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Robust Quantitative Measurement of Flows and Transparent or Highly Reflective Objects

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ROBUST QUANTITATIVE MEASUREMENT OF FLOWS AND TRANSPARENT OR HIGHLY REFLECTIVE OBJECTS

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ABSTRACT

The liquid crystal point diffraction interferometer (LCPDI) is a new instrument that has been developed for the measurement of phase objects. The LCPDI uses the compact, robust design of Linnik's point diffraction interferometer and adds to it phase stepping capability for quantitative interferogram analysis. The result is a compact, simple to align, environmentally insensitive interferometer capable of accurately measuring optical wave-fronts. A solid state camera provides very high data density and automated data reduction. The instrument can measure either transparent objects like fluids and lenses, or highly reflective opaque objects like mirrors. In the former case, the refractive index distribution is measured and then related to various properties like temperature, density, chemical composition, or thickness. In the latter case, the measured phase distribution is related to the object shape. The objects measured must be stationary or quasi-steady state because the measurement requires the acquisition of several frames of image data during which time the object's properties must not have changed. The data acquisition time depends on the speed of the frame grabber and the required number of data frames. Typically, three to five frames taking 1 to 2 seconds are required. The potential for faster data acquisition exists.

1. INTRODUCTION

The point diffraction interferometer (PDI)[1,2] has long been used for optical testing,[3] and recently for fluid studies.[4,5,6,7] The PDI's elegant design makes it both inexpensive and robust. It consists simply of a neutral density filter containing a pinhole. Coherent light is passed through a test object, and the focused light is centered on the pinhole in the PDI. The pinhole diffracts the central portion of the light and forms a spherical wave. The rest of the light is attenuated by the neutral density filter but retains the phase information about the test system. This attenuated object beam travels coincidentally with the diffracted spherical wave behind the PDI. The two beams interfere with each other, producing an interferogram on a screen or a recording device.

The shape of the interference pattern indicates the quality of the wavefront passing through the test system and can be interpreted to extract information about the test object.

The test object can be an optically transparent object such as a lens, plastic sheet, gas, or liquid, or it can be a highly reflective object such as a mirror. In the former case, refractive index variations in transparent objects modify the laser beam passing through them, and this refractive index distribution is revealed by the interferogram. The refractive index distribution can then be related to parameters of interest such as temperature, density, or material composition by appropriate experimental design. Interferograms created by reflecting light off specularly reflecting objects, such as mirrors, can be used to determine the shape of the reflecting object.

Since the object and reference beams both travel identical paths behind the PDI filter, the interference pattern is extremely robust in the presence of vibration. Conventional Mach-Zehnder or Michelson interferometers require two optical paths, one for the object beam and the other for the reference. The common-path design of the PDI is especially advantageous when measuring large objects like wind tunnel flows where the optical paths are very long and air turbulence must be minimized along the paths. A single path is also advantageous when the size of the instrument must be kept small. The common-path design requires relatively few optical elements, reducing the cost, size, and weight of the instrument, and simplifying alignment.

Like any interferometer, the interferograms produced by the LCPDI must be interpreted to extract information about the object wavefront. The most accurate and effective way to measure both the magnitude and the sign of wavefront phase deviations is to use phase shifting interferometry.[8] This technique permits the object-beam phase distribution to be calculated at each pixel in the interferogram. This quantitative analysis is obtained by recording several interferograms, each differing only by a fixed phase shift between the object and reference beams. Traditionally it has not been possible to do this with common-path interferometers because of the difficulty in shifting the phase of one beam relative to the other. The liquid crystal point diffraction interferometer[9] (LCPDI) was invented to combine the power of phase stepping interferometry with the robust design of the common-path PDI.

2. DESCRIPTION OF LCPDI

The LCPDI consists of a microsphere embedded in a liquid crystal layer sandwiched between glass plates. The microsphere locally generates a reference beam, and the object beam is phase shifted by modulating a voltage applied across the liquid crystals. This allows completely flexible phase stepping interferometry capability while retaining the fully common-path optical design.

The LCPDI is shown schematically in Figure 1. Nematic liquid crystals (LC) are sandwiched between two glass plates (G), each nominally 0.5 millimeter thick and 3.0 x 3.5 centimeters across. Nine micron diameter cylindrical rods (R) are placed at the edges of the plates to serve as spacers. Transparent plastic microspheres (M), nominally 9 microns in diameter, are scattered throughout the liquid crystal layer. Each microsphere replaces a small volume of liquid crystals as the filler between the glass plates. Transparent electrodes (E) are deposited on plates' inner surfaces, and leads (L) are soldered onto the electrodes so that an alternating current can be applied across the liquid crystal layer. The LCPDI is tilted to reduce the effects of multiple reflections. This tilt introduces aberrations into the wave being measured, but these can be subtracted out in software. Alternatively, anti-reflection coatings on the glass surfaces can reduce the multiple reflections and eliminate the need for tilt.

The microsphere diameter must be large enough to provide a full 450 degrees of phase delay and small enough to be approximately one-half of the focused spot diameter. Dye is added to the liquid crystals to attenuate the object beam so its amplitude is roughly equal to that of the reference beam. These design parameters thus set the optimum performance of the LCPDI to a specific f-number, just as the PDI is optimized for one f-number.

Finally, the measurements made with the LCPDI are relative. To obtain absolute measurements, one point in the two-dimensional LCPDI measurement must be linked to an independent measurement. In the data presented in this paper, a thermocouple provided the link to absolute temperature.

3. DEMONSTRATION OF ROBUSTNESS

Because the two beams of the interferometer travel identical paths in the LCPDI, the interferogram is relatively insensitive to mechanical vibrations in the optical train. A Mach-Zehnder interferometer[10] and the LCPDI were configured to measure a wavefront simultaneously (Figure 2). To compare the robustness of the fringes formed by the two systems, both interferometers recorded a wavefront that traveled just through an open chamber of air rather than through an object of interest. A 10 mW Helium-Neon laser was used as the light source and high quality mounts were used for all optical components. A neutral density filter (ND) reduced the laser intensity to about 2 mW. Lenses L1 and L2 formed a nominally 50 cm diameter collimated beam and beamsplitter BS1 split the beam in two. Mirror M3 directed one portion of the beam through an empty test chamber; the other portion was used as a reference beam for the Mach-Zehnder interferometer. Beamsplitter BS2 recombined the two Mach-Zehnder beams and the resultant interferogram was recorded by camera CAM2. Beamsplitter BS3 sampled off a portion of the object beam and lens L3 focused this beam onto the LCPDI. The interferogram formed by the LCPDI was recorded with camera CAM1.

Figure 3 shows the interferograms produced with the two interferometers. A pointer appears in both frames for reference. The fringes formed by the Mach-Zehnder appear as tilted straight lines because tilt was introduced between the two beams, and the LCPDI fringes are decentered circular sections because both defocus and tilt were added. For this test, the fringe contrast is of interest, not the fringe shape. The Mach-Zehnder fringes have better contrast than the LCPDI fringes because the LCPDI was operated off its design wavelength of 514 nm.

A 7 Hz vibration was applied to the table on which the instruments were mounted. The interference fringes formed by the Mach-Zehnder vibrated with the driving force but the LCPDI interferogram remained unaffected. Both interferograms were videotaped, and four consecutive frames were added together (Figure 4). The Mach-Zehnder fringes are clearly washed out while the LCPDI fringes remain clear. While the Mach-Zehnder fringes have better contrast than the LCPDI, environmental disturbances that destroy the Mach-Zehnder interferogram do not affect the LCPDI fringes at all.

Both the LCPDI and Mach-Zehnder interferometers are sensitive to thermal disturbances along the optical path of the object beam, but the Mach-Zehnder is sensitive to environmental effects along the reference path as well. In the LCPDI, the sensitive path is between the pinhole (PH in Figure 2) and the liquid crystal plate. The sensitive path in the Mach Zehnder is twice as long: it extends along both beams between the pinhole (PH) and the final beamsplitter (BS2).

4. APPLICATION

Two-dimensional temperature distributions across an oil bath were measured with the LCPDI using the apparatus shown in Figure 5.[11] A 45 x 45 x 60 mm double-walled chamber was constructed with 30 mm diameter viewing windows. Recirculating water controlled the temperature of the top and bottom chamber plates. The chamber was filled with 50 centistokes silicone oil.

A collimated beam of 514.5 nm laser light was passed through the windows of the chamber. The light was generated by an Argon ion laser operated without an etalon, and without a constant intensity feedback mechanism. The output intensity was nominally 120 mW, but fluctuated about 20% from this value. We normalized our interferograms to handle this large frame-to-frame intensity variation. Collimating optics produced a 24 mm diameter collimated beam with a power density of nominally 1.5 mW/cm^2, or 6.8 mW total power. The horizontally polarized light traveled through the test chamber windows and was truncated by a 16 mm diameter aperture behind the last window. A 100 mm Cooke triplet lens focused the light, forming an f/6.3 beam. The LCPDI was oriented with the relaxed liquid crystal molecules lying horizontally; mounted on a 3-axis positioner; and placed just behind the focused spot. A ground glass screen was placed 21 cm behind the LCPDI, and a 50 mm Nikkor lens at f/5.8 imaged the interferogram onto a 768x493 pixel CCD detector array.

Images from the camera were digitized into a personal computer by a frame grabber. A computer controlled programmable function generator was used to generate the AC voltage for phase stepping. A delay of 7 seconds was inserted between the time that the voltage was changed and the image was acquired, and it took an additional 6 seconds to write the images to the hard drive. The total time for acquiring five phase-stepped interferograms was therefore about 65 seconds. This long acquisition time is not required. We now take data at the rate of about 2 seconds for five frames and expect to further decrease this acquisition time.

To measure the temperature distribution across the central portion of the test chamber, two wavefronts were measured. First, five phase-stepped interferograms were recorded to measure the wavefront passing through the chamber with the test fluid at room temperature (isothermal condition). Then the top and bottom chamber plates were set to the desired temperatures and left there for about an hour to allow the oil to reach its steady state condition. The top plate was kept hotter than the bottom plate to allow stable stratification in the presence of gravity. This stable condition was verified by continuously observing the interference fringes. Five more phase-stepped interferograms were then recorded to measure the wavefront passing through the heated oil. The difference between these measured wavefronts was then used to determine the temperature distribution across the oil. The measured temperature distribution is shown in Figure 6. Note that it appears to be nearly a linear gradient, as expected. To verify the accuracy of the measurement, a thermocouple was traversed from top to bottom across the chamber. Figure 7 shows the temperature distribution measured along a line with both the traversing thermocouple and the LCPDI. The data sets show very good agreement,

Finally, the LCPDI was used to measure a more complex temperature distribution across the same chamber. The experimental apparatus was similar to that shown in Figure 5, but a spacer was inserted into the chamber to produce an oil volume with dimensions in the ratio 10:1:5 (width:height:depth). This time the bottom plate was heated and the top plate was cooled. This combination of temperature inversion and chamber dimensions permitted the formation of ten Benard convection cells across the chamber.[12] The temperature distribution was measured using the LCPDI; the results are shown in Figure 8. Only the central five convection cells are shown because the windows did not cover the entire width of the chamber.

5. SUMMARY

The liquid crystal point diffraction interferometer combines a robust, common-path design with a simple method of optical phase control. The result is a compact new instrument for the measurement of optical wavefronts that uses phase stepping interferometry for high data density and automatic data reduction. It can be used to measure a transparent object such as a lens, plastic sheet, gas, or liquid, or highly reflective object such as a mirror.

Because the LCPDI itself introduces aberrations into the interferograms, it is best used in applications where wavefront differences are of interest. The difference operation will automatically compensate for the induced aberrations. Nonetheless, the instrument can be used to test optical elements such as lenses and mirrors provided either a reference optic is available, or the initial aberrations can be quantified for subsequent subtraction.

We used the LCPDI to measure two steady-state temperature distributions across an oil bath. Simple linear gradients and convection cells were measured and the results agree with thermocouple data. The robustness of the device was demonstrated compared to a conventional Mach-Zehnder interferometer.

We expect that the LCPDI will become a useful tool for providing automated data acquisition and reduction, with very high data density, for applications requiring a compact, inexpensive, robust interferometer. Such applications may include lens testing, fluid studies, inspections of transparent objects, and biological inspections.

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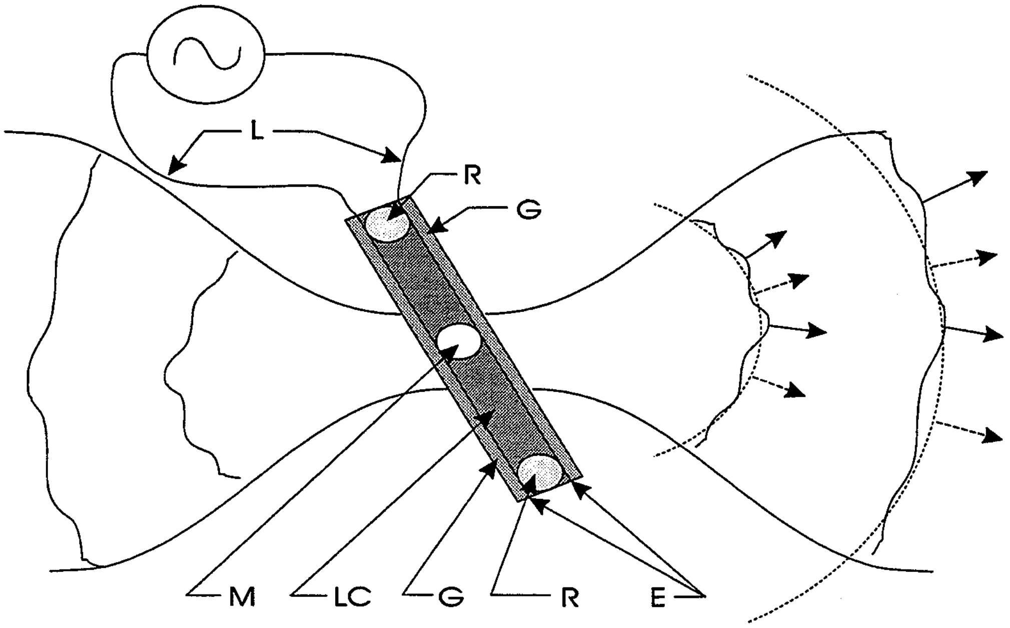

FIGURE 1. Schematic of LCPDI showing the liquid crystal layer (LC), glass plates (G), microsphere (M), spacing rods (R), electrodes (E), and leads (L). The object wave is shown as a solid line, and the reference wave is shown as a dashed line.

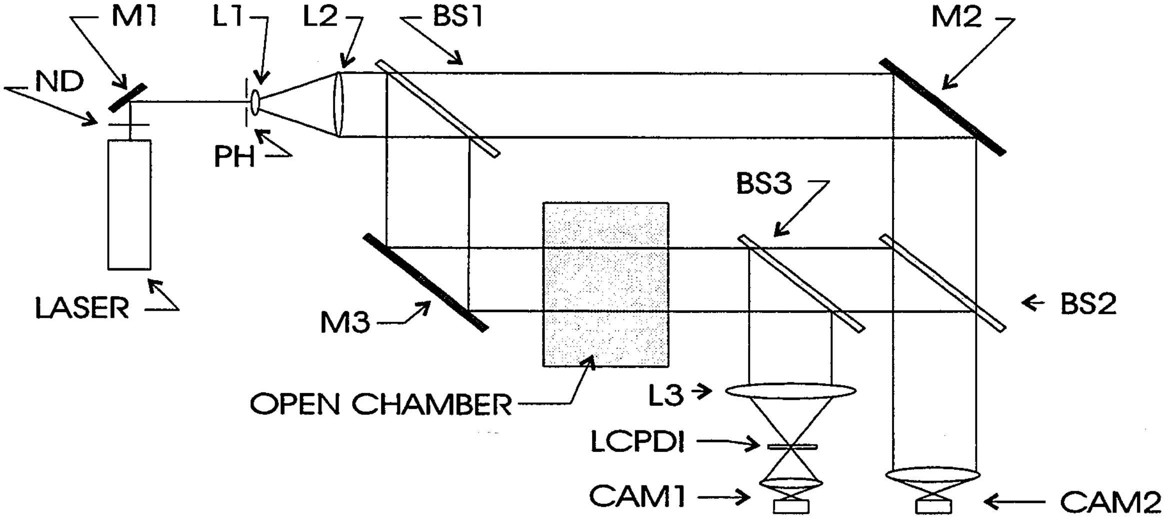

FIGURE 2. Simultaneous measurement using LCPDI and Mach-Zehnder interferometers. The beam is filtered and collimated with a pinhole (PH) and two lenses (L1, L2). Beamsplitters (BS1, BS2) form the Mach-Zehnder, and BS3 splits off a portion of the object beam for the LCPDI. Mirrors (M1, M2, M3) direct the beams. One camera (CAM1) records the interferogram generated by the LCPDI, another (CAM2) records the Mach-Zehnder interferogram.

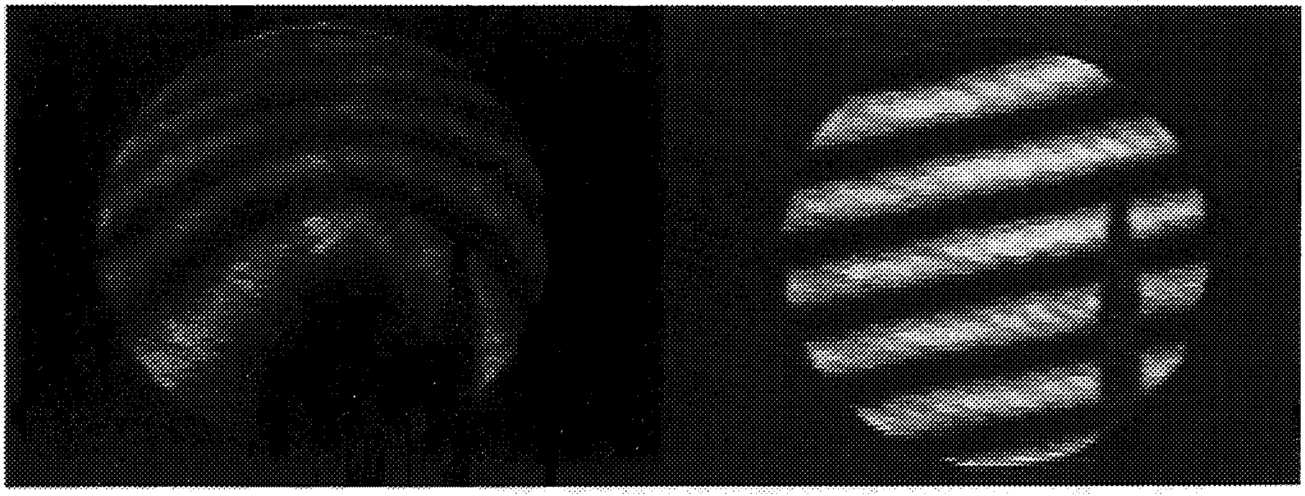

FIGURE 3. Single frames recorded simultaneously using the (a) LCPDI and (b) Mach-Zehnder interferometers. A pointer is visible in the object beam.

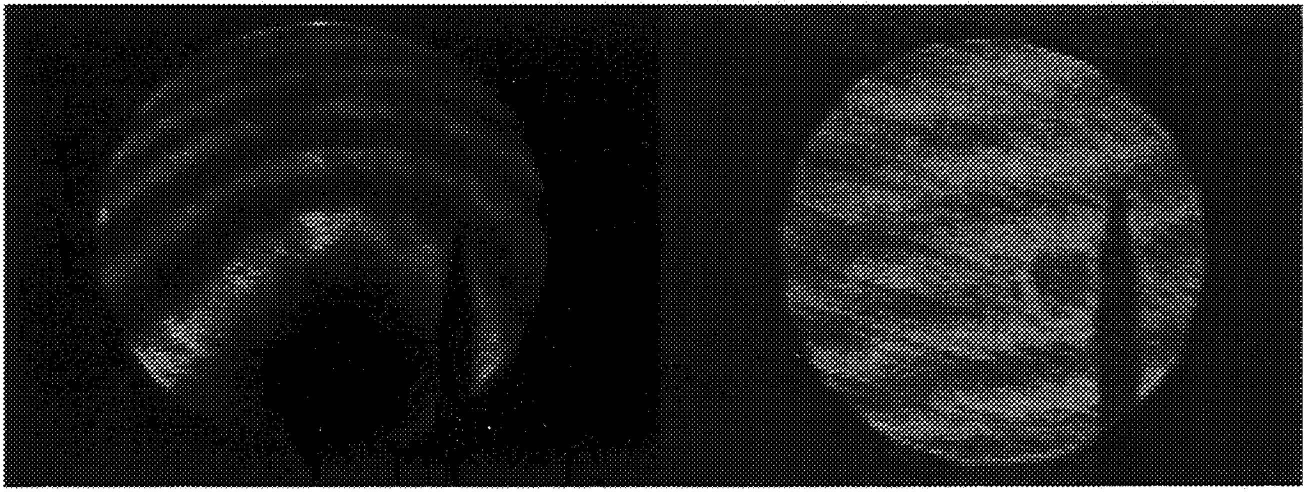

FIGURE 4. Four consecutive frames added together from (a) LCPDI and (b) Mach-Zehnder interferometers. The images were recorded in the presence of a 7 Hz table vibration.

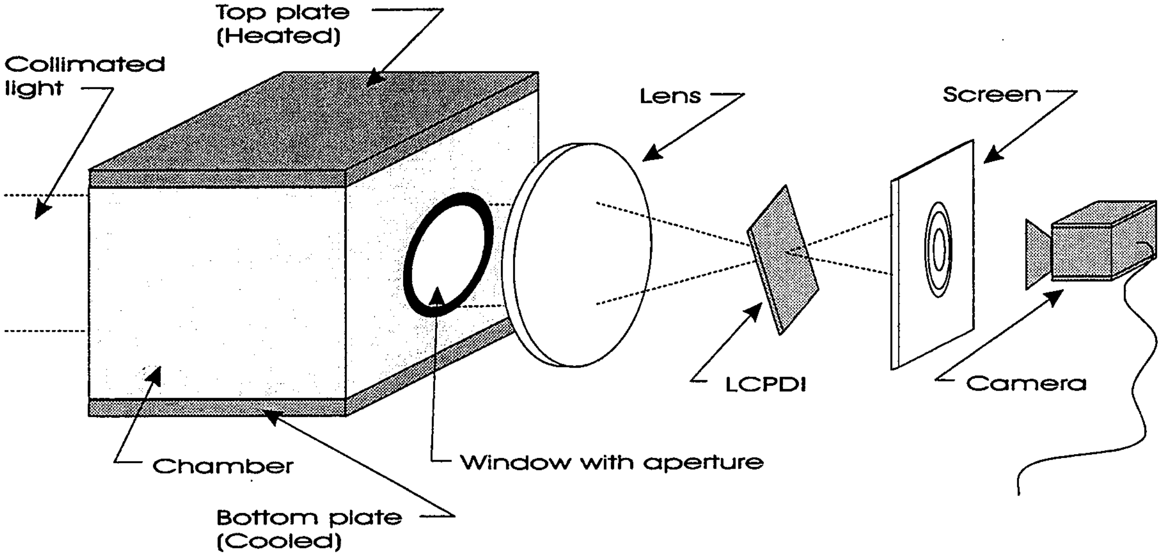

FIGURE 5. Experimental apparatus to measure temperature distribution throughout central section of oil-filled chamber.

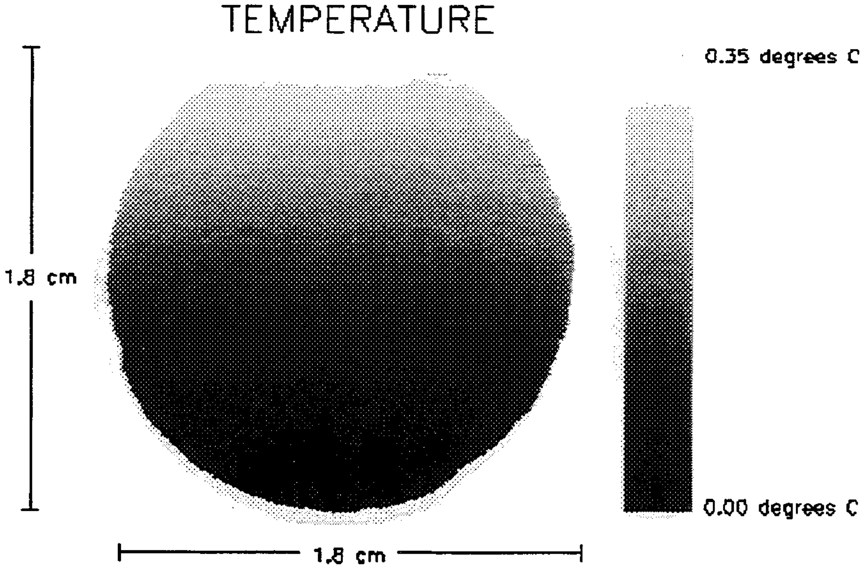

FIGURE 6. Temperature across central section of oil chamber measured with LCPDI. Top chamber plate was heated.

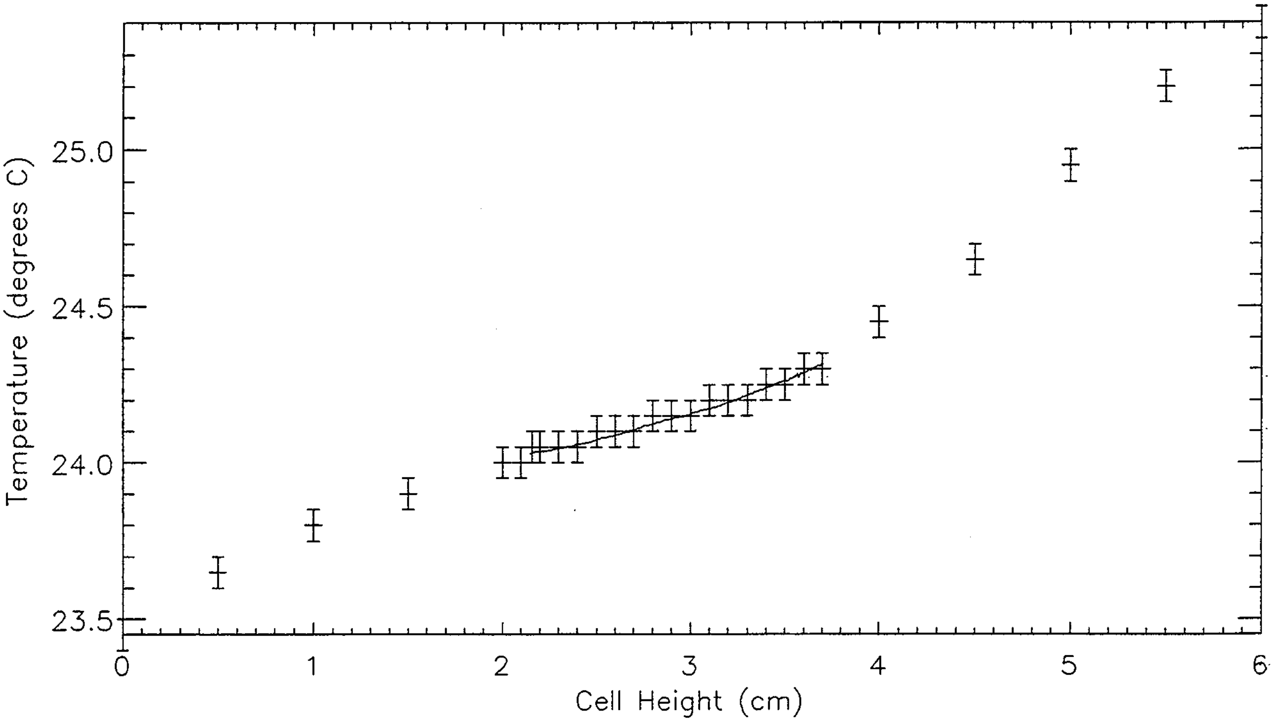

FIGURE 7. Temperature measured with LCPDI compared to thermocouple readings. LCPDI data shown as dots (they're closely spaced and appear as a solid line). Thermocouple data shown as symbols with error bars.

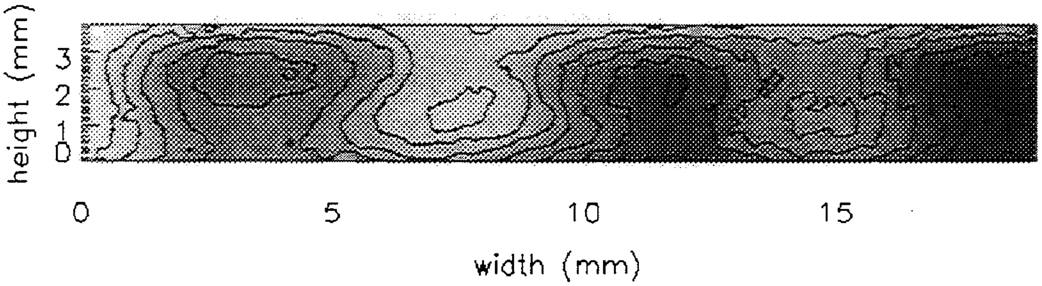

FIGURE 8. Bernard convection cells between two horizontal plates measured with LCPDI. Each contour represents a change of 0.1 degrees C.

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