In this experiment, an apparatus that mimics the Czochralski crystal growth chamber has been utilized.

The experimental setup consists of a glass beaker, a copper cylinder placed at the top surface of water representing a growing crystal, traversing mechanism to control the motion of the crucible and the cylinder, and instrumentation for visualization of the convection patterns (Figure 1). To facilitate comparison with numerical simulation, the beaker, representing the Czochralski crucible, is specially made of borosilicate glass, and has a flat base. The copper cylinder plays the role of the growing crystal of the Czochralski process. It is however passive, in the sense that a phase change occurring in the real process is not replicated. The crucible is placed on a platform within a constant temperature bath. The copper cylinder is held by a rod that is in turn connected to a stepper motor. Two constant temperature water baths (Raaga) have been used to maintain distinct temperature boundary conditions along the crucible walls and the copper cylinder. The traversing arrangement allows for careful positioning of the cylinder with respect to the beaker axis as well as the light sheet.

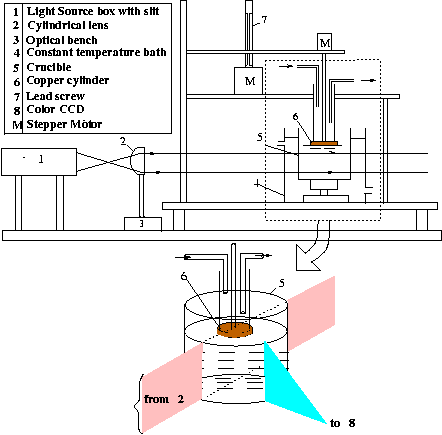


Figure1. Schematic diagram of the experimental setup

Water in the beaker is distilled, de-mineralized, and de-ionized to prevent contamination of the LCT powder, as well as to keep the beaker surface free of deposits. It is mixed with LCT powder (R35C15W, Hallcrest, USA) to provide the nuclei for scattering of light. The LCT specification refers to the activation of the red color at 35oC and a bandwidth of 15oC. The amount of powder added, finalized after several trials, was about 10 grams to half-a-liter of water. Light from a halogen lamp (500 Watts) is passed through a slit and a cylindrical lens to develop a sheet of light in the vertical plane. Light scattered by LCT particles is recorded at normal incidence by a three-color CCD camera.

The image acquisition system used in the present investigation consists of an 8-bit, 512 × 512 resolution color CCD camera (Sony), frame grabber (Basler A201bc) with 25 mm focal length lens (VCL-16WM) and a P-3 PC (HCL, 256MB RAM). These systems store the appropriate intensities of red, green, and blue in the scattered light needed to produce a matched color response corresponding to temperature at each point in the image.

The temperature levels in the experimental setup are much lower than in a real Czochralski set up, but the inter-play of buoyant convection and rotation could be visualized. Typical temperatures realized in the experiment were in the range of 34 to 45oC, the maximum temperature difference applied being 6oC. Rotational speeds of up to 25 rpm were employed. For a beaker diameter of 100 mm and a cylinder diameter of 50 mm, the largest Grashof number Gr was 3.2×106, the largest Reynolds number Re of the rotating cylinder being 3.25×103. Radius of the crucible is used as the length scale for non-dimensionalization. The mixed convection parameter, defined as Gr/Re2, could be varied. Values of the order of unity indicate a strong interaction between the forced and buoyancy-driven flow fields.

Compared to surface thermography, the use of TLC as dilute suspension in a fluid bears additional difficulties in measurement. First, the color images of the flow are discrete as they represent a discontinuous mist of points. Secondly, due to secondary light scattering from particles between the sheet of light and the camera, and its reflections from the sidewalls, the overall color response is distorted. It was seen in the present work that the signal strength, and hence the image quality was good in the central portion of the crucible over 80% of the diameter; it deteriorated in regions near the crucible walls.

## Experimental procedure

Liquid crystals are uniformly dispersed in water by stirring and introduced in the crucible. The crucible walls and the copper cylinder are maintained at two different temperatures by circulating water individually from constant temperature baths. Sufficient time is allowed to elapse for the flow and thermal fields to stabilize in the beaker. This time period is around one hour for pure buoyancy experiments. Rotation to the copper cylinder is imparted after buoyancy-driven convection is fully established in the beaker. For high rotation rates, a forced convection pattern was seen to be established in around 30 minutes. In the mixed convection regime, a clear steady state was visible only in selected experiments.

For measurements, light from a white light source is passed through a slit and a cylindrical lens to develop a sheet of light in the vertical plane of the crucible. The scattered light is recorded at normal incidence by the CCD camera. All experiments have been conducted in a controlled environment, with temperature and humidity carefully regulated. The ambient temperature during the experiments was maintained in the range of 30+0.2oC. In any particular experiment, the change in the ambient temperature was smaller.

## Liquid crystal calibration

The primary purpose of calibration is to establish a relationship between the color displayed by the crystals and their respective temperatures. The color of scattered light recorded in the experiment depends on the viewing angle of the camera. For the choice of the LCT powder and camera position, the hue-angle relationship was found to be mostly linear with a slope equivalent to 0.07oC per 10o change of angle. The color-temperature calibration was conducted with the axes of the light source and camera remaining at right angles.

The calibration technique of the present study is essentially a point-wise routine for the entire illuminated plane in the beaker. In order to calibrate the color output of the liquid crystals, a series of images are recorded while the test section is at spatially uniform temperature. To create a uniform temperature environment, a circular copper plate of diameter equal to that of the beaker is positioned over a small volume of water, all other solid walls being maintained at constant temperature. At steady state, water is at a spatially uniform temperature. Consequently, the LCT image is nominally of uniform color, except for the possibility of noise. A series of 30 such images are recorded over the full range of temperatures considered in the study. These images are digitized into 8-bit color images, and subsequently converted to hue, saturation and intensity. A third order polynomial was found to be appropriate to fit the hue-temperature data.

In video 1, the rotation of the copper block kept above the water surface is zero. Hence, convection is purely driven by density differences. A central plume can be seen to descend from the heated surface above. Cold fluid is displaced from the base to form a circulation loop.

In video 2, the copper block is given mild rotation with velocities that are comparable to those generated by buoyancy. However, rotational velocities are opposed to those generated in a gravity field, giving rise to apparently chaotic flow in the beaker.

In video 3, the rotation of the copper block is quite strong and overwhelms natural circulation. The flow in the beaker is then in the forced convection regime.