ARCHIVES OF ACOUSTICS
17, 2, 249–259 (1992)

ACOUSTIC WAVE DAMPING ANISOTROPY IN NEMATIC LIQUID CRYSTALS

H. HERBA and A. DRZYMAŁA

Department of Physics, Technical University in Rzeszów
(35-959 Rzeszów, W. Pola 2)

This paper presents the results of damping and velocity measurements of an ultrasonic wave with 5 MHz frequency performed in two nematic liquid crystals: pentylcyanobiphenyl (PCB) and 4-n-methoxybenzoate-4-n-pentylphenyl. Measurements were carried out in materials oriented with an external magnetic field.

An acoustic wave damping anisotropy was observed. It manifested itself with a dependence between the damping coefficient and angle between the direction of wave propagation and the direction of the magnetic field which orientates the material.

The obtained results were confronted with the results of rheological measurements carried out for mentioned materials by other authors.

1. Introduction

Theoretical foundations of the rheology of nematic liquid crystals, treated as incompressible liquids, have been formulated by Ericksen and Leslie [1, 2, 3], as well as Parodi [4]. Flows of the nematic without the assumption of its incompressibility have been considered by Foster and collaborators [5], and Huang [6]. Foster and his collaborators have also introduced a relation describing the behaviour of the ultrasonic wave damping coefficient in terms of the angle θ between the direction of propagation of the sound wave and the orientation direction of the nematic. This relationship can be expressed as follows

$$\alpha(\theta) = \frac{\omega^2}{2\rho c^3}\left\{\left[(2\nu_1 + \nu_2 - \nu_4 + 2\nu_5 + (\frac{1}{c_v} - \frac{1}{c_p})\,\kappa_\| + \right] - \left[2(\nu_1 - \nu_4 + \nu_{5)} + (\frac{1}{c_v} - \frac{1}{c_p})(\kappa_\| - \kappa_\perp)\right]\sin^2\theta + -\frac{1}{2}(\nu_1 + \nu_2 - 2\nu_3)\sin^2 2\theta\right\} \tag{1}$$

Where: ν_i ($i = 1,...5$) – coefficients expressed in viscosity units, $\kappa_\perp$ – heat conduction in a direction perpendicular to the orientation direction of molecules, $\kappa_\parallel$ – heat conduction in a direction parallel to the orientation direction of molecules, ω – wave frequency, ρ – density of the nematic, c – wave velocity.
Expression (1) changes into a known expression for an isotropic liquid if:

$$\begin{gathered} \nu_1 = \nu_2 = \nu_3 = \eta_s, \\ \nu_5 = \nu_4 - \nu_2 = \eta_v - 2/3\,\eta_s, \\ \kappa_\perp = \kappa_\parallel = \kappa, \end{gathered} \tag{2}$$

where: η_s – shear viscosity, η_v – volumetric viscosity, κ – heat conductivity.
Substituting in the expression (1), we have:

$$\begin{aligned} A &= \frac{\omega^2}{2\rho c^3}\left[2\nu_1 + \nu_2 - \nu_4 + 2\nu_s + \left(\frac{1}{c_v} - \frac{1}{c_p}\right)\kappa_\parallel\right], \\ B &= \frac{\omega^2}{2\rho c^3}\left[2(\nu_1 - \nu_4 + \nu_5) + \left(\frac{1}{c_v} - \frac{1}{c_p}\right)(\kappa_\parallel - \kappa_\perp)\right], \\ C &= \frac{\omega^2}{2\rho c^3}\frac{1}{2}(\nu_1 + \nu_2 - 2\nu_3). \end{aligned} \tag{3}$$

It is clear that:

$$\begin{gathered} \alpha(0) = A, \quad \alpha(\Pi/2) = A - B, \\ \Delta\alpha = \alpha(0) - \alpha(\Pi/2) = B. \end{gathered} \tag{4}$$

Foster's theory does not include velocity anisotropy. The occurrence of this phenomenon for high frequencies (7) can be caused by the fact that the reaction of the material to compression requires a definite amount of time. If the period during which compression is applied is short in comparison with this time, then compressibility can be anisotropic.

2. Measuring apparatus

An original ultrasonic system was used to perform measurements. It made possible damping and velocity measurements of an ultrasonic wave in liquid crystals. An external magnetic field was applied to orientate the material. The mechanical system including ultrasonic transducers and measuring vessel is considerably miniatured and the ultrasonic wave propagates horizontally. This makes it easier to apply typical electromagnets. The minimal distance between pole shoes necessary to place the device in the magnetic field is equal to 80 mm. The block diagram of the system is presented in Fig. 1. This system was made in the Institute of Fundamental Technological Research of PAS in Warsaw. Temperature stabilization not worse than 0.1°C was archieved by using an ultrathermostat. Damping and velocity of the ultrasonic wave were measured with the application of a magnetic field with induction of 0.7 T.

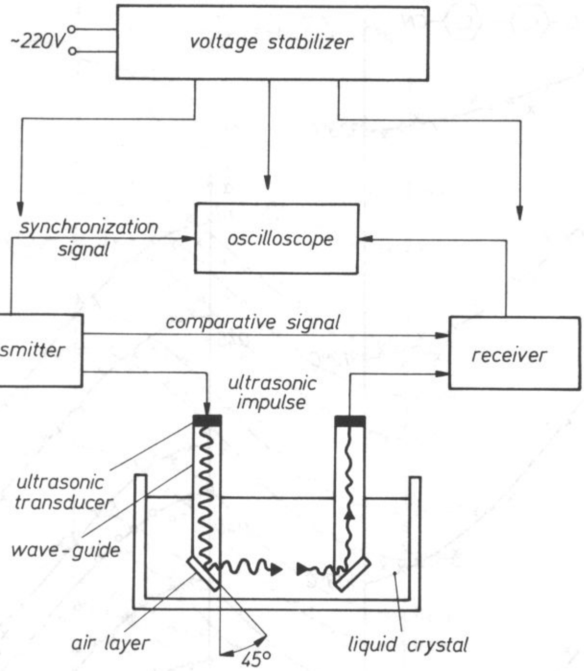

FIG. 1. Block diagram of the system for ultrasonic wave damping and velocity in liquid crystals.

3. Characteristic of tested liquid crystals

Measurements were performed for two nematic liquid crystals: p-pentyl-p′-cyanobiphenyl (PCB) and 4-n-methoxybenzoate 4-n-pentylphenyl (MBPP). Structural formulae and phase transition of tested materials are given in Table 1.

Table 1.

Material	Method	Phase trans. temperature [°C] solid state nematic	nematic isotropic
p–pentyl–*p′*–cyanobiphenyl	Microscopic observation (cooling)	18,9	33,9
$C_5H_{11}-\langle\overline{O}\rangle-\langle\overline{O}\rangle-CN$	DSC (heating)	–	35,0
4–n–methoxybenzoate–4n–pentylophenyl	Microscopic observation (cooling)	25,1	40,4
$C_5H_{11}-\langle\overline{O}\rangle-COO-\langle\overline{O}\rangle-OCH_3$	DSC (heating)	–	41,3

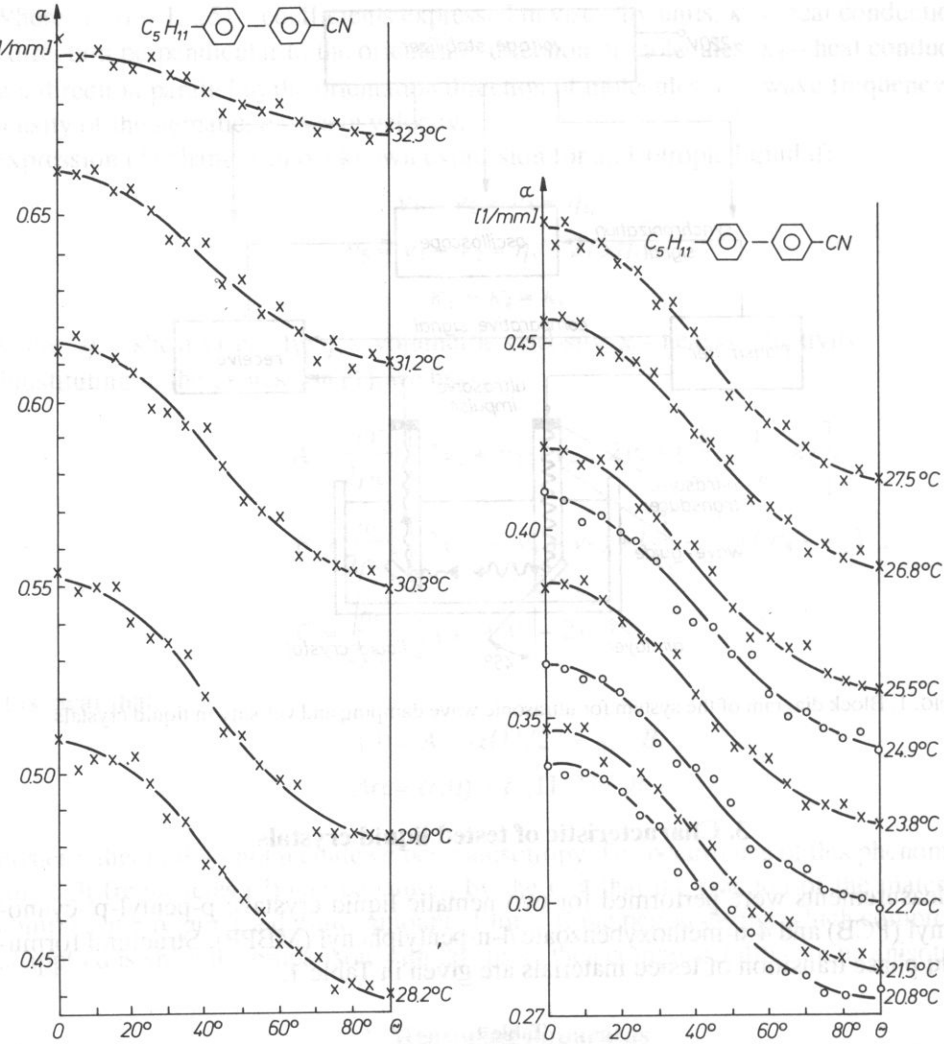

FIG. 2. Results of damping measurements for an ultrasonic wave with 5 MHz frequency in PCB material.

4. Ultrasonic wave damping and velocity measurements

Damping and velocity were measured for an ultrasonic wave with 5 MHz frequency in terms of temperature and angle between the direction of wave propagation and direction of orientating magnetic field. Their relation (1) was matched using the method of least squares with results achieved at a given temperature and quantities A, B and C were determined (Formula (3)). Measurement results for PCB and 4-n-methoxybenzoate 4-n-pentylphenyl are presented in Figs. 2 and 3, respectively. Full curves in Figs. 2 and 3 are

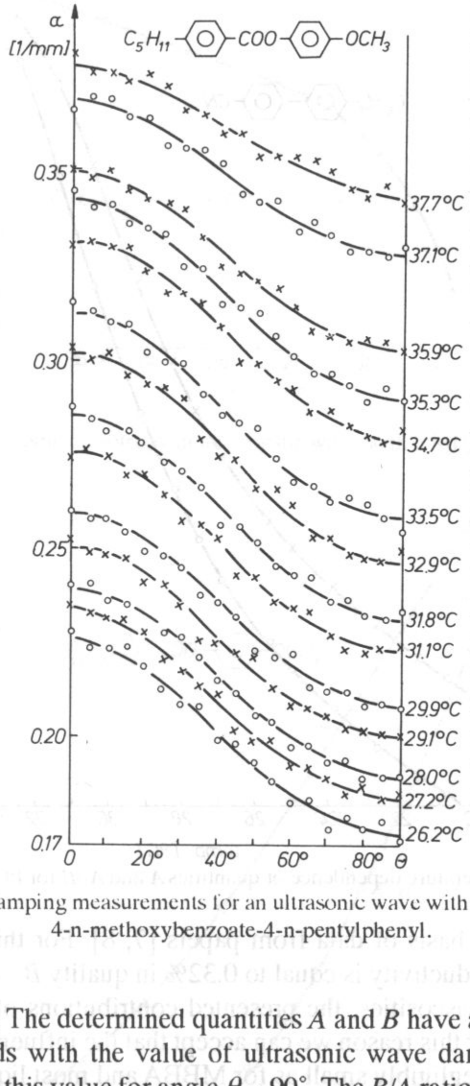

FIG. 3. Results of damping measurements for an ultrasonic wave with 5 MHz frequency in 4-n-methoxybenzoate-4-n-pentylphenyl.

described with Eq. (1). The determined quantities A and B have a simple physical sense. Quantity A corresponds with the value of ultrasonic wave damping for angle $\theta = 0°$, while value $A - B$ with this value for angle $\theta = 90°$. The B/A ratio defines damping anisotropy. The values A, $(A - B)$ and B/A in terms of temperature is shown in Figs. 4 and 5 for PCB and Figs. 6 and 7 for 4-n-methoxybenzoate-4-n-pentylphenyl. Standard deviation of A and $A - B$ quantities, calculated on the basis of matching the expression (1) and experimental data with the method of least squares are marked in Figs. 4 and 6.

Once the quantities A and B are known, the coefficients of volumetric viscosity, ν_4 and ν_5, can be calculated. However, this requires knowledge of the coefficients for shear viscosity, ν_1, ν_2, ν_3, and the coefficients of heat conductivity, $\kappa_\perp$ and $\kappa_\parallel$. In the case of most liquids the contribution of heat conductivity in ultrasonic wave damping is small in comparison with the contributions of shear viscosity and volumetric viscosity.

The estimation of the influence of heat conductivity was impossible because of the lack of complete data for tested materials. Such an estimation can be carried out for

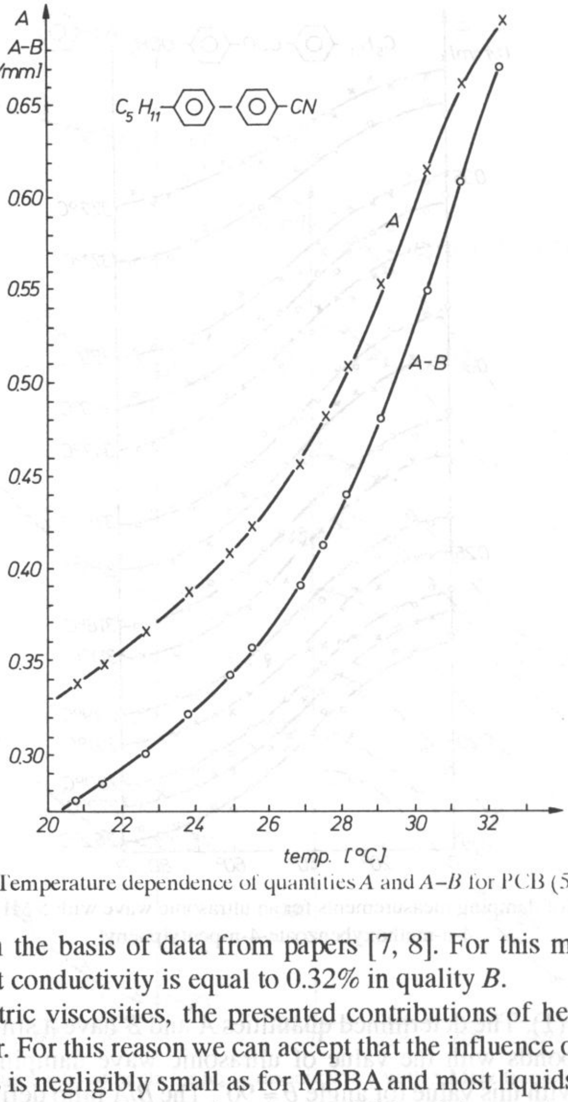

FIG. 4. Temperature dependence of quantities A and A–B for PCB (5 MHz).

nematic MBBA on the basis of data from papers [7, 8]. For this material at 30°C the temperature of heat conductivity is equal to 0.32% in quality B.

As for volumetric viscosities, the presented contributions of heat conductivity are many times smaller. For this reason we can accept that the influence of heat conductivity for tested materials is negligibly small as for MBBA and most liquids. The authors have determined the coefficients of shear viscosity for PCB and 4-n-methoxybenzoate-4-pentylphenyl by testing the flow of the material oriented with a magnetic field through a capillary with a rectangular section [9]. Taking the coefficients of shear viscosity given in [9] into consideration, the quantities ν_4 and ν_5 were calculated.

The velocity of an ultrasonic wave necessary to determine ν_4 and ν_5 was measured using the pulse-phase method with the application of the previously described system. The results of velocity measurements are presented in Figs. 8 and 9. The temperature dependence of volumetric viscosity is illustrated in Figs. 10 and 11. Quantity C (Expression (3)) depends only on the coefficients of shear viscosity. Adequate comparisons were made using the quantities given in the paper. The results of these comparisons are shown in Figs. 12 and 13. Also measuring errors are included in these figures.

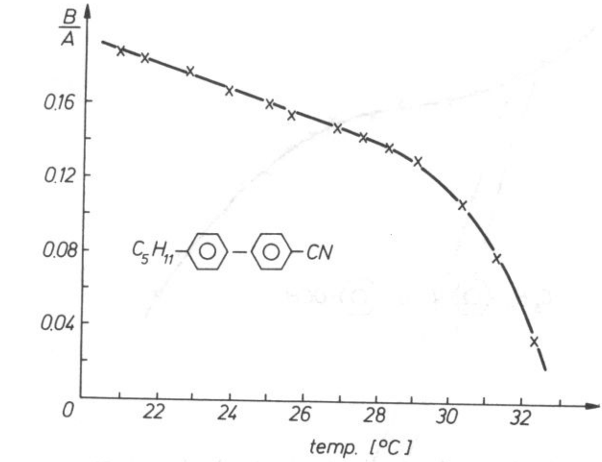

FIG. 5. Damping anisotropy of an acoustic wave with 5 MHz frequency in PCB.

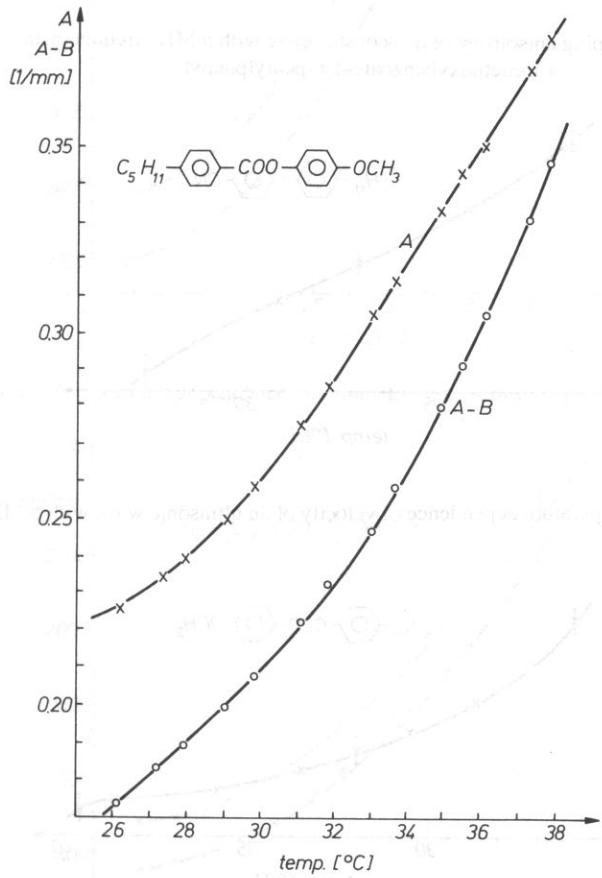

FIG. 6. Temperature dependence of quantities A and $A–B$ for 4-n-methoxybenzoate-4-n-pentylphenyl (5 MHz).

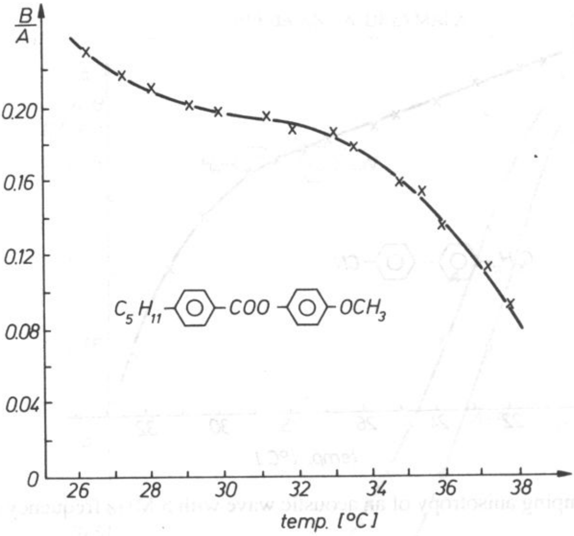

Fig. 7. Damping anisotropy of an acoustic wave with 5 MHz frequency in 4-n-methoxybenzoate-4-n-pentylphenyl.

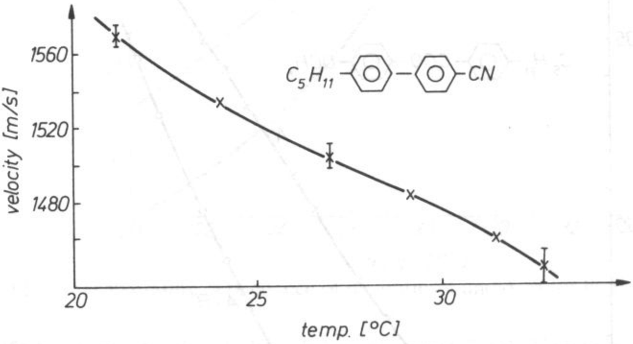

FIG. 8. Temperature dependence of velocity of an ultrasonic wave with 5 MHz for PCB.

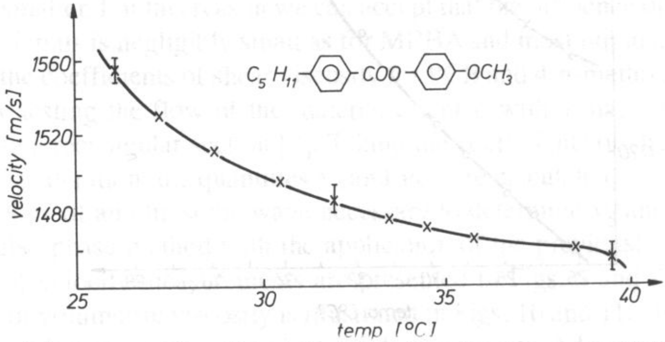

FIG. 9. Temperature dependence of velocity of an ultrasonic wave with 5 MHz frequency for 4-n-methoxybenzoate-4-n-pentylphenyl.

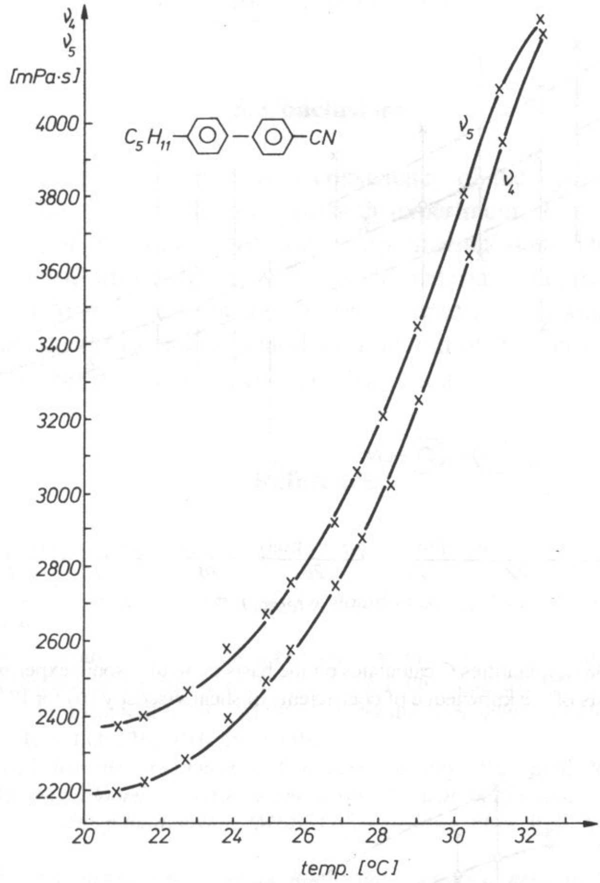

FIG. 10. Temperature dependence of volumetric viscosities for PCB.

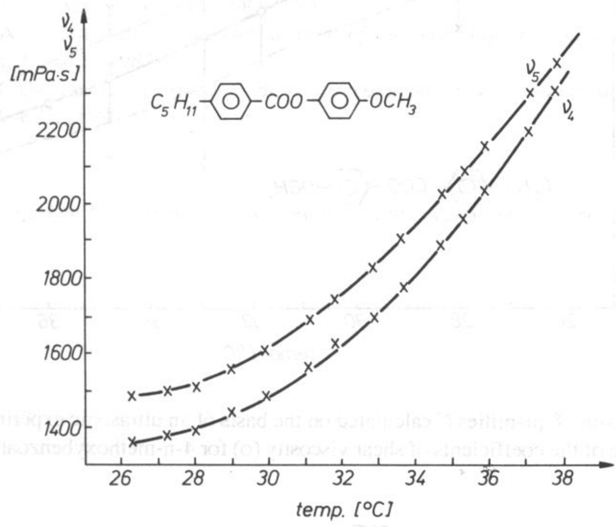

FIG. 11. Temperature dependence of volumetric viscosities for 4-n-methoxybenzoate-4-n-pentylphenyl.

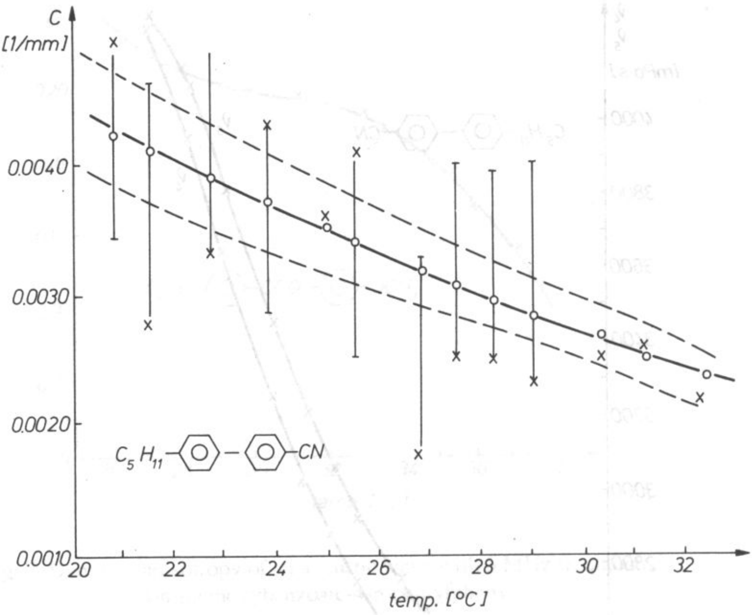

FIG. 12. Comparison of quantities C calculates on the basis of an ultrasonic experiment (x) and on the basis of the knowledge of coefficients of shear viscosity (o) for PCB.

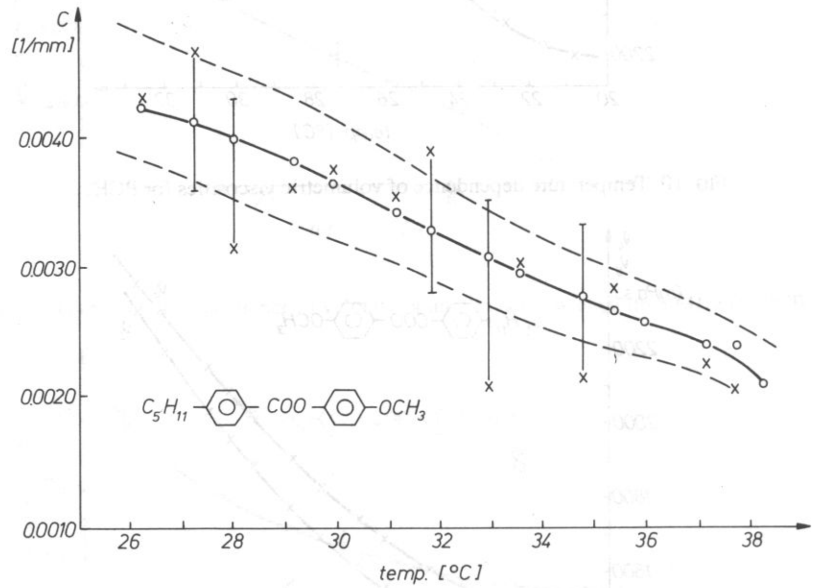

FIG. 13. Comparison of quantities C calculated on the basis of an ultrasonic experiment (x) and on the basis of knowledge of the coefficients of shear viscosity (o) for 4-n-methoxybenzoate-4-n-pentylphenyl.

5. Conclusions

The presented measurements prove a consistency of the hydrodynamic theory of FOSTER and co-author [5]; and HUANG [6] with experiment. This is indicated by the quality of matching of theoretical curves and experimental data. The anisotropy of the damping coefficient of ultrasonic waves for tested materials in experimental conditions 5 MHz is caused mainly by the anisotropy of volumetric viscosities which are many times greater than shear viscosities. The determination of volumetric viscosities is important [10] for further research of acoustic absorption and relaxation processes in the presented materials.

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Received on November 24, 1987, revised English version October 21, 1991