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A Photometric Technique for Determining Fluid Concentration Using Consumer-Grade Hardware

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TECHNICAL MEMORANDUM

A PHOTOMETRIC TECHNIQUE FOR DETERMINING FLUID CONCENTRATION USING CONSUMER-GRADE HARDWARE

I. BACKGROUND

A great number of crystals grown in space are plagued by convective motions, which contribute to structural flaws. The character of these instabilities is not well understood but is associated with density variations in the presence of residual gravity (g-jitter). As a specific example, past HgCdTe crystal growth space experiments by Lehoczky and co-workers (see Gillies et al.)[1] indicate radial compositional asymmetry in the grown crystals. In the case of HgCdTe, the rejected component into the melt upon solidification is HgTe which is denser than the melt. The space-grown crystals indicate the presence of three-dimensional flow with the heavier HgTe-rich material clearly aligned with the residual gravity (0.55–1.55 μg) vector. This flow stems from multicomponent convection, namely, thermal and solutal buoyancy-driven flow in the melt. A model fluid experiment to study this problem in space requires the rapid development of a concentration (density) gradient, which is difficult to establish in the absence of a stabilizing gravitational field. An important objective of a companion study (Ramachandran et al.)[2] is to evaluate the feasibility of using a magnetic fluid to study this phenomenon. Essential to that effort is the confirmation that the concentration of the fluid be known in a two-dimensional plane.

This report will describe a technique for measuring the fluid concentration in a test cell using photometric techniques and consumer-grade equipment. Although results will be presented for a magnetic fluid for use in a complementary study, the procedure is generic and can be applied to a variety of fluids whose transmittance changes with concentration. This work was guided by the efforts of Mihailovic and Beckermann[3] who used an argon ion laser as a monochromatic source and a 12-bit digital camera. In addition to lower costs, the advantage of using a white backlight with filters is that a greater selection of wavelength can be used to determine the optimum color for light attenuation through a particular fluid. Also, the speckle nature of laser light which may be nonuniform on small scales can present a problem. However, the use of a 12-bit digital monochrome camera over a consumer-grade 8-bit color camera is advantageous because the former generally has a superior dynamic range and linear relation between light intensity and the associated pixel value. Of course, the 12-bit camera requires much more computer memory for storing and manipulating the images.

II. THEORY AND APPROACH

Refer to figure 1 which depicts a test cell partially filled with a liquid. The incident uniform light intensity I_o passes through the cell and liquid. (A more general approach for the case when the backlight is not uniform is given in the appendix.) Using the Lambert-Beer law for light absorption, the light intensity at point *a* (after being slightly reduced by the attenuation through the cell) is

$$I_a = I_o \exp(-\alpha_{\lambda,cell} d) \quad , \tag{1}$$

where $\alpha_{\lambda,cell}$ is the extinction coefficient for the test cell material, and *d* is the path length. Similarly, the intensity at point *b* after additionally passing through the liquid is

$$I_b = I_a \exp(-\alpha_\lambda \, s \, C) \quad , \tag{2}$$

where s is the path length through the liquid, α_λ is the extinction coefficient for the liquid per unit concentration at wavelength λ, and *C* is the concentration by volume of the liquid.

Finally, the intensity of the light emerging at point *c* is

$$I_c = I_b \exp(-\alpha_{\lambda,cell} d) \quad , \tag{3}$$

or substituting equation (1) and equation (2) into equation (3) yields

$$I_c = I_o \exp(-2 \, d \, \alpha_{\lambda,cell}) \exp(-\alpha_\lambda \, s \, C) \quad . \tag{4}$$

The light passing above the liquid (ignoring the difference in reflection of the light passing through the liquid with that passing overhead; consequences of this assumption will be discussed further in section V) at point *d* has an intensity of

$$I_d = I_o \exp(-2 \, d \, \alpha_{\lambda,cell}) \quad . \tag{5}$$

Finally, dividing equation (4) by equation (5) gives the light emerging from *c*

$$I_c = I_d \exp(-\alpha_\lambda \, s \, C) \quad . \tag{6}$$

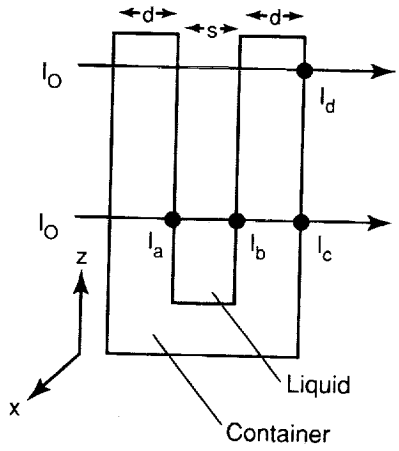

Figure 1. Light rays passing through a test cell partially filled with a liquid.

So, by measuring the intensity I_d and the intensity distribution I_c and determining α_λ from a calibration test, the concentration distribution of the fluid C can be determined. Because the absorption and scattering of light by a particular fluid depends on the wavelength, it is important to select a specific color that allows α_λ to be less sensitive to the concentration. This can be done with the help of a spectrophotometer or determined empirically during a calibration.

III. CALIBRATION USING THE SPECTROPHOTOMETER

A solution was made up of 0.5 percent (by volume) EMG 909 ferro-fluid in a carrier liquid EMG 911 both manufactured by FerroFluidics Corp. This material, hereafter known as the *test solution*, was selected only because it is used in a companion effort and similar results were obtained using food color in water. Six different concentrations of the test fluid were prepared in cells and placed in a Coleman 44 Linear Absorbance Spectrophotometer, which measured the attenuation of light at selected wavelengths of 650, 635, 600, 520, and 440 nm. The spectrophotometer results are shown in table 1. The first row of the table shows the concentrations of the test solution prepared with a precision dispenser. The second row shows the relative reduction of the light intensity after passing through the cell, I/I_o. The third row is the extinction coefficient computed from equation (6) in an effort to determine a particular wavelength where it might decouple from the concentration.

Table 1. Spectrophotometer measurements.

Wavelength = 650	CELL 1	CELL 2	CELL 3	CELL 4	CELL 5	CELL 6
Known concentraton (ml/ml)	0.7500	0.5000	0.4000	0.2500	0.1500	0.0500
I / Io	0.3910	0.5100	0.5900	0.7410	0.8260	0.9060
Computed extinction (cm^{-1})	1.252E+00	1.347E+00	1.319E+00	1.199E+00	1.274E+00	1.974E+00

Wavelength = 635	CELL 1	CELL 2	CELL 3	CELL 4	CELL 5	CELL 6
Known concentration (ml/ml)	0.7500	0.5000	0.4000	0.2500	0.1500	0.0500
I / Io	0.3180	0.4720	0.5470	0.6810	0.7910	0.8900
Computed extinction (cm^{-1})	1.528E+00	1.502E+00	1.508E+00	1.537E+00	1.563E+00	2.331E+00

Wavelength = 600	CELL 1	CELL 2	CELL 3	CELL 4	CELL 5	CELL 6
Known concentration (ml/ml)	0.7500	0.5000	0.4000	0.2500	0.1500	0.0500
I / Io	0.1960	0.3500	0.4310	0.5890	0.7230	0.8600
Computed extinction (cm^{-1})	2.173E+00	2.100E+00	2.104E+00	2.117E+00	2.162E+00	3.016E+00

Wavelength = 520	CELL 1	CELL 2	CELL 3	CELL 4	CELL 5	CELL 6
Known concentration (ml/ml)	0.7500	0.5000	0.4000	0.2500	0.1500	0.0500
I / Io	0.0090	0.0220	0.0430	0.1310	0.2910	0.6230
Computed extinction (cm^{-1})	6.281E+00	7.633E+00	7.866E+00	8.130E+00	8.230E+00	9.464E+00

Wavelength = 440	CELL 1	CELL 2	CELL 3	CELL 4	CELL 5	CELL 6
Known concentration (ml/ml)	0.7500	0.5000	0.4000	0.2500	0.1500	0.0500
I / Io	0.0050	0.0070	0.0080	0.0110	0.0400	0.2910
Computed extinction(cm^{-1})	7.064E+00	9.924E+00	1.207E+01	1.804E+01	2.146E+01	2.469E+01

A plot of the spectrophotometer measurements is shown in figure 2. It is clear that the extinction coefficient is fairly independent of concentration for the longer wavelengths so that red and green light would be the best candidates to use for photometrically measuring the concentration. However, for the final calibration, a number of filter combinations were used and are discussed in the next section.

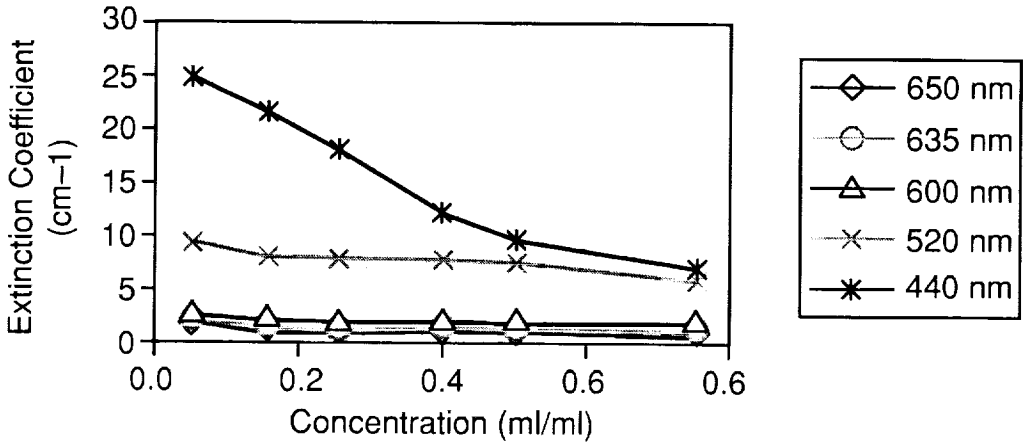

Figure 2. The extinction coefficient versus concentration measured at several wavelengths using a spectrophotometer.

IV. FIRST CALIBRATION USING TEST CELLS

Six different concentrations were prepared again by diluting the test solution (see section III) with additional carrier liquid and placing it in optical quality vials measuring about 4.3 cm×1 cm×1 cm with 1-mm thick walls. Table 2 shows the concentrations in the various cells. The first row is the volume of the test solution as determined by a precision dispenser while the second row is the volume of carrier liquid used. The concentration shown on the fourth row is then just the volume of the test solution divided by the total volume (row 3).

Table 2. Concentrations in various cells.

	CELL 1	CELL 2	CELL 3	CELL 4	CELL 5	CELL 6	*TOTAL*
Vol of test soln. (ml)	2.4	2	1.6	1	0.6	0.2	*7.8*
Vol of carrier (ml)	0.6	1	1.4	2	2.4	2.8	*10.2*
Total volume (ml)	3	3	3	3	3	3	*18*
Concentration (ml/ml)	0.8000	0.6667	0.5333	0.3333	0.2000	0.0667	

The vials were placed in front of a Dolan-Jenner Model 180 light source with area backlight and photographed by a Sony DCR VX1000 digital camcorder with 8-bit resolution for each red, green, and blue charged coupled device (CCD) chip. Several backlighting configurations were photographed: (1) unfiltered white light, (2) a Kodak No. 25 red filter with peak transmission around 650 nm placed between the backlight and the vials as well as, (3) a Kodak No. 58 green filter with peak transmission around 520 nm, and (4) a Kodak No. 47 blue filter with peak transmission around 440 nm. The camera f-stop was bracketed in order to get proper exposures for all camera chips where possible.

Once the image of the vials was captured, the analysis was performed using ScionImage software downloaded from the Internet from the Scion Corporation web site. Figure 3 shows the six vials against the backlight. The average pixel value above the liquid interface was assumed proportional to the intensity I_d. The average pixel value coming through the liquid was assumed to be proportional to I_c. Since it is the ratio of these two quantities that is important, the proportionality constant is irrelevant. Knowing the concentrations, and with the use of equation (6), the extinction coefficients were computed for each of the six vials. The average absorption was then used to determine the computed concentration and compared with the actual values.

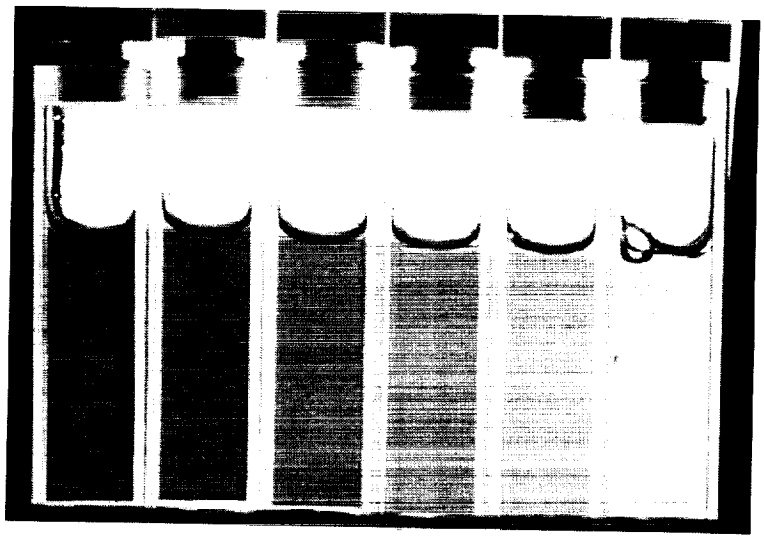

Figure 3. A view of the six vials with concentration of the test solution decreasing to the right.

Table 3 shows the computed extinction coefficients and corresponding computed concentrations using a white backlight with no filter in place. Results are for the green and blue CCD chips within the camera as well as when the color image was converted to a gray scale. The red chip was nearly saturated and not suitable for analysis in this particular case. When the vials were photographed, the camera f-stop was bracketed to provide several exposures. The particular frame selected for analysis was later chosen so as to have the darkest regions of the frame with pixel values near zero, while the brightest regions had values near 255. In only a few cases were the frames hopelessly overexposed or underexposed.

The first row of table 3 gives the average pixel value of the light passing through the fluid with each cell, I_c. This value was obtained from the ScionImage software by enclosing an area of the image with the cursor and using the "measure" function which provides an area average as well as a standard deviation. The second row gives the average intensity of light passing above the liquid I_d, obtained as above. It is evident from the data that the backlight is slightly brighter in the center near cells 3 and 4, although independent measures of the backlight showed that there is much less variation in the vertical direction. The third row is simply the concentration of the solution that was prepared using known volumes of the test solution and the carrier liquid. The fourth row denotes the extinction coefficient for each cell as computed by equation (6). The fifth row shows the retrieved concentration computed from equation (6) and using the average extinction coefficient. Finally, row six shows the error in concentration determined from the absolute difference between the known concentration and the computed concentration. The least error for this configuration using a white backlight was obtained using only the green chip resulting in an average error of 0.0463 ml/ml. As will be shown, this error can be substantially reduced using different filters.

Table 3. White light (no filter).

GREEN CHIP	CELL 1	CELL 2	CELL 3	CELL 4	CELL 5	CELL 6	AVERAGE
Average I_c	26.16	35.42	53.17	99.24	137.98	188.31	
Average I_d	212.83	215.93	217.19	217.47	214.88	210.44	
Known concentration (ml/ml)	0.8	0.6667	0.5333	0.3333	0.2	0.0667	
Computed extinction, α_λ (cm^{-1})	2.6203	2.7114	2.6388	2.3538	2.2149	1.6658	2.3675
Computed concentration with average α_λ(ml/ml)	0.8854	0.7635	0.5944	0.3314	0.1871	0.0469	
Error in computed concentration (ml/ml)	0.0854	0.0968	0.0611	0.0019	0.0129	0.0198	0.0463

BLUE CHIP	CELL 1	CELL 2	CELL 3	CELL 4	CELL 5	CELL 6	AVERAGE
Average I_c	14.84	13.7	14.56	15.56	24.03	74.96	
Average I_d	150.53	154.04	155.58	155.59	154.1	150.04	
Known concentration (ml/ml)	0.8	0.6667	0.5333	0.3333	0.2	0.0667	
Computed extinction, α_λ(cm^{-1})	2.8960	3.6295	4.4419	6.9083	9.2915	10.4040	6.2619
Computed concentration with average α_λ (ml/ml)	0.3700	0.3864	0.3783	0.3677	0.2968	0.1108	
Error in computed concentration (ml/ml)	0.4300	0.2803	0.1550	0.0344	0.0968	0.0441	0.1734

GRAY CONVERSION	CELL 1	CELL 2	CELL 3	CELL 4	CELL 5	CELL 6	AVERAGE
Average I_c	71.74	81.24	95.32	121.63	138.53	172.05	
Average I_d	204.93	208.23	208.79	208.92	207.71	204.57	
Known concentration (ml/ml)	0.8	0.6667	0.5333	0.3333	0.2	0.0667	
Computed extinction, α_λ (cm^{-1})	1.3120	1.4118	1.4703	1.6231	2.0253	2.5956	1.7397
Computed concentration with average α_λ (ml/ml)	0.6033	0.5410	0.4507	0.3110	0.2328	0.0995	
Error in computed concentration (ml/ml)	0.1967	0.1257	0.0826	0.0223	0.0328	0.0328	0.0821

Table 4 shows the same analysis with a blue filter between the backlight and the test cells. The red CCD signal indicated the greatest error in the retrieved concentration although none of these runs with the blue filter were particularly accurate, consistent with the spectrophotometer measurements. Once again the green chip showed a low error, although the gray scale conversion of the full color image was just slightly better.

Table 4. Blue Kodak™ filter.

RED CHIP	CELL 1	CELL 2	CELL 3	CELL 4	CELL 5	CELL 6	AVERAGE
Average I_c	32.9	36.37	39.98	44.89	45.71	46.31	
Average I_d	87.91	93.19	95.54	95.12	90.31	79.71	
Known concentration (m/ml)	0.8	0.6667	0.5333	0.3333	0.2	0.0667	
Computed extinction, α_λ (cm^{-1})	1.2286	1.4113	1.6335	2.2530	3.4047	8.1415	3.0121
Computed concentration with average α_λ (ml/ml)	0.3263	0.3124	0.2892	0.2493	0.2261	0.1803	
Error in computed concentration (ml/ml)	0.4737	0.3543	0.2441	0.0840	0.0261	0.1136	0.2160

GREEN CHIP	CELL 1	CELL 2	CELL 3	CELL 4	CELL 5	CELL 6	AVERAGE
Average I_c	10.79	12.31	14.37	23.98	41.35	81.95	
Average I_d	149.83	156.52	157.75	155.98	146.6	129.78	
Known concentration (ml/ml)	0.8	0.6667	0.5333	0.3333	0.2	0.0667	
Computed extinction, α_λ (cm^{-1})	3.2886	3.8140	4.4925	5.6181	6.3282	6.8925	5.0723
Computed concentration with average α_λ (ml/ml)	0.5187	0.5013	0.4723	0.3692	0.2495	0.0906	
Error in computed concentration (ml/ml)	0.2813	0.1654	0.0610	0.0359	0.0495	0.0239	0.1028

BLUE CHIP	CELL 1	CELL 2	CELL 3	CELL 4	CELL 5	CELL 6	AVERAGE
Average I_c	7.39	7.43	7.58	8.37	12.08	42.09	
Average I_d	109.74	114.81	115.3	114.76	110.68	102.5	
Known concentration (ml/ml)	0.8	0.6667	0.5333	0.3333	0.2	0.0667	
Computed extinction, α_λ (cm^{-1})	3.3725	4.1064	5.1041	7.8554	11.0755	13.3441	7.4763
Computed concentration with average α_λ (ml/ml)	0.3609	0.3662	0.3641	0.3502	0.2963	0.1190	
Error in computed concentration (ml/ml)	0.4391	0.3005	0.1692	0.0169	0.0963	0.0523	0.1791

GRAY CONVERSION	CELL 1	CELL 2	CELL 3	CELL 4	CELL 5	CELL 6	AVERAGE
Average I_c	22.42	24.51	27.13	35.6	58.42	127.24	
Average I_d	163.04	167.28	168.31	167.69	163.4	154.28	
Known concentration (ml/ml)	0.8	0.6667	0.5333	0.3333	0.2	0.0667	
Computed extinction, α_λ (cm^{-1})	2.4801	2.8807	3.4224	4.6498	5.1427	2.8890	3.5774
Computed concentration with average α_λ (ml/ml)	0.5546	0.5369	0.5102	0.4332	0.2875	0.0539	
Error in computed concentration (ml/ml)	0.2454	0.1298	0.0231	0.0999	0.0875	0.0128	0.0998

Table 5 shows the results with a green filter between the backlight and the cells. Once again, the green chip and gray conversion showed the least error. In fact, not surprisingly, all of the errors were smaller with the use of the green filter. This is consistent with figure 2 which indicates that the extinction coefficient of green light is decoupled from concentration so that the light attenuation can be attributed solely to the value of concentration (see equation (6)).

Table 5. Green Kodak™ filter.

RED CHIP	CELL 1	CELL 2	CELL 3	CELL 4	CELL 5	CELL 6	AVERAGE
Average I_c	63.55	76.14	93.19	118.45	148.86	172.08	
Average I_d	182.64	190.79	194.06	194.38	189.85	181.54	
Known concentration (ml/ml)	0.8	0.6667	0.5333	0.3333	0.2	0.0667	
Computed extinction, α_λ (cm^{-1})	1.3196	1.3778	1.3754	1.4861	1.2161	0.8023	1.2629
Computed concentration with average α_λ (ml/ml)	0.8359	0.7274	0.5808	0.3922	0.1926	0.0424	
Error in computed concentration (ml/ml)	0.0359	0.0607	0.0475	0.0589	0.0074	0.0243	0.0391

GREEN CHIP	CELL 1	CELL 2	CELL 3	CELL 4	CELL 5	CELL 6	AVERAGE
Average I_c	14.8	20.22	28.91	53.88	80.46	121.91	
Average I_d	159.17	166.14	168.3	168.81	164.91	157.53	
Known concentration (ml/ml)	0.8	0.6667	0.5333	0.3333	0.2	0.0667	
Computed extinction, α_λ (cm^{-1})	2.9692	3.1591	3.3031	3.4264	3.5882	3.8431	3.3815
Computed concentration with average α_λ (ml/ml)	0.7025	0.6228	0.5209	0.3377	0.2122	0.0758	
Error in computed concentration (ml/ml)	0.0975	0.0439	0.0124	0.0044	0.0122	0.0091	0.0299

BLUE CHIP	CELL 1	CELL 2	CELL 3	CELL 4	CELL 5	CELL 6	AVERAGE
Average I_c	9.62	7.49	7.53	11.86	41.37	96.5	
Average I_d	145.04	152.99	155.97	156.53	153.01	145.45	
Known concentration (ml/ml)	0.8	0.6667	0.5333	0.3333	0.2	0.0667	
Computed extinction, α_λ (cm^{-1})	3.3915	4.5250	5.6830	7.7410	6.5397	6.1513	5.6719
Computed concentration with average α_λ (ml/ml)	0.4784	0.5319	0.5343	0.4549	0.2306	0.0723	
Error in computed concentration (ml/ml)	0.3216	0.1348	0.0010	0.1216	0.0306	0.0056	0.1026

GRAY CONVERSION	CELL 1	CELL 2	CELL 3	CELL 4	CELL 5	CELL 6	AVERAGE
Average I_c	27.21	34.65	43.59	65.71	89.32	110.03	
Average I_d	122.82	125.76	126.55	126.5	125.61	122.48	
Known concentration (ml/ml)	0.8	0.6667	0.5333	0.3333	0.2	0.0667	
Computed extinction, α_λ (cm^{-1})	1.8839	1.9335	1.9985	1.9652	1.7048	1.6071	1.8488
Computed concentration with average α_λ (ml/ml)	0.8152	0.6972	0.5765	0.3543	0.1844	0.0580	
Error in computed concentration (ml/ml)	0.0152	0.0305	0.0432	0.0210	0.0156	0.0087	0.0224

Finally, table 6 shows the results with a red filter between the backlight and the test cells although the blue chip was underexposed and not suitable for analysis. The software also had difficulty with the gray scale conversion producing $I_c > I_d$ resulting in negative values of the extinction coefficient which is clearly not physical. However, the red and green chips produced very low errors associated with the computed concentration. If fact, the latter produced an average error in computed concentration of only 0.0190 ml/ml. The data for this configuration are plotted in figure 3 as the computed concentration versus the known concentration showing good agreement for remotely sensing concentration. Clearly, for many applications this approach yields accurate retrievals of the fluid concentration field where a sample extraction would be impractical.

Table 6. Red Kodak™ filter.

RED CHIP	CELL 1	CELL 2	CELL 3	CELL 4	CELL 5	CELL 6	AVERAGE
Average I_c	147.86	167.71	187.46	213.64	224.08	235.36	
Average I_d	250.62	254.3	254.69	254.69	251.93	244.92	
Known concentration (ml/ml)	0.8	0.6667	0.5333	0.3333	0.2	0.0667	
Computed extinction, α_λ (cm^{-1})	0.6596	0.6244	0.5747	0.5273	0.5857	0.5969	0.5948
Computed concentration with average α_λ (ml/ml)	0.8872	0.6999	0.5153	0.2955	0.1970	0.0669	
Error in computed concentration (ml/ml)	0.0872	0.0332	0.0180	0.0378	0.0030	0.0002	0.0299

GREEN CHIP	CELL 1	CELL 2	CELL 3	CELL 4	CELL 5	CELL 6	AVERAGE
Average I_c	41.78	56.55	65.45	81.86	94.03	105.26	
Average I_d	120.39	124.45	125.21	125.94	120.74	115.07	
Known concentration (ml/ml)	0.8	0.6667	0.5333	0.3333	0.2	0.0667	
Computed extinction, α_λ (cm^{-1})	1.3229	1.1831	1.2164	1.2925	1.2501	1.3359	1.2668
Computed concentration with average α_λ (ml/ml)	0.8354	0.6226	0.5121	0.3401	0.1974	0.0703	
Error in computed concentration (ml/ml)	0.0354	0.0441	0.0212	0.0068	0.0026	0.0036	0.0190

GRAY CONVERSION	CELL 1	CELL 2	CELL 3	CELL 4	CELL 5	CELL 6	AVERAGE
Average I_c	181.56	175.97	169.29	162.57	162.19	160.37	
Average I_d	159	158.75	158.91	159.14	159.24	159.31	
Known concentration (ml/ml)	0.8	0.6667	0.5333	0.3333	0.2	0.0667	
Computed extinction, α_λ (cm^{-1})	-0.1659	-0.1545	-0.1186	-0.0640	-0.0918	-0.0994	-0.1157
Computed concentration with average α_λ (ml/ml)	1.1469	0.8901	0.5469	0.1843	0.1587	0.0573	
Error in computed concentration (ml/ml)	0.3469	0.2234	0.0136	0.1490	0.0413	0.0094	0.1306

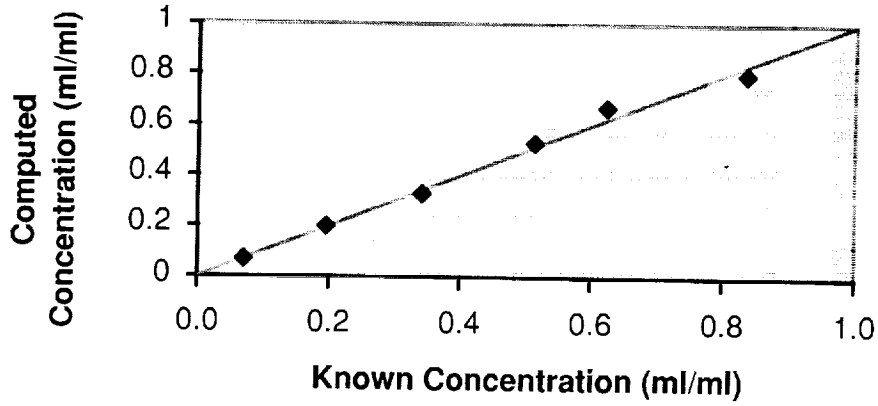

Figure 4. The photometrically determined concentration of the fluid using a red filter and the camera's green CCD chip.

V. SECOND CALIBRATION USING TEST CELLS

Suspecting that reflection of the incident light from the test cell could be an important factor in the transmittance of light, additional spectrophotometer measurements were made of a sample of the carrier fluid and compared with that of air only. These data showed that the transmittance of light through the carrier liquid was higher than for air, not because there was less absorption in the liquid, but because there was less reflection of the incident light than for the container of air. This result motivated a repeat of the calibration of the previous section but allowing I_o to pass through a cell containing carrier liquid only in order to ensure less backscattering of the incident light.

The same concentration samples were prepared as shown in table 2 and placed in front of the backlight. However, with this configuration, vials of pure carrier fluid were placed on top of the samples as shown in figure 5. The analysis for each cell was repeated except that the values of I_d were taken from the light passing through the carrier fluid above the cells.

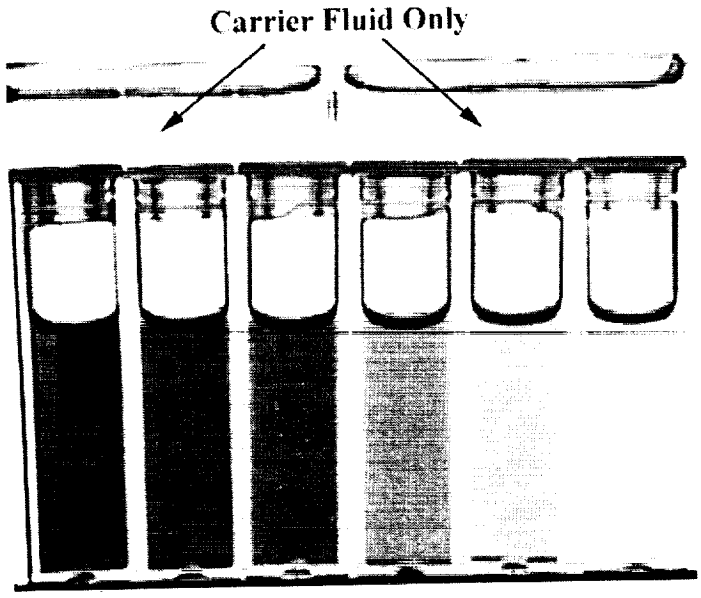

Figure 5. A photograph of the test cell configuration for the second calibration showing containers of carrier fluid above the ferrofluid vials through which I_d was determined.

The results are shown in tables 7 through 10 for completeness. A comparison of the errors in computed concentration for both calibrations at various configurations is shown in figure 6. The second calibration indicates that the least error occurs using a green backlight and converting the image to a gray scale. This configuration gave an error of only 0.0095 ml/ml, an improvement over the best case for the previous calibration (0.0190 ml/ml). A plot of the resulting computed concentration versus the known concentration is shown in figure 7.

Table 7. White light (no filter).

GREEN CHIP	CELL 1	CELL 2	CELL 3	CELL 4	CELL 5	CELL 6	AVERAGE
Average I_c	38.07	46.96	57.6	96.16	136.04	197.27	
Average I_d	237.01	232.13	224.85	221.84	220.58	224.62	
Known concentration (ml/ml)	0.8000	0.6667	0.5333	0.3333	0.2000	0.0667	
Computed extinction, α_λ (cm^{-1})	2.2858	2.3969	2.5537	2.5081	2.4166	1.9466	2.3513
Computed concentration with average α_λ (ml/ml)	0.7777	0.6796	0.5792	0.3555	0.2056	0.0552	
Error in computed concentration (ml/ml)	0.0223	0.01293	0.045921	0.0222	0.005552	0.01148	0.0201

BLUE CHIP	CELL 1	CELL 2	CELL 3	CELL 4	CELL 5	CELL 6	AVERAGE
Average I_c	19.53	20.61	22.19	27.09	36.82	95.42	
Average I_d	188.71	180.56	175.28	171.58	169.42	174.03	
Known concentration (ml/ml)	0.8000	0.6667	0.5333	0.3333	0.2000	0.0667	
Computed extinction, α_λ (cm^{-1})	2.8353	3.2553	3.8754	5.5382	7.6317	9.0096	5.3576
Computed concentration with average α_λ (ml/ml)	0.4234	0.4051	0.3858	0.3445	0.2849	0.1122	
Error in computed concentration (ml/ml)	0.3766	0.261613	0.147539	0.0112	0.084894	0.04547	0.1546

GRAY CONVERSION	CELL 1	CELL 2	CELL 3	CELL 4	CELL 5	CELL 6	AVERAGE
Average I_c	74.82	82.01	87.1	109.87	132.77	181.19	
Average I_d	225.11	222.06	217.92	215.16	214.65	217.33	
Known concentration (ml/ml)	0.8000	0.6667	0.5333	0.3333	0.2000	0.0667	
Computed extinction, α_λ (cm^{-1})	1.3769	1.4941	1.7196	2.0165	2.4020	2.7267	1.9559
Computed concentration with average α_λ (ml/ml)	0.5632	0.5093	0.4689	0.3436	0.2456	0.0930	
Error in computed concentration (ml/ml)	0.2368	0.157429	0.064437	0.0103	0.045605	0.02628	0.0902

Table 8. Green Kodak™ filter.

RED CHIP	CELL 1	CELL 2	CELL 3	CELL 4	CELL 5	CELL 6	AVERAGE
Average I_c	73.49	83.71	91.85	117.35	146.3	188.72	
Average I_d	215.83	212.89	205.58	202.59	201.87	210.08	
Known concentration (ml/ml)	0.8000	0.6667	0.5333	0.3333	0.2000	0.0667	
Computed extinction, α_λ (cm^{-1})	1.3467	1.4001	1.5107	1.6382	1.6098	1.6076	1.5188
Computed concentration with average α_λ (ml/ml)	0.7093	0.6146	0.5305	0.3595	0.2120	0.0706	
Error in computed concentration (ml/ml)	0.0907	0.05214	0.00285	0.0262	0.01198	0.0039	0.0313

BLUE CHIP	CELL 1	CELL 2	CELL 3	CELL 4	CELL 5	CELL 6	AVERAGE
Average I_c	23.53	25.52	28.71	39.05	61.92	123.74	
Average I_d	180.96	177.33	171.49	167.58	165.34	173.07	
Known concentration (ml/ml)	0.8000	0.6667	0.5333	0.3333	0.2000	0.0667	
Computed extinction, α_λ (cm^{-1})	2.5500	2.9077	3.3514	4.3703	4.9108	5.0302	3.8534
Computed concentration with average α_λ (ml/ml)	0.5294	0.5031	0.4638	0.3780	0.2549	0.0871	
Error in computed concentration (ml/ml)	0.2706	0.16362	0.06948	0.04471	0.05488	0.02037	0.1039

GREEN CHIP	CELL 1	CELL 2	CELL 3	CELL 4	CELL 5	CELL 6	AVERAGE
Average I_c	22.13	28.55	36.09	62.1	93.15	153.9	
Average I_d	224.95	217.82	205.04	198.92	197.12	201.74	
Known concentration (ml/ml)	0.8000	0.6667	0.5333	0.3333	0.2000	0.0667	
Computed extinction, α_λ (cm^{-1})	2.8987	3.0479	3.2574	3.4928	3.7480	4.0581	3.4172
Computed concentration with average α_λ (ml/ml)	0.6786	0.5947	0.5084	0.3407	0.2194	0.0792	
Error in computed concentration (ml/ml)	0.1214	0.07205	0.02493	0.00738	0.01936	0.01251	0.0429

GRAY CONVERSION	CELL 1	CELL 2	CELL 3	CELL 4	CELL 5	CELL 6	AVERAGE
Average I_c	65.97	79.4	94.12	131.45	153.93	189.05	
Average I_d	216.24	214.81	209.67	208.02	206.97	211.63	
Known concentration (ml/ml)	0.8000	0.6667	0.5333	0.3333	0.2000	0.0667	
Computed extinction, α_λ (cm^{-1})	1.4840	1.4928	1.5019	1.3772	1.4804	1.6916	1.5046
Computed concentration with average α_λ (ml/ml)	0.7890	0.6615	0.5323	0.3051	0.1968	0.0750	
Error in computed concentration (ml/ml)	0.0110	0.00524	0.00097	0.02824	0.00322	0.00829	0.0095

Table 9. Red Kodak™ filter.

RED CHIP	CELL 1	CELL 2	CELL 3	CELL 4	CELL 5	CELL 6	AVERAGE
Average I_c	74.98	81.01	81.62	93.4	104.01	118.09	
Average I_d	154.11	148.08	138.19	131.92	131.36	133.58	
Known concentration (ml/ml)	0.8000	0.6667	0.5333	0.3333	0.2000	0.0667	
Computed extinction, α_λ (cm^{-1})	0.9006	0.9047	0.9874	1.0360	1.1673	1.8479	1.1406
Computed concentration with average α_λ (ml/ml)	0.6316	0.5288	0.4616	0.3027	0.2047	0.1081	
Error in computed concentration (ml/ml)	0.1684	0.13789	0.07167	0.03057	0.00467	0.04136	0.0758

GREEN CHIP	CELL 1	CELL 2	CELL 3	CELL 4	CELL 5	CELL 6	AVERAGE
Average I_c	69.41	74.06	76.37	90.12	103.66	127.53	
Average I_d	161.42	152.74	140.58	135.18	136.49	145.04	
Known concentration (ml/ml)	0.8000	0.6667	0.5333	0.3333	0.2000	0.0667	
Computed extinction, α_λ (cm^{-1})	1.0550	1.0857	1.1442	1.2165	1.3757	1.9289	1.3010
Computed concentration with average α_λ (ml/ml)	0.6487	0.5564	0.4690	0.3117	0.2115	0.0989	
Error in computed concentration (ml/ml)	0.1513	0.11031	0.06429	0.02164	0.01148	0.03219	0.0652

GRAY CONVERSION	CELL 1	CELL 2	CELL 3	CELL 4	CELL 5	CELL 6	AVERAGE
Average I_c	88.14	92.4	93.64	100.4	102.77	107.78	
Average I_d	115.79	113.33	110.81	109.55	110.02	111.92	
Known concentration (ml/ml)	0.8000	0.6667	0.5333	0.3333	0.2000	0.0667	
Computed extinction, α_λ (cm^{-1})	0.3411	0.3063	0.3157	0.2617	0.3408	0.5651	0.3551
Computed concentration with average α_λ (ml/ml)	0.7684	0.5750	0.4741	0.2456	0.1920	0.1061	
Error in computed concentration (ml/ml)	0.0316	0.09173	0.05919	0.08769	0.00803	0.03944	0.0530

Table 10. Blue Kodak™ filter.

RED CHIP	CELL 1	CELL 2	CELL 3	CELL 4	CELL 5	CELL 6	AVERAGE
Average I_c	54.06	44.2	42.78	45.94	53.03	85.84	
Average I_d	120.74	109.27	101.55	97.63	99	110.95	
Known concentration (ml/ml)	0.8000	0.6667	0.5333	0.3333	0.2000	0.0667	
Computed extinction, α_λ (cm^{-1})	1.0044	1.3576	1.6210	2.2618	3.1213	3.8470	2.2022
Computed concentration with average α_λ (ml/ml)	0.3649	0.4110	0.3926	0.3423	0.2835	0.1165	
Error in computed concentration (ml/ml)	0.4351	0.2557	0.14074	0.00902	0.08347	0.04982	0.1623

GREEN CHIP	CELL 1	CELL 2	CELL 3	CELL 4	CELL 5	CELL 6	AVERAGE
Average I_c	31.68	25.09	24.7	31.35	46.28	95.73	
Average I_d	181.07	171.38	159.09	150.24	146.13	150.74	
Known concentration (ml/ml)	0.8000	0.6667	0.5333	0.3333	0.2000	0.0667	
Computed extinction, α_λ (cm^{-1})	2.1790	2.8820	3.4927	4.7015	5.7489	6.8070	4.3019
Computed concentration with average α_λ (ml/ml)	0.4052	0.4466	0.4330	0.3643	0.2673	0.1055	
Error in computed concentration (ml/ml)	0.3948	0.22005	0.10031	0.03097	0.06728	0.03884	0.1420

BLUE CHIP	CELL 1	CELL 2	CELL 3	CELL 4	CELL 5	CELL 6	AVERAGE
Average I_c	18.92	17.88	17.69	19.39	30.03	115.65	
Average I_d	249.56	242.72	232.98	225.68	222.19	224.18	
Known concentration (ml/ml)	0.8000	0.6667	0.5333	0.3333	0.2000	0.0667	
Computed extinction, α_λ (cm^{-1})	3.2243	3.9121	4.8340	7.3638	10.0067	9.9233	6.5440
Computed concentration with average α_λ (ml/ml)	0.3942	0.3986	0.3939	0.3751	0.3058	0.1011	
Error in computed concentration (ml/ml)	0.4058	0.26813	0.13936	0.04175	0.10583	0.03444	0.1659

GRAY CONVERSION	CELL 1	CELL 2	CELL 3	CELL 4	CELL 5	CELL 6	AVERAGE
Average I_c	41.11	35.94	35.27	41.09	59.08	135.62	
Average I_d	184.75	177.42	171.07	166.93	166.15	171.22	
Known concentration (ml/ml)	0.8000	0.6667	0.5333	0.3333	0.2000	0.0667	
Computed extinction, α_λ (cm^{-1})	1.8784	2.3949	2.9609	4.2058	5.1700	3.4946	3.3508
Computed concentration with average α_λ (ml/ml)	0.4485	0.4765	0.4712	0.4184	0.3086	0.0696	
Error in computed concentration (ml/ml)	0.3515	0.19019	0.06205	0.08505	0.10858	0.00286	0.1334

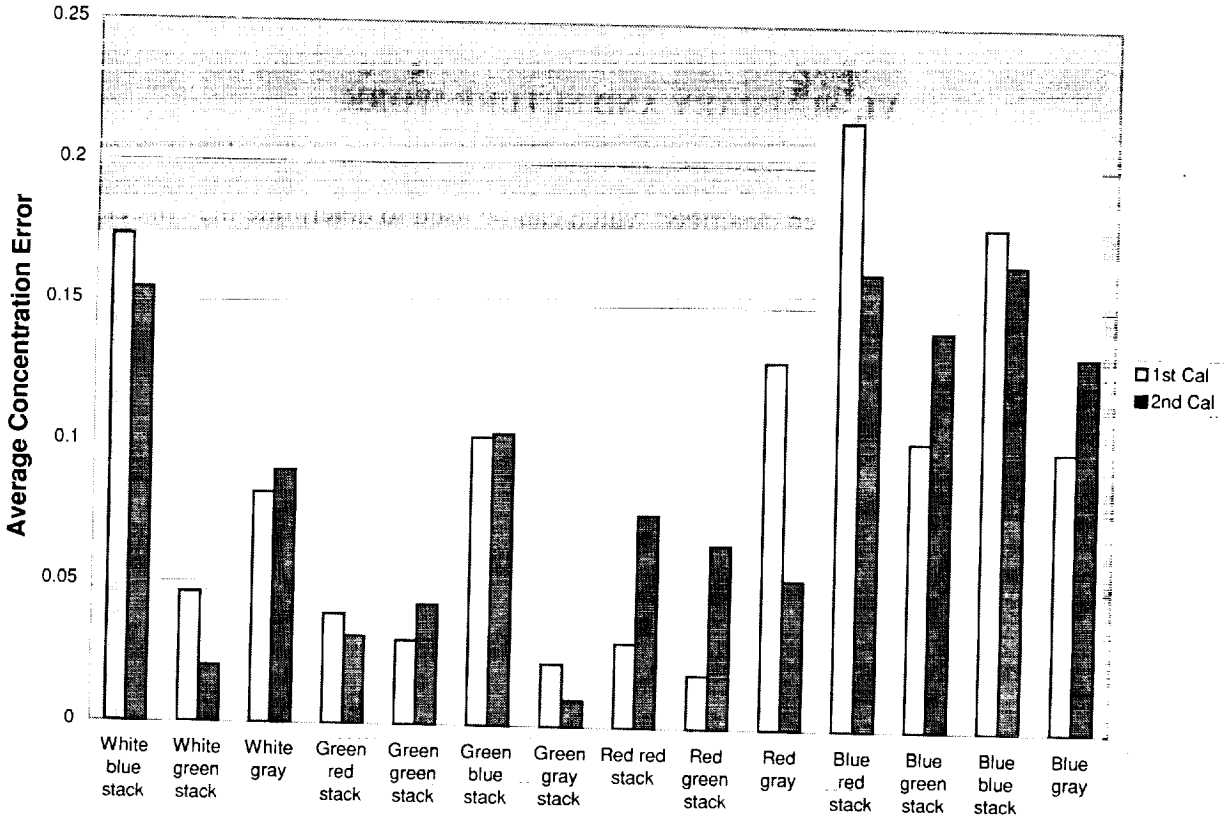

Figure 6. A comparison of the concentration errors for the first and second calibration for different configurations (e.g., "white blue stack" means the test cell was illuminated with white light and the analysis was performed using the image from the color camera's blue chip).

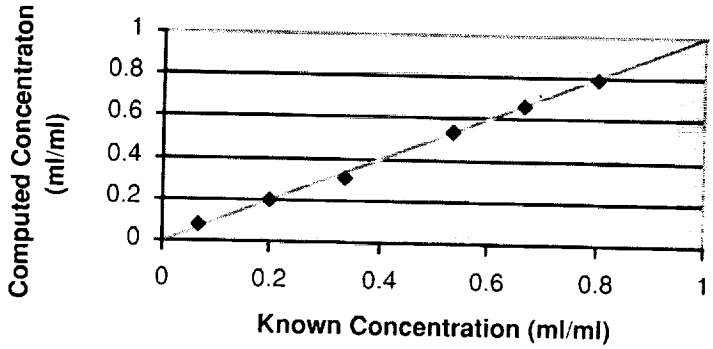

Figure 7. The second calibration showing the photometrically determined concentration of the fluid using a green filter with the image converted to gray.

VI. SUMMARY AND FUTURE WORK

A noninvasive method has been described which can be used to determine the concentration of suitable liquids using inexpensive consumer-grade equipment. The system was calibrated with known concentrations illuminated with a filtered backlight and captured with an 8-bit CCD color camera. The filter was selected such that the extinction coefficient from equation (6) is independent of concentration. The image of the cells was then analyzed to determine the light attenuation and the average extinction coefficient was computed. Then the concentration in experiment test cells was calculated from the camera imagery. One particular calibration configuration determined the concentration of the liquid with an average error of <0.01 ml/ml. This approach is particularly useful in experiments where it is prohibitive or impractical to remove samples for constituent analysis. This technique also has the advantage of showing the two-dimensional distribution of concentration as well as any time-dependent nature of the fluid.

A more sophisticated system with the potential for smaller errors in the measurement of concentration is being considered for future work. This includes a multiline laser that will produce a more narrow bandwidth for test cell illumination, an optical system to provide collimated (parallel) light through the test cell (as compared to locating the camera far from the test cell and zooming in), and the use of a 10-bit digital camera system that would provide higher resolution of intensity as well as a linear relation between light intensity and the corresponding pixel values.

APPENDIX—THE CASE OF A VARIABLE BACKLIGHT ILLUMINATION

Consideration should also be given to the more realistic case where the incident light varies across the test cell or may change temporally from calibration to experiment or even from frame to frame such that $I_o=I_o(x,z,t)$. There is a temptation to "subtract" off the background illumination on a pixel-by-pixel basis. However, the more prudent approach is to first determine the spatial variation of the incident illumination and then use the light passing over the liquid through point d as a means to monitor any time variation of the illumination.

Let us assume that the incident light varies as $I_o(x,z,t) = S_o(x,z)T_o(t)$. Thus, we can separate the spatial and temporal variations. At any given time the illumination may vary over the area of the backlight and at any position the intensity may vary in time as the backlight intensity changes. However, we would not expect that in one region of the backlight the relative intensity is increasing while decreasing in another region. So $S_o(x,z)$ represents how the light intensity varies spatially due to the construction of the backlight elements, while $T_o(t)$ represents how the output of the light might change in time.

Consider having the cell containing a liquid of zero concentration at $t=t_o$. Then equation (4) gives the light emerging from c in figure 1 as

$$I_c^{C=0}(x,z,t_o) = S_o(x,z)T_o(t_o)\exp(-2\,d\alpha_{\lambda,cell}) \text{ (valid for } z < \text{liquid level)} \ , \tag{7}$$

where the superscript is a reminder that the concentration is zero. The light coming from d above the liquid is given by equation (5)

$$I_d(x,z,t_o) = S_o(x,z)T_o(t_o)\exp(-2\,d\alpha_{\lambda,cell}) \text{ (valid for } z > \text{liquid level)} \ . \tag{8}$$

Now for any concentration at any time, the light from **c** is again given by equation (4)

$$I_c(x,z,t) = S_o(x,z)T_o(t)\exp(-2\,d\alpha_{\lambda,cell})\exp[-\alpha_\lambda\, s\, C(x,z)]$$
$$\text{(valid for } z < \text{liquid level)} \ . \tag{9}$$

The light from **d** at any time is given by equation (5) as

$$I_d(x,z,t) = S_o(x,z)T_o(t)\exp(-2\,d\alpha_{\lambda,cell}) \text{ (valid for } z > \text{liquid level)} \ . \tag{10}$$

If we divide equation (10) by equation (8), we get

$$\frac{I_d(x,z,t)}{I_d(x,z,t_o)} = \frac{T_o(t)}{T_o(t_o)} \quad . \tag{11}$$

Note that the right-hand side of equation (11) is only a function of time so that the left-hand side must also be independent of position. It simply represents how much the light has increased or decreased (which is the same for every pixel). Now if we divide equation (9) by equation (7), we get

$$\frac{I_c(x,z,t)}{I_c^{C=0}(x,z,t_o)} = \frac{T_o(t)}{T_o(t_o)} \exp[-\alpha_\lambda \, s\, C(x,z)] \quad . \tag{12}$$

Finally, substituting equation (11) into equation (12) yields

$$\boxed{\frac{I_c(x,z,t)}{I_c^{C=0}(x,z,t_o)} = \frac{I_d(x,z,t)}{I_d(x,z,t_o)} \exp[-\alpha_\lambda \, s\, C(x,z)]} \quad . \tag{13}$$

Keep in mind that the ratio on the right-hand side depends on time only and represents how much the light has increased or decreased compared to the calibration. Note that if $C(x,z)=0$, then the ratios on both sides are equal to unity as expected. Note also that if the incident intensity does not change with time, then with use of the above equations, equation (13) reduces to equation (6). So, to use equation (13) the following procedure should be adopted:

1. Fill the test cell with zero concentration fluid to the level that will be used for subsequent experiments.

2. Digitize the image (see fig. 1) and measure the light from d as $I_d(x,z,t_o)$ and the light from c as $I_c^{C=0}(x,z,t_o)$. These are simply spatial arrays at time t_o.

3. Now fill the test cell with known concentrations. Digitize the image to measure $I_c(x,z,t)$ and $I_d(x,z,t)$ and calculate α_λ from equation (13). As before, the best wavelength of light to select is the one where α_λ is independent of concentration.

4. The experiment can now be performed and $I_c(x,z,t)$ along with $I_d(x,z,t)$ are measured with the camera. As mentioned previously, the ratio $I_d(x,z,t)/I_d(x,z,t_o)$ is independent of space and just represents how the intensity might have changed since the calibration with $C=0$ and is valid at any pixel. However, averaging over an area would be prudent.

5. The distribution of concentration $C(x,z)$ can now be calculated from equation (13).

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In support of a separate study to produce an exponential concentration gradient in a magnetic fluid, a noninvasive technique for determining species concentration from off-the-shelf hardware has been developed. The approach uses a backlighted fluid test cell photographed with a commercial digital camcorder. Because the light extinction coefficient is wavelength dependent, tests were conducted to determine the best filter color to use, although some guidance was also provided using an absorption spectrophotometer. With the appropriate filter in place, the attenuation of the light passing through the test cell was captured by the camcorder. The digital image was analyzed for intensity using software from Scion Image Corp. downloaded from the Internet. The analysis provides a two-dimensional array of concentration with an average error of 0.0095 ml/ml. This technique is superior to invasive techniques, which require extraction of a sample that disturbs the concentration distribution in the test cell. Refinements of this technique using a true monochromatic laser light source are also discussed.

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