulose sodium salt (of the molecular mass $M = 250{,}000$ and $M = 700{,}000$ [kg/kmol], Aldrich Company) aqueous solutions as non-Newtonian fluids (of the polyelectrolyte concentration in solutions ranged from 1000 to 5000 w.ppm). Experiments were performed at temperatures changed in the range from 299K to 315K. The shear rate range studied was $0 \leq \gamma \leq 750$ [s^{-1}]. It was confirmed that the thermal conductivity λ of Newtonian liquids at $T = \text{const}$ is independent of shear rate. For the non-Newtonian aqueous solutions studied the relation of $\lambda = f(T, \gamma)$ is evident and should be taken into account in all design practices. The thermal conductivity increases linearly with shear rate increase. The maximal effect was observed at temperature 315K for the carboxymethylcellulose sodium salt solution of the concentration of 1000 w.ppm and molecular mass $M = 700{,}000$ [kg/kmol].

Keywords: heat transfer, power-law fluids, shear effect, thermal conductivity coefficient of non-Newtonian fluids

1. Introduction

Many important industrial fluids, which are non-Newtonian or rheologically complex in their flow characteristics are often used in the chemical processes and food industries, as well as in many other practical applications. As no other literature data being available the previous papers on heat transfer coefficient in non-Newtonian fluids heat transfer in various constructional solutions were based on the thermal conductivity of the clear solvent. It was a very rough approximation that existed long. Of significance in the experimental investigations of non-Newtonian fluid thermal conductivities is the fact that many of the measurements were made under static conditions [Bellet *et al.*, 1975, Lee *et al.*, 1981]. The measurements should be made over a range of shear rates when the fluid is in motion. Only few previous measurements (Fig. 1), investigating the effect of shear rate on the thermal conductivity of viscoelastic polymer fluids, have been found (Cocci and Picot, 1973, Chitranged and Picot, 1981, Picot et al., 1982, Wallace et al., 1985, Loulou et al., 1992, Chaliche et al., 1994, Lee and Irvine, 1997, Kostic and Tong, 1999, Shin and Lee, 2000, Lin et al., 2003).

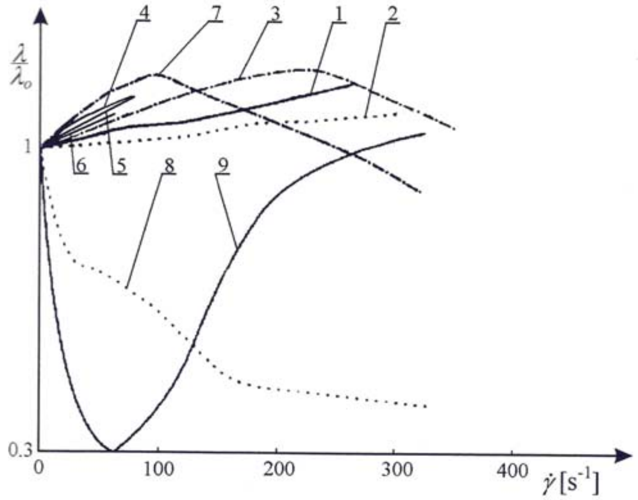


Fig. 1. Comparison of the shear rate dependent thermal conductivity of non-Newtonian fluids resulted from literature (Lee and Irvine, 1997):
1 – Cocci and Picot (1973), Dow 200, T = 288,7K; 2 – Cocci and Picot (1973), Dow 200, T = 327K;
3 – Chitrangad and Picot (1981), Dow 200, T = 298K; 4 – Chaliche *et al.* (1994), Na-CMC, 8%, T = 298K;
5 – Loulou *et a*l. (1992), Carbopol, 0.1%, T = 298K; 6 – Loulou *et al.* (1992), Carbopol, 0.2%, T = 298K;
7 – Picot *et al.* (1982), polyethylene melt, T = 423K; 8 – Wallace *et al.* (1985), low molecular weight polyethylene melt, T = 433K; 9 – Wallace *et al.* (1985), high molecular weight polyethylene melt, T = 433K

Cocci and Picot (1973) showed that the thermal conductivity of Dow 200 fluids increased with increasing shear rate over the shear rate region $0 \leq \gamma \leq 300$ [s^{-1}]. Chitrangad and Picot (1981) and Picot et al. (1982) reported that, for low shear rates ($\gamma \leq 200$ [s^{-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 ($0 \leq \gamma \leq 400$ [s^{-1}]). Cocci and Picot (1973) also found the rate of thermal conductivity increase for Dow 200 fluids decreased with increasing temperature. Picot *et al.* (1982) reported that the thermal conductivities of polymeric materials increase with molecular weight. In contrast, Wallace *et al.* (1985) observed that, depending on polymer molecular weight, there existed either an increase of thermal conductivity of polyethylene melts with shear rate or a decrease of thermal conductivity with shear rate over the shear rate region ($0 \leq \gamma \leq 400$ [s^{-1}]). The low molecular weight polymer melt experiments resulted in changes with shear rate of as much as a 55% decrease. The higher molecular weight polymer melts first showed a decrease in thermal conductivity but after that an increase at higher shear rates.

Loulou *et al.* (1992) and Chaliche *et al.* (1994) reported that the shear rate dependent thermal conductivity changed slightly by as much as 3% at the shear rate of 20 [s^{-1}] for Carbopol solutions (1000 and 2000 w.ppm) and 5% at the shear rate of 50 [s^{-1}] for carboxymethylcellulose solutions (30000 to 80000 w.ppm). They reported that at the lower the concentrations of the polymer solution, the larger changes in thermal conductivity took place. In addition Chaliche *et al.* (1994) showed a gradual increase of thermal conductivity with increasing shear rate, depending either on temperature or on polymer concentrations. A higher temperature as well as a lower concentration bring about a higher thermal conductivity.

Lee and Irvine (1997) researched water solutions of CMC at concentrations of 1500, 2500 and 5000 w.ppm and Separan AP-273 (polyacrylamide) at concentrations of 1000 and 2000 w.ppm. They observed that the thermal conductivity increased with increasing shear rate for both CMC ($100 \leq \gamma \leq 900$ [s^{-1}]) and Separan solutions ($50 \leq \gamma \leq 600$ [s^{-1}]) by an amount of 20÷70% and 20÷50%, respectively, depending on temperature (293÷323K). The increase in thermal conductivity with shear rate was greater for lower concentration solutions. The thermal conductivity of both CMC and Separan solutions increased with increasing temperature and shear rate. In the study of Kostic and Tong (1999) the 1000 and 2000 w.ppm polyacrylamide (Praestol 2273) solutions were examined at varying shear rates ($50 \leq \gamma \leq 510$ [s^{-1}]) for fluid temperature 300K. The thermal conductivity increases more with shear rate in the lower concentrated 1000 w.ppm Praestol solution (17%) than in the higher concentrated 2000 w.ppm solution (13%).

Shin and Lee (2000) have experimentally investigated rheological behavior and the thermal conductivity of suspensions of polyethylene and polypropylene by examining the effects of shear rate, particle size, and volume concentrations. Four different sizes of plastic particles (25÷300 μm) were used in suspensions. The volume concentration of the particles and shear rate varied within the ranges of 0÷10% and 0÷900 [s^{-1}], respectively. Authors found that for the suspensions of large particles ($d \geq 100$ μm), the thermal conductivity increased with shear rate, implying its strong dependence on the size of dispersed particles. A shear rate dependence of thermal conductivity is increased with volume concentrations. Shin and Lee (2000) proposed a new correlation for shear rate dependent thermal conductivity of suspensions including the effects of volume concentration and particle size.

Lin *et al.* (2003) described thermal conductivity measurements of two concentrated fruit juices (orange and mango) at varying shear rates ($0 \leq \gamma \leq 1100$ [s^{-1}]) for three temperatures: 305K, 315K and 325K. It has been found that the thermal conductivity for both fluids increases as shear rate increases.

Shin (1996) has presented theoretical study where the linear model was adopted (Fig. 2). The model can be formulated as follows.

$$\lambda = \lambda_0 + \left(\gamma - \gamma_0\right) tg\alpha \tag{1}$$

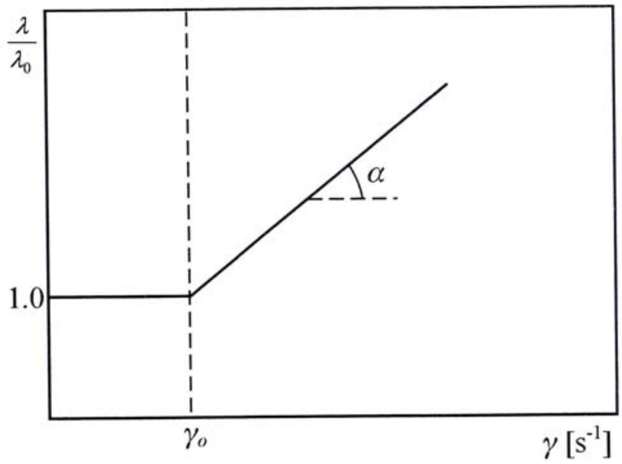


Fig. 2. Theoretical model of thermal conductivity at shear rate for non-Newtonian fluids (Shin, 1996)

Author showed the dimensionless thermal conductivity (λ/λ_0) vs. shear rate, where λ_0 represents the stationary thermal conductivity of fluid. γ_0 indicates the lower bound of the linear region. Below of that shear rate bound, the thermal conductivity seems to be invariable and independent of the shear rate.

2. Innovative thermal conductivity apparatus

In the present paper the results of the experimental studies directed on the correlation of the non-Newtonian fluids rheological behavior and thermal conductivity taking into account the shear rate effect, have been presented. The designed new measure installation (Fig. 3a) which permitted the determination of heat conductivity coefficient for power-law fluids basing on the rheometric technique and very accurate temperature measurement on outside cylinder, has been applied. The system is schematically shown in Fig. 3b. It is based on the coaxial cylinder system in which the inner cylinder is mounted as stationary and the outer cylinder is rotating. Cylinders made of steel used in food technology are of the following dimensions: outer cylinder with inner diameter 72 mm and inner cylinder with outer diameter 69 mm. The test fluid was located in the annular gap of 1.5 mm between the two cylinders. The inner cylinder consists of the resistance sensors and the heater (main and two guards). Three calibrated sensors were used to measure the surface temperature of the inner cylinder. The resistance sensors were positioned in the middle of the test section, and uniformly distributed at 120° interval.

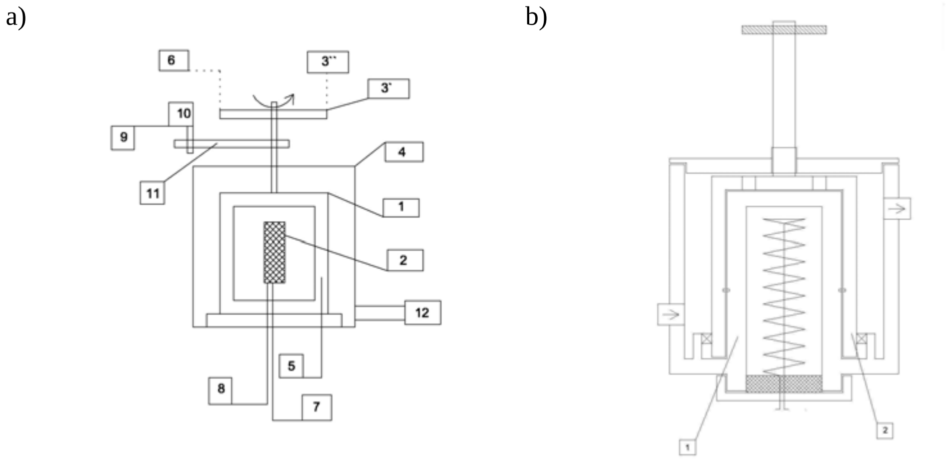


Fig. 3. Schemes of the experimental setup (a) and two coaxial cylinders system (b):
1 – coaxial cylinders, 2 – heater, 3 – integrated circuit for measure temperature of outer cylinder,
4 – water jacket, 5 – meter for measure temperature of inner cylinder , 6 – tachometer, 7 – power supply,
8 – ammeter/voltmeter, 9 – motor speed controller, 10 – motor, 11 – rotating mechanism, 12 – water bath

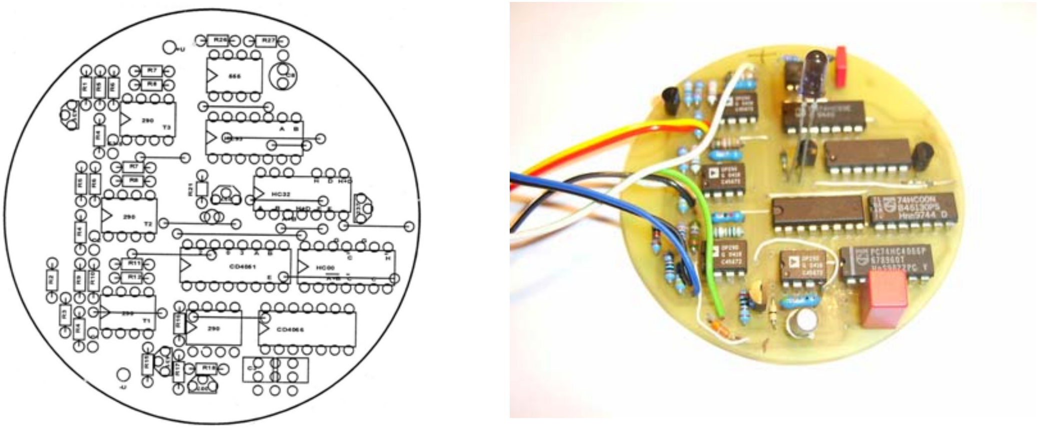


Fig. 4. Transmitter used in a novel thermal conductivity apparatus for non-Newtonian fluids to measure temperature of the outer cylinder

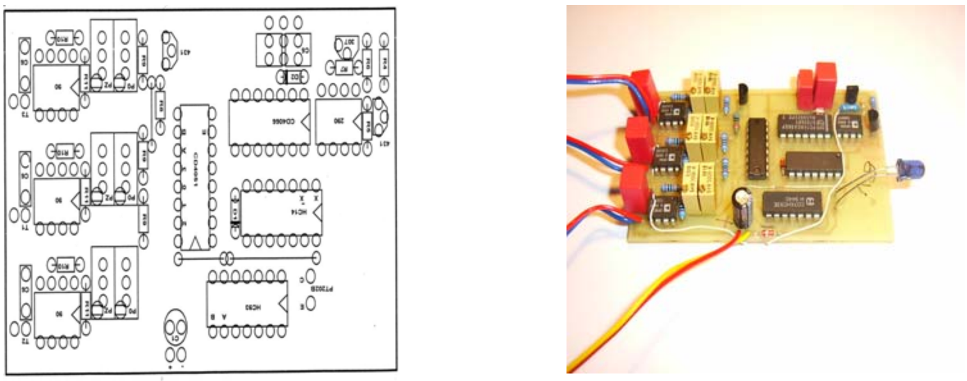


Fig. 5. Receiver used in a novel thermal conductivity apparatus for non-Newtonian fluids to measure temperature of the outer cylinder

Analogically, three sensors were mounted in the surface of the outer cylinder. This novel element of experimental setup consists of two parts as integrated circuits: transmitter and receiver (Figs. 4 and 5). Transmitter was mounted on the outer cylinder. Receiver was connected with measurer which indicated temperature on the rotating cylinder. There is an innovatory element of temperature measurement of the outer cylinder based on wireless communication.

Provided that Fourier`s law of conduction is applicable, the apparatus is operated at steady state, the shear rate variation across the gap is negligible, and the thermal conductivity of the liquid in the gap is considered to be independent of temperature, the following equation is used to calculate the thermal conductivity:

$$\lambda = \frac{Q\, ln\left(\frac{d_o}{d_i}\right)}{2\,\pi\, L\, \Delta T} \tag{2}$$

where Q is calculated from the measurement of current and voltage through the main heater:

$$Q = I\ V \tag{3}$$

3. Experimental results

The liquids tested were water, glycerol (50%) and petrol, as Newtonian fluids, and carboxymethylcellulose sodium salt (of the molecular masses 250,000 and 700,000, delivered by Aldrich Company) aqueous solutions as non-Newtonian fluids (of the polyelectrolyte concentrations in solutions ranged from 1000 to 5000 w.ppm).

Table 1. The rheological characteristics of the carboxymethylcellulose sodium salt used

Polymer molecular mass *M* [kg/kmol]	Temperature *T* [K]	Concentration of CMC in aqueous solution, w.ppm					
		1000		3000		5000	
		Rheological parameters of power-law fluids used					
		n	*K* [Pa·s^n]	*n*	*K* [Pa·s^n]	*n*	*K* [Pa·s^n]
250,000	299	0.91	0.0068	0.87	0.0147	0.85	0.0279
	307	0.92	0.0053	0.91	0.0098	0.88	0.0184
	315	0.98	0.0030	0.95	0.0062	0.95	0.0100
700,000	299	0.64	0.0600	0.63	0.1993	0.56	0.5563
	307	0.96	0.0049	0.72	0.0936	0.63	0.3032
	315	0.97	0.0039	0.65	0.1203	0.63	0.2596

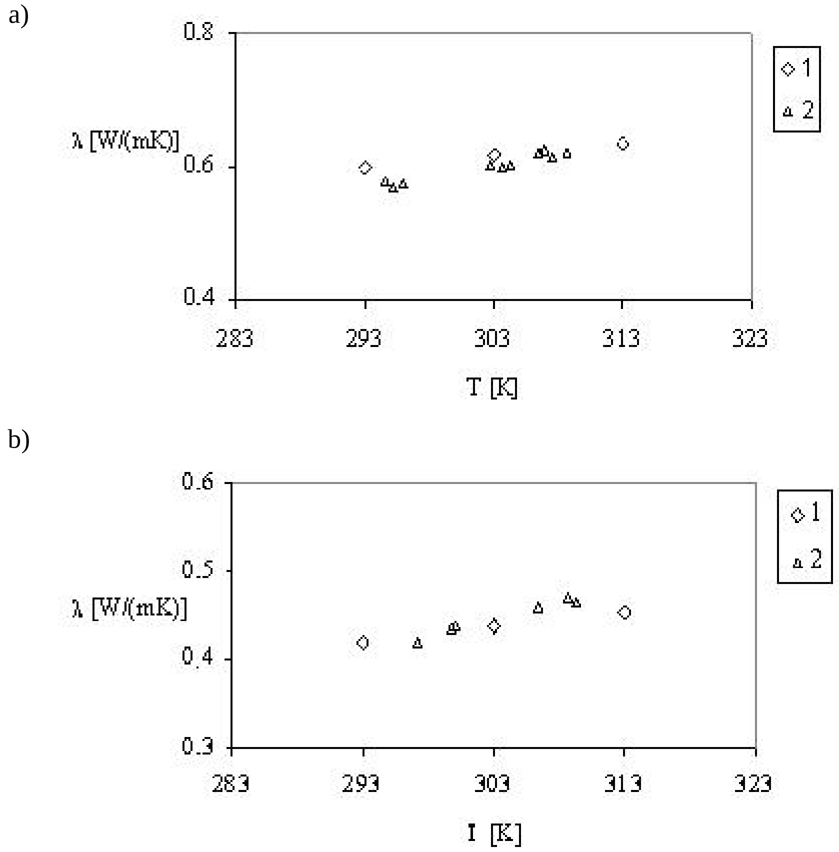


Fig. 6. Experimental data for water (a) and glycerol-50% (b): 1 – literature data (Perry and Chilton, 1973), 2 – authors' results

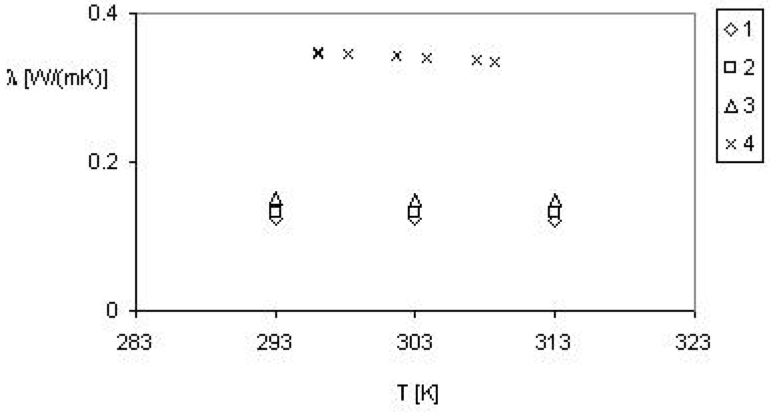


Fig. 7. Relationship $\lambda = f(T)$ for various oils: 1 – transformer oil (Cherednichenko et al., 1986), 2 –oil 30A (Cherednichenko et al., 1986), 3 – oil 20A (Cherednichenko et al., 1986), 4 – authors' results

All polymer solutions used were non-elastic power-law fluids:

$$\tau = K\gamma^n \tag{4}$$

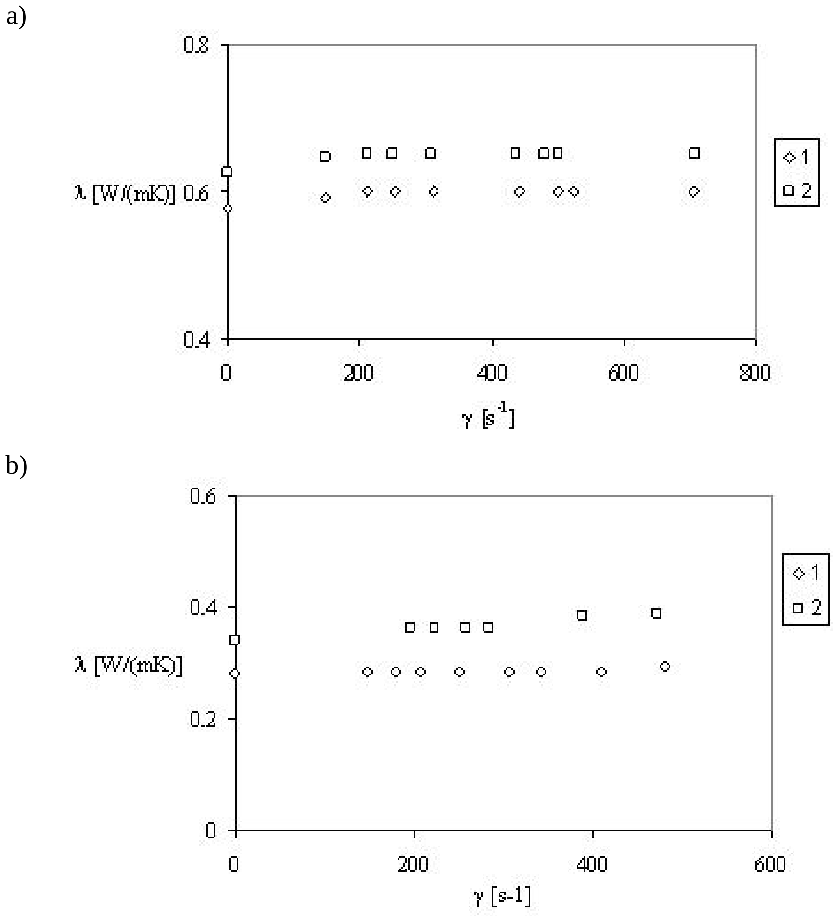


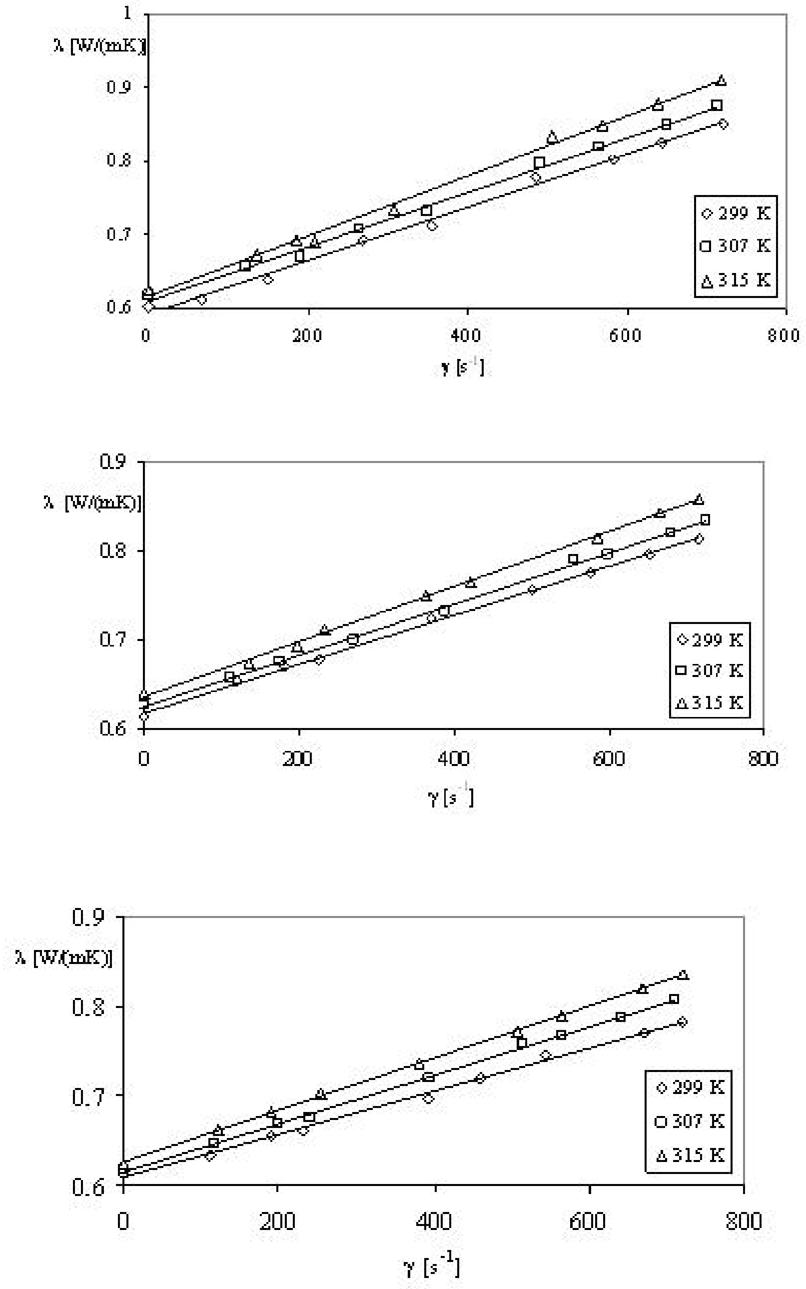
Fig. 8. Experimental results of the test on potential effect of shear rate on heat conductivity coefficients for water (a) and petrol (b) at two chosen temperatures: 1 – 295K, 2 – 307K

Table 2. Correlation relationships for heat conductivity coefficients for model Newtonian liquids

Newtonian Fluids	Correlation
water	$\lambda = 1{,}11\ 10^{-5} T^{1{,}91}$ (5)
petrol	$\lambda = 1{,}57\ 10^{-7} T^{2{,}6}$ (6)
glycerol (50%)	$\lambda = 33{,}5 T^{-0{,}803}$ (7)

Rheological parameters of the carboxymethylcellulose sodium salt used in the study are shown in Table 1. Experiments were performed at temperatures changed in the range from 299K to 315K. The shear rate range studied was $0 \leq \gamma \leq 750$ [s^{-1}]. First some Newtonian fluids were tested on apparatus. Experimental results were good with literature data (Figs. 6 and 7).

It was confirmed that thermal conductivity of Newtonian liquids at constant temperature is independent of shear rate (Fig. 8). On the ground of experimental studies the relationships $\lambda = f(T)$ for analyzed model Newtonian fluids were found (Table 2).


a)

b)

c)

Fig. 9. Heat conductivity coefficient λ vs. shear rate γ for polymer (M = 250,000 [kg/kmol]) solutions of concentration: a) 1000 w.ppm, b) 3000 w.ppm, c) 5000 w.ppm

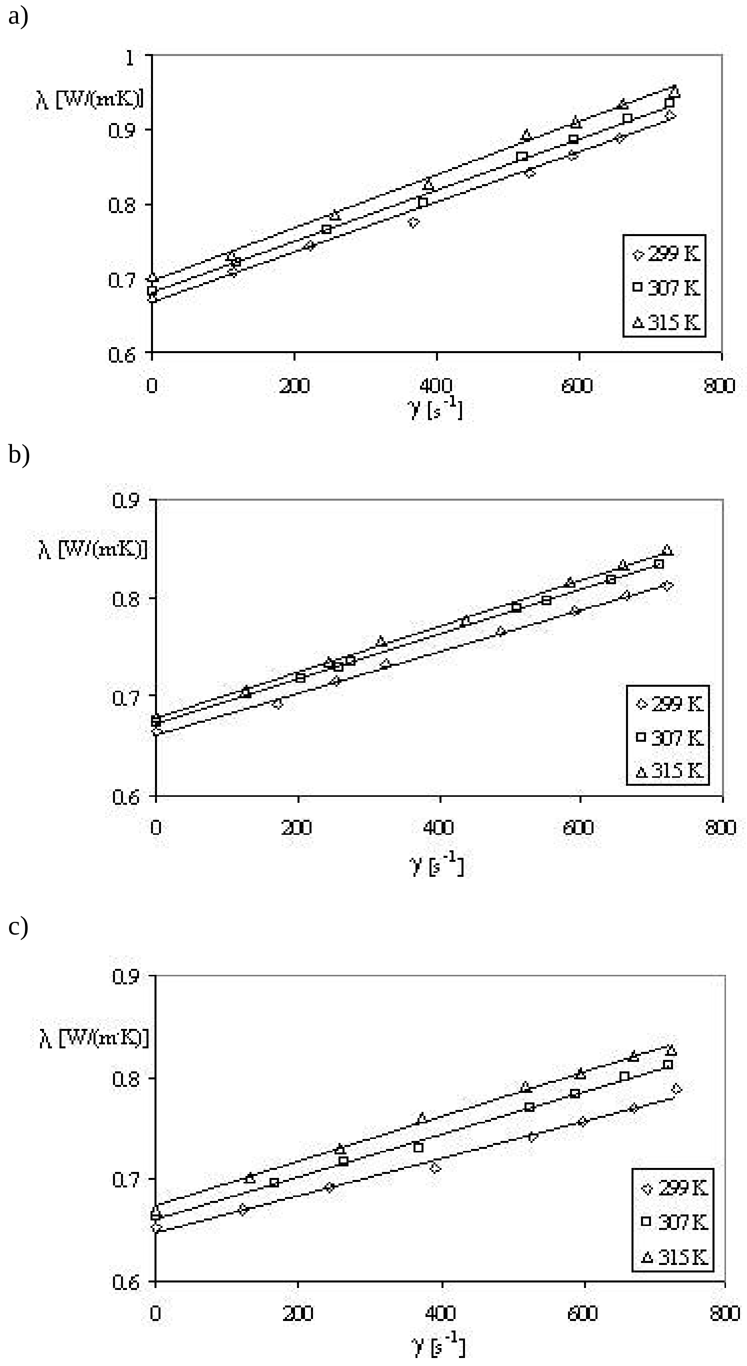


Fig. 10. Heat conductivity coefficient λ vs. shear rate γ for polymer (M = 700,000 [kg/kmol]) solutions of concentration: a) 1000 w.ppm, b) 3000 w.ppm, c) 5000 w.ppm

Figs. 9 and 10 show the curves of thermal conductivity vs. shear rate for CMC solutions. Polymers were examined at shear rates varying from 0 to 750 [s^{-1}]. The thermal conductivity at a higher temperature at a certain shear rate is greater than at a lower temperature. The temperature effect is significant, and the increase in thermal conductivity at higher temperatures with respect to shear rate is larger than at lower temperatures. The general trends of the curves are similar in all graphs. The solution of the lowest concentration (1000 w.ppm) has a greater change in thermal conductivity with shear rate in comparison with the solution of the highest concentration (5000 w.ppm).

In the result of experimental data elaboration the correlation relationships $\lambda = \mathrm{f}(T)$ were determined. The previous observations of Lee and Irvine (1997) have been confirmed. Thermal conductivity coefficients for CMC aqueous solutions increase linearly with increasing shear rate and temperature. Correlation equation at given temperature is as follows:

$$\lambda = A\gamma + B \tag{8}$$

Table 3.Values of the coefficients in Equation (8) obtained in studies on heat conductivity coefficients for CMC solutions

Polymer molecular mass M [kg/kmol]	Temperature T [K]	Concentration of polymer in aqueous solution, w.ppm					
		1000		3000		5000	
		Values of coefficients					
		A	*B*	*A*	*B*	*A*	*B*
250000	299	0.00036	0.593	0.00027	0.620	0.00024	0.609
	307	0.00037	0.610	0.00029	0.624	0.00027	0.615
	315	0.00041	0.616	0.00032	0.630	0.00029	0.627
700000	299	0.00033	0.670	0.00021	0.662	0.00018	0.648
	307	0.00035	0.680	0.00023	0.670	0.00021	0.661
	315	0.00037	0.690	0.00024	0.675	0.00022	0.673

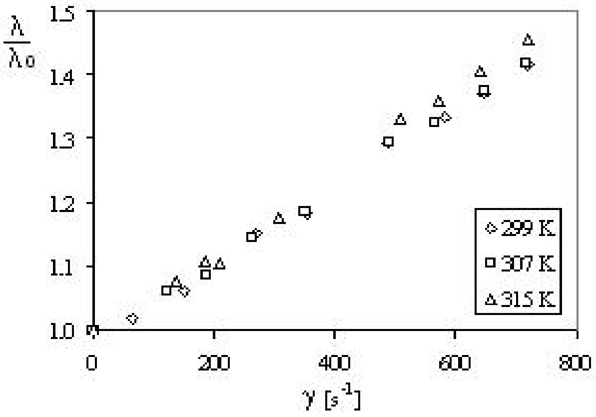


Fig. 11. Heat conductivity coefficient increase λ/λ_0 vs. shear rate γ for polymer (M = 250,000 [kg/kmol]) solution of concentration of 1000 w.ppm

The coefficients of relationship (8) are presented in Table 3. The evident increase of the thermal conductivity (in comparison with water) for all polymer solutions used has been observed (Fig. 11).

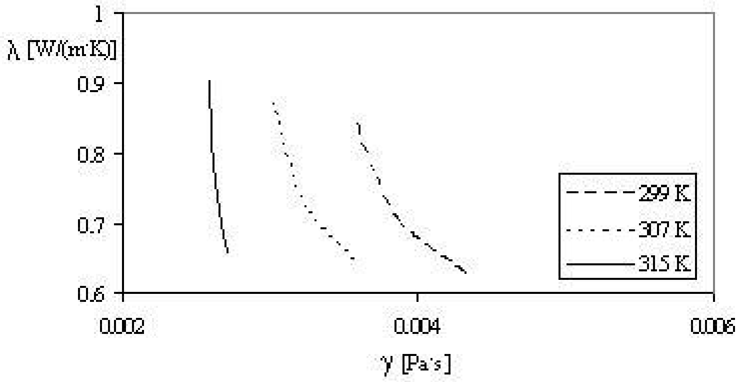


Fig. 12. Heat conductivity coefficient λ vs. viscosity η for polymer (M = 250,000 [kg/kmol]) solution of concentration of 1000 w.ppm

Next, basing on thermal conductivity and rheological measurements the effect of the non-Newtonian viscosity η on thermal conductivity, has been determined. The thermal conductivity decreased with increasing the viscosity (Fig. 12). It has been shown that the relation of λ vs. η depends considerably on molecular mass of the polymer presented and temperature.

4. Conclusions

It has been confirmed that the thermal conductivity for Newtonian fluids is independent of shear rate while it is dependent on temperature. The effect of temperature, shear rate, molecular mass of polymer present in non-Newtonian solution and its concentration on thermal conductivity, have been observed. It was found that thermal conductivity of CMC aqueous solutions at constant temperature increased linearly with shear rate. For a given solution studied the thermal conductivity increased with temperature and polymer molecular mass. The increase in concentration of CMC aqueous solutions caused the decrease in values of thermal conductivity coefficient λ.

Nomenclature

I – current intensity, A
K – consistency factor, $\mathrm{Pa\cdot s^n}$
L – main heating region, m
M – molar mass, kg/kmol
Q – heat flux, W
T – mean temperature between inside and outsider cylinders, K
V – voltage, V
d_i – diameter of inner cylinder, m
d_o – diameter of outer cylinder, m
n – flow behaviour index
γ – shear rate, $\mathrm{s^{-1}}$
η – viscosity, Pa·s

λ – heat conductivity coefficient, W/(m·K)
τ – shear stress, Pa

References

Bellet, D., Sengelin, M. and Thirriot, C., (2005) *International Journal of Heat and Mass Transfer*, 48, 1177-1181.

Chaliche, M., Delaunay, D. and Bardon, P., (1994) *International Journal of Heat and Mass Transfer*, 37, 2381-2389.

Cherednichenko, G. I., Frojshteter, G. B. and Stupak, P. M., *Fiziko-khimicheskie i Teplofizicheskie Svojstva Smazovych Materialov*, Khimija, Leningrad (1986).

Chitrangad, B. and Picot, J. J. C., (1981) *Polymer Engineering Science*, 21, 782-786.

Cocci, A. A. and Picot, J. J. C., (1973) *Polymer Engineering Science*, 13, 337-341.

Kostic, M. and Tong, H., (1999) *American Society of Mechanical Engineering Proceedings*, 364-4, 15.

Lee, D.-L. and Irvine, T. F., (1997) *Experimental Thermal and Fluid Science*, 15, 16-24.

Lee, W. Y., Cho, Y. I. and Hartnett, A., (1981) *Letters in Heat and Mass Transfer*, 8, 255-259.

Lin, S. X. Q., Chen, X .D., Chen, Z. D., Bandopadhayay, P, (2003) *Journal of Food Engineering*, 57, 217-224.

Loulou, T., Peerhossaini, H. and Bardon, J. P., (1992) *International Journal of Heat and Mass Transfer*, 35, 2557-2562.

Perry, J.H., Chilton, C. H., *Chemical Engineers` Handbook*, McGraw Hill, USA (1973).

Picot, J. J. C., Goobie, G. I. and Mawhinney, G. S., (1982) *Polymer Engineering Science*, 22, 154-157.

Shin, S. and Lee, S. H., (2000) *International Journal of Heat and Mass Transfer*, 43, 4275-4284.

Shin, S., (1996) *International Communications in Heat and Mass Transfer*, 23, 665-678.

Wallace, D. J., Moreland, C. and Picot, J. J. C., (1985) *Polymer Engineering Science*, 25, 70-74.