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LC ELECTROHYDRODYNAMIC PUMP

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We present results of a study of the movement of ions in nematic liquid crystals (LCs).Just after applying of the driven voltage, the flow of ions is arisen in LC-medium and the ion front begins to move to one of the electrodes. The movable ionic carries involve in the movement neighboring LC molecules (neutral in the electrical charge). If the LCmedium has a limited volume, then a closed system of internal hydrodynamic flows is arisen, which looks like a slowly moved pattern of the curved interference strips.

If the lateral end faces of the studied LC cell are closed to each other by an external pipeline, the neutral LC molecules move in the direction of the flow of ions all the time while the driven voltage is applying to the cell electrodes (electrohydrodynamical pump mode). If the external pipeline is open, the flow of LC is stopped in a little while after the driven voltage applying, the LC levels are different in the height for the each pipeline ends. The difference in LC levels characterizes the magnitude of the pressure created by such an electrohydrodynamical pump.

The obtained results are discussed with the possible applying the given experimental technique for LC parameters studying.

Keywords: ions; LC; pump; volumetric charge

INTRODUCTION

It is well known that electric field application can induce a motion of isotropic liquids due to a number of mechanisms [1,2]. In some cases this motion is intensive enough to use it in electric-hydrodynamic pumps of different construction. The meaning of electrically induced motion of anisotropic liquids for liquid crystal displays characteristics are conscious too (back-flow effects, for example). In the latter case EHD phenomena take place in thin layers of nematics placed in confined cells. A constant electric

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field induces in this case closed EHD flows visualized as domains of different topology (Williams-Kapustin domains, loop-like domains etc.). The space structure of the flows is determined by electric characteristics of liquid crystal samples, boundary conditions and by the direction of electric field. In particular, we observed the slow chaotic motion of fluid induced by positive ion moving under the action of the field, applied in the plane of nematic layer [3]. Of course the character of motion of anisotropic liquid has to be quite different in the cell with two open edges. Such cells were previously used in our experiments with alternating Poiseuille flows [4], where a liquid crystal motion was induced by pressure gradient and quasi-isotropic parabolic velocity profile was formed at a linear regime of director distortions.

The aim of the experiments described in present paper is to show that analogous type of motion can be realized in the cell mentioned above due to constant electric field application in the plane of the layer.

It is known [1] that there are two main methods to induce the flows in isotropic liquid dielectric with the help of electric field (Fig. 1). Firstly a high voltage can be applied directly to the sample of homogeneous liquid. In the case of moderate values of field strength ($E \leq 1\,kV/cm$ for most liquids including organic dielectrics) the flow of fluid is induced by field due to the motion of ions, which are originated under the action of dissociation processes (the Ohm's Law is fulfilled in this case). In more intensive fields the injection of charges from electrodes begin to play an essential role and an inclination from Ohm's Law takes place. The intensive fluid motion observed at high values of E can be used at an elaboration of different constructions of electro-hydrodynamic pumps [1,5].

More complicated phenomena take place when two electrodes are separated by an inhomogeneous partition consisted of a number of microscopic pores (some micrometers in diameter) in a dielectric material filled by a polar liquid under consideration. The system glass- water may be used for example. In this case the absorption of polar molecules on the boundary liquid-solid leads to an existence of a binary electric layer. The outer diffuse part of this layer of thickness about 1 μm has a surplus charge, which can move under electric field applied along the pores. The sign of the charge depends presumably on the difference of dielectric constants of solid ε_s and liquid ε_l (the positive charge takes place if $\varepsilon_l > \varepsilon_s$). The flow velocity V in pore is proportional to the boundary potential jump (ς-potential) and applied voltage U:

$$V = S.(\varsigma.U)/(4\pi\eta 1), \tag{1}$$

where S - a cross-section area of the pore, l - the distance between electrodes, η - the shear viscosity of the liquid. The described phenomena were used in some constructions of electro-hydrodynamic pump [5].

In this work the first attempt (to our knowledge) of realization of phenomena mentioned above for the case of an anisotropic liquid is described.

EXPERIMENTAL

Liquid crystal cell of a special construction was used to study the electric field induced motion of an anisotropic fluid (Fig. 2). The cell consists of two connected parts. The first one (the left part in Fig. 2) serves as a generator of fluid motion while the second part (the right part in Fig. 1) is used to detect this motion. The last-mentioned part made of two glass plates 1,2 with transparent electrodes 3, 4 is analogous to the sandwich-like

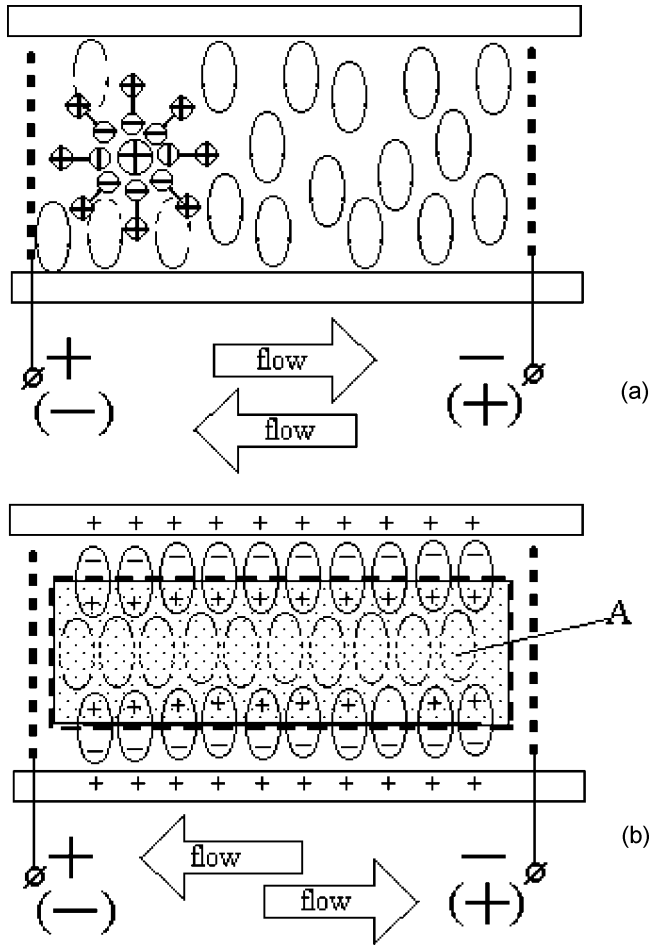

FIGURE 1 Two mechanisms of flows occurrence: a-ionic, b-electro-kinetic.

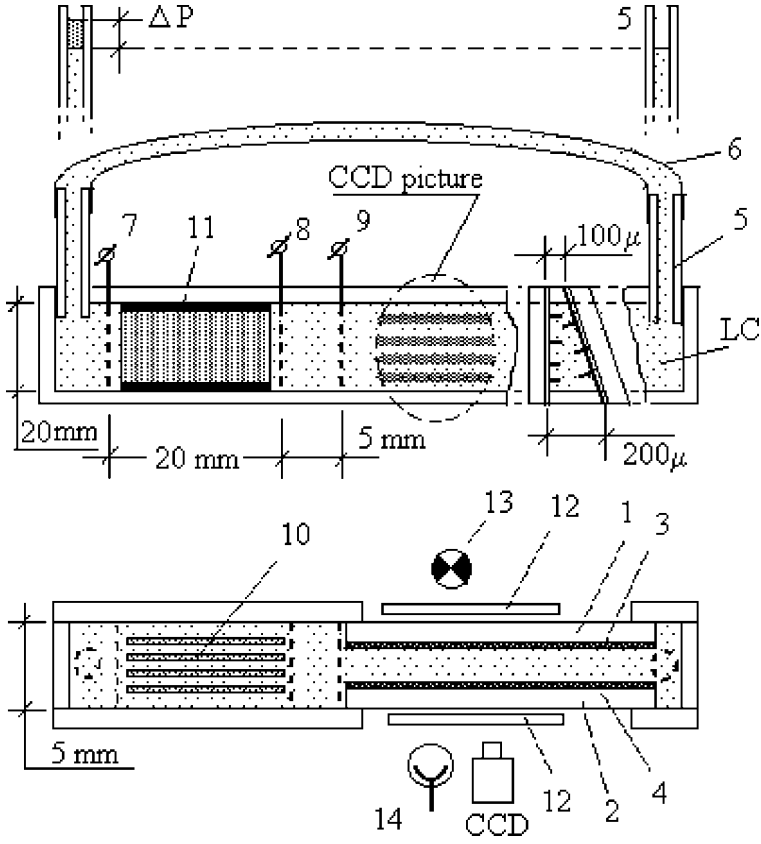

FIGURE 2 Experimental setup.

cell of a variable thickness (100...300 μm in the described experiments) used by us earlier to register a low-pressure difference [6]. It can be approximated by a number of plane channels of different thickness due to a small value ($\sim 0.3^{\circ}$) of the angle between 1 and 2 plates. The inlet pipes 5 and the tube 6 are needed to create a circular fluid motion (there are equal levels in inlet pipes in the absence of the tube 6 and electric field).

The left part of the cell contains metallic (iron-nickel alloy) reticular electrodes 7, 8, 9 with the integrated cross-section of holes equal to a half of the total cross-section of the electrodes. The stack 10 of 20 glass plates separated by spacers (a thickness of spacers and plates is equal to 100 μm) is immersed into a fluid between the electrodes 7, 8 to get an electric-kinetic pump, while the electrodes 8, 9 can be considered as an ionic pump.

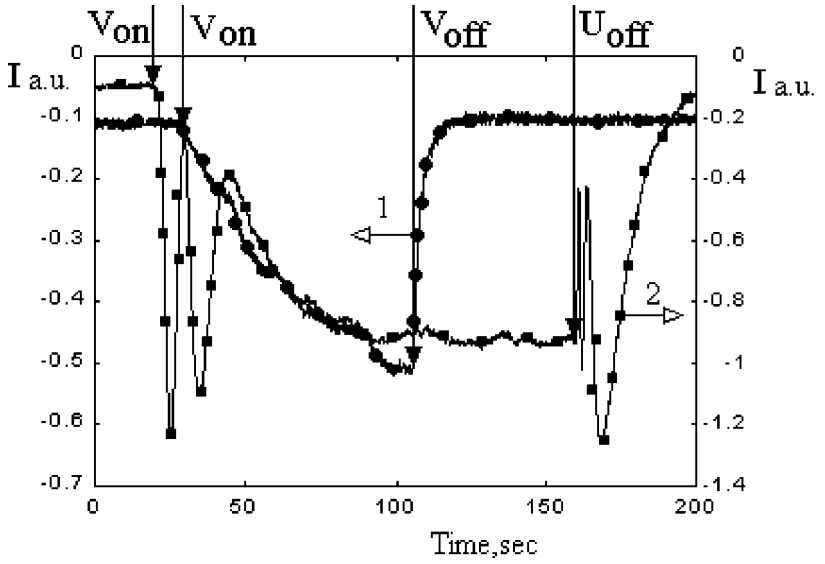

FIGURE 3 Response of the measuring part of LC cell on the driving voltage applied to pump electrodes: 1–542 V to ionic pump, 2–411 V to elector-kinetic pump.

The stack plays the same role as the porous partition in the mentioned above electric-kinetic phenomena, which takes place at a boundary isotropic liquid-solid. At the same time the simple flow geometry realized in the stack is very perspective for further study of peculiarities of such phenomena in an anisotropic fluid taking into account the possibility of a control of LC orientation due to fields and surfaces.

The registration of the electrically induced fluid motion can be achieved due to connection between the orientation and the velocity field in nematics. It provides the optical changes, which were observed in the right part of the cell via CCD camera using the crossed polarizes 12, oriented at 45° to the direction of flow motion. The local optical response was registered with the help of the light source 13 (He-Ne laser, $\lambda = 0.63\,\mu m$) and the photodiode 14.

The liquid crystal mixture LC 616 with a positive value of a dielectric permittivity anisotropy ($\Delta\varepsilon = +3.4$) produced by NIOPiK. Quasi-homeotropic initial orientation was created in the measuring part of the cell due to a polymer coating.

RESULTS AND DISCUSSION

In the absence of electric field and flows the measuring part of the cell looks in crossed polarizes like a homogeneous dark area due to an initial

quasi-homeotropic orientation. The electric voltage applied to 7, 8 or 8, 9 electrodes leads to the changes of the intensity ΔI of a polarized light passing through the cell. These changes are the stationary ones in the case of usage of the connecting tube 6, which means that electric field produces a stationary circular shear flow in the system under consideration. It is easy to show that the changes of the orientation (and of the optical transmission) have to be different for different parts of the liquid crystal layer of a variable thickness. Indeed, taking into account the mentioned above approximation of the cell by a number of plane channels of a local thickness **h** one can find from the linearized hydrodynamic equations solved for a stationary flow and strong boundary anchoring [4], that

$$\langle\theta^2\rangle \sim \mathrm{G}^2 * \mathrm{h}^6 \tag{1}$$

where $\langle\theta^2\rangle$ - the average squared value of the angle θ between the director and the normal to the glass plates, G - the pressure gradient, which is the same for different channels. So, the phase difference δ between an extraordinary and an ordinary rays:

$$\delta = 2\pi h \ \triangle n \ \lambda^{-1}\langle\theta^2\rangle \sim h^7 \tag{2}$$

and the flow induced changes of the light intensity:

$$\Delta\mathrm{I} = \mathrm{I}_0 * \sin^2(\delta/2) \tag{3}$$

have to depend strongly on the local thickness **h** (in Eq. (2–3) Δn and I_0 - an anisotropy of refractive indexes and input light intensity). The last dependence provides a visualization of weak shear flows in the cell of a variable thickness as a number of interference stripes parallel to the flow direction. The estimates made on the base of (1)–(3) have shown that the first dark stripe in the middle of the cell (where optical response was recorded) has to be observed at $\mathrm{G} \cong 40\,\mathrm{Pa/m}$ for $\mathrm{h} = 150\,\mu\mathrm{m}$ and $\lambda = 0.63\,\mu\mathrm{m}$. For these conditions the maximal velocity of fluid in the center of channel is about $5\,\mu\mathrm{m/sec}$ and the total volume flux of LC through the cell approximately equal to $0.05\,\mathrm{mm}^3/\mathrm{sec}$). Indeed, we have observed the existence of a stationary system of interference stripes at high enough voltage applied to the electrodes, which can be moved to the region of lower thickness by voltage increasing. The time dependence of the light intensity, obtained under an application of electric voltage to the stack of glass plates (electric-kinetic pump) is presented in Figure 3. One can point out a relatively long time (about 30 s) of relaxation of the system to the stationary state presumably connected with a formation of a binary electric layer (the time of a relaxation of the layer to the initial state is essentially less and is about some seconds). The local extremes on the I(t) dependence reflect the moving of interference stripes described above. Using

experimental I(t) dependencies one can calculate the maximal phase difference δ to compare it with the theoretical estimates and to establish the dependence of the field induced pressure difference ΔP on electric voltage (at a linear regime of a director motion $\delta \sim \Delta P^2$ accordingly to Eq. (1–2)). The obtained dependence $\Delta P(U)$ is closer to the quadratic low than to the linear one, which takes place in the case of isotropic liquids. Presumably this fact can be connected with non-Newtonian behavior of flows of liquid crystals.

Under applying voltage to 8, 9 electrodes (the ion pump) we have observed the phenomena similar to described above. But in this case a higher value of electric strength has to be used to get the same optical response as in the case of electric-kinetic pump. For example, the minimal values of E at which we have registered the optical changes were about 20 V/mm and 5 V/mm accordingly for the ionic and the electric-kinetic pumps. It is worthwhile to note that these values of E are essentially lower than those ($\sim$100 V/mm) obtained for EHD effects in usual thin cells.

To determine the direction of flow motion we have removed the tube 6. In this case the flow of liquid has to be stopped under the action of a hydrostatic pressure which arises due to the difference of levels in the inlet pipes. It demands some minutes, so one can try to create the opposite pressure difference (relatively to that induced by electric field) by a change of the level in the first or the second inlet pipe at the first stage of fluid motion. Inserting the known volume of LC in one of the inlet pipes did this.

We have performed such experiments and established that in the two types of pumps under consideration the flow motion is induced by the motion of bulk charges of different signs (namely plus for the ionic pump and minus - for the electric-kinetic pump). Moreover we were able to create the hydrostatic pressure difference ΔP_c which is needed to stop the fluid motion (in this case the LC layer returns to an initial homeotropic orientation which is easy to observe in the proposed cell). The calculated value of ΔP_c was about 1 Pa at 264 V for the electric-kinetic pump and 1 Pa at 540 V for ionic one. This value is in accordance with the estimates of the field induced pressure gradients made above from the analysis of an optical response.

In conclusion we want to point out that there a lot of possibilities to prolong this first investigation using controlling electric (magnetic) fields, different surface treatment, the LC substances with different electric characteristics and so on. Of course, the effectiveness of the described pumps is low enough in the comparison with the existing "isotropic" devices used for pumping of liquids in industry, but it may be very useful in scientific studies of EHD effects and flow phenomena in liquid crystals.

CONCLUSION

1. We observed a movement LC at extremely low levels of electrical fields in the comparison with those for usual LC cells. This movement is precisely fixed at voltage more than 100 V. For ionic pump intensity of the electrical field, at which the movement is fixed, makes 100 V/5 mm or 0.02 V/μm, for electro-kinetic pump - 100 V/20 mm or 0.005 V/μm. In recalculation for usual LC cell with LC layer thickness of 10 μm the voltage, at which the movements are fixed, make 0.5–0.2 V. This value of voltage lower, than threshold voltage of the majority of electrooptical effects in LCs. It is possible, that flows under consideration arising at voltage lower, than the threshold voltage of electrooptical effects, can essentially influence them, and have to be taking into account in a theoretical description of such phenomena.
2. There are a lot of possibilities to extend the described studies of anisotropic fluid flows induced by ions motion. In particular, one can study an influence of electric carries of different types (different sizes of ions, different valences, different mobility's on the action of the ionic pump). The presented results on the movement of LC under the action of driven ions show the opportunity to operate this movement in a wide range. It provides the ample opportunities for researches of influence of a different type of carriers (for the ionic pump). In the case of the electro-kinetic pump it is interesting to realize the experiments with LC of different dielectric permittivity and it's anisotropy under various types of surfaces (dielectric, conductor polished, conductor relief etc.) and various initial orientation. It is possible to estimate the thickness of a near substrate-polarizing layer by measuring the pressure produced by the pump. Moreover, the external electric and magnetic fields can be effectively used to control the action of the pumps on the contrary to the case of isotropic liquids.
3. The pumps with such small pressure will be hardly used for swapping, for example, petroleum. However stable, the well adjustable sources of small pressure will be the good tool in scientific researches of liquid crystals.

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