Effect of the Width of a Bar Substrate on the Dynamic Curvature of a Thermocapillary Depression and the Shape of the Thermocapillary Response

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Abstract—The effect of the width of an absorbing bar substrate on the radial symmetry of a thermocapillary depression is investigated by studying the velocity field of a convective vortex induced by the thermal effect of a He–Ne laser beam in a thin layer of transparent liquid. The beam reflected from the depression forms an elliptical fringe pattern on a screen placed at the beam cross section. This pattern is caused by the fact that the radius of the curvature of the depression across the substrate is smaller than that along the substrate. This circumstance is explained by the higher losses to viscous friction for the flow directed along the bar. In the case of a flat and infinitely extended substrate, the substrate begins to affect the shape of the fringe pattern when the bar width becomes comparable with the diameter of the thermocapillary depression. As the bar width increases, the eccentricity of the pattern increases. An increase in the liquid viscosity leads to a decrease in the depression diameter, and the fringe pattern tends to a circular shape. © 2005 Pleiades Publishing, Inc.

1. INTRODUCTION

As is well known, the surface deformation of a thin liquid layer on a low-conductivity substrate can be caused by thermocapillary (TC) convection induced by a laser beam [1]. The liquid surface curvature is a result of the liquid flow in the form of a TC vortex. A fringe pattern—a TC response—arises on a screen placed at the cross section of the caustic of the inducing beam reflected from the depression [1–3]. In the case of normal incidence of a Gaussian beam and a flat, infinitely extended substrate, the vortex is axisymmetric and the response is circular [1–4].

From the diameter $D$ of the response, it is possible to determine the physical properties of the liquid, as well as parameters of the liquid layer and the laser radiation [5–9]. In [10], we proposed to use the optical properties of a TC depression for transformation of the intensity distribution in a laser beam.

If a free surface of a liquid is shaped as a cylindrical meniscus, the response becomes elliptical [1]. A high sensitivity of the response eccentricity $e$ to the static curvature of the liquid meniscus can be used for controlling the flatness of a free liquid surface [11] and, in a modification of the tilting plate method, for measuring the contact angle [12]. In this study, we undertook an attempt to dynamically affect the curvature of the TC depression by employing a bar-shaped substrate, which distorts the radial symmetry of the velocity field (the $v$ field).

2. EXPERIMENTAL

The experimental setup shown schematically in Fig. 1a incorporates (1) a He–Ne laser with $\lambda = 633$ nm (an LGN 207-A or an LG-111 laser); (2) a filter; (3, 4) mirrors; (5, 6) screens $W_1$ and $W_2$; (7) a petri dish with an inner diameter of 104 mm; (8) a liquid layer; (9) a bar substrate (either made of carbolite and $45 \times 4 \times 7$ mm in size or of ebonite and 60 mm long by 8 mm high by 4, 6, or 8 mm wide) or a plate substrate (made of carbolite and $40 \times 40 \times 4$ mm in size); (10) a calibrated wire section; (11) a Stefan cylinder 11 cm in height; and (12) a micrometer tripod. Figure 1 also shows the negatives of the modal structure of the LG-111 laser beam (cross section AA’) and of the TC response for the plate substrate (cross section BB’). The experiments were conducted at a temperature of 24 ± 1°C. The techniques of adjusting the horizontality of the upper face of the substrate and the layer thickness are described in [13]. The physical properties of the substances used are summarized in Table 1.

The experiments with octane and butanol-1 were conducted with the LGN 207-A single-mode laser, whose beam diameter $d$ on the substrate was equal to 3 mm. Taking into account the losses at mirror 3, the power $P$ of the beam incident on the layer was $0.9 \pm 0.1$ mW. Because of the higher viscosity of benzyl alcohol, we had to use the more powerful (20 mW) but multimode LG-111 laser, whose beam had an elliptical shape in cross section with the dimensions on the substrate $d_1 \times d_2 = 3 \times 3.5$ mm (Fig. 1a, cross section AA’). The beam was oriented so that its major diameter was...
parallel to the longer side of the bar. In this case, two dark spots (white spots on the negative in cross section AA'), located symmetrically in the intensity distribution, lay on the line parallel to the bar axis (Fig. 1a) and served as convenient markers for controlling the axis position in the incident beam and in the response

Fig. 1. (a) Schematic of the experimental setup and (b) shape of the response for the bar substrate as a function of the screen position. The negatives are shown on an arbitrary scale. (See explanations in the text.)