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## Liquid Crystals

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# Anisotropic shear viscosity in nematic liquid crystals: new optical measurement method

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We propose a new optical method and the experimental set-up for measuring the anisotropic shear viscosities of nematic liquid crystals (LCs). LC shear viscosities can be optimized to improve liquid crystal display (LCD) response times, e.g. in vertical aligned nematic (VAN) or bistable nematic displays (BND). In this case a strong back-flow effect essentially determines the LCD dynamic characteristics. A number of shear viscosity coefficients defines the LCD response time. The proposed method is based on the special type of a shear flow, namely, the decay flow, in the LC cell with suitably treated substrates instead of magnetic or electric field application. A linear regime of a quasi-stationary director motion induced by a pressure difference and a proper configuration of a LC cell produces decay flow conditions in the LC cell. We determine three principal shear viscosity coefficients by measuring relative time variations of the intensity of the light passed through LC cells. The shear viscosity coefficient measurements provide a new opportunity for the development of new LC mixtures with fast response times in VAN, BND and other important LCD types.

## 1. Introduction

The viscosity coefficients of a liquid crystal (LC) are a key factor in defining the response times of LC displays (LCDs). Five independent Leslie viscosity coefficients,  $\alpha_i$  enter into the equations that define the LC dynamic response. They describe the energy dissipation for different types of liquid crystal motion (figure 1). For example, pure rotation of the LC director  $\mathbf{n}$  without fluid motion (T-deformation) can be described via the coefficient of rotational viscosity  $\gamma_1 = \alpha_3 - \alpha_2$ . This parameter is the most important for the characterization of LCD dynamic behaviour. However, a back-flow effect takes place under fast reorientation of a liquid crystal sample in different geometries [1]. Although the back flow phenomenon was described more than 20 years ago, recently new interest in it has arisen due to the rapid progress in LCD technology. Back-flow takes place because of the strong connection between velocity gradients and orientational deformations in nematic liquid crystals (NLCs) and can essentially modify the LCD dynamic response in electro-optical effects [2]. In particular, for a frequently used twisted nematic (TN) mode—which includes twist,

bend and splay deformations—back flow results in an increase of the response time [1]. By contrast, in the optically compensated bend (OCB) mode the back-flow effect plays the main role, providing several times faster response times in comparison with the TN mode [2]. The critical improvement of inertial properties of LC displays via back-flow effects is of great importance in, for example, TV LCD applications, where the vertical

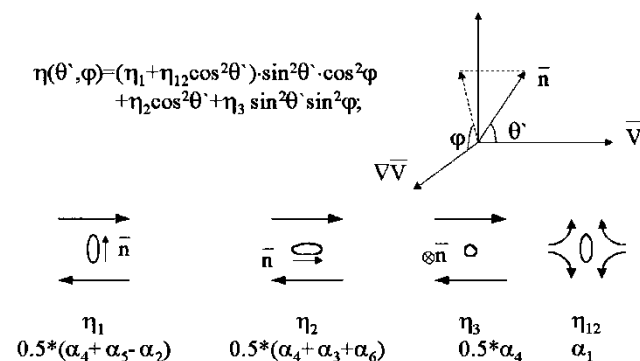


Figure 1. Shear flow viscosities for different angles  $\theta'$  and  $\varphi$  describing the orientation of LC director  $\mathbf{n}$  relatively to the flow velocity ( $\mathbf{v}$ ) and flow velocity gradient ( $\nabla \mathbf{v}$ );  $\eta_1$ ,  $\eta_2$ ,  $\eta_3$  are the principal shear viscosities.

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aligned nematic (VAN) mode and its modifications are perfectly suited for the purpose [3]. Such effects are also very important for bistable nematic displays (BNDs), where back-flow is the main reason for proper switching between two bistable LC states [4].

The exact calculations of the dynamical orientational changes and optical response of LC cells taking account of back-flow effects are usually based on a computer modelling of the problem and demand a knowledge of a number of anisotropic viscosity coefficients [2, 5, 6]. Nevertheless, such information is known only for a few nematic LCs and almost completely unknown for new nematic mixtures synthesized for important LCD applications. Moreover, further progress in LCD technology cannot be achieved without the optimization of liquid crystal material parameters, and of their viscosities in particular [1]. In addition, attempts to calculate the dynamic electro-optical response of LC cells in various modes without allowing for back-flow effects results in a large difference between theoretical and experimental values, especially in cases where strong bend deformations are involved [2].

It was shown recently [5, 6] that only some Leslie coefficients or their combinations play a dominant role in the back-flow effect. For example, the  $\alpha_1$  coefficient is of low importance [5], as is the  $\alpha_3$  coefficient because its value far from clearing temperature is usually small in comparison with the other coefficients (the opposite case can be realized in discotic nematics [6] and opens new ways of optimization of LC materials). Thus the most important viscosity coefficients for the back-flow problem, referred to as 'back-flow viscosities', can be easily calculated from the anisotropic shear viscosity coefficients  $\eta_1, \eta_2, \eta_3$  usually measured in classical flow experiments [7]. The principal geometries of such experiments are shown in figure 1.

The shear viscosity (and back-flow viscosity) coefficients of only a few LCs (individual substances and mixtures) have been determined properly. The experimental technique for such measurements usually requires a relatively large amount of a liquid crystal (several grams). This prevents the efficient evaluation of the newly synthesized LC materials. Also the application of a powerful magnetic field (about 1 T) is needed to overcome LC reorientation during the measurements, which makes such set-ups rather complicated and expensive [7]. Thus the development of new and relatively simple experimental methods for the measurement of LC anisotropic shear viscosities is very useful for the rational development of new LCDs with fast response times.

## 2. Physical background

In the method described here a specific type of pressure-induced shear flow, namely *decay flow* is used to measure the anisotropic shear viscosities in liquid crystal samples, oriented by boundaries. This technique was first proposed to measure the viscosity of a homeotropic layer of a nematic liquid crystal oriented by a surface treatment and stabilizing electric field [8]. Such a flow can be realized if we take an LC cell with two open edges connected with certain vessels (figure 2).

There is no flow through this cell in the equilibrium state (the levels of LC in the vessels are the same). But if we change the initial position of the levels by putting some amount of LC into one vessel or by inclining the cell, shear flow will be induced by the hydrostatic pressure difference  $\Delta P$ . This difference will decrease with time, and obviously a certain time is required for complete cessation of the LC motion, which depends on the shear viscosity. Actually such a decay flow takes place not only in liquid crystals, but also in isotropic fluids. In the latter case a Newtonian-like behaviour with a constant value of shear viscosity is realized. By contrast, there is a connection between the velocity gradients and the LC alignment in the liquid crystalline media. Thus the shear flow can change the initial LC orientation (e.g. homeotropic as shown in figure 3) and thus non-Newtonian flow is observed (the shear viscosity depends on time).

Electric or magnetic fields can be used to stabilize the initial homeotropic LC alignment in this case [1].

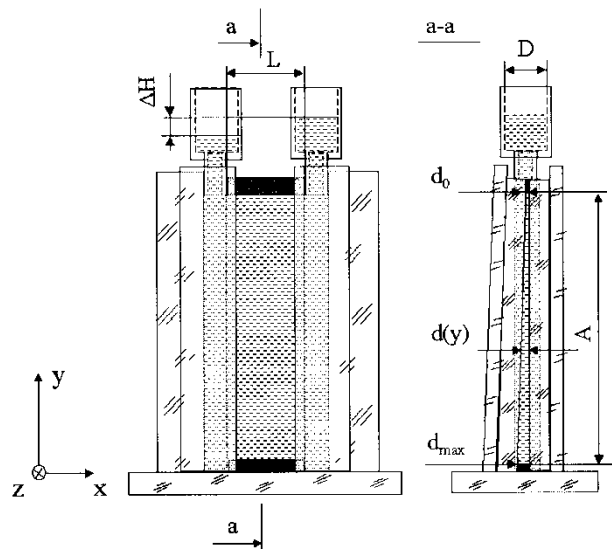


Figure 2. Construction of the wedge-like measuring LC cell. A decay shear flow arises in the channel of a variable thickness  $d(y)$  via the difference of levels  $\Delta H$  in the open tubes of diameter  $D$  connected by the channel.  $d_0$  and  $d_{\max}$  are minimum and maximum thicknesses of the cell,  $A$  is the cell width.

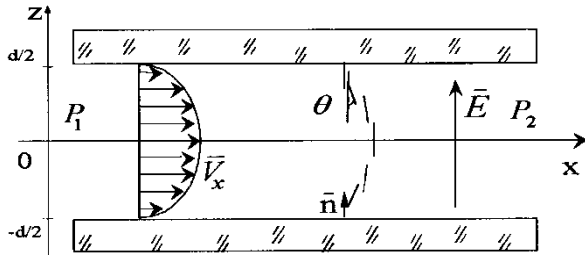


Figure 3. The linear flow of LC induced by a pressure difference  $\Delta P = P_2 - P_1$ . A parabolic velocity profile  $v(z)$  occurs in the case of small values of the angle  $\theta(z)$  describing orientational changes in the homeotropic LC sample;  $\mathbf{E}$  is the electric field usually used for additional control of LC orientation.

However, for a weak flow the linear approximation is valid and the flow can be considered as quasi-Newtonian (the shear viscosity is approximately constant). At the same time slight flow-induced variations of the initial homeotropic structure described by the angle  $\theta$  are quite sufficient and can be observed by measuring the intensity of polarized light passing through the LC cell. The latter correlates with time-dependent pressure variations needed to determine the shear viscosity coefficient.

The theory of a linear non-stationary flow induced in a homeotropic layer of an LC (figure 3) by an oscillating pressure gradient has previously been used to describe the combined action of the shear flow and of the stabilizing electric field on the optical response of an LC cell [9, 10]. It is based on the system of coupled hydrodynamic equations describing a time evolution of the velocity  $v_x(z, t)$  and orientation  $\theta(z, t)$  fields for a plane flow [10]:

$$\rho \frac{\partial v_x}{\partial t} = - \frac{\partial P}{\partial x} + \eta_1 \frac{\partial^2 v_x}{\partial z^2} + \alpha_2 \frac{\partial^2 \theta}{\partial z \partial t} \quad (1)$$

$$k_{33} \frac{\partial^2 \theta}{\partial z^2} = \alpha_2 \frac{\partial v_x}{\partial z} + \gamma_1 \frac{\partial \theta}{\partial t} + \varepsilon_0 \Delta \varepsilon E^2 \theta \quad (2)$$

where  $\rho$ ,  $\eta_1$ ,  $\Delta \varepsilon$  and  $K_{33}$  are the density, the maximum shear viscosity, the dielectric permittivity anisotropy and the Frank constant of the LC, respectively, and  $d$  is the thickness of the layer. This system can be easily solved if the quasi-stationary approximation is valid [9]. It takes place when the characteristic time of a pressure variation is much longer than the time of an orientational relaxation ( $\tau \gg \tau_o = \gamma_1 d^2 / K_{33}$ ), and the LC director  $\mathbf{n} = [\sin \theta(z, t), 0, \cos \theta(z, t)]$  will vary in phase with pressure.

In particular, the equation for the flow velocity  $v_x$  for slow varying flows ( $\tau \gg \rho d^2 / \alpha_2$ ) will be essentially the

same as in the case of isotropic liquids:

$$\eta_1 \frac{\partial^2 v_x}{\partial z^2} = - \frac{\partial P}{\partial x} = - G \quad (3)$$

where the pressure gradient  $G(t) = \Delta P(t) / L$  ( $L$  is the length of the channel) can be considered as a parameter slowly varying with time. So the common parabolic profile of the velocity field takes place in this case:

$$v_x(z, t) = - \frac{G(t)}{2\eta_1} \cdot \left( z^2 - \frac{d^2}{4} \right) \quad (4)$$

where  $-d/2 \leq z \leq d/2$  is the relative distance along the normal to the LC layer.

The expression obtained for  $v_x(z, t)$  can be used to derive the time-dependent field of the LC orientation. For a linear regime the director moves in the  $(x, z)$  plane ('in plane' motion), so the equation describing this motion in the absence of external fields is rather simple

$$K_{33} \frac{\partial^2 \theta}{\partial z^2} = \alpha_2 \frac{\partial v_x}{\partial z} \quad (5)$$

and can be easily integrated to obtain the profile of an orientation through the cell

$$\theta(z, t) = - \frac{\alpha_2}{6K_{33}\eta_1} z \left( z^2 - \frac{d^2}{4} \right) G. \quad (6)$$

This result is valid only for small deformations of the initial homeotropic orientation (in the opposite case, 'out of plane' motion of a director can exist for the flow under consideration [11]).

Let us note that the expressions for  $v_x$  and  $\theta$  were obtained for often used boundary conditions:

$$V(z = \pm d/2) = 0 \quad (\text{non-gliding}) \quad (7)$$

$$\theta(z = \pm d/2) = 0 \quad (\text{strong anchoring}). \quad (8)$$

The strong boundary anchoring for the LC director that corresponds to an infinite anchoring energy is not valid in a general case [1]. However, the main result of the linear theory states that the LC director deviation  $\theta(z, t)$  is proportional to the time-dependent pressure variations, i.e.

$$\theta(z, t) \sim G(t) \quad (9)$$

which is quite general and does not depend on the anchoring energy for non-stationary linear flows [12]. Thus the time-dependent pressure gradient can be controlled via the optical study of orientational changes induced in the LC layer by the shear flow. This result is the key to the practical realization of the proposed optical method for shear viscosity measurements.

In particular, the intensity of light passing through the LC cell with an initial homeotropic orientation, placed between crossed polarizers (oriented at  $45^\circ$

relatively to the flow direction) can be expressed as [1]:

$$I = I_0 \sin^2(\delta/2) \quad (10)$$

where  $I_0$  is the input light intensity and the phase difference  $\delta$  between the extraordinary (e) ray and the ordinary (o) rays is

$$\delta(t) = \frac{2\pi d}{\lambda} \langle \Delta n(\theta) \rangle = \frac{2\pi}{\lambda} \int_{-d/2}^{d/2} [n(\theta) - n_o] dz \quad (11)$$

where

$$n(\theta) = n_o [1 - \sin^2 \theta (n_e^2 - n_o^2) / n_e^2]^{-1/2} \quad (12)$$

$n_e$  and  $n_o$  are the refractive indexes of the (e) and (o) rays,  $\lambda$  is the light wavelength.

It is easy to show that for sufficiently small values of  $\theta$  this expression can be simplified to

$$\begin{aligned} \delta(t) &\cong \frac{2\pi d n_o (n_e^2 - n_o^2)}{\lambda 2n_e^2} \langle \theta^2 \rangle \\ &= \frac{1}{15120} \frac{\pi d n_o (n_e^2 - n_o^2)}{\lambda 2n_e^2} \left( \frac{\alpha_2 G d^3}{K_{33} \eta_1} \right)^2. \end{aligned} \quad (13)$$

Expression (13) states that the phase difference  $\delta$  is proportional to the square of the pressure gradient and hence to the square of the hydrostatic pressure difference  $\Delta P$  applied to the open edges of the cell:

$$\delta(t) \sim G^2(t) \sim [\Delta P(t)]^2. \quad (14)$$

The obtained expression provides a control of the time-dependent pressure difference  $\Delta P(t)$  via the time-dependent phase difference  $\delta(t)$ , which can be found through the analysis of the flow-induced changes of polarized light intensity  $I(t)$ .

It is easy to show, for the given quasi-stationary decay flow, that at each moment of a fluid motion the hydrostatic pressure difference

$$\Delta P(t) = \rho g \Delta H(t) \quad (15)$$

is compensated by the viscous pressure losses ( $\Delta P_{\eta}$ ) arising in the channel that connects the open edges of the cell. For a rectangular channel having a length  $L$ , a width  $A$  and a constant thickness  $d$ , such losses are proportional to the fluid volumetric flow rate  $Q = dV/dt$  ( $V$  is the volume of a liquid flowing through the cross-section of the channel) [13]:

$$\Delta P_{\eta} = - \frac{12\eta_1 L}{d^3 A} Q = - RQ \quad (16)$$

where  $R$  is a hydrodynamic resistance of the capillary,

$$R = \eta_1 / K_c \quad (17)$$

and the constant

$$K_c = \frac{d^3 A}{12L} \quad (18)$$

which depends only on the geometric dimensions of the capillary,  $\eta_1 = 1/2(\alpha_4 + \alpha_5 - \alpha_2)$  is the viscosity, which corresponds to a homeotropic orientation of the LC director on the boundary (figure 1). Taking into account the simple relationship (figure 2)

$$Q = \frac{S d(\Delta H)}{2 dt} \quad (19)$$

where  $S = \pi D^2/4$ , a cross-section of the open tubes (figure 2), we can easily obtain from equations (16) and (19) the differential equations for the pressure difference  $\Delta H$  ( $\Delta P$ ):

$$\frac{d(\Delta H)}{dt} = - \frac{(\Delta H)}{\tau} \quad (20a)$$

$$\frac{d(\Delta P)}{dt} = - \frac{(\Delta P)}{\tau} \quad (20b)$$

where

$$\tau = \frac{\eta_1 S}{2\rho g K_c} = 2 \frac{\eta_1}{K} \quad (21)$$

$$K = \frac{4K_c}{S} \rho g = \frac{4}{3} \left( \frac{d^3 A}{L\pi D^2} \right) \rho g \quad (22)$$

the parameter that includes the sizes both of the capillary and of the open tubes. Solving the equations (20) and (21) we conclude that:

- (1) The hydrostatic pressure difference  $\Delta P$  (proportional to the difference of levels  $\Delta H$  in the vessels), which induces the shear flow decays exponentially with time:

$$\Delta P(t) = \Delta P_0 \exp(-t/\tau). \quad (23)$$

- (2) The characteristic decay time  $\tau$  is proportional to the shear viscosity coefficient  $\eta_1$ ,

$$\tau \sim \eta_1. \quad (24)$$

- (3) According to equation (14) the phase difference also decays exponentially with time,

$$\delta(t) = \delta_0 \exp(-t/\tau_\delta) \quad (25)$$

where the relaxation time of the phase difference is

$$\tau_\delta = \tau/2 = \eta_1 / K. \quad (26)$$

We note that similar conclusions are also valid for the channel of the variable thickness shown in figure 2, so we can determine the different shear viscosities of liquid crystals also from equation (26). It is easy to show that in this case (for a sufficiently small value of the angle of the wedge-like cell) the parameter  $K$  can be expressed as:

$$K = \frac{A(d_{\max} + d_0)(d_{\max}^2 + d_0^2)}{3\pi D^2 L}. \quad (27)$$

The value  $\eta_1$  in expression (21) for the decay time must be replaced by a proper shear viscosity  $\eta_i$  if the boundary was treated in the corresponding way (figure 1). We will show later that the application of the cells with combined types of a boundary orientation allows us to determine the three principal coefficients of the shear viscosity using a certain universal procedure.

### 3. Experimental set-up

We have constructed the experimental set-up to measure the back flow LC viscosities, using the decay flow method described already. The specially prepared wedge-like cells with a variable layer thickness provide the measurement of different shear viscosity coefficients (figure 2). Previously cells of this type with a homeotropic orientation were used to investigate both linear and non-linear phenomena in liquid crystals by observing the decay of oscillating flows [11, 14]. The angle of the edge was chosen to be sufficiently small (about 0.002 rad), so that the capillary of variable thickness could be described as a number of plane capillaries with a parallel connection enabling us to use expression (27). The inner surfaces of the channel were coated with transparent electrodes and treated by standard methods to obtain different types of orientation for measurements of different viscosity coefficients (figure 4). In the simplest case of homeotropic orientation throughout the cell it is possible to determine the maximum shear viscosity  $\eta_1 = 1/2(-\alpha_2 + \alpha_4 + \alpha_5)$  by analysing the light intensity variation induced by a flow [11]. A cell of constant thickness can also be used in this case [8]. To obtain the other principal shear viscosities: the minimum viscosity  $\eta_2 = 1/2(\alpha_3 + \alpha_4 + \alpha_6)$  and intermediate viscosity  $\eta_3 = 1/2\alpha_4$ , planar orientations along and normal to the flow direction were used (figure 1). In this case a narrow stripe with homeotropic

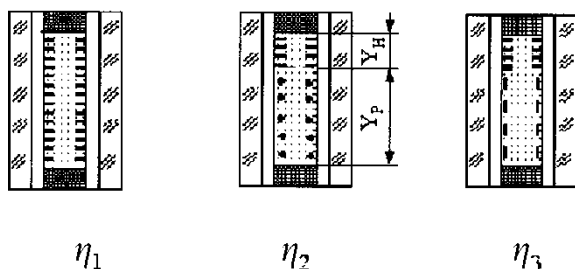


Figure 4. LC cells with different types of surface treatment used for the measurement of three shear principal viscosity coefficients; narrow homeotropic stripes are used to control the time variations of the hydrostatic pressure difference applied to the planar parts of the cells (the measurements of  $\eta_2$  and  $\eta_3$  viscosity coefficients).

orientation was also formed in the part of the LC cell with lowest thickness, to register the time variation of the light intensity and obtain the phase difference  $\delta(t)$ . According to equation (14),  $\delta(t)$  is proportional to the square of the pressure difference applied to the cell. So the change of phase difference can be used to control the time variation of a pressure difference. To make more precise measurements, we include the homeotropically oriented part of the LC cell, arranged onto a very narrow surface area (figure 4).

The homeotropic stripe does not affect the value of the measured viscosity, due to its very small contribution to the LC surface area, but allows us to obtain the time dependence of pressure with the highest accuracy. In all cases the measurements of viscosities were performed without external fields, so a small amount of LC (about 0.2 g) is quite sufficient to obtain surface stabilized samples.

The optical set-up is shown in figure 5. The LC cell was placed between two crossed polarizers oriented at  $45^\circ$  relative to the flow direction to register the flow-induced variations of the intensity of the light (He-Ne laser beam) passing through the homeotropic part of the cell. Two polarizers, a long focal-length lens and a diaphragm were used to scan a small area of the wedge-like LC cell. The optical signal was transformed into an electrical signal by the photodiode and was recorded and analysed by computer. The LC flow decay was induced by adding a quantity of LC to one of the vessels or by inclining the cell to provide the initial pressure difference. We do not need to know the exact value of the pressure difference  $\Delta P$ , as only relative changes of the optical intensity are used to determine the required viscosity coefficient. Nevertheless it is important to use relatively low values of the pressure difference to realize a linear regime of the director motion and to avoid possible hydrodynamic instabilities in the LC [11]. All the measurements were carried out at room temperature  $T = 22.5 \pm 0.5^\circ\text{C}$ .

Our attention was mainly concentrated on the LC mixture MLC 6609 produced for VAN LCD applications in which back-flow effects play an essential role.

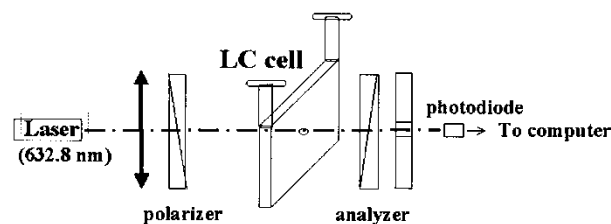


Figure 5. The experimental set-up for shear viscosity measurements.

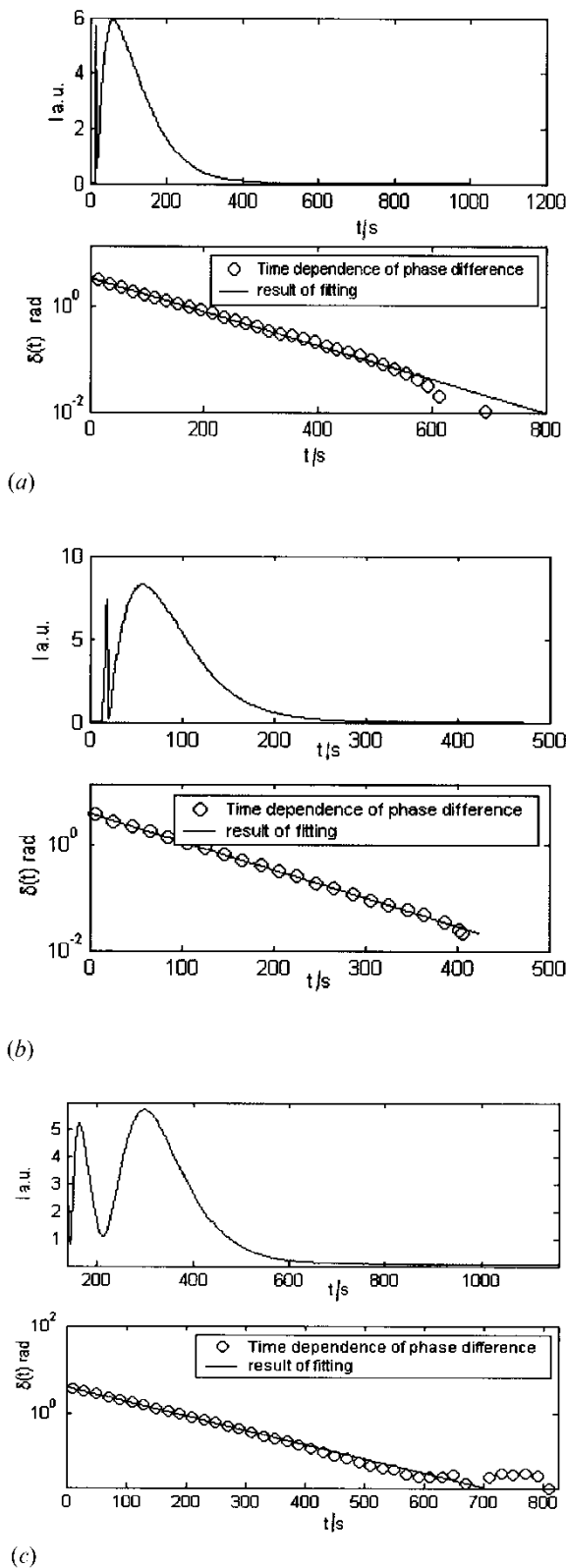


Figure 6. Optical response and time dependence of the measured phase difference in MLC6609 for the three principal geometries of a shear flow. The time-dependent phase retardations  $\delta(t)$ , equation (25), define

This mixture, with a high negative value of dielectric permittivity anisotropy ( $\Delta\epsilon = -3.7$ ), shows a low value of anisotropy of refractive index ( $\Delta n = 0.0777$ ). In this respect it differs considerably from nematic mixtures traditionally used in TN or STN (super twisted nematic) displays, where high values of  $\Delta n \approx 0.2$  are needed. It is simple to show that the accuracy of shear viscosity measurements via the optical method described will be increased for higher values of  $\Delta n$ , at least for a homeotropically aligned LC sample (see the Appendix).

#### 4. Results and discussion

The time dependence of the optical response of LC cells with different initial orientations in a decay flow is shown in figure 6. There is a relatively short time period after the initial jump of hydrostatic pressure difference needed to stabilize the free LC surfaces in the open tubes (this process is characterized by fast changes of light intensity). After that a quasi-stationary decay, shear flow takes place until a complete stop of the flow (slow variations of the light intensity). The variations of light intensity with time in this stage are non-monotonic and the local minima are less pronounced for cells of varying thickness in comparison with a homeotropic LC cell of constant thickness. This takes place due to the strong dependence, equation (13), of the phase difference  $\delta$  on the local thickness ( $\delta \sim d^7$ ). Thus relatively small thickness variations (about  $2 \mu\text{m}$ ) in a homeotropic part of a cell of a variable thickness result in rather large differences in the instant values of the parameter  $\delta$  (and light intensity  $I$ ) for light passing through different parts of the cell. Thus the registered average light intensity measured over a certain cell surface area does not reach the zero value predicted by the theory [1] (figure 6).

Nevertheless at the last stage of the relaxation process the calculated dependence of a phase delay  $\delta$  on time is quite well described by the simple exponential law (25) (figure 6). It confirms the validity of the simple linear model of the decay flow presented, and provides a calculation of the three principal viscosities of the investigated liquid crystal mixture which were found to be:  $\eta_1 = 0.156$ ,  $\eta_2 = 0.022$ ,  $\eta_3 = 0.037$  Pa s.

We need to know the parameter  $K$  (22) to obtain the values of the shear viscosities. The value of  $K$  can be calculated if the exact geometric dimensions of a plane capillary are known. We used this procedure for

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the corresponding decay times  $\tau_\delta$  and anisotropic shear viscosities  $\eta_i$  of the LC. (a)  $\tau_\delta = 132$  s,  $\eta_1 = 0.156$  Pa s; (b)  $\tau_\delta = 81.8$  s,  $\eta_2 = 0.022$  Pa s; (c)  $\tau_\delta = 134.8$  s,  $\eta_3 = 0.0371$  Pa s.

homeotropic cells of variable and constant thickness [11, 14] (in the latter case the local thickness of the cell was obtained via electric field application and found to be  $80.5 \pm 2 \mu\text{m}$ ). However this method does not provide a sufficiently high accuracy; experimental errors are about 10% because of boundary layers and thickness inhomogeneity through the cell. Better results were obtained via calibration of the capillary using liquid crystals with known values of the anisotropic shear viscosities, e.g. 4-pentyl-4'-cyanobiphenyl (5CB) [15] or isotropic liquids. Our model works quite well in these cases. For isotropic liquids the capillary can be calibrated via visual observation of the motion of the levels in the open tubes. To obtain good accuracy, a sufficiently high initial difference of the levels must be provided. This problem can be easily solved, at least for simple liquids showing Newtonian-like behaviour. In particular, in experiments using distilled water we found that our model described the decay flow quite well up to an initial pressure difference of about 5000 Pa (in the experiments with liquid crystals this parameter was less than 20 Pa to provide quasi-Newtonian behaviour). We have shown that in most cases the experimental errors did not exceed 5%, if a calibration procedure was performed appropriately. Some specific errors of the method described are discussed in the Appendix.

We previously used the same model of the decay flow to analyse flow-induced optical transformation in a homeotropic sample of MBBA with variable thickness [11]. The value of the shear viscosity estimated from these experiments was in an accord with the existing data.

We also recently observed the same behaviour for the LC mixture LC440 (NIOPIK production) with material parameters ( $\Delta\varepsilon = -0.35$   $\Delta n = 0.238$ ) quite different from those of MLC 6609 [16]. The values of anisotropic viscosities in this case, determined by the proposed method, were found to agree with independent measurement data [17]. Thus the method described here can be considered as quite general for the determination of anisotropic shear viscosity coefficients of nematic liquid crystals.

### 5. Conclusion

A new optical method for the determination of anisotropic shear viscosities of nematic liquid crystals is proposed. Liquid crystal cells oriented by surface treatment are used without the application of magnetic fields. The quasi-stationary flow decay induced by a pressure difference is controlled by the optical set-up. The time-dependent intensity of light passed through the crossed polarizers is used to determine the decay time of the flow, which is proportional to the

corresponding LC shear viscosity, defined by LC director alignment on the cell surface. The experimental set-up requires inexpensive equipment and a relatively small amount of LC (about 0.2 g). The proposed method is very useful for studying the viscous properties of newly synthesized liquid crystals, yielding information needed to optimize LC devices in which back-flow effects plays an essential role, e.g. vertical aligned nematic LCDs used in modern TV LCD applications [3].

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### Appendix

We now consider the possible errors induced into the measured shear viscosity coefficients due to the approximations used. First we must take into account the effect of slight changes of the initial orientation on the calculated viscosity. This effect is most pronounced for a homeotropic cell of constant thickness, where such changes take place throughout the whole cell. It is easy to show that for linear deformations of a homeotropic orientation the effective viscosity can be expressed as:

$$\eta = \eta_1 - (\eta_1 - \eta_2) \langle \theta^2 \rangle \quad (\text{A1})$$

where  $\langle \theta^2 \rangle$  is the value of the director angle  $\theta^2$  averaged over the cell thickness, and the motion of the director is considered to be in the plane of the flow. Thus the deviation  $\Delta\eta$  of the effective viscosity from the principal viscosity coefficient  $\eta_1$  can be estimated as:

$$\Delta\eta/\eta_1 = (1 - \eta_2/\eta_1) \langle \theta^2 \rangle. \quad (\text{A2})$$

The value of  $\langle \theta^2 \rangle$  can be calculated from expression (13) for the phase difference  $\delta$ . For the LC mixture under investigation we have found that a maximum relative deviation  $\Delta\eta/\eta_1$ , that corresponds to the maximum value of the phase difference presented in figure 6, is about 4%. Taking into account that the shear viscosity  $\eta_1$  was calculated using the light intensity data averaged through the whole time of the final relaxation process (see figure 6), we believe that an error of about 2% can be induced by the effect mentioned above. This leads to a certain decrease of the calculated effective viscosity in comparison with the real value.

For LC cells of a variable thickness with different types of orientation, the influence of the homeotropic part of the cell on the calculated viscosities must be taken into account. A liquid crystal cell of this type can be considered as two channels ('homeotropic' and 'planar'), connected in parallel, filled with fluids of different viscosities, e.g.  $\eta_1$  and  $\eta_2$ . The total hydrodynamic



conductivity  $Y$  of such a system is equal to the sum of the conductivities ( $Y_H$  and  $Y_P$ ) of these channels (figure 4):

$$Y = - (Q/\Delta P \eta) = Y_H + Y_P \quad (\text{A3})$$

where, due to the expressions (17), (18), (21) and (27):

$$Y_H = R_H^{-1} = 6K_H S = \frac{A_H(d_b + d_0)(d_b^2 + d_0^2)}{2L\eta_1} \quad (\text{A4})$$

$$Y_P = R_P^{-1} = 6K_P S = \frac{A_P(d_{\max} + d_b)(d_{\max}^2 + d_b^2)}{2L\eta_2} \quad (\text{A5})$$

where  $d_b = d_0 + (d_{\max} - d_0)(A_H/A)$  = the local thickness in the vicinity of the boundary between the homeotropic part of the cell and the planar part,  $A_H(A_P)$  = the width of the 'homeotropic' ('planar') channel, and  $A = A_H + A_P$  = the total width of the cell (figure 2).

The effective shear viscosity  $\eta$  entering into the model is determined by the expression:

$$Y = R^{-1} = 6KS = \frac{A(d_{\max} + d_0)(d_{\max}^2 + d_0^2)}{2L\eta}. \quad (\text{A6})$$

Taking into account expressions (A3)–(A6) one can easily derive an equation for the effective viscosity:

$$\eta = \frac{(\eta_1 \eta_2) A (d_{\max} + d_0) (d_{\max}^2 + d_0^2)}{\eta_2 A_H (d_b + d_0) (d_b^2 + d_0^2) + \eta_1 A_P (d_b + d_{\max}) (d_b^2 + d_{\max}^2)}. \quad (\text{A7})$$

For the cells used in this work the value  $A/A_H$  was chosen to be about 10 and so the experimental errors connected with the effect under consideration are less than 3%. It is worthwhile to note that the same errors can exceed 10% if a cell of constant thickness with the same ratio  $A/A_H$  is used.

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