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Thermal positioning of point defects in smectic films: the thermal tweezer

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We have developed a simple, inexpensive, and easily incorporated technique for positioning point defects in free-standing smectic films, simplifying the study of defect structures in the moderate temperature window through probes such as depolarized reflected light microscopy. The technique exploits thermal flow in the smectic films to position and hold a point defect in place. We present details of the experimental design as well as measurements of the thermal flow induced by the device.

1. Introduction

The imaging of point defects through depolarized reflected light microscopy (DRLM) has been a remarkably powerful tool for the study of free-standing liquid crystal films [1–4]. Although the technique is simple in principle, a number of complications can arise in practice. One such complication is that at the moderate or sufficiently high temperature window small thermal gradients in the experimental set-up can induce flow in a film, causing the defect of interest to drift (or move) to the edge of the film and disappear into the reservoir of material at the edge of the film-hole. This action abruptly terminates an attempt at acquiring data if the experimenter is, as in our case, using DRLM to observe how the morphology of a given defect evolves with temperature. In principle, any problems due to thermally induced flow can be solved through a careful experimental design, but it is easier said than done, since even very small gradients at the moderate or sufficiently high temperature window can cause enough flow to ruin a critical experimental run. We have developed a simple and inexpensive technique that allows the experimenter to exploit thermal flow in order to position a defect and hold it in place for study. The basic idea is to introduce an adjustable thermal gradient to balance the gradients intrinsic to the experimental system.

2. Experimental design

The films are prepared and observed within a sealed, three-stage oven in an argon environment at 1/2 atm. The oven is designed to minimize temperature gradients in the film; figure 1 shows a diagram of the oven. The outer stage is an airtight aluminum cylinder that isolates the films from the environment. The intermediate stage is a temperature-controlled copper cylinder (closed, but not airtight). The goal with this stage is to provide a nearly isothermal boundary surrounding the film and to allow manipulation of the film's ambient temperature. The copper cylinder is mechanically mounted to the outer stage. The mechanical mounts are of thin walled stainless steel tubing, however, so that the primary thermal link between the copper cylinder and the outer stage is the argon exchange gas. The inner stage is a stainless steel chamber (not airtight). This chamber is also mechanically mounted to the copper cylinder so that the argon is the main thermal link. The top of the chamber (the film-plate) has a circular hole of ~1 cm in diameter where the films are prepared. The film-hole is radially centred in the oven. By coupling the film to a large mass within the copper cylinder, thermally induced flow in the films is noticeably reduced when compared with a film-plate with no attached chamber. Even with these precautions at 85°C, our videotaped DRLM images of the film still show enough gradual drift to allow defects to flow to the film-plate edge

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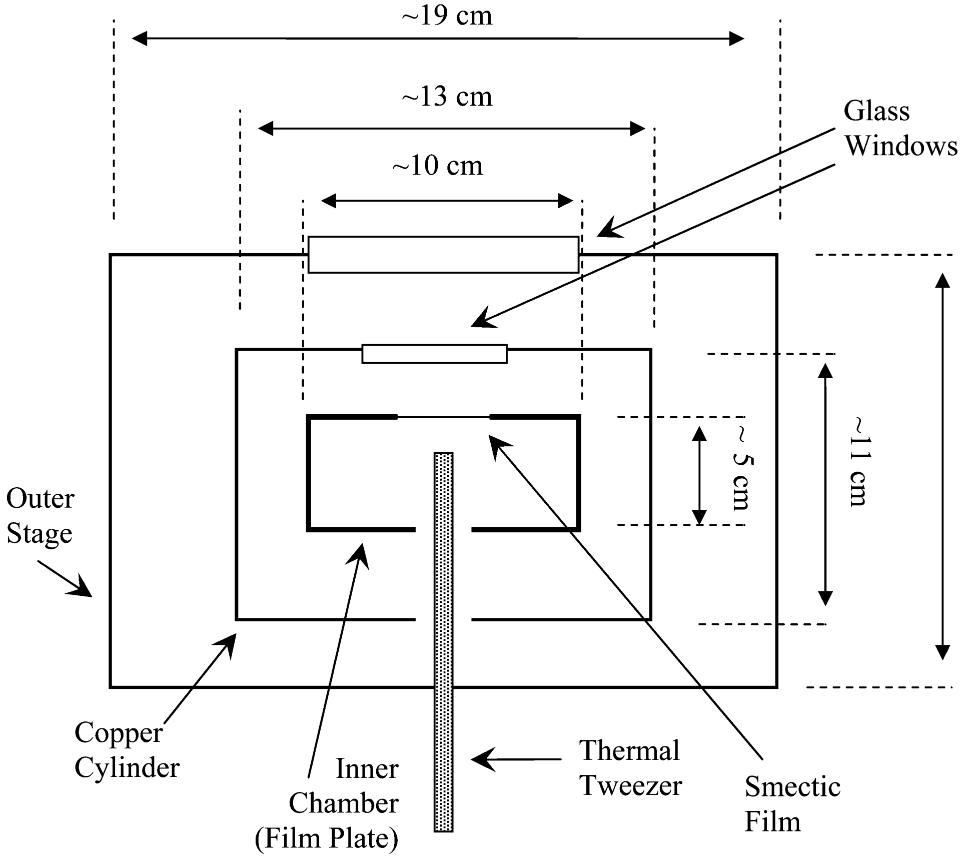

Figure 1. Schematic of the oven. The film is observed through the glass windows. The film-hole is ~1 cm in diameter and is centred radially in the oven. The thermal tweezer is a 0.635 cm dia. brass rod, roughly 20 cm long, and centred on the film-hole. The tweezer is fed into the outer shell through an Ultra-Torr fitting so that it can be raised, lowered, and rotated with the outer stage holding vacuum.

on a time scale short enough to ruin a data run of ~1 h [4]†. The flow will be discussed in greater detail below.

Note that in figure 1 there is also a rod labelled 'thermal tweezer'. This simple device is the subject of this paper. The tweezer, a 0.635 cm diameter brass rod of roughly 20 cm length, spans from outside the oven into the film-plate chamber, creating a heat leak into the chamber. The long axis of the tweezer is normal to the plane of the film and is centred on the film-hole. The tweezer is fed into the base of the oven through a Cajon Ultra-Torr$^{\mathrm{TM}}$ fitting (Swagelok Inc. Salon, OH) so that, by hand, the tweezer can be rotated azimuthally and moved closer to or farther from the film without breaking the seal between the outer stage and the laboratory environment. The end of the tweezer closest to the film was crudely machined in a wedge shape to the dimensions shown in figure 2.

Note that the wedge-shaped portion of the tweezer has a knife-edge that is parallel to the plane of the film and perpendicular to the long axis of the tweezer. Furthermore, from the dimensions in figure 2, it can be seen that the wedge is off-centre relative to the tweezer long axis. Thus, this 'cold' wedge-shaped piece of metal is offset from the film centre and parallel to the film plane. The thermal gradient between the film-plate and the tweezer induces flow in the film in the direction of the knife-edge. Figure 3 roughly depicts the flow as observed through video-monitored DRLM. Although the direction of flow is not completely uniform across the film, the direction is predictable relative to the knife-edge of the tweezer. Note that, in general, the intrinsic flow with no tweezer in place is similar to that depicted figure 3, albeit slower and a little more

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†In [4] the motion of the SmC* defect in thin free-standing films was studied as a function of time during a period of 2 h. The experiment was done at a relatively low temperature ($T \approx 55.1°C$); thus the motion of the defect is somewhat limited. We plan to study the morphology of the five-arm defect on a curved surface. In free-standing films of the compound 2M4P9OBC, such a defect can only be observed at a moderate temperature ($T \approx 76°C$).

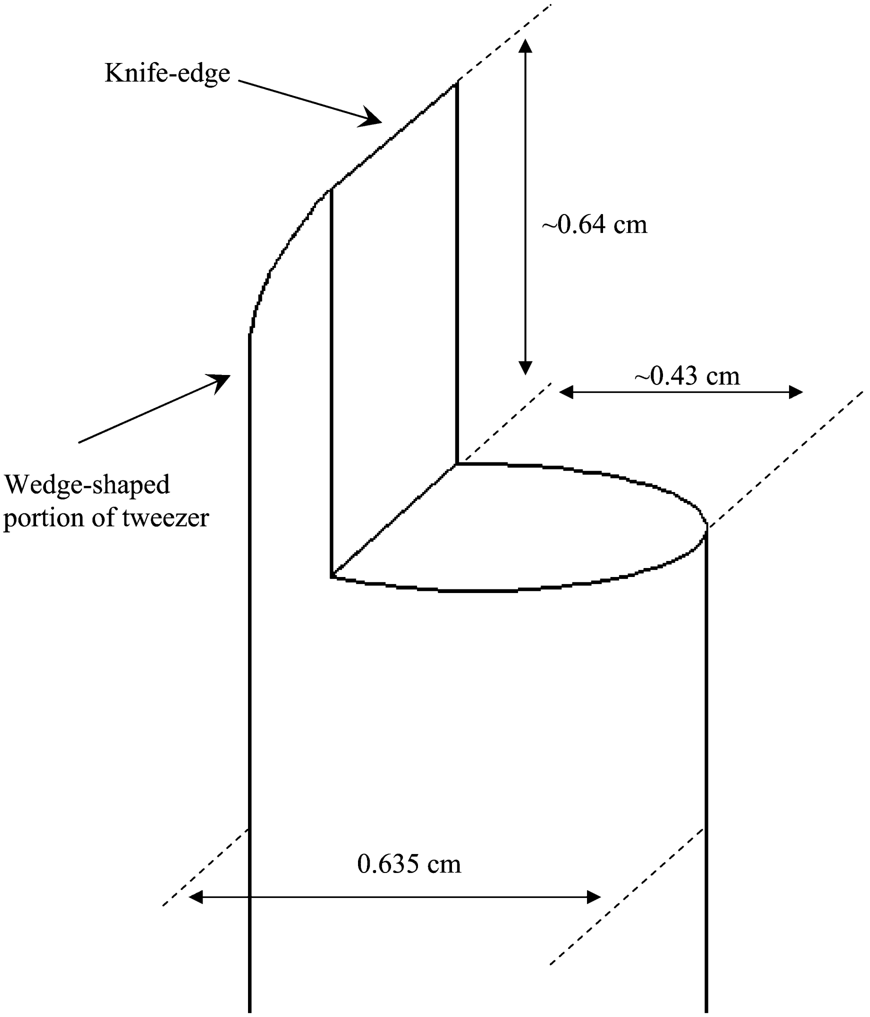


Figure 2. Diagram of the tweezer end. The top end of the 0.635 cm dia. brass rod is crudely machined in the shape and dimensions shown to create a wedge-shaped piece that can be positioned near the film. The long axis of the tweezer is centred on the film-hole and is normal to the plane of the film. The top edge of the wedge-shaped portion is parallel to the film plane and is off-centre relative to the film-hole. The thermal gradient introduced by this piece of metal is used to offset gradients intrinsic to the oven. The system is tunable since the tweezer can be raised, lowered, and rotated.

chaotic. The rates of the flow will be discussed quantitatively below.

At first glance, it may seem that the tweezer will exacerbate the problem of thermal flow, but recall that the tweezer can be rotated, raised or lowered. Thus, the experimenter can control both the direction and the rate of flow induced by the tweezer. With a little practice, we were easily able to move an existing defect to the centre of the film-hole (thus the term ‘thermal tweezer’). Furthermore, we could effectively hold the defect in place by positioning the tweezer at just the right height and orientation to counter the intrinsic thermal gradients due to imperfections in the oven construction. The process is depicted in figure 4. By monitoring the DRLM video image of the defect and making slight adjustments to the position and orientation of the tweezer as needed, we could easily hold the defect near the centre of the film hole over an entire workday. It is important to mention that we detected no influence on the size or structure of the defects due to the tweezer in our studies. This is perhaps not too surprising since the tweezer is designed simply to offset small, intrinsic temperature gradients in a carefully constructed oven.

3. Measurement of flow rates

In order to quantify our findings, we measured the speed of a point defect as a function of the film–tweezer

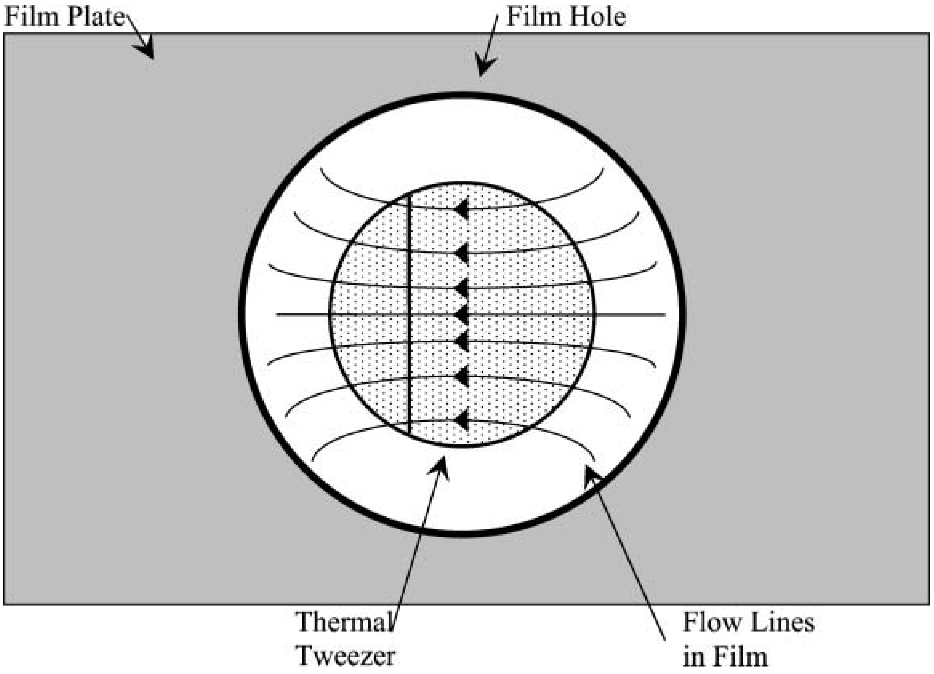


Figure 3. Depiction of the flow in a film induced by the tweezer as observed through DRLM video. The shaded rectangle is the film plate. The larger circle is the film hole; the smaller, shaded circle is a top view of the tweezer. The vertical line across the tweezer is the knife-edge of the tweezer. Defect structures in the film are observed to flow toward the knife-edge. Regions near the line that bisects the knife-edge are observed to flow approximately along that line with the fastest rates toward the centre of the film hole. Regions further from the bisecting line tend to flow more slowly and show slight curvature in their path.

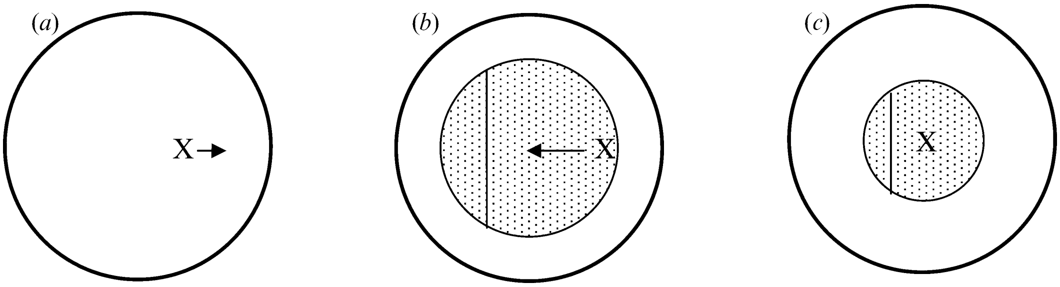
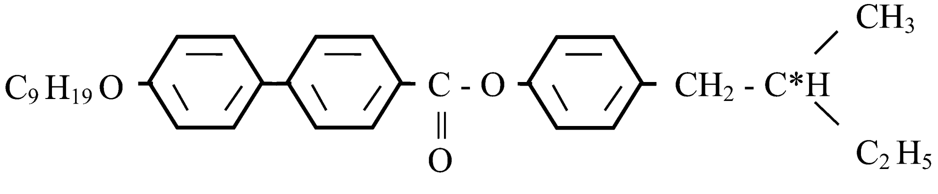


Figure 4. Depiction of the process to position and hold a point defect. The larger circle in each picture is the film hole. The 'X' is a point defect in the film. In (*a*) the tweezer (not shown) is too far below the film to induce flow, but intrinsic thermal gradients cause the defect to drift to the right. In (*b*) the experimenter responds by raising the tweezer (smaller, shaded circle) so the defect will flow to the left until positioned near the centre. In (*c*) the experimenter lowers the tweezer until no flow is observed.



Isotropic (170) N (168) SmA (132) SmC* (78) SmI*

Figure 5. Molecular structure and phase sequence of 2M4P9OBC. Transition temperatures are in °C.

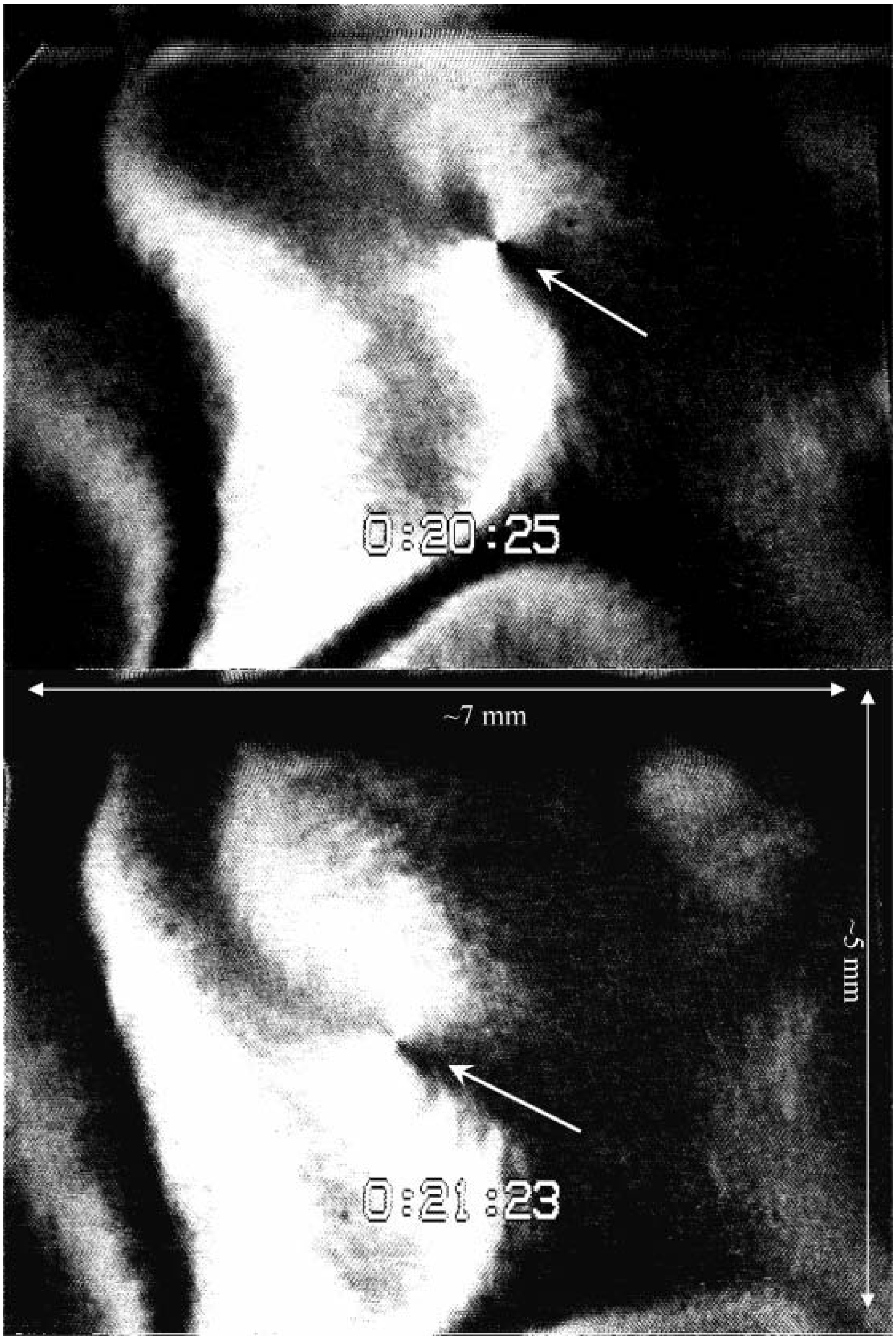


Figure 6. An example of a set of images used to calculate the speed of a point defect in a 2M4P9OBC free-standing film. The two successive images were digitally captured from a DRLM videotape with the tape counter displayed on the screen. In the roughly one minute between images, the point defect (indicated by the diagonal white arrows) moved down and slightly to the left. The defect drifted nearly in a straight line, with a slight curvature in the clockwise direction. The approximate dimensions of the frames are shown.

distance for two distinct temperature differences between the film-plate and the wedge-shaped portion of the tweezer. We performed these studies with four-layer films of the compound 2M4P9OBC in the smectic C* (SmC*) phase (film-plate temperature ~85°C). Figure 5 shows the molecular structure and phase sequence of 2M4P9OBC.

The temperatures of the film-plate and the tweezer were monitored with two separate type-E thermocouple junctions. One junction was mechanically pressed to the

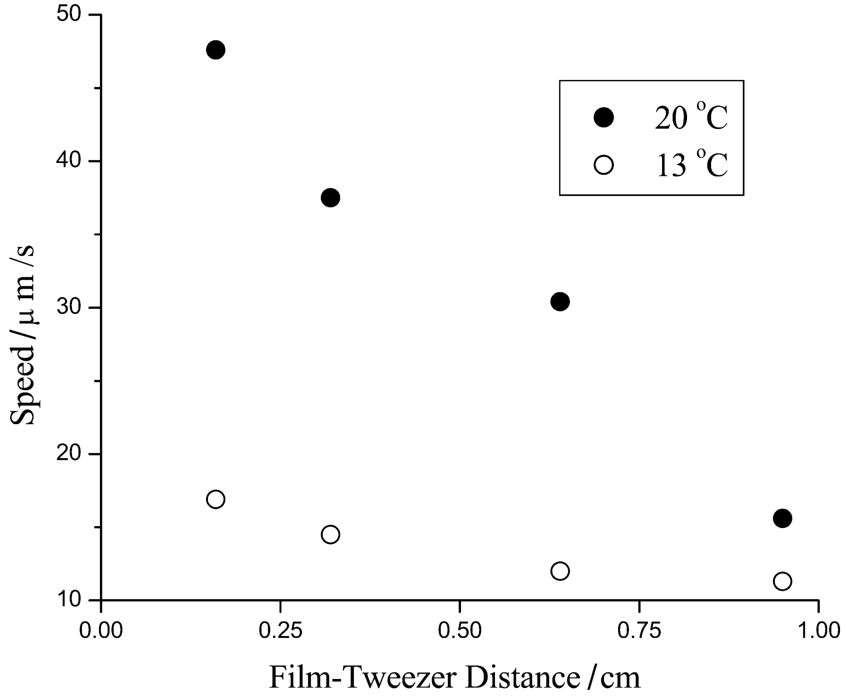


Figure 7. Graph of speed versus film–tweezer distance for two temperature differences between the film-plate and tweezer. Each data point is an average for flow in four directions.

film-plate near the edge of the film-hole. The second junction was fixed with epoxy just below the knife-edge of the tweezer. A small resistive heater was attached to the bottom of the tweezer, outside the oven, allowing variation of the temperature difference between the film-plate and the tweezer. To quantify the distance between the film and tweezer, the tweezer was raised until the knife-edge just touched the film; all distances were then measured relative to this point. The average speed of a defect was determined using the distance and time acquired from two frames of DRLM video. Figure 6 shows an example of two such frames.

Figure 7 shows the speeds of defect flow as a function of film–tweezer distance for two distinct temperature differences between the film-plate and the knife-edge of the tweezer. Each data point in figure 7 represents an average for flow in four directions (up, down, left, and right as viewed in figure 6) as a result of changing the orientation of the wedge. We averaged over multiple directions in order to reduce the error introduced by thermal gradients due to imperfect construction of the oven. Not surprisingly, the rate of flow monotonically increases as the tweezer approaches the film for both temperature differences. Additionally, the larger temperature difference shows larger speeds and a steeper slope. We captured images for distances greater than those shown in figure 7, but at distances of ~1 cm, the flow rate induced by the tweezer is comparable to the thermal flow rate induced by imperfections in the construction of the oven ($\sim 10\,\mu\mathrm{m\,s^{-1}}$). As a result, it was difficult to calculate reliably the flow rate induced by the tweezer alone at distances greater than 1 cm. However, one does easily see that a distance of ~1 cm is required to hold the defect in place over long periods of time. We should mention that we also experimented with a tweezer of roughly the same dimensions made from stainless steel. Due to the smaller thermal conductivity as compared with brass, the stainless steel tweezer was not effective enough with our set up to warrant significant study. Nonetheless, it does illustrate another variable that can be manipulated in designing a tweezer for any given experiment.

4. Summary

In conclusion, we have developed a simple and inexpensive technique to position point defects in free-standing liquid crystal films. Our device, which we call a 'thermal tweezer', can be of great assistance to the experimenter who wishes to study point defects since the defect can be held in place for observation over long periods of time. The simple and inexpensive design can be quickly incorporated into existing experiments. The adjustability of the tweezer puts fine control into the hands of the experimenter rather than in the experimental design.

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