# Evaluation of wall influence on the free-fall of an immersed sphere + low-Re flow observation

May 28- Jun 01, 2012

**Objective:** (1) practice image processing to examine how a nearby solid surface affects the free-fall motion of a solid sphere in a viscous liquid (Glycerol) column; (2) visualize flow developed in a low-*Re* rotating tank; (3) post analysis.

**Please bring the MPEG movie or the exported images you recorded during the lab two weeks ago to analyze in class!**

**Report:** 預報問題 Q1~Q4; 結報問題 P1~P13 at the end.

## Part 1: Image analysis procedures

Objective: obtain the position-time data for each sphere dropped near the center and the wall. Please work in a group of 1-2 persons. Play with *ImageJ* to develop you own methods to process the digital video. Bring the result (MS Excel or *.txt file) back for post-analysis.
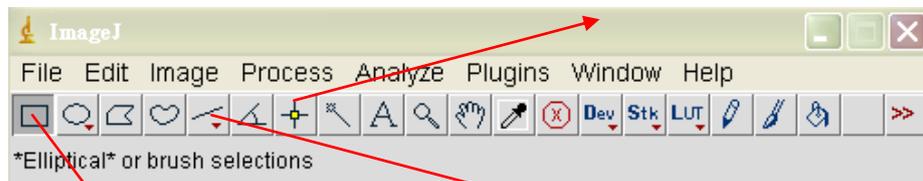
## Image conversion:

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. (It is OK if you did thi last time using other frame rates) **[Q1]**



Scroll bar

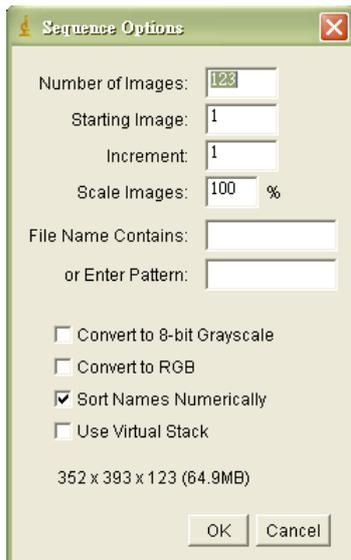## Image processing:

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

C: Point selection tool
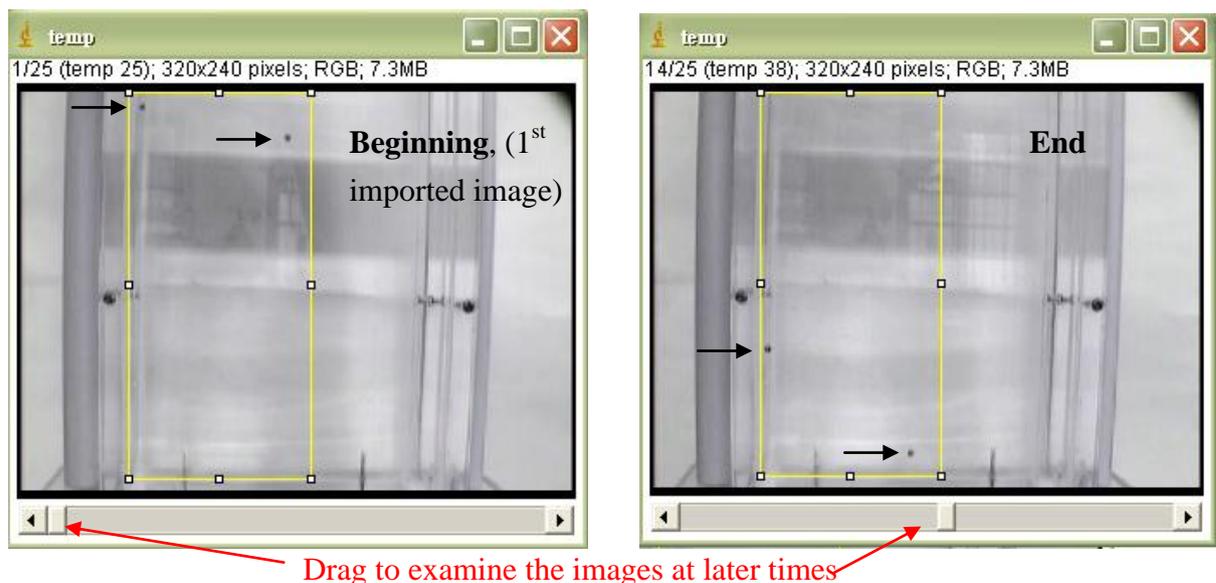


A: Rectangle selection tool    B: Segment selection tool

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

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

**Please note that "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 is 4*(1/10) second.

**3.** Use the Rectangle selection tool (A, above) 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, above) or Point selection (C, above) to estimate the sphere size (in pixels!) [for step 7] ; once you laid the mark, use Analyze→Measure to obtain the data (length or position). A Results window will pop out showing the results.

**5.** Use Segment selection tool (B, above) to measure the lateral distance from the sphere to the "closer" lateral wall [P2]

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

**Illustration**
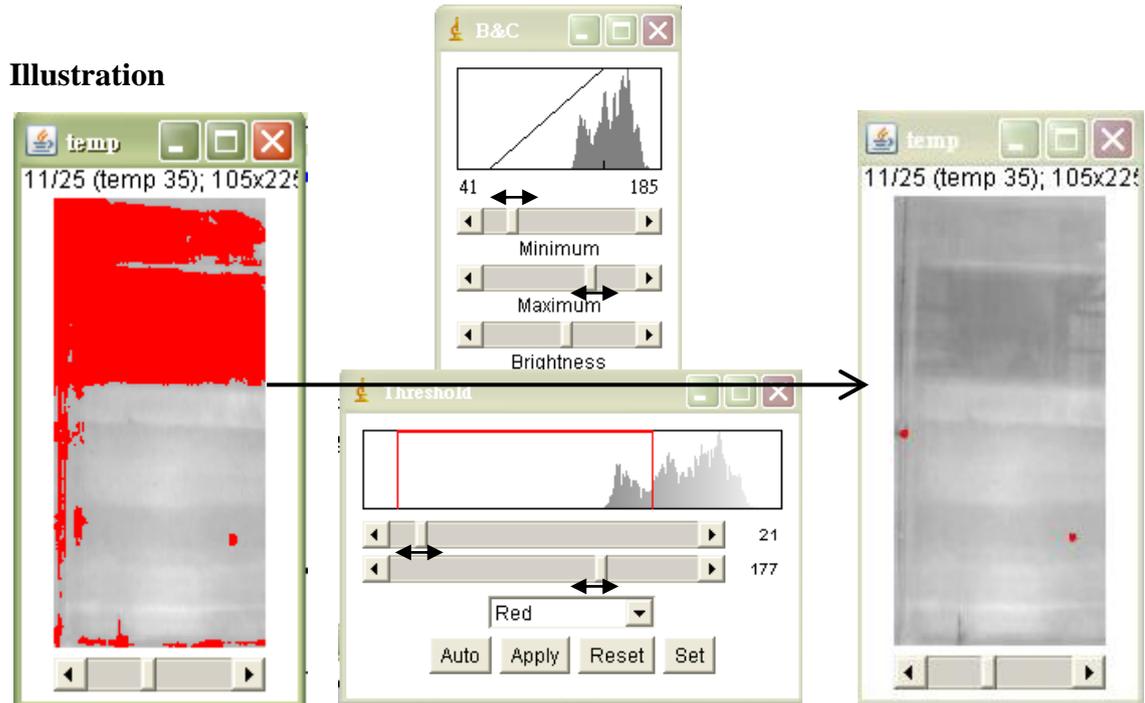


7. **Track the particles:**

**--**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 to specify the lower and upper bounds of interested object size (太大太小的都不處理); consult to the data from step 4.

--A "Results" window will appear (as shown on the right) listing the center of mass position (in pixels!) on each frame (frame no. 1,2,3,….. on the first column).

--Use File→Save As to save it as a *.txt or an excel file.

8. **Length conversion:** Need to convert the length scale in *pixels* (on a digital image) to a physical length scale in *mm* or *cm*. Always use something easy to measure in both reality and in the recorded images. **[Q2][P3]**

## Part2 Flow line observation for low Reynolds Couette flow flow

由於實驗組件有限，請同學輪流合作操作實驗。
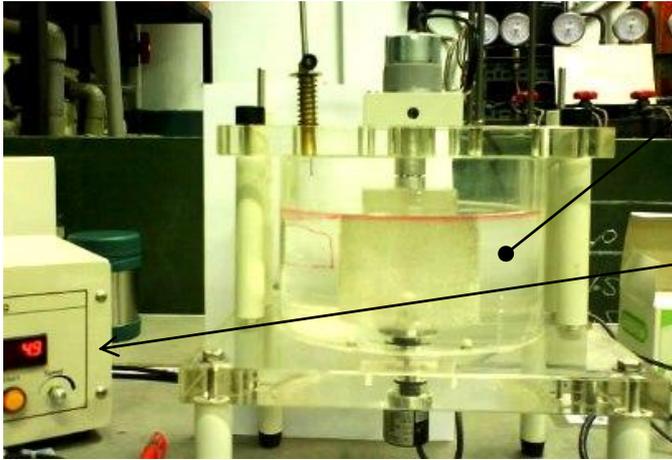
實驗器材：

--透明旋轉圓筒一組，配合不同尺寸及表面粗糙度、可控制轉數**以定轉速**旋轉內筒。

--轉數控制器，定轉速定角度正反轉控制。

--100%甘油為工作液體(牛頓流體)。

--純甘油染色的染料及 注入針。

內筒旋轉控制：

1. 打開控制裝置，面板右方 CW / CCW 轉鈕選擇內筒旋轉方向(順/逆時針)，將轉鈕調到 CW 端。Speed 鈕調整馬達轉速至一定值**(<12.0)**，Start 按鈕啟動馬達。如果馬達沒有啟動 將轉鈕調至 CCW 再試著啟動一次。

2. 馬達設定為順逆時針轉 150 度自動停止，等馬達停下，將轉鈕調至反方向 (CW → CCW or CCW → CW)，再按下 Start，確定馬達往反方向旋轉一定角度之後停下。如此反複"轉鈕調整轉向，Start"可以操作馬達正反來回運動。

3. 找到最低馬達轉速 (a specific Reading < 10.0)，可使正反轉皆順利。
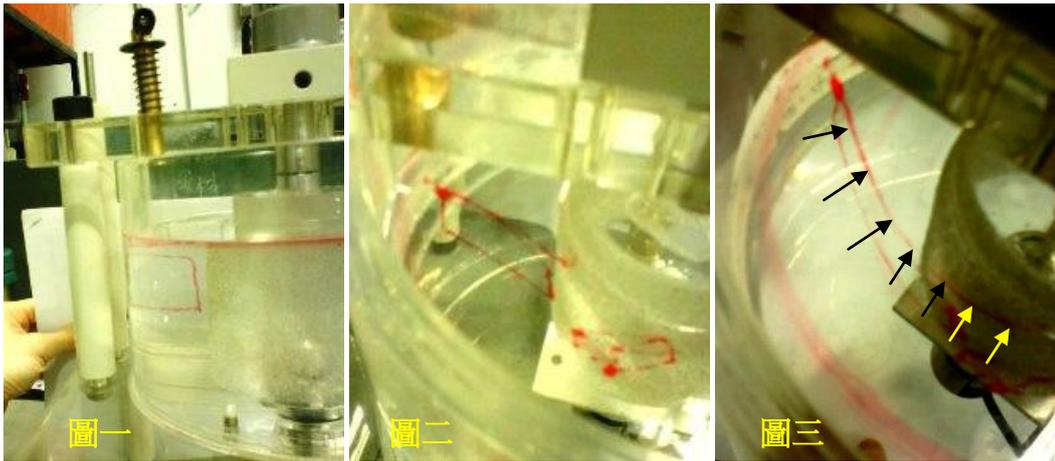
實驗一

在圓筒內的液體中注入一個小染料球(約 2-3 mm 直徑)，如圖所示緩慢取出探針，觀察染料隨探針移動，盡可能讓染料球保持原狀
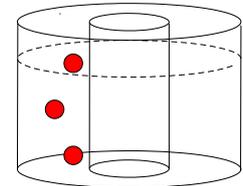
1. 啟動馬達，觀察染料液滴隨流場的變化。反轉馬達，觀察染料的運動。**[P8]**

2. 再正反轉內轉統幾次，染料的運動及分布有沒有變化? **[P9]**

3. 拿一杯清水 把甘油染料滴入，乾油滴會如何? **[Q3][P10]**

實驗二

1. 試著在液體中畫製一個垂直於圓筒的方形(vertically spanned in the glycerol)，如下圖一，垂直邊盡量貼近內轉筒及外壁。

2. 將馬達轉速設在馬達操作步驟 3 所找到的最低轉速，啟動馬達，正轉之後觀察染料方形變形 (下圖二、三是兩個時間影像，注意圖三上的箭頭)。**[Q4]**

3. 反轉馬達，觀察染料方形形狀變化，回答結報問題。**[P11-12]**

圖一　　圖二　　圖三

實驗三

重複實驗二步驟，但這次畫水平的方形，觀察正轉反轉的變形。**[P13]**

## 預報 Questions:

[Q1] If you recorded the image at 30fps but exported them at 5Hz, what is the elapsed time between two exported images?

[Q2] Describe how you want to determine the length scale conversion between the digital image and the physical world.

[Q3] How would you expect the glycerine dye droplet to move in water? Why?

[Q4] The rectangle sides that crosses the gap (in radial direction) is stretched by the inner rotor as indicated in 圖三 above. Does the radial distance of the dye to the rotor correlate to boundary layer thickness, , you learn in boundary layer theory?
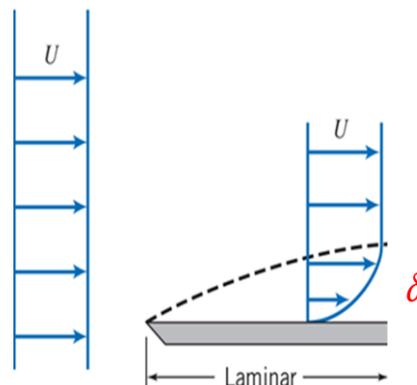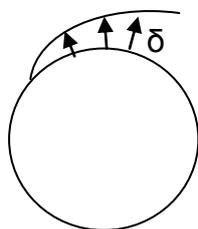


software we use to achieve quantitative measurement of digital images?

## 結報 Questions:

Free-fall experiment

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? How many pixels correspond to 1cm from your IJ image? Identify the possible sources of errors.

P3: Use the position-time data to obtain the sphere velocity temporal profile (use the <u>difference equation</u> introduced in class). Plot the velocity-time profile for each sphere (in mm/sec) on the same plot. Does the lateral wall decelerate or accelerate the sphere free fall?

P4: 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. The sphere is made of POM of density $\rho_s = 1.4 g/cm^3$; use the size you measured last time. Apply the terminal velocity expression you obtained in last report to calculate the theoretical **terminal velocity** $U_T$

P5. Compare the measured velocity to the predicted value <u>that assumed no additional boundary effects from the lateral container walls and the co-existing sphere.</u> Use $U_T$ to scale the velocity profiles and compare them on the same plot. Did the two spheres reach their $U_T$?

P6: Plot the acceleration-time profile. Scale it by the **effective gravity**—gravity minus buoyancy force.

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

| Glycerol (% wt.) | Viscosity (cP)† | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 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 |

† $1 cP = 1 \times 10^{-3} Pa \cdot s$.

P7. Liquid properties: Glycerol is a water-soluble Newtonian liquid whose physical properties change greatly with temperature. Use the tabulated data to make two plots $\mu_f$-T (in unit:

g/cm sec) and $\rho_f$-T (in unit: g/cm$^3$) for glycerol-water solution of three weight percentages: 100% (pure glycerol), 50%, 1% (very dilute G-W solution).Is density or the viscosity more sensitive to temperature variations? How does this sensitivity changes with weight percentage (portion of glycerol).

## Low-Re flow line observation

P8. Describe and sketch how the dye droplet deforms as the inner rotor moved forwards and backwards. Does it come back to its original shape? If yes, it implies that low Re flow motion is reversible. If not, speculate some causes for flow irreversibility.

P9. After a few times of rotations, did you observe any displacement of the dye droplet, in the radial or in the circumferential directions?

P10. How does the glycerol droplet form in water? Dissolve or not? Descend or ascend?

P11. Sketch how the vertical rectangle deforms with rotor. Did you observe the no-slip boundary condition and the boundary layer formation from your experiments?

P12. For the vertical dye rectangle, which side distort more clearly? Why??

The following equation that describes the velocity field between two <u>infinitely-long</u> con-centric cylinders in constant rotation may be useful.

$$\frac{u_\theta(r)}{R_i\omega_i} = \frac{R_o^2}{R_o^2 - R_i^2}\frac{R_i}{r} - \frac{R_i^2}{R_o^2 - R_i^2}\frac{r}{R_i} \quad \text{for} \quad R_o > r > R_i$$

$R_o$, $R_i$ are the radius of the outer (stationary) and the inner (rotating) cylinder.
**Notice the tangential motion can be decomposed into $u_\theta(r) = ar + b/r$ where $ar$ is the component of a solid-body rotation and $b/r$ represents the line vortex motion.

P13. Sketch how the horizontal rectangle deforms with the rotor. Use the pattern to describe strain rate developed in this flow.

$$\varepsilon_{rr} \sim \frac{\partial u_r}{\partial r} ; \varepsilon_{r\theta} \sim r\frac{\partial}{\partial r}\left(\frac{u_\theta}{r}\right) + \frac{1}{r}\frac{\partial u_r}{\partial \theta} ; \varepsilon_{\theta\theta} \sim \frac{1}{r}\frac{\partial u_\theta}{\partial \theta} + \frac{u_r}{r}$$