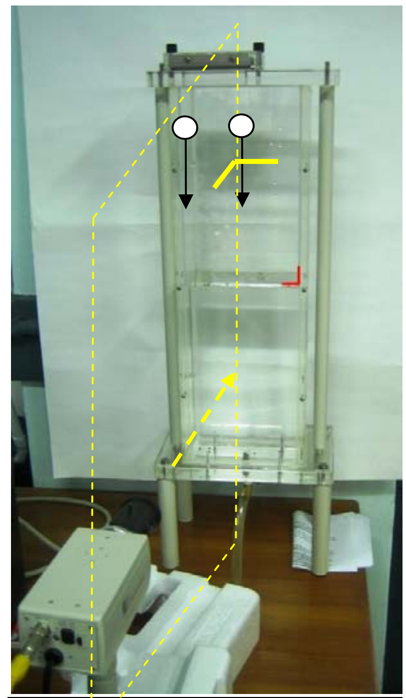
Flow observation with a digital camera: Wall influences on the motion of a free-fall object

June 02-06, 2011



Objective: Examine how a nearby solid surface affects the free-fall motion of a solid object in a viscous liquid (Glycerol) column via digital image analysis. Experience the significance of image quality to a successful measurement via error analysis. Relate the results to fluid mechanics theory.

Facility: a transparent square tank filled with pure glycerol, test objects--glass beads of diameter 3mm, digital camera;

Report: 預報問題 Q1~Q5; 結報問題 P1~P6 at the end.

Exp procedures: Free-falling spheres

(1) Glue black paper to the back of the tank

(2) Set up the camera: adjust position, alignment, focus, aperture,…etc until a clear image is obtained. Try to cover the liquid column of 20-25cm high from the free surface.

(3) Put one sphere in the center of the tank. Start the camera. Then, use a thin rod to force the sphere to submerge into the

(4) Convert the digital video with a frame rate of 5fps. Save the images (as MPEG) for future image analysis.

(5) Repeat (3) but with an initial position closer to the wall. Record the initial distance. Then convert the second digital video at 5fps. Save the second image group for analysis.

Image analysis procedures

Data: The MPEG movie you recorded for each experiment

Software: *QuickTime Pro* and *ImageJ*

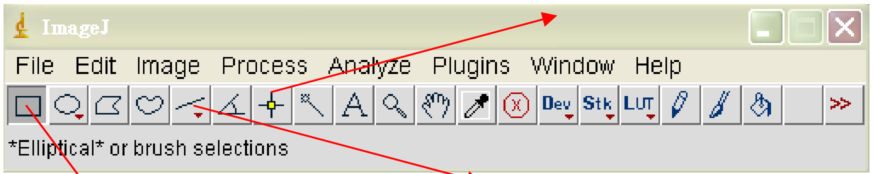
Please work in a group of 1-2 persons. Play with ImageJ to develop you own methods to process the digital video. The goal is to obtain the position-time data for each sphere during the class. Bring the result (MS Excel or *.txt file) back for post-analysis. Try to write down information that you think will be useful in post-analysis.

Image conversion:

1. Load the movie into "***QuickTime Pro***", use the scroll bar to delete unnecessary segments (discard the beginning waiting time, etc). Then Export 匯出 the interested segment into "Image sequence 影像序列" at 5fps. [Q1]

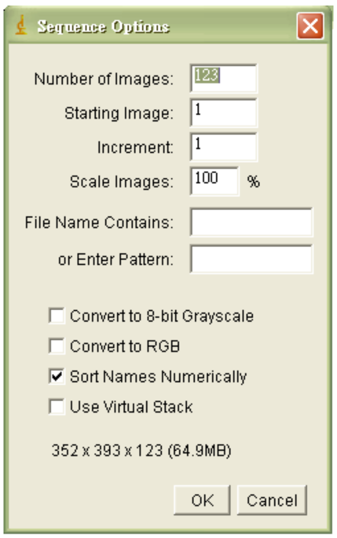
Image processing:

2. Open "*ImageJ*" and load the images



--Use File→ Import→Image Sequence to load in the image sequence you just generated.

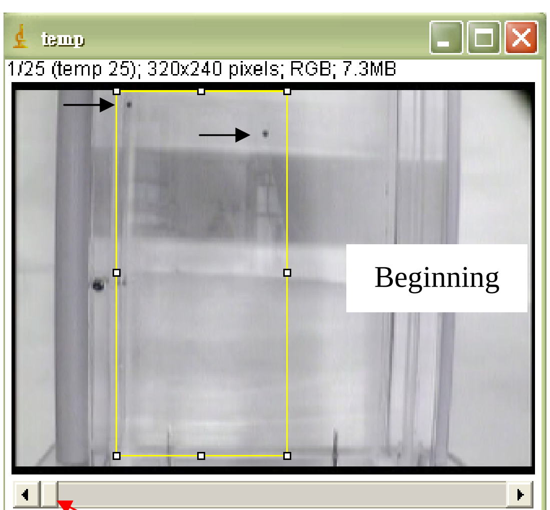
--In a pop-out window entitled "Sequence Options" (as shown below), specify the total 'Number of Images' to import, starting where and with what increment. [P1]

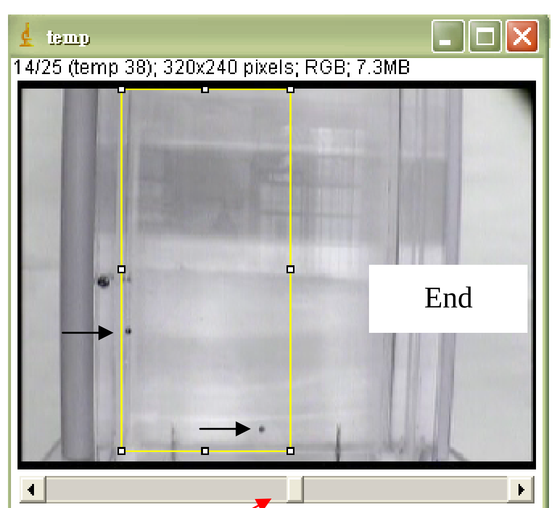


**Please note that the increment will change the actual time difference between the images that you are about the process. For example, for a image sequence that was exported from QuickTime at 10fps, if we import them in ImageJ with a "4" increment, the actual time difference between two consecutive ImageJ images are 4*(1/10) second.

3. Use the Rectangle selection tool (A) to select the interested section of the images. Try to align the left side of the box with the left container wall. Make sure that the rectangle contains the tested spheres throughout the event (See below).

Use Image→Crop to cut out the interested zone.





Drag to examine the images at later times

4. Use the segment selection tool [B] to measure the lateral distance between the wall and the center of each sphere. Write down the measurement. [P2]

Before we process the images, we need to know the scale between the actual and the digital worlds. So try to use something that's easy to measure in both reality and in the recorded images. **[Q2][P3]

5. Measure the reference length in your image using the segment selection tool (B), to mark the line segment and hit Analyze→ Measure to obtain the length (readings in *pixels*). Then, measure the actual size in ***mm or cm***. Write down both measurement!! Since this length conversion is important, you may want to do more than on measurements and obtain an average.

6. **Image processing:** the following functions may be useful.

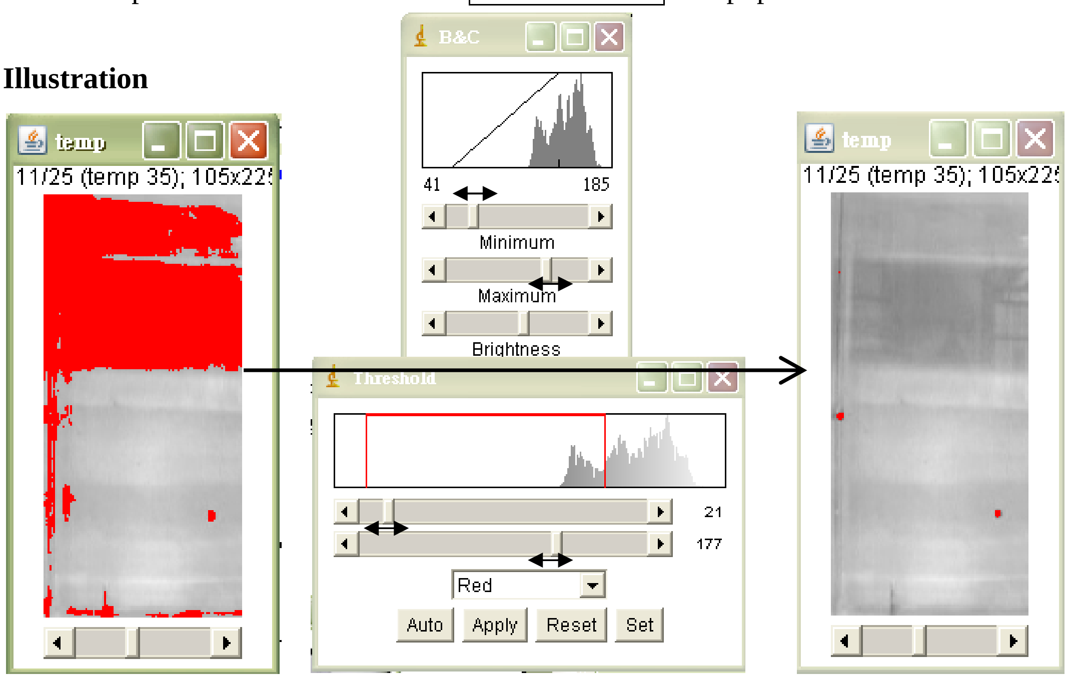
Image→Type→8-bit convert a RGB images into a 8-bit grayscale image

Image→Adjust→Brightness/Contrast modify the image quality (try to make the spheres distinguishable from the background)

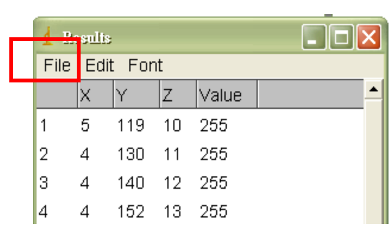
Image→Adjust→Threshold covert grayscale image into binary format using a threshold specified by you (Pixels with grayness above the threshold will be highlighted in red (See illustration on the next page). Once you setup the threshold value, choose Apply to convert all images into B/W binary images

Point selection (Element C) to mark the position of one pixel. Use Analyze→Measure to record the position of the laid mark. A Results window will pop out

Illustration



7. **Track the particles:** after you are satisfied with the binary images of falling spheres, go to Plugins→Stacks→ MultiTracker to monitor the "center of mass" of each 'object'. A pop-out window lets you decide the size range of the objects. A "Results" window will appear, which can be



Post Analysis (you can do this during the class or afterwards)

8. Obtain the falling velocity:

--Use the position-time data (in pixel-frame) to estimate the sphere velocity (Recall the difference equation introduced in class).

--Convert the obtained velocity (in pixel/per IJ frame) into cm/s.

9. **Comparison between the measured and the predicted data:**

--The liquid used in the experiment is 100% glycerol. Assume that the experiment was performed at 25℃, get the liquid density and viscosity from the tables. Then apply the terminal velocity expression you obtained in [Q3] to calculate the predicted falling velocity. (The sphere is made of POM of density $\rho_s = 1.4 g / cm^3$.)

--Compare the measured velocity to the predicted value that assumed no additional boundary effects from the lateral container walls and the co-existing sphere(s): Calculate the ratio of $U_{measure}/U_T$ for each sphere. [P6]

預報 Questions:

Preparation:

[Q1] If you recorded the image at 5fps, what is the elapsed time between two recorded images?

[Q2] What property you plan to use?

[Q3] Since gravity is the only driving force in the experiment, we want to make sure that the tank is leveled. Instead of using a level meter (水平儀), come up a method to ensure that the tank is leveled.

[Q4] Camera alignment: The best situation is the camera focus point lies on the plane formed by the object trajectory and the surface normal of the front wall—as indicated by the dashed plane shown in the picture. Can you explain why we want the camera to be vertical to the tank front wall? Think of a method that can help you to align the camera.

[Q5] Consider a single sphere of radius a and density ρ_s that descends in an unbounded viscous fluid of dynamic viscosity and density μ and ρ_f. Assume that the sphere motion is at low Reynolds number and has reached a steady state—reached its **terminal velocity** U_T. Use force balance to obtain an expression for U_T. (Hint: For a solid sphere that falls at a constant velocity U_T at low Reynolds number flow condition, the quasi-steady viscous drag can be described by **Stokes' drag law** $FD=6\pi\mu a U_T$).

結報 Questions:

P1: Exporting image: What increment you use to load the image sequence into ImageJ? Calculate the actual elapsed time (in second) between the two IJ images.

P2: What are the lateral distances between the center of the spheres and the side wall? Estimate the error and identify the possible sources of errors.

P3: Scale conversion: How many measurements did you take? How many pixels correspond to 1cm from your IJ image? Estimate the error and identify the possible sources of errors.

P4: Plot the velocity-time profile for each sphere (in cm/s and sec). Have these particles reached their terminal velocity? If not, estimate the 'acceleration' for each sphere. Compare this acceleration to 'effective gravity'—gravity minus buoyancy force.

P5: Estimate "qualitatively" the error in your velocity measurement.

P6: Use the final velocity from your experiment and compare $U_{measure}/U_T$ for both spheres (at different lateral distances from the lateral wall). If the wall effects are negligible, then the calculated velocity ratio should approach unity. From the numbers you get, which sphere motion is subjected to greater influence from the wall?

P7. Liquid properties: The liquid is 100% glycerol which is a water-soluble Newtonian liquid whose physical properties change greatly with temperature variations. Use the attached table to calculate the density and the viscosity of a glycerol-water solution at 5 different temperatures: 10, 15, 20, 25, 30℃. Compare glycerol-water solution of various weight percentages: 100% (pure glycerol), 75%, 50%, 25%, and 1% (very dilute G-W solution). Generate two plots μ_f-T (in unit: g/cm sec) and ρ_f-T (in unit: g/cm^3) that contains the data of all these solutions. In general, is the density or the viscosity more sensitive to temperature variations? Compare the sensitivity to temperature changes for solutions at different concentration. **Note that the table is for dynamic viscosity μ_f with a dimension of [[M/LT]], not the kinematic viscosity $\nu_f=\mu_f/\rho_f$ has a dimension of [[L^2/T]].

Table C.3: Viscosity of glycerol–water solutions.

Glycerol	Viscosity (cP)†							
(% wt.)	10°C	20°C	25°C	30°C	40°C	50°C	60°C	70°C
100	3900	1410	906	612	284	142	81.3	50.6
99	3090	1150	743	500	235	122	69.1	43.6
98	2460	939	603	409	196	104	59.8	38.5
97	1950	765	501	340	166	88.9	51.9	33.6
96	1580	624	417	281	142	77.8	45.4	29.7
95	1270	523	350	237	121	67.0	39.9	26.4
94	1040	437	296	202	105	58.4	35.4	23.6
93	860	367	251	172	89	51.5	31.6	21.2
92	729	310	213	147	78.3	44.8	28.0	19.0
91	592	259	181	127	68.1	39.8	25.1	17.1
90	498	219	157	109	60.0	35.5	22.5	15.5
85	223	109	78	58	33.5	21.2	14.2	10.0
80	116	60.1	45.3	33.9	20.8	13.6	9.42	6.94
75	65.2	35.5	27.1	21.2	13.6	9.25	6.61	5.01
70	38.8	22.5	17.6	14.1	9.40	6.61	4.86	3.78
65	25.3	15.2	12.06	9.85	6.80	4.89	3.66	2.91
60	17.4	10.8	8.673	7.19	5.08	3.76	2.85	2.29
50	9.01	6.00	5.041	4.21	3.10	2.37	1.86	1.53
40	5.37	3.72	3.181	2.72	2.07	1.62	1.30	1.09
30	3.49	2.50	2.157	1.87	1.46	1.16	0.956	0.816
20	2.41	1.76	1.542	1.35	1.07	0.879	0.731	0.635
10	1.74	1.31	1.153	1.03	0.826	0.680	0.575	0.500
0	1.308	1.005	0.893	0.800	0.656	0.549	0.469	0.406

† 1 cP = 1×10^{-3} Pa · s.