

Article

Laser-Driven Vortex Flow in a Nematic Droplet: Experimental and Numerical Results

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Abstract

The dynamic evolution of an optically induced vortex flow in nematic microliter droplets caused by exposure to a focused laser beam has been studied both experimentally using polarized optical microscopy and numerically within the framework of a corresponding nonlinear extension of the Ericksen–Leslie theory supplemented by thermomechanical correction of the stress tensor and the entropy balance equation. The vortex flow in nematic droplets consisting of 4-pentyl-4'-cyanobiphenyl molecules spreading over the functionalized surface was visualized in microliter droplets doped with monodisperse polystyrene tracers, under exposure to a laser beam with an optical power equal to 8.0 mW. Using the computer vision detection algorithm, we have identified radial symmetry in the tracers motion, where comet-like tracks are aligned along the rays emanating from the center of the resulting structure. At the same time, some of the “comets” are flying towards the center, while others are moving away from it. This allowed us to estimate the average value of tracer flows, which is of 17 $\mu\text{m/s}$. All these observations indicate that vortex currents are excited in the droplet under the action of the focused laser beam. The nature of thermally excited vortex flows in the microliter hybrid aligned nematic droplet with a free upper LC/air interface and spreading over the solid surface under the influence of the heat flux directed through the lower bounding surface is also numerically investigated. It was shown that due to the interaction between ∇T and the gradient of the director field $\nabla \hat{n}$, the thermally driven bi-vortical flow is maintained in nematic microvolume.

Keywords: nematic liquid crystals; vortex flow; thermomechanical force

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1. Introduction

In recent decades, nano-medicine has become a revolutionary technology that has revolutionized the diagnosis and therapy of a wide range of diseases [1–3]. For instance, the micro-fluidic-based delivery systems have significantly improved the results of therapeutic diagnostics [3,4]. This increased efficiency can be explained by the advantages inherent in devices based on micro-fluidic technology, including improved drug delivery,

improved permeability through biological barriers, and increased cell internalization [5]. The development of micro-fluidics-based technologies and applications requires a fundamental understanding of how the manipulation of tiny amounts of molecular fluids and liquid crystals (LCs) in channels ranging in size from tens to hundreds of micro-liters makes it possible to quickly and cost-effectively simulate the development of new and potentially improved devices for biotechnology and nano-medicine. The manipulation of molecular liquids in micro-liters has become a separate field called microfluidics [6–8]. Microfluidics has become a paradigm in various fields, from chemical synthesis and biological analysis to optics and information technology [9–11]. Complex fluids such as LCs [10] or systems with biological materials [11] are characterized by a non-trivial coupling between fluid flow and structural deformations. Decreasing of channel sizes down to the nanoscale provides a close connection between the nematic and biological fluids [12]. Traditionally, an external electric field is used to control the motion of a liquid and liquid crystals [13]. On the other hand, with a significant reduction of LC volume, a number of other factors affects the flow dynamics. Among these factors, the temperature gradient ∇T , caused by focused laser radiation is beginning to play an important role and may affect the nature of the hydrodynamic flow $\mathbf{v}$ in micro- or nanosized LC channels [14–18]. One of the nonmechanical method to excite a flow in a nematic microfluidic channel is based on the coupling between the temperature ∇T and the director field $\nabla \mathbf{\hat{n}}$ gradients [19,20], the other is based on the coupling between ∇T and the surface tension $\nabla \gamma$ gradient [21,22]. The problem of displacement associated with ultra-small (several microliters) isotropic and liquid crystal droplets under the influence of a temperature gradient caused by a laser beam has attracted considerable attention, and the possibility of using a laser as a heat source has been considered by several groups of researchers [14,15,17,18]. Lasers provide the ability to fine-tune the spatial and temporal characteristics of optical radiation, providing controlled heating of the LC system [23]. Understanding how LC materials can be manipulated under the influence of the temperature gradient is also of great fundamental interest and is an integral part of knowledge in the field of soft materials science. Despite the fact that certain qualitative and quantitative advances in a hydrodynamic description of the relaxation processes in the LC phase under the influence of the temperature gradient have been achieved, it is still too early to talk about understanding the dissipation processes in confined LC phase caused by focusing laser heating. This problem of visualization and formation of vortex flows in microliter nematic droplets doped with tracers on a functionalized substrate under the influence of a focused laser beam will be studied using the polarized optical microscopy (POM) technique. In addition, the nature of thermally excited vortex flows in the microliter hybrid-aligned nematic droplet with a free upper LC/air interface and spreading over the functionalized surface caused by the heat flux directed across the bounding surface will be also numerically studied.

The outline of this paper is as follows: materials, methods, and details of the experiment are given in Section 2. The results for typical textures and flow regimes are given in Section 3. A description of the numerical procedure and the results are given in Section 4. Conclusions are summarized in Section 5.

2. Materials, Methods, and Some Details of the Experiment

As a model system for LC micro-volume with the free upper LC/air interface we used a 1 μL droplet of 5CB (4-pentyl-4-cyanobiphenyl) (Sigma-Aldrich, Merck Life Science LLC, Moscow, Russia) on the glass substrate functionalized with CTAB (cetyl-tri-methyl-ammonium bromide, Sigma-Aldrich) and ITO (indium tin oxide) layers. The ITO film serves as partially-absorbing light film and provides an opportunity to create the temperature gradient using the focused laser beam. ITO layer was deposited on the substrate using

the magnetron sputtering with procedure fully described in [24]. The CTAB layer determines predominant vertical orientation of LC molecules on the interface with the substrate. To obtain the CTAB layer, the 1 mg/mL CTAB solution was prepared in deionized water with following heating up to 50 °C and mixed using a vortex mixer up to total dissolution. The glass substrates with an ITO layer immersed in the prepared solution for 24 h. After extraction from the solution, the substrates were dried at 70 °C. For the observation of the induced vortex flow we used the microscopic set-up developed in Ref. [23]. Shortly, the setup is an advanced polarized microscopic scheme with an additional laser beam with a wavelength of 1064 nm (VENUS, Connet Laser Technology, Emden, Germany) in continuous mode. The polarized microscopic branch can be described as follows. The white light from the LED source passes through the polarizer, and the linearly polarized light is focused on the LC sample using a lens. To observe the droplet, we used the objective with a magnification of $\times 50$ and a relatively large working distance of 6 mm. Such a setup allows us to obtain the top views of LC droplets. The images were collected using the objective and a CCD camera (Greteyes GmbH, Berlin, Germany) located after the color filter and the crossed analyzer. A CCD camera with a frame rate of 50 fps and a resolution of 640×480 pixels was used. The laser beam was focused onto the ITO surface using the same objective and dichroic mirror that passes the light in visible spectrum range, and reflects the near infra red light. The laser spot in the plane of focus (xy -plane) was approximately 20 μm . In this work, we conducted the study using laser irradiation at an output power of 8 mW.

To visualize the vortex flow we use 30 μm polystyrene micro-spheres as tracers. The big size of microparticles allows us to optically detect them, even if it gets out of focus. Indeed, after they get out of the focus plane of objective, they become rather blurred, but do not disappear as point-like tracers. Thus big particles open up an opportunity to detect all the depth of the drop even with one position of the focal plane. To prepare the suspensions, 1 mg of dry micro-spheres was added to 250 μL of 5CB, followed by sonication in an ultrasonic bath for 30 min at 40 °C. Then, 1 μL of the obtained suspension was dropped onto a functionalized substrate using a micropipette. The droplet contact angle in our experiments was close to 43 degree, the base radius of the droplet was close to 1.12 mm, the maximal height is 480 μm .

The main idea of the experimental demonstration is as follows. After starting video recording, the laser is switched on. The ITO layer partially absorbs laser irradiation and provides the gradient of the temperature. As a result of the temperature gradient action, the vortex flow is excited. The video recording was performed for 3 min. Since in this work we only discuss the phenomena qualitatively, we performed the same procedure several times on different droplets to be sure of the qualitative reproducibility of results.

After the experimental routines we performed, the images were post processed using computer vision techniques. To detect the displacement of tracer particles, the following computer vision pipeline was applied to the experimental data. First, the raw video frames were split into their Red–Green–Blue color channels. Next, the Canny edge detection algorithm [25] was applied to the negative green channel to extract the contours on the image. Finally, the morphological post-processing steps, including dilation and hole-filling, were performed to visualize tracers positions. We also extract particle trajectories from the video by applying background subtraction frame-by-frame followed by an averaging procedure (“tracking method”). The background reference was computed as the pixel-wise median intensity over a 150-s acquisition sequence.

3. Tracers Visualization Results

POM images and the results of their post-processing representing vortex flow excited by the focused laser beam with the optical power of 8 mW in the LC microvolume is shown in Figure 1a–d. Examples of two POM frames separated by an interval of 1 s are shown in Figure 1a and Figure 1b, respectively. The images of some tracers are well focused, while others are out of focus, which means that their instantaneous position at the moment corresponds to the capture of the corresponding frame, characterized by varying depths. To show the particle displacement after 1 s, we applied the computer vision detection algorithm according to the procedure described in the Section 2. The processed results for the given two frames are shown in Figure 1c, where the contours recognized by the first frame are indicated in blue (see Figure 1a), and the contours after 1 s are highlighted in red. The algorithm fills in the closed counters, and we can define this as the position of the particles. Along with the particles, the algorithm detected and highlighted some contours corresponding to the texture of a LC drop, while some tracers were lost. But despite this, it is clear that the position of the particles is changing, and while some particles are shifting towards the observed region, others are moving away from it. However, two frames are not enough to say anything even at a qualitative level. That is why, using the tracking method described in the Section 2, we reconstructed the trajectories of the particles within a 7 s on a single image, as shown in Figure 1d. As is seen, the image has a radially symmetrical structure, where comet-like tracks are aligned along the rays emanating from the center of the structure. At the same time, some of the “comets” are flying towards the center, while others are moving away from it. We also estimated the average value of tracer flows, which is $17 \mu\text{m/s}$. All these observations indicate that vortex currents are excited in the droplet under the action of the focused laser beam. In this flow, the particles move in the plane of the substrate towards the center of the structure corresponding to the laser spot. After reaching the center, they change the depth of their displacement and the direction of their intra-plane displacement. Thus, we have shown the formation of a vortex flow only on the qualitative level. In the following section we numerically investigate this phenomena and try to explain it using the formalism of thermomechanical force.

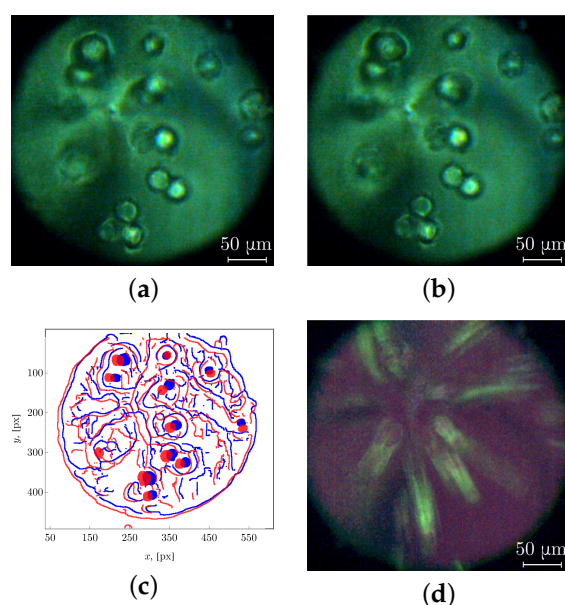


Figure 1. POM images and the results of their post-processing representing vortex flow excited by the focused laser beam with the optical power of 8 mW in the LC micro-volume: (a,b)—two frame with time delay of 1 s, (c)—the results of Canny algorithm with morphological post-processing application, (d)—superposition of 7 s. tracers motion in the vortex flow.

4. Description of Numerical Procedure and Results

We will consider the microliter droplet delimited by one lower horizontal solid surface, located at $z = -d$, one upper free flat LC/air interface, initially located at $z = d$, and two lateral solid surfaces at distance $2L$ ($L \gg d$) on scale on the order of micrometers. Now our main goal is to show how the vortex flow can be excited in the LC channel with a free upper LC/air interface under the influence of the heat flux caused by focused laser radiation. This will be done using the thermomechanical coupling mechanism, which is based on the coupling between the temperature ∇T and the director $\nabla \hat{\mathbf{n}}$ gradients [19,20].

It should be noted that the size of the nematic channel is several hundred micrometers, and in this case the driving Rayleigh–Benard force is weak enough to excite the motion of the LC material [26]. The control parameter responsible for the occurrence of motion by the Rayleigh–Benard mechanism is the Rayleigh number R , and the motion occurs at the value $R = R_c \sim 1708$, independent of the fluid under consideration. In our case $R \ll R_c$, and the driving force is weak enough to excite the motion of the LC material via the Rayleigh–Benard mechanism.

We will consider the nature of a thermally excited vortex flow $\mathbf{v} = u\hat{\mathbf{i}} + w\hat{\mathbf{k}}$ in the microliter nematic droplet with a free upper LC/air interface and spreading over the solid surface under the influence of the heat flux $\mathbf{q}$ directed through the lower bounding surface [27]. The coordinate system defined by our task assumes that the director $\hat{\mathbf{n}} = (n_x, 0, n_z) = \sin\theta\hat{\mathbf{i}} + \cos\theta\hat{\mathbf{k}}$ is in the XZ plane, where $\hat{\mathbf{i}}$ is the unit vector directed parallel to the lower restricted surface, whereas the unit vector $\hat{\mathbf{k}}$ is directed normal to the lower restricted surface, which coincides with the homeotropic director orientation on the lower boundary ($\hat{\mathbf{k}} \parallel \hat{\mathbf{n}}_{z=-d}$) and two director orientation on the lateral boundaries ($\hat{\mathbf{i}} \parallel \hat{\mathbf{n}}_{x=\pm L}$), respectively. Here $\theta \equiv \theta(x, z, t)$ denotes the polar angle, i.e., the angle between the direction of the director $\hat{\mathbf{n}}$ and the unit vector $\hat{\mathbf{k}}$, and $\hat{\mathbf{j}} = \hat{\mathbf{k}} \times \hat{\mathbf{i}}$. Moreover, we will work with the dimensionless space variables $\bar{x} = \frac{x}{d}$ and $\bar{z} = \frac{z}{d}$, and in the following equations the overbars will be eliminated.

This problem will be treated in the framework of the appropriate nonlinear extension of the Ericksen–Leslie theory [28,29], supplemented by the thermomechanical correction of shear stress [19,20], and the entropy balance equation [30]. This 2D hydrodynamic model is based on the interaction effect of the director $\hat{\mathbf{n}}$ and temperature T gradients with the velocity $\mathbf{v}$ field, the magnitude of which is proportional to $v \sim \frac{d}{\eta} \sigma_{zx}^{tm}$, where σ_{zx}^{tm} is the tangential component of the thermomechanical stress tensor (ST), η is the viscosity of the nematic phase, and d is the thickness of the microliter nematic drop spreading over the solid surface. It will be shown below that the tangential component of the thermomechanical ST plays a crucial role in the formation of the thermally excited vortical flow in the nematic droplet with the free upper surface. In this case the temperature gradient ∇T is formed by the laser beam focused on the nematic/solid interface.

Therefore, the nematic phase contains a gradient of $\nabla \hat{\mathbf{n}}$ from homeotropic orientation on the lower and planar on both lateral surfaces to homeotropic orientation on the upper free LC/air interface Γ , i.e.,

$$(n_x)_{x=\pm L, -1 < z < 1} = 1, \quad (n_x)_{-L < x < L, z=-1} = 0, \\ (\vec{n} \cdot \vec{\nu})_{\Gamma} = -1. \quad (1)$$

Here $\vec{\nu} = \left[-\frac{H_x}{\sqrt{H_x^2 + 1}}, 1 \right]$ is the normal to the free LC/air interface Γ at any time and is directed from the nematic phase into air, $H(x, t)$ is the height of the LC film on the top of the smooth surface, and $H_x = \frac{\partial H}{\partial x}$. We will work with the dimensionless size $\bar{L} = \frac{L}{d}$,

and the overbar has been and will be eliminated. We consider the temperature regime without the heat flux $\vec{q}$ across the free LC/air interface Γ

$$(\vec{q} \cdot \vec{\nu})_{\Gamma} = 0, \quad (2)$$

and with a constant temperature at the lateral and part of the lower boundaries

$$T_{-L < x < -\text{ffi}, z = -1} = T_{\text{ffi} < x < L, z = -1} = T_{x = \pm L, -1 < z < 1} = T_0, \quad (3)$$

while across the lower bounding surface we are dealing with the heat flux

$$(T_{,z})_{-\text{ffi} \leq x \leq \text{ffi}, z = -1} = q, \quad (4)$$

caused by exposure to the focused laser beam. The heat flux q across the lower bounding surface is $q = \mathcal{O}(x, z) = \mathcal{O}_0 \exp \left[-2 \frac{(x-x_0)^2 + (z-z_0)^2}{\delta^2} \right] \mathcal{H}(t_{\text{in}} - t)$, where $\mathcal{H}(t_{\text{in}} - t)$ is the Heaviside step function, $\mathcal{O}_0 = \frac{2}{\pi} \frac{\alpha \mathcal{V}}{\delta^2}$ is the heat flux coefficient, α is the coefficient of absorption, $\mathcal{V}$ is the laser beam power, δ is the Gaussian dimensionless spot size, and t_{in} is the duration of the energy injection into the LC droplet, respectively. We will assume the no-slip boundary conditions for the nematogenic molecules on these solid bounding surfaces, i.e.,

$$\mathbf{v}_{-L < x < L, z = -1} = \mathbf{v}_{x = \pm L, -1 < z < 1} = 0, \quad (5)$$

where $\mathbf{v} = u\hat{\mathbf{i}} + w\hat{\mathbf{k}}$ is the velocity vector with the horizontal $u \equiv v_x(x, z, t)$ and vertical $w \equiv v_z(x, z, t)$ components. The bounding condition for the velocity on the upper free LC/air interface Γ can be obtained from the linear balance equation transmitted to the surface Γ . In our case that balance leads to the tangential

$$[\vec{\nu} \cdot \sigma \cdot \vec{l}]_{\Gamma} = 0, \quad (6)$$

and normal

$$[\vec{\nu} \cdot \sigma \cdot \vec{\nu}]_{\Gamma} = 2\gamma\kappa, \quad (7)$$

force balances, where $\vec{l} = \left[1, \frac{H_x}{\sqrt{H_x^2 + 1}} \right]$ is an additional unit tangent vector, γ is the LC/air surface tension, $\kappa = \frac{H_{xx}}{\sqrt{1 + H_x^2}}$ is the curvature of free LC/air interface Γ at any time, and σ is the full stress tensor (ST). Taking into account the micro-sized nematic volume, one can assume the mass density ρ to be constant across the microliter droplet, and thus deal with an incompressible fluid. The incompressibility condition $\nabla \cdot \mathbf{v} = 0$ assumes that

$$u_{,x} + w_{,z} = 0, \quad (8)$$

where $u_{,x} = \frac{\partial u}{\partial x}$, and $w_{,z} = \frac{\partial w}{\partial z}$.

The hydrodynamic equations describing the reorientation of the LC phase in 2D case, when the system is subjected to a temperature gradient ∇T , due to uniform heat flux $\mathbf{q}$, can be derived from the torque balance equation (see Equation (5), Ref. [20]), the linear momentum equation for the velocity field $\mathbf{v}$ (see Equation (6), Ref. [26]), and the heat conduction equation (see Equation (7), Ref. [26]), respectively.

The dynamics of the height $H(x, t)$ of the LC/air interface under the influence of the temperature gradient can be obtained by solving the equation (see Ref. [15])

$$\frac{\partial H}{\partial t} = w_{\Gamma} - u_{\Gamma} H_{,x}, \quad (9)$$

where u_{Γ} and w_{Γ} are the horizontal and vertical components of the velocity $\mathbf{v}$ on the LC/air interface Γ , respectively.

In our case, the understanding of how the temperature gradient ∇T , caused due to the heat flux $\mathbf{q}$, can excite the vortical flow in the interior of the micro-sized HAN volume with the free nematic/air interface can be provided by solution of the dimensionless torque balance equation (see Equation (8), [27]), the dimensionless linear momentum balance equation (see Equation (9), [27]), and the entropy balance equation (see Equation (10), [27]), respectively. Below, a set of dimensionless variables is used, where $\tau = \frac{t}{t_T}$ is the dimensionless time, $t_T = \frac{\rho C_p d^2}{\lambda_{\perp}}$, $\bar{\psi} = \frac{t_T}{d^2} \psi$ is the scaled analog of the stream function ψ for the velocity field $\mathbf{v} = u\hat{\mathbf{i}} + w\hat{\mathbf{k}} = -\nabla \times \hat{\mathbf{j}}\psi$ (for details, see Ref. [27]), $\chi(x, z, \tau) = T(x, z, \tau)/T_{NI}$ is the dimensionless temperature, T_{NI} is the temperature of the nematic-isotropic phase transition. Notice that the overbars in the stream function ψ have been (and will be) eliminated in the last as well as in the following equations.

The reorientation of the director in the nematic microvolume confined between one solid and one free LC/air surfaces and two lateral solid surfaces, when the relaxation regime is produced by the tightly focused infrared laser heating, can be obtained by solving the system of abovementioned nonlinear partial differential equations with the appropriate dimensionless boundary and initial conditions. The later were written in the form of Equations (11) and (12), in Ref. [27].

The calculations have been carried out by using both the relaxation [31] and the sweep [32] methods. The initial distribution of the director field $\hat{\mathbf{n}}_{el}(x, z)$ has been obtained by means of the relaxation method with $(\psi)_{,x} = (\psi)_{,z} = (\chi)_{,x} = (\chi)_{,z} = 0$, and with the boundary $(n_x)_{x=\pm 10, -1 \leq z \leq 1} = (n_x)_{z=1, -10 \leq x \leq 10} = 0$, $(n_x)_{z=-1, -10 \leq x \leq 10} = 1$, and initial $n_x = \frac{1-z}{2}$, for $-10 < x < 10$, and $n_x = 0$, for $x = \pm 10$, conditions. Having obtained the initial distribution of the director field $\hat{\mathbf{n}}_{el}(x, z)$, the initial distribution of the temperature field $\chi(x, z, \Delta\tau)$, corresponding to the first time step $\Delta\tau$, has been obtained by means of the relaxation method with $(\psi)_{,x} = (\psi)_{,z} = 0$ and with the boundary and initial conditions, for the case of the flat interface. Having obtained the initial distributions of the director and the temperature fields, one can calculate the initial distribution of the stream function $\psi(x, z, \Delta\tau)$, corresponding to the first time step $\Delta\tau$. The next time step $\Delta\tau$ for the velocity and temperature fields, as well as for the director's distribution across the LC sample with the free flexible upper boundary is initiated by the sweep method. The stability of the numerical procedure was defined by the conditions [31]: $\frac{\Delta\tau}{\delta^3} \left(\frac{1}{(\Delta x)^2} + \frac{1}{(\Delta z)^2} \right) \leq \frac{1}{2}$, $\frac{3a_5}{(\Delta x)^4} - \frac{2a_1}{(\Delta z)^4} > 0$, where Δx and Δz are the space steps in the x and z directions, and a_1 and a_5 are the coefficients defined in Ref. [32]. In the calculations, the relaxation criterion $\epsilon = |(\chi_{(m+1)}(x, z, \emptyset) - \chi_{(m)}(x, z, \emptyset)) / \chi_{(m)}(x, z, \emptyset)|$ was chosen to be equal to 10^{-4} , and the numerical procedure was then carried out until a prescribed accuracy has been achieved. Here, m is the iteration number.

Our experimental results showed that under the effect of the focused laser beam, the vortex flow is excited, which was visualized using micro-particles doped in the nematic micro-volume. The LC texture is formed under the action of the laser beam with the optical power of 8 mW, and analysis of these POM images showed that the images have a radially symmetrical structure, where comet-like tracks are aligned along the rays emanating from the center of the structure. At the same time, some of the “comets” are flying towards

the center, while others are moving away from it. Thus, these POM images demonstrate the simple and illustrative example of the vortex flow in the microliter nematic droplet spreading over the functionalized substrate under the effect of the focused laser beam. Now our primary task is to show how, in the framework of the corresponding Ericksen–Leslie theory supplemented by the entropy balance equation, the excitation of the vortical flows can be described.

The evolution of $w - u$ diagram in micro-sized nematic droplet during the heating regime, at different times, from $\tau_1 = 0.001$ to $\tau_{10} = \tau_{in} = 0.01$, respectively, is shown in Figure 2a. This behavior is characterized by a monotonic decrease in the absolute values of both velocity components u and w , with the horizontal component of the velocity directed in the negative sense, while the vertical component is oscillated with respect to the x axis. It should be noted that the value of u is, on average, an order of magnitude higher than w . According to our calculations, the evolution of the dimensionless height $h(x, \tau_i) (i = 1, \dots, 10) = H(x, \tau_i)/d (i = 1, \dots, 10)$ of the nematic/air interface is characterized by the wavelike profile along the x -axis ($-0.5 < x < 0.5$) (see Figure 2b). At the final stage of the evolution process, for $\tau = \tau_{10} = \tau_{in}$, the highest value of $|h| \sim 2 \times 10^{-8}$ is reached in the vicinity of points $x \sim \pm 0.125$, whereas the evolution of the temperature χ is characterized by symmetric profile of $\chi(x, \tau_i)_{x \in \Gamma} (i = 1, \dots, 10)$ with respect to the middle point ($x = 0.0$) of the LC/air interface Γ (see Figure 2c). In that case, during the heat step ($\tau \sim \tau_{in} \sim 0.01$ (~ 2 [μ s])) the evolution of the temperature profile $\chi(x, \tau)_{x \in \Gamma}$ is characterized by its strong growth in the vicinity of the middle point $x = 0.0$, up to the highest value of 0.987 (~ 307 K), whereas the evolution of the dimensionless height h of the LC/air interface is characterized by two combs with the highest value of $|h| \sim 2 \times 10^{-8}$ (~ 0.1 [nm]), which are directed in the opposite sense with respect to their centre $x = 0.0$ (see Figure 2b). The thermally excited flow in this heating regime is characterized by the maintenance of two vortices, as shown in Figure 3.

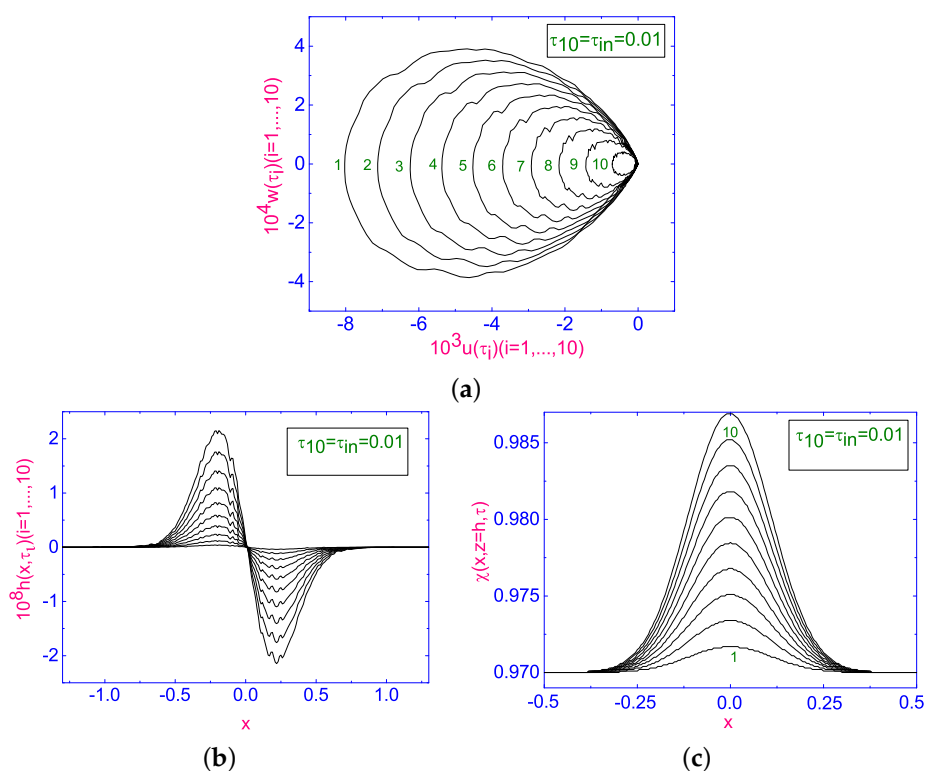


Figure 2. Evolution of $w - u$ diagram (a) in micro-sized nematic droplet, the height $h(x, \tau_i)$ (b) and the dimensionless temperature $\chi(x, \tau_i)$ (c) on the free nematic/air interface Γ , during the heating regime, at different times, from $\tau_1 = 0.001$ to $\tau_{10} = \tau_{in} = 0.01$, respectively.

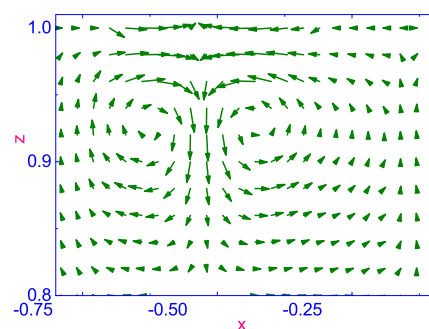


Figure 3. Velocity field distribution $\mathbf{v} = u\hat{i} + w\hat{k} = -\nabla \times \hat{j}\psi$ near the nematic-air interface of the microliter nematic droplet initiated by exposure to the laser beam with the power of 8 mW. In this case 1 mm of the arrow length is equal to $3.0 \mu\text{m/s}$.

According to our calculations, in this heating regime, the thermally driven bi-vortical flow is maintained on the left-hand side of the LC sample (see Figure 3). Notice that the focuses of both vortices are shifted to the left-hand side of the LC sample due to strong, up to $\sim 4 \times 10^{-4}$ ($\sim 17.7 \mu\text{m/s}$), horizontal flow directed in the negative sense. Thus, it was numerically shown that, within the framework of the corresponding hydrodynamic approach, supplemented by thermomechanical correction of the stress tensor and the entropy balance equation, it is possible to describe the excitation of a vortex flow.

5. Conclusions

Using the polarized optical microscopy technique (POM), the formation of vortex flows in microliter nematic droplets on the functionalized substrate under the effect of focused laser heating was investigated. That vortex flow was visualized in 5CB microliter droplet doped with monodisperse polystyrene spheres with a diameter of $30 \mu\text{m}$, under the effect of a laser beam with the optical power equal to 8 mW. The images of some tracers give us the opportunity to show the movement of particles after a while. Using the computer vision detection algorithm, the closed counters of the motion of these particles were restored. It was shown that the images of the flow excitation in the LC micro-volume have a radially symmetrical structure, where comet-like tracks are aligned along the rays emanating from the center of the structure. At the same time, some of the “comets” are flying towards the center, while others are moving away from it. This allowed us to estimate the average value of tracer flows, which is $17 \mu\text{m/s}$. All these observations indicate that vortex currents are excited in the droplet under the action of the focused laser beam. In this flow, the particles move in the plane of the substrate towards the center of the structure corresponding to the laser spot. After reaching the center, they change the depth of their displacement and the direction of their intra-plane displacement.

In addition, we have numerically investigated the reorientational dynamics in microliter nematic droplet spreading over the functionalized surface under the influence of the temperature gradient ∇T , caused by a laser beam focused on the nematic/solid interface. It was shown that due to the interaction between ∇T and the gradient of the director field $\nabla \hat{n}$, the thermally driven bi-vortical flow is maintained in nematic micro-volume.

We believe that the present study may shed some light on the problem of the microfluids dynamics in a micro-sized nematic volume under the heating effect of a focusing laser beam and such studies will lead to the appearance of new micro-fluidic and micro-cargo devices.

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editing. P.V.M.: Investigation. A.V.Z.: Conceptualization; Supervision; Writing, review and editing. All authors have read and agreed to the published version of the manuscript.

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