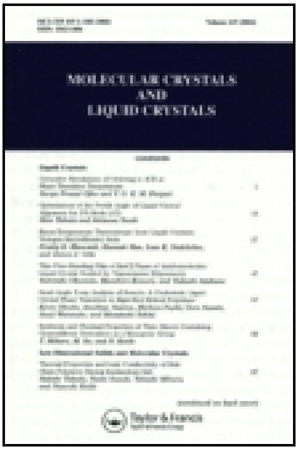

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S. V. Pasechnik [a], D. V. Shmeliova [a], V. A. Tsvetkov [a], A. P. Krekhov [b] & I. Sh. Nasibullayev [b]

[a] Moscow State Academy of Instrument Engineering and Computer Science, Moscow, Russia

[b] Institute of Molecule and Crystal Physics, Russian Academy of Sciences, Ufa, Russia

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ORIENTATIONAL DYNAMICS IN NEMATIC LIQUID CRYSTAL UNDER DECAY POISEUILLE FLOW

S. V. Pasechnik, D. V. Shmeliova, and V. A. Tsvetkov
Moscow State Academy of Instrument Engineering and Computer Science, Stromynka 20, Moscow 107846, Russia

A. P. Krekhov and I. Sh. Nasibullayev
Institute of Molecule and Crystal Physics, Russian Academy of Sciences, prosp. Oktyabrya 151, Ufa 450075, Russia

We report the results on the orientational dynamics and instabilities in nematic liquid crystal MBBA induced by decaying Poiseuille flow. The experiments were carried out in the rectangular wedge-shape LC cell with thickness varying perpendicular to the flow direction and the confining plates provided homeotropic alignment of a nematic liquid crystal. Increasing the values of initial pressure difference the orientational instability corresponding to the escape of the director out of the shear plane was observed for the first time. This "out-of-plane" transition takes place at some critical pressure difference ΔP_c which depends on the local thickness of NLC layer. The results of numerical simulations of governing nematodynamic equations are in a good agreement with experimental data on the threshold of "out-of-plane" instability.

Keywords: nematic liquid crystal; orientational instability; Poiseuille flow

INTRODUCTION

Low molecular weight nematic liquid crystals (NLCs) represent the simplest anisotropic fluid and serve as a paradigm in the study of rheological behavior and structural transformations of different types of complex

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Address correspondence to S. V. Pasechnik, Moscow State Academy of Instrument Engineering and Computer Science, Stromynka 20, 107846, Moscow, Russia. E-mail: s-p-a-s-m@hotmail.ru

fluids, such as, e.g., lamellar phases of surfactant solutions, liquid crystal polymers and block copolymer melts. In NLCs complex flow behavior arises from the strong coupling between the translational motion (velocity field $\mathbf{v}$) and the preferred local molecular orientation described by the director $\mathbf{n}$. Orientational instabilities in NLCs under steady flows were intensively studied in the past. There are two different cases depending on whether the initial alignment of the director provided by the confining plates is perpendicular to the shear plane (defined by $\mathbf{v}$ and $\nabla\mathbf{v}$) or within the shear plane. The first case has been investigated in classical experiments by Pieranski and Guyon [1,2] and theoretical works of Dubois-Violette and Manneville [3]. One finds that the type of instability strongly depends on the sign of the product of Leslie viscosity coefficients α_2 and α_3. For nematics with $\alpha_2\alpha_3 > 0$ in the absence of external fields the first instability is homogeneous in both steady Couette and Poiseuille flows. In the case of $\alpha_2\alpha_3 < 0$ (non-flow-aligning materials) only rolls are expected. In the situation when the director is prealigned within the shear plane the initial orientation is non-uniformly distorted by the flow and the orientational behavior of NLCs can be quite complex. Many aspects of NLC dynamics for such prealigning have not yet been clarified completely. The only instability observed in a such geometry is a tumbling motion in NLCs with $\alpha_2\alpha_3 < 0$ [4,5] whereas for usual nematics with $\alpha_2\alpha_3 > 0$ there were no instabilities under steady flows found up to now. The analysis of steady Poiseuille flow in NLC with homeotropic anchoring (director is perpendicular to the confining plates) shows that the distorted within shear plane director orientation becomes unstable above certain critical value of the pressure gradient and the director escapes the flow plane [6]. Similar instability was predicted for the oscillatory Poiseuille flow [7] and found recently in experiments [8].

In this paper we present experimental and theoretical results on the orientational behavior and instabilities in nematic liquid crystal MBBA subjected to the decaying Poiseuille flow.

EXPERIMENTAL

We used special rectangular wedge-shape cell with the thickness varying in the direction perpendicular to the flow (Fig. 1). Such construction allows to perform simultaneous observations and measurements for the local thickness of NLC layer over the range $33 \div 210\,\mu\text{m}$. The confining glass plates with transparent electrodes were treated by chromolan to provide homeotropic alignment of NLC. The decaying Poiseuille flow (along x axis) was induced by the initial pressure difference ΔP_0 imposed by the difference of the levels of NLC ΔH_0 in the tubes attached to the opposite sides

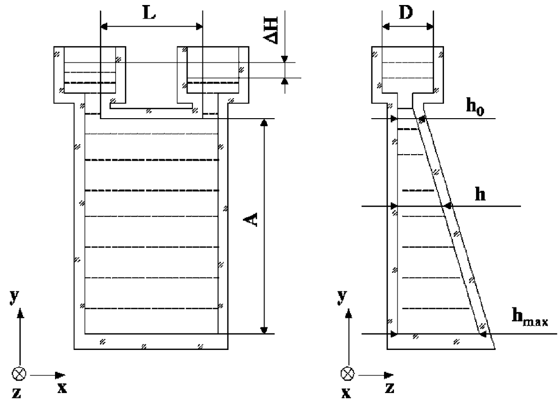

FIGURE 1 The wedge-shape LC cell: front-view (left) and side-view (right). $A = 10\,\text{cm}$, $L = 1\,\text{cm}$, $D = 1.5\,\text{cm}$, $h_{max} = 210\,\mu\text{m}$, $h_0 = 33\,\mu\text{m}$.

of the cell. Introducing given amount of NLC in one of the tubes allow to control the initial pressure difference ΔP_0 with the accuracy 5%. Using this setup we were able to produce slow decaying Poiseuille flow with typical decay time in $6 \div 10$ times larger than the director relaxation time. The experiments were performed with NLC MBBA and the temperature of the cell was kept at $T = 22 \pm 0.5°\text{C}$.

The response of the NLC was detected optically by exploiting its birefringence. The transmitted light intensity (along z axis) at wavelength 632 nm (He-Ne laser) was measured by a photo diode integrating over the cell area of 0.3 mm in diameter for two geometries of crossed polars: “a” – polariser at 45° with respect to the flow direction; “b” – polariser parallel to the flow direction. The latter geometry allows to monitor the possible escape of the director orientation out of the shear plane (x-z plane). The optical system was designed in such a way that one can combine the registration of the transmitted light intensity at some given position along y axis together with recording of the microscopic images of the whole cell. Due to the large aspect ratio of the cell $[\mathrm{A}/((\mathrm{h}_0 + \mathrm{h}_{\max})/2) \approx 800]$ one may expect rectilinear Poiseuille flow along x axis except in thin boundary layers near the edges. Indeed, from the motion of small trace particles ($2 \div 4\,\mu\text{m}$ in diameter) immersed in NLC no y-component of the flow was detected.

RESULTS AND DISCUSSION

For small initial pressure difference ($\Delta P_0 \sim 1\,\text{Pa}$) no signal of the transmitted light intensity was detected in geometry “b” therefore director remained within the shear plane (x-z). The dependencies of the phase retardation between extraordinary and ordinary rays $\delta(t)$ recalculated from the data on the transmitted light intensity $I(t)$ measured in geometry "a" demonstrate an exponentially decaying behavior for different values of the local thickness of NLC layer. Typical example is shown in Figure 2 (curve 1). Considering small deviations of the director orientation from the initial homeotropic alignment one can deduce the following expression for the time evolution of the phase retardation $\delta(t)$ [9]:

$$\begin{aligned} \delta(t) &= \delta_0\, exp(-t/\tau^{\delta}), \quad \tau_\delta = \eta_{hom}/(\rho g k_0), \\ k_0 &= A(h_{max}+h_0)(h_{max}^2+h_0^2)/(3\pi D^2 L), \end{aligned} \tag{1}$$

where $\eta_{hom} = (-\alpha_2 + \alpha_4 + \alpha_5)/2$ is the viscosity of the homeotropically oriented NLC, ρ is the mass density of NLC, g is the gravity acceleration and k_O (has dimension of length) is the capillary constant. The experimental data on $\delta(t)$ can be very well approximated by (1) with η_{hom} as a fit parameter and we obtained for MBBA $\eta_{hom} = 0.16 \pm 0.02$ Pa·s which perfectly agrees with independent measurements [10,11]. Our results demonstrate a good ability to exploit a decay Poiseuille flow for the measurements of the viscosity coefficients of NLCs.

With increasing of initial pressure difference ΔP_0 up to ~ 10 Pa the dependencies $\delta(t)$ start to deviate from the simple exponential behavior (1). The transmitted light intensity $I(t)$ registered in the geometry "b" in

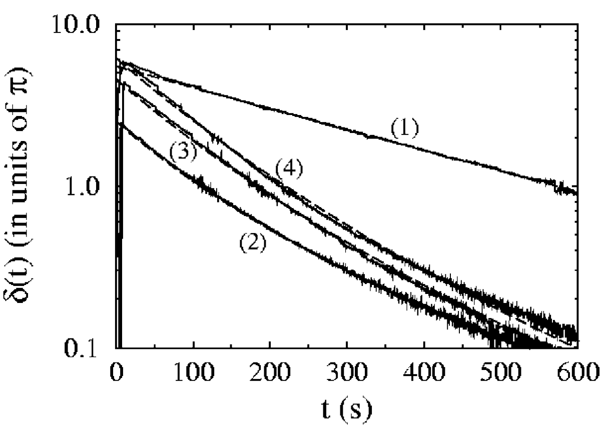

FIGURE 2 Time dependence of the phase retardation δ(t). Experimental data (solid lines) and best fit (dashed lines): (1) $-\Delta P_0 = 1.5$ Pa, $h = 164\,\mu$m; (2) $-\Delta P_0 = 9.4$ Pa, $h = 70\,\mu$m; (3) $-\Delta P_0 = 12.8$ Pa, $h = 70\,\mu$m; (4) $-\Delta P_0 = 15.5$ Pa, $h = 70\,\mu$m.

the region of large local thicknesses of NLC layer shows two peaks which signals the director escapes out of the shear plane. This out-of-plane transition is clearly visible on the microscopic images of the cell (Fig. 3). The boundary with y-coordinate y_b and corresponding thickness of NLC layer h_b separates two regions with the local thickness $h < h_b$ (I) and $h > h_b$ (II). In geometry "a" one observes wide interference stripes in the region I changing to narrow interference stripes in region II. Using the geometry "b" one can identify that the region I corresponds to the director orientation within the shear plane (dark image field) whereas in the region II one has out of the shear plane director component (white image field). Below the region II where the out-of-plane transition is developed the transmitted light intensity in geometry "b" is decreased as the local thickness is increased. This points out that the director orientation becomes perpendicular to the flow plane for larger local thicknesses of NLC layer. The dynamics of the out-of-plane transition can be described as follows. Immediately after applying the initial pressure difference the white band similar to the region II in Figure 3 (b) observes in the part of LC cell corresponding to the large local thicknesses.

This white band moves quite fast in y direction to the region of smaller local thicknesses and becomes narrow. After this initial process the white band stops at some y position and starts slow reverse motion in the direction of larger local thicknesses. This last stage allows to detect the time

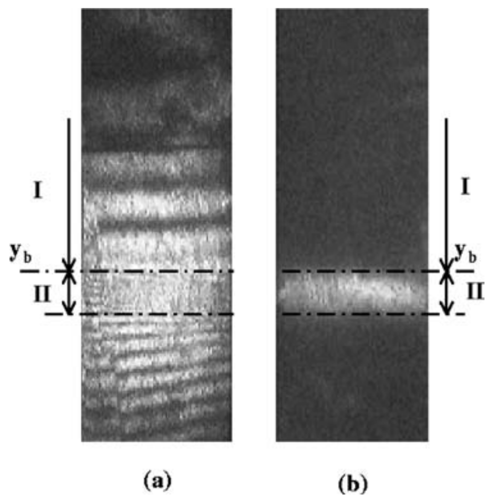

FIGURE 3 Microscopic images of the cell in crossed polars in geometry "a" (a) and "b" (b) taken at $t = 90\,\mathrm{s}$ and $\Delta P_0 = 15\,\mathrm{Pa}$.

dependence y_b (t) of the position of boundary between the regions of in-plane and out-of-plane director orientations. The time dependence of the pressure difference $\Delta P(t)$ can be restored from the data on phase retardation $\delta(t)$ obtained simultaneously in the region of small local thickness. Here the director always remains within the shear plane and the deviations from the homeotropic alignment are small, therefore $\delta(t) \sim [\Delta P(t)]^2$ [12,10]. In the case of large initial pressure difference the phase retardation $\delta(t)$ can be approximated by the exponential dependence with slow varying relaxation time $\tau_\delta = \tau_\delta(t)$. Since after applying the initial pressure difference the director orientation becomes nearly perpendicular to the shear plane in the main part of the cell and during flow decaying the director returns back into the shear plane we deduce the following semi-empirical expression for $\tau_\delta(t)$:

$$\tau_\delta(t) = \eta_{hom}/(\rho g k_0)[1 - (1 - \eta_{per}/\eta_{hom})\, exp(-t/\tau_0)], \tag{2}$$

where $\eta_{per} = \alpha_4/2$ is the viscosity corresponding to the director orientation perpendicular to the shear plane and τ_0 is a fit parameter. The relative change of the relaxation time stipulated by the change of the effective viscosity during the director reorientation from the position perpendicular to the shear plane to the homeotropic alignment reads $\tau_\delta(0)/\tau_\delta(\infty) = \eta_{per}/\eta_{hom}$ and for the material parameters of MBBA at $T = 22°C$ $\eta_{per}/\eta_{hom} = 0.31$ [10,11]. The experimental data on $\delta(t)$ obtained for different initial pressure differences are described very good by the dependence $\delta(t) = \delta_0\, exp[-t/\tau_\delta(t)]$ with slow varying $\tau_\delta(t)$ from (2) (Fig. 2, curves 2, 3 and 4).

Using the data on $y_b(t)$ and $\Delta P(t)$ one can find the dependence of the critical pressure difference ΔP_c for the out-of-plane transition on the local thickness of NLC layer h_b. In Figure 4 we show $\Delta P_c(h_b)$ obtained for the different values of initial pressure difference ΔP_0. The data become close as the thickness increases (larger times and more quasistationary flow).

On Figure 4 we also present the results obtained from the direct numerical simulations of the standard set of nematodynamic equations [13] where the director and velocity are functions only of the coordinate z and time t (see [14] for details). The material parameters of MBBA at $T = 22°C$ were used [15,11]. For the set of thicknesses of plane NLC layer and given from the experiment dependence $\Delta P(t)$ the orientational dynamics was simulated. One finds that starting from the homeotropic director orientation for the thicknesses larger than certain critical value (depending on ΔP_0) the out-of-plane transition is occurred and as the flow decays the director returns back to its initial alignment. The critical value of ΔP_c corresponds to the current value of $\Delta P(t)$ at which the director goes back into the shear plane. The results of simulations are in a good agreement with the experimental data taking into account the approximation of the wedge-shape cell

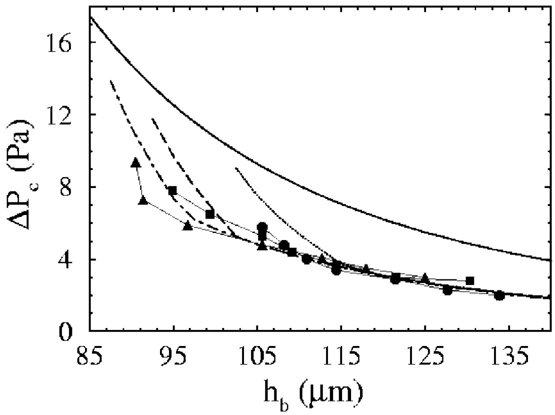

FIGURE 4 Critical pressure difference for the out-of-plane transition as a function of NLC layer thickness. Experimental data (symbols) and calculated (lines): $\Delta P_0 = 9.4\,\mathrm{Pa}$ – circles and dotted line; $\Delta P_0 = 12.8\,\mathrm{Pa}$ – squares and dashed line; $\Delta P_0 = 15.5\,\mathrm{Pa}$ – triangles and dot-dashed line. Solid line corresponds to steady Poiseuille flow.

by a set of rectangular capillaries and some inaccuracies due to the indirect determination of $\Delta P(t)$ in the experiments. Comparing with the case of steady Poiseuille flow (Fig. 4) where the critical pressure difference for the out-of-plane transition $\Delta P_c^{st} \sim 1/h^3$ we found that in decay flow ΔP_c is smaller. This can be explained by the following: after the current pressure difference in decaying flow becomes smaller than the critical one for the steady flow it takes some time for the director to return into the shear plane.

CONCLUSION

We have investigated experimentally and theoretically the orientational behavior of NLC under decaying Poiseuille flow. It was shown that the described experimental setup is suitable for the measurements of the viscosity coefficients of NLCs with a good accuracy. For the first time we have observed the out-of-plane instability in NLC MBBA subjected to quasistationary Poiseuille flow and obtained the dependence of the critical pressure difference on the thickness of NLC layer. The experimental results are in a good quantitative agreement with theoretical calculations without any adjustable parameters. Further studies of the influence of an electric field applied across the NLC layer on the scenario of orientational instabilities under decay Poiseuille flow are in progress.

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