The Lecture Contains:

COLOR SCHLIEREN TECHNIQUE

The color schlieren technique (also called rainbow schlieren deflectometry) uses a white light source instead of a laser. Images formed are in color and hence a color CCD camera is used to record the schlieren patterns. The basic principle of a color schlieren technique is identical to that of the monochrome schlieren, in the sense that density gradients are mapped into light beam deflection. The knife edge enables the measurement of the angle of deflection in a monochrome technique. In color schlieren, the knife edge is replaced by a color filter. Here, a photographic film on which a color scale is printed is employed. The scale varies from red-to-green-to-blue (or the VIBGYOR scale). Light deflection shifts the light beam from one color zone to another. Changes in color in the image, thus, determine the angle of deflection and in turn, the density gradient field in the test section. Clearly, the color filter can be designed in such a way that appropriate resolution in measurement is possible.

The schematic diagram of the color schlieren deflectometry technique set up by the authors is shown in Figure 1(a). A twin halogen cold white light source (Optochem International, $150W)$ is connected to a $230\mu m$ pinhole with a fiber optic cable for obtaining a point light source. The pinhole is placed at the focus of an achromatic lens of 500 mm focal length and 65 mm diameter. A collimated light beam of size 65 mm is thus generated. It passes through the test cell and falls on another achromatic lens of 750 mm focal length and 100 mm diameter. This lens decollimates the beam and focuses it onto the color (rainbow) filter. A 3-color CCD camera (Basler, model A201bc), 648×648 pixels spatial resolution connected to a personal computer through an 8-bit A/D frame grabber card is used to record the color images formed on the plane of the filter.

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The rainbow filter is one-dimensional with color variation in one direction. The changes in color are arranged in the direction in which the density gradients are to be observed. Image formation on the filter is caused by the light deflected due to the non-uniformities in the refractive index field of the test region. For extracting quantitative information from the color images, HSI (hue-saturation-intensity) representation of color can be selected. Hue is obtained from direct transformation of the RGB tristimulus values (discussed in module 6). The color filter is calibrated by traversing the filter mounted on a micrometer assembly with simultaneous acquisition of the filter images. The calibration data relates filter displacement to change in hue. In a convection experiment, the change in hue at a point is converted into
beam deflection by reference to the calibration curve. Figure 1(b) shows a sample one dimensional color filter and the associated calibration curve. Minor deviation of the calibration curve from a truly linear behavior can be attributed to the errors during image processing and development of the filter on the photographic film.

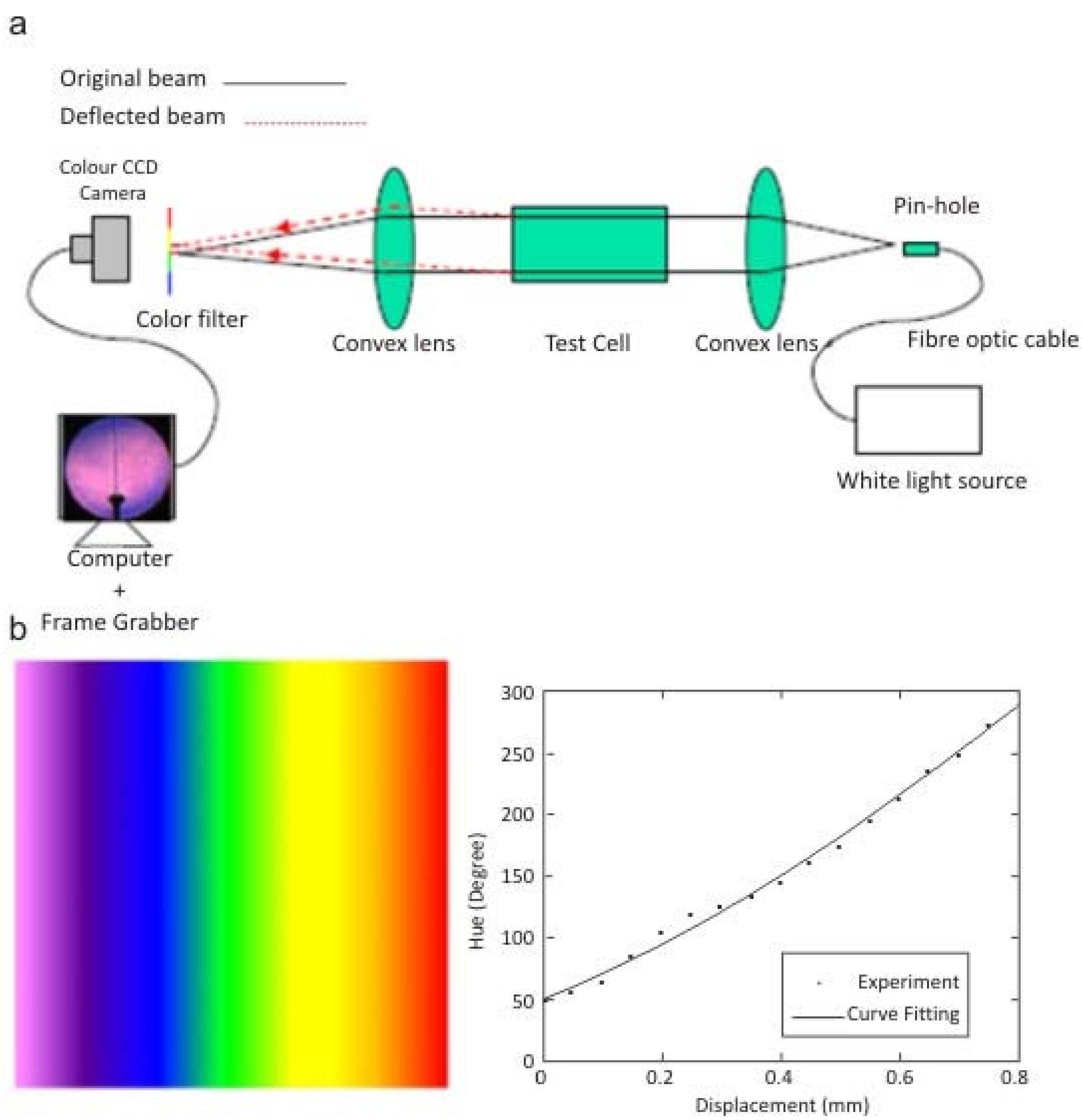

Figure 1: (a) Schematic diagram of a color schlieren deflectometry setup and (b) an image of the 1-D rainbow filter with the corresponding hue-displacement calibration curve.

A variety of color filters may be designed to suit the problem being studied. The one dimensional filter is the simplest of all. Other types of color filters are shown in Figure 1(c).

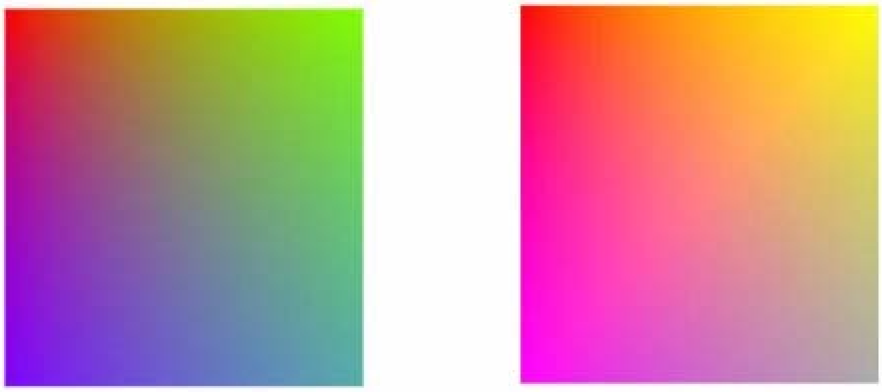

Figure 1(c): Examples of two dimensional color filters.

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Imaging Rayleigh-Benard convection

The apparatus used for the study of Rayleigh-Benard convection is shown schematically in Figure 2. The test cell consists of three sections namely the top tank, the middle test section and the bottom tank. The cavity is 447 mm in length with a square cross-section $(32 \times 32 \mathrm{mm}^2)$,, the dimensional tolerance being $\pm 0.1 \mathrm{mm}$.. The top and bottom surfaces of the cavity are made of aluminum, 3 mm thick. The side walls of the cavity are made of Plexiglas, 10 mm thickness and bakelite sheet of thickness 15 mm to provide thermally insulating side wall conditions. Optical windows (Standa, BK-7 glass, $\lambda/4$) are used to confine the fluid inside the test cavity and the passage of light is arranged in the direction normal to their planes and parallel to the side walls. Temperature differences between the top and bottom wall of the cavity are set equal to 10 K and 15 K.

For maintaining uniform cold temperature over the top surface, a tank carrying cold fluid is fixed above it (Figure 2). Special arrangements ensure that the lower surface of the tank and the top surface of the cold wall are in good thermal contact. For the lower heated surface, an aluminum tank with baffles is fabricated and assembled with the test cavity. These baffles introduce a tortuous path to the flow of hot water and increase the effective interfacial contact area. For maintaining uniform and constant temperatures at the upper and lower surfaces of the cavity, a large volume of water is circulated from constant temperature baths (Huber-variostat and Raaga-cryostat). Temperature measurements at the heated and cooled surfaces are carried out using thermocouples that are connected to a 32-channel temperature recorder (Sanei, hybrid recorder).

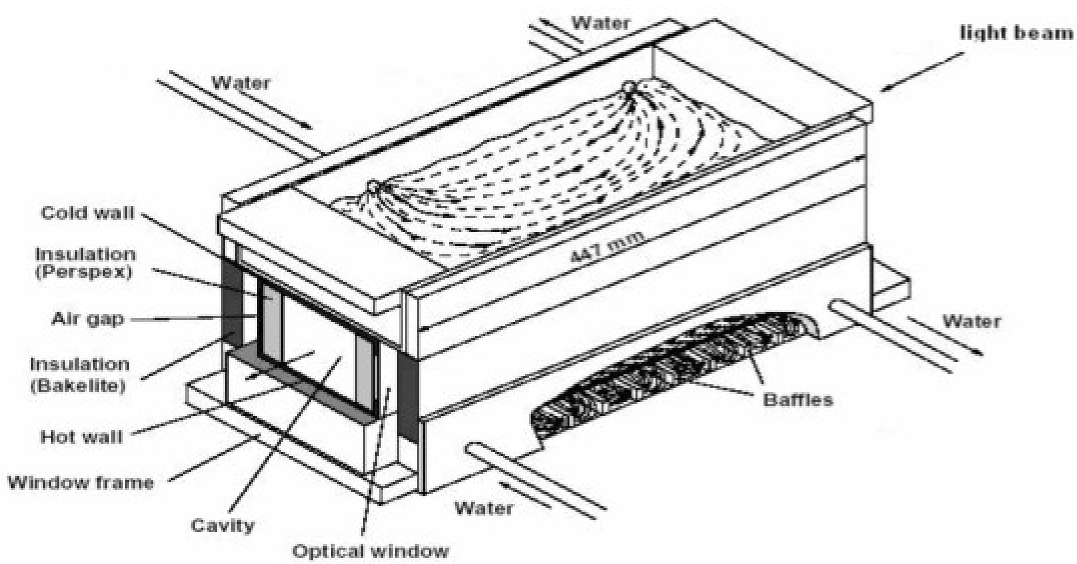

Figure 2: Test cell for imaging Rayleigh-Benard convestion in a rectangular cavity.

Data analysis

The color schlieren images are representative of cross-sectional distribution of refractive index gradient of the medium integrated along the passage of light. They can be processed to obtain both thermal and concentration field information. These images carry information related to the first derivative of the refractive index. Since refractive index of a transparent material is related to its density and, in turn, temperature and concentration, thermal and solutal gradients are mapped by the schlieren technique. For quantitative processing of schlieren images, the path of a light beam in a medium whose index of refraction is a function of position is analyzed. The outline of the data analysis procedure is described in the following paragraph

During a color schlieren experiment, the base image namely the filter itself without the test section in place is initially recorded. Subsequently, test images are recorded by introducing the test cell with the appropriate heat and mass transfer processes in progress. These images are subsequently converted into a matrix of R, G, and B values. From the RGB values, the hue (H) function is evaluated using the formula.

$$H = \arctan\left[\frac{\sqrt{3}(G-B)}{2R-G-B}\right] \qquad (1)$$

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Corresponding to the local hue value in the test image, the beam displacement due to an applied thermal/solutal gradient is obtained from the calibration curve. The beam displacement Δa of the light beam at the position of the color filter due to the deflection of light beam passing through the test cell by an angle Ψ is given as:

$$\Delta a = \pm f_2 \Psi \qquad (2)$$

In Equation (2), the sign on the right side is determined by the change in hue in the filter plane and f_2 is the focal length of the decollimator lens. The displacement field is related to the change in refractive index and hence the thermal or the concentration gradient. The gradient of the physical quantity is integrated from a known boundary condition to obtain the respective thermal and concentration fields. The analytical expressions involved in the data analysis procedure are described in the following paragraphs.

For Rayleigh-Benard convection experiments in air at constant pressure P , the beam displacement is related to the temperature gradient as:

$$\Delta a = \frac{f_2}{n_0} \frac{n-1}{\rho_0} \frac{P}{RT^2} \frac{\partial T}{\partial y} L \qquad (3)$$

Here n_0 is the refractive index of the medium, ρ_0 is the density of fluid medium and L is the length of the test cell in the direction of the light beam.

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Resolution

The deflection of the incident light beam by the test medium is measured on the color filter during the color schlieren measurements. The image of the filter is recorded with a certain number of pixels (648×648) in two directions and is digitized over the RGB scale of $0 - 255$ (8-bit). The hue-displacement information is contained in the calibration curve where the hue is plotted as a function of the spot position. The quality of the calibration curve depends on the pixel size, the color scale, the micrometer used for vertical movement of the filter, and the spot sized attained after decollimation.

The sensitivity of color schlieren measurements is generally quite high and is adjustable by proper selection of the optical components and design of the color filter. Equation 3 shows that the deflection of the light beam is proportional to L, the length of the test section in the direction of propagation of light and f_2, the focal length of the decollimating lens. Thus, large values of L and f_2, can be used to detect small gradients in temperature and concentration. The measuring range (ε_{range}) of the color schlieren is the maximum deflection angle at which linear range of color indicator i.e. hue value is achieved. It is defined as:

$$\varepsilon_{range} = \frac{b_f - b_s}{f_2} \qquad (6)$$

where b_f and b_S are the dimensions of the color filter and the source respectively. In the present case, b_f = 2.6 mm, b_s = 0.23 mm and f_2 =750 mm, returning $\varepsilon_{range} = 3.16$ mrad. For the 8-bit color camera, the theoretical sensitivity is 0.39% of the full range. When the filter is at the central position corresponding to the zero beam deflection, the deflection can be measured in the interval $[-1.58, +1.58]$mrad. Thus, the dynamic range is equal to 128 with minimum detectable deflection angle of 0.012 mrad.

The sensitivity of the color schlieren technique is inversely proportional to the range and therefore the color filter can be designed for required resolution. The sensitivity also depends on the change in refractive index with respect to temperature and concentration. In terms of temperature, this derivative $(-dn/dT, K^{-1})$ *is* 0.9×10^{-6} in air and 0.88×10^{-4} in water. Clearly, sensitive measurements can be carried out in water since it has a higher sensitivity compared to air, by around two orders of magnitude.

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Results and Discussion

The present study reports the effectiveness of color schlieren deflectometry in the characterization of buoyancy-driven convection. In this context, a direct comparison with monochrome schlieren is useful. Laser schlieren has certain disadvantages that are absent when a white light source is used. Thus, in color schlieren, one obtains the following features:

(i) Diffraction effect at a knife edge is avoided since a color filter is used;

(ii) Speckle, common in coherent optics, is not present in color-based measurements;

(iii) Three intensities (RGB) instead of one gray scale provide three-fold information and hence fundamental advantages in the measurement;

(iv) Difficulty with the CCD saturation, common when lasers are used, can be easily alleviated;

(v) The laser schlieren technique can not provide both positive and negative gradient information simultaneously contrary to that of color schlieren; and

(vi) The color filter can be designed to yield the required resolution. The attractiveness of a color image is yet another advantage. Since data analysis is based on light intensity itself, factors (i) and (ii) pose serious limitations in laser schlieren.

The validation of the measurement and quantitative analysis procedures in color schlieren is demonstrated in the following sections from an experiment on Rayleigh–Bernard convection. Additional applications related to ice cube melting in water and crystal growth from an aqueous solution are also presented.

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Quantitative analysis and validation

The Rayleigh-Bernard (R-B) experiment is conducted to demonstrate and quantitatively validate the data analysis procedure of the color schlieren technique. Figure 3 shows the transient sequence of color schlieren images of R-B convection. Initially, the beam is focused at the red region of the color filter, Figure 3(a), which is used as the reference image for subsequent calculations. After recording the base image, a temperature difference is applied between the top and bottom walls of the cavity by circulating cold and hot water in the respective tanks. Unstable density gradients are created in the fluid medium as the air near the top cold wall becomes denser compared to air near the lower hot wall, setting up convection currents across the cavity. The density gradients lead to a change in the index of refraction of the media and the light beam deflects from its original path. The deflected beam falls on various regions of the color filter depending on the strength of the refractive index gradient, creating a range of colors. Figure 3(f) shows the steady state convection pattern. Here, a large color variation is observed near the horizontal walls and no color variation is seen in the central region. This is due to high thermal gradients in the near wall region because of diffusion mode of heat transfer compared to the central region, where convection mode is predominant. The color change near the vertical sides is not very prominent because of the insulated boundary conditions. Thus, the color schlieren image clearly brings out the thermal boundary-layer type of the flow structure in the cavity with an overall circulation loop.

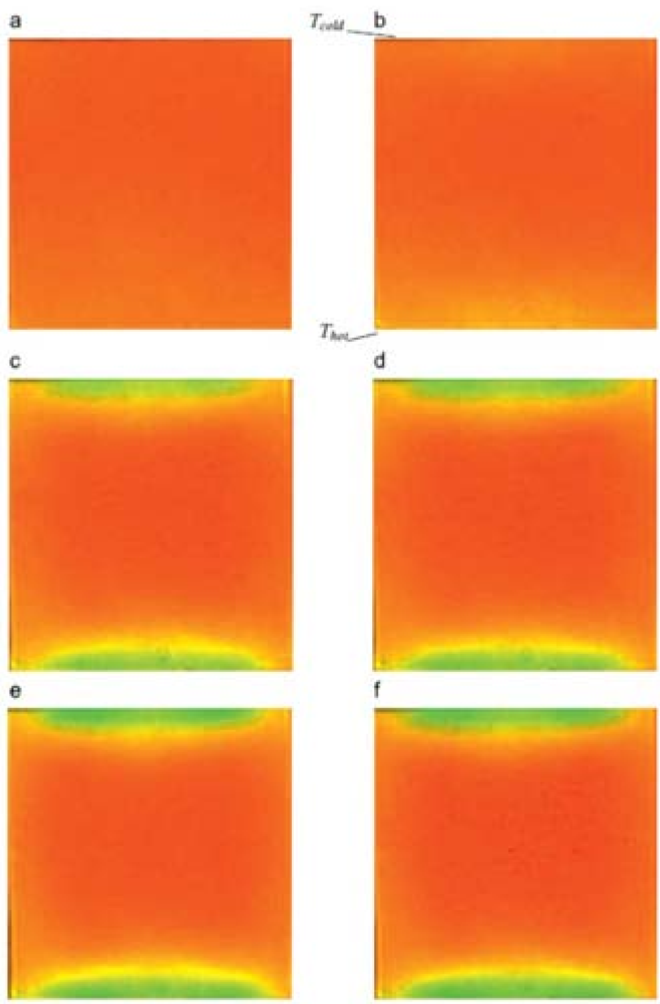

Figure 3: Transient evolution of the convective ield in an ir filled rectangular cavity with top surface temperature, $T_{cold} = 15°C$ and bottom surface temperature $T_{hot} = 30°C$ The corresponding Rayleigh number is Ra=48,000: (a) base image (t=0 h); (b) t=0.25 h; (c) t=0.5h; (d) t=1; (e) t=2h and (f) t=4h

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Figure 4 presents the results of the

data analysis procedure of schlieren images for evaluation of the temperature field and the Nusselt number distribution. Figure 4(a) shows the hue variation with respect to the non-dimensional height (y/H) at cavity widths of $x/H = {}^1/_4, {}^1/_2$ and ${}^3/_4$. The hue variation is large near the walls $(y/H = 0$ to 0.2 representing the lower wall region and $y/H = 0.8$ to 1 for the top wall region). Hue is nearly constant in the central region i.e. for the range y/H = 0.2 to 0.8. Figure 4(b) shows the temperature gradient variation obtained using the calibration curve and Equation 3. The integration of the temperature gradient of Figure 4(b) along with the known wall temperatures leads to the temperature distribution shown in Figure 4(c). The temperature profiles show a steep variation in the near wall region and almost a zero slope at the centre of the cavity. The temperature gradient in the near wall region from Figure 4(c) is used in Equation 7 leading to the spanwise Nusselt number distribution in Figure 4(d). The central region of the lower wall shows a nearly constant Nusselt number, which decreases towards the corners of the cavity. This reduction in the Nusselt number is related to a zero heat flux at the side walls arising from the insulated boundary condition.

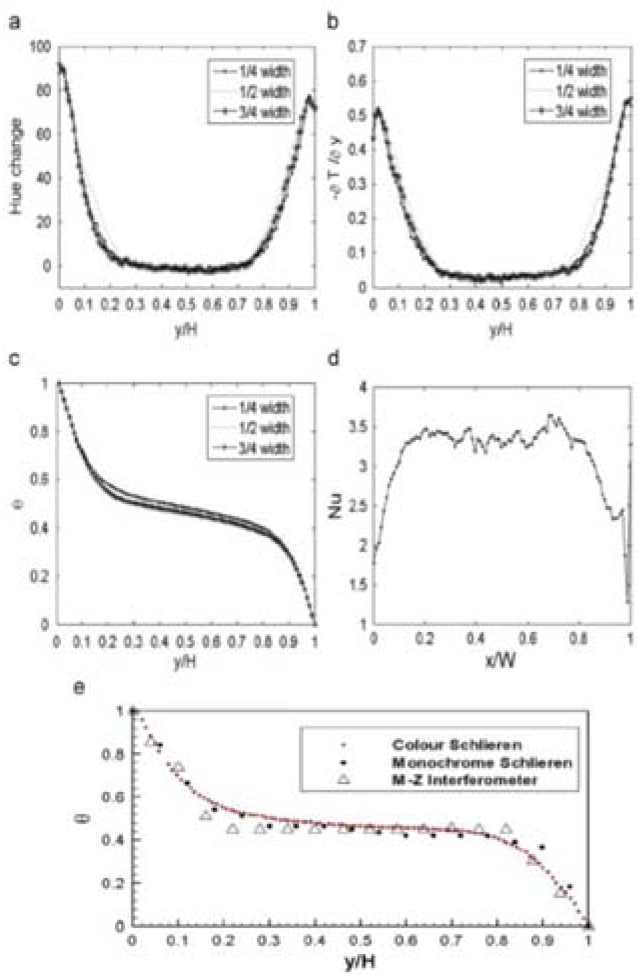

Figure 4: The steps involved during the quantitative analysis of color schlieren; (a) change in hue, (b) temperature gradient, (c) non-dimensional temperature and (d) Nusselt number. The non-dimensional temperature from the present experiment is compared with previous work in (e)

Figure 4(e) compares the dimensionless temperature profiles at steady state along the centerline of the cavity obtained from the color schlieren measurements with those reported from measurements. A reasonably good match among color schlieren measurements of the present work with laser schlieren and interferometry validates the data analysis procedure.

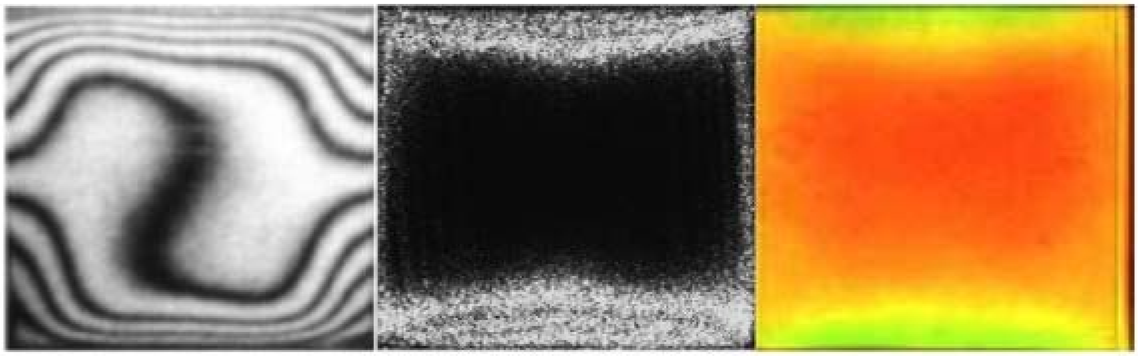

Figure 5: Comparision of interferometry, monochrome schlieren, and color schlieren applied to convection in a differently heated cavity.

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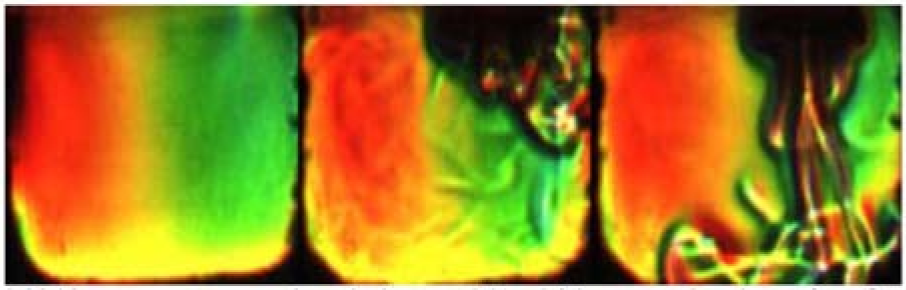

Figure 6: Color schlieren imaging of buoyant convection around an ice cube melting in water.

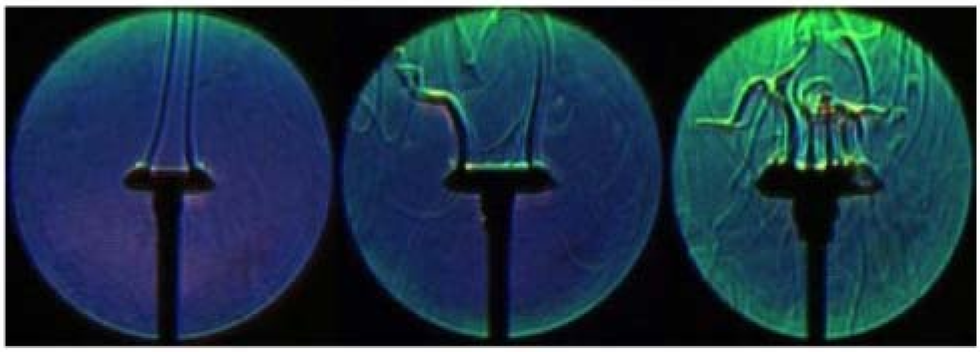

Figure 7: Convection plumes strengthening with time during growth of a KDP crystal from its aqueous solution.

Additional color schlieren images are presented in Figures 5-7. In Figure 5, interferometry, laser schlieren and color schlieren are directly compared for a Rayleigh-Benard experiment wherein buoyancy-driven convection in a fluid-filled horizontal differentially heated cavity is generated. Figure 6 shows convection pattern in a beaker containing water when an ice cube, suddenly placed on its surface, starts to melt. In Figure 7, convection plumes around a crystal growing from its aqueous, supersaturated solution are imaged.

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Shadowgraph imaging has been performed for crystal growth in the platform geometry to observe the strength and transition sequence of buoyant plumes. The growth parameters during the experiment are as follows. The experiment has been performed under free convection conditions. A symmetrical KDP seed crystal in the shape of a cuboid without pyramidal facets is placed in a small cavity on the platform made of Plexiglas. The dimensions of the seed crystal are 2 × 2 × 4 mm^3. The c-axis of the crystal is along the gravity vector and the crystal is glued to the platform by self-curing silicone sealant that is chemically inert. The pH of the solution is 4.3 and the impurities in the solution are as-present in the commercially available KDP chemical of 99.5% purity. The solution has a saturation temperature of 60^oC and the average cooling rate adopted during the growth is 0.02^oC/hr. The experiment is performed for 250 hours, cooling the solution by 5^oC. In the video above, a steady buoyant plume formed after 200 hours is seen in the shadowgraph.

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A crystal growth experiment is carried out with a crystal placed on top of a glass rod. The rod is mounted on a Plexiglas platform. The chosen geometry permits better visualization of the convective plumes over the top face of the growing crystal. The parameters of growth during the experiment are as follows: A small KDP crystal with bi-pyramidal morphology having its c-axis horizontal is glued to one end of a thin glass rod (1.5 mm diameter). The dimensions of the seed crystal are $2 \times 1 \times 2$ mm^3. The aqueous solution has a saturation temperature of 55.2^oC and the average cooling rate adopted during the growth is $0.02^oC/hr$. The experiment is continued for 195 hours of which the initial 45 hours are required to reach the saturation temperature and heat the solution to avoid spurious nucleation. Crystal growth continues for 150 hours during which the solution is cooled by 3.5^oC. After about 60 hours of growth the crystal dimension increases and the plumes become strong. The plumes are seen to rise from the edges of the crystal. After about 100 hours of growth, plumes are seen to emerge from several spots on the top surface of the crystal. This indicates that there are several locations on the top surface where the accumulation of solution depleted of solute act as sources of plumes. At this stage the plume behavior becomes unsteady. Subsequently, the buoyant flow displays chaotic behavior as seen in the irregular plumes of the video.

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Growth of a potassium dihydrogen phosphate (KDP) crystal from its aqueous solution has been considered under forced convection conditions. The KDP crystal is grown in a top hanging geometry. Forced convection conditions are created by rotating the crystal about a vertical axis. The rotational rpm is varied in a cycle, creating an accelerated rotation cycle (ARC) paradigm. The effect of varying the rotational rpm on the concentration field around the crystal was investigated. Mach-Zehnder interferometry was adopted as an optical technique to image the evolving concentration fields. Six different experiments were performed to obtain the specific set of time periods and rotation rates of the acceleration cycle that result in a uniform concentration field around the growing crystal. The Reynolds number, an index of the strength of forced convection was kept at 1625 in all the experiments. ARC parameters are not optimized here. As a result, the dark fringe in the video does not cover the crystal with any degree of uniformity. The next video shows the interferogram under optimized crystal growth conditions.

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This video is similar to the shadowgraph sequence of Video 2. A stronger level of flow unsteadiness is seen here since the crystal size is larger.

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