臺灣二ＯＯ六年國際科學展覽會

科　　　別：工程學

作 品 名 稱：氣流式薄膜測厚儀

得 獎 獎 項：第一名
美國團隊正選代表:美國第57屆國際科技展覽會
赫伯特胡佛青年工程獎 第一名

學校 / 作者：臺北市立麗山高級中學　李詔熙
臺北市立麗山高級中學　陳永介

個人簡介

李詔熙

我出生於台北的小康家庭中，從國一開始接觸科學展覽比賽，高一下學期受到啓蒙，正式步入研究的領域中，埋頭其中，無怨無悔。生物領域中，曾研究過以水生植物淨化水的重金屬污染；地球科學領域中，曾研究過氣球載具火箭發射的評估；物理領域曾研究過表面張力的測定方法；工程應用學類則是雙軸阻尼運動及其在電學、光學、力學上的應用，以及氣動式薄膜測厚儀，檢測軟性物質的厚度。

陳永介

我於 1987 年出生於台北，自幼承庭訓瞭解語文與科學的重要性，對英文、設計與自然科學尤其有濃厚的興趣。九歲至紐西蘭讀小學與初中，因此對於西方文化有些許認知。十三歲回台就學重新從國一讀起。對自然科學發生興趣與父親的工作有直接關係，因爲自然科學需要讀外文書籍，我的英文能力得以訓練說寫讀，高一順利通過全民英檢中高級認證。高一就參加物理專題，並有幸參加多項物理與工程科學展獲得獎項。

摘要

醫學上的植皮手術成功率受皮膚厚度影響，皮膚愈薄癒合速度愈快，其中以取皮厚度介於 0.05mm 到 0.1mm 爲佳。在實驗量測時，需要經過一連串繁複的薄皮標本製作，再放到光學顯微鏡下測量，這種厚度測量方式不但耗時，又因嚴重損毀皮膚而不精確。

由於使用螺旋測微器做接觸式測量會有形變的問題，因此我們想做間接接觸式的測量，所以採用氣體爲媒介，做非破壞性檢測膜厚，這對於在皮膚上的施力遠小於螺旋測微器或是接觸式膜厚計。

我們設計一套三頭連管線，使用空氣爲媒介，儀器運作原理爲在管線一端針頭非常靠近被測物時，所流出的氣體會受到被測物阻礙產生反壓使管線內的壓力上升，導致連通於另一管路的氣泡指示計壓出氣泡，當氣泡爲最大氣泡時（半球形）視爲達到平衡狀態。實驗時先用已知厚度且不變形的蓋玻片來當作被測物，此時可以算出針尖至蓋玻片的實際距離做爲參考值。在量測軟性薄膜時，設計上採用兩側雙針頭靠近軟性被測薄膜兩側以達到氣流氣泡平衡，這時使用螺旋測微器讀取兩針尖距離，減去已知參考值的兩倍距離，即可測出未形變的軟物質厚度。

本研究開發一套能測量軟性薄膜的厚度裝置，尤其在皮膚厚度測定上，不但不會直接接觸標本造成損毀，並且能夠快速地測量出厚度值，此爲本儀器的最大特色。

Abstract

The thickness of skin graft has deterministic influences on the success of graft surgery. Experimental measurements of skin graft thickness involve complicated specimen preparation processes followed by optical microscopic examination, which are time-consuming and may incur inaccuracy due to possible damage. Here we propose a novel method using air as the media to avoid direct contact of the measured object.

The physical operation relies on the following principles: When the tip of a needle connecting to a catheter system is placed close to the object to be measured, the air pumped forward from the catheter system becomes impeded by the object. The resulting backflow pressure opposing the air flow causes an increase in air pressure within the catheter and inflates the bubble connected at the other end. Balance at maximal surface tension is attained when the bubble reaches its maximum volume in hemispherical shape. In practice, a two-needle design was used, each approaching simultaneously from each side of the object. A micrometer was then used to read the distance between the two needle tips, from which the film thickness was derived, subtracting the thickness of the air layer pre-calibrated using cover glass with known thickness.

The system implemented was capable of measuring thickness on soft thin films with an accuracy of ± 0.001mm. In addition to rapid measurements with high accuracy, since the pressure exerted on the skin graft is much less than in conventional calipers requiring direct contact, our method has the unique non-distorted and non-destructive advantages.

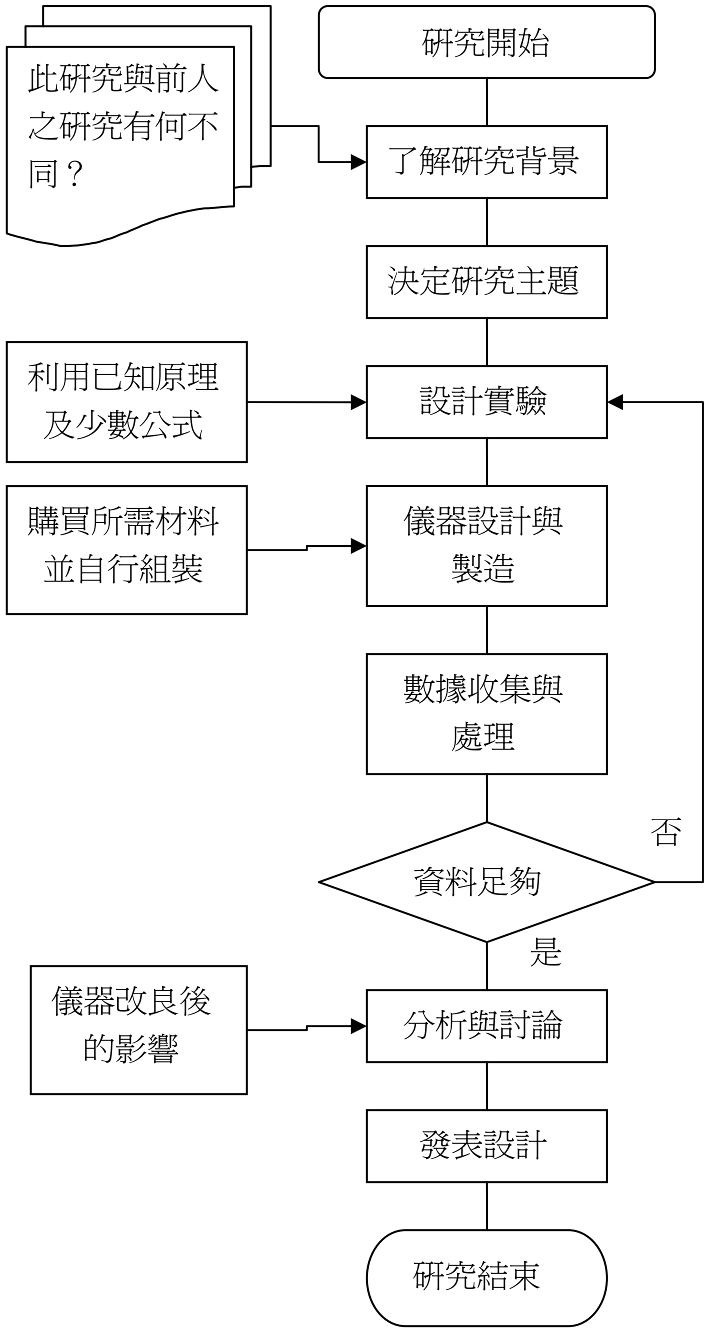
目錄

壹、 前言

目前醫學上使用的皮膚厚度測量方法，必須經過一連串繁複費時的標本製作，其中需要利用急速冰凍法固定標本，放置在光學顯微鏡下測量，但是標本在製作過程中容易遭受嚴重毀損，導致測量結果產生誤差。若使用其他接觸式測量法，例如使用一般的膜厚計或螺旋測微器，會在固定過程中造成軟性被測物質產生形變；如果使用其他非接觸式測量的膜厚計，其可適用的被測物也只能針對特定的材質。由於以上方法都無法精準測量生物薄膜的厚度，因此我們想發展出一套非破壞性檢測的儀器，採用氣動式非接觸測量法，簡單精準又可以解決生物薄膜測定的問題。

氣動式非接觸測量法於 1995 年提出，原本設計是用來測量蔬果及牡蠣的厚度，但是後來被廣泛應用於工業界，例如測量磁帶或金屬薄片的厚度，近期在醫學的應用上則是提出利用氣動式非接觸測量法測量隱形眼鏡的厚度。上述應用的共通點，在於當儀器設計成雙邊同步測量時，都沒有考慮到待測物需置中的問題，但是帶測物置中卻是影響儀器測量精確度非常重要的因素。如何使帶測物置中也將是本題目重要的一項研究。

貳、 研究流程



研究開始
此研究與前人之研究有何不同？
了解研究背景
決定研究主題
利用已知原理及少數公式
設計實驗
購買所需材料並自行組裝
儀器設計與製造
數據收集與處理
資料足夠
否
是
儀器改良後的影響
分析與討論
發表設計
研究結束

參、 研究器材

一、 自製器材

1. 氣流式薄膜測厚儀
2. 氣泡指示計
3. 伸展軸承基座

二、 廠製成品器材

1. 小型空氣幫浦(水族箱用，吐出量 800(c.c./min)
2. 螺旋測微器(解析度 0.01mm)
3. 高倍放大鏡(22X)

三、 電子零件類

1. 微壓感測晶片(型號：MPXV5004GC6U；測壓範圍：0~4kPa；輸出電壓：0~4.98V)

四、 電路基本零件

1. 五金機械類
2. 線性軸承與專用鋼棒
3. 各式螺絲、螺帽一批
4. 各式彈簧一批

五、 玻璃、塑膠材料類

1. 壓克力材料
2. PE 板
3. 二氯甲烷與粘合劑
4. 各式矽膠管
5. 各式塑膠接頭
6. 玻璃瓶
7. 針閥

六、 醫療用品

1. 各式皮下注射針頭
2. 各式針筒

肆、 醫學上皮膚測厚方式

醫學上厚度測定方法有很多種，我們挑其中對生物組織破壞性較小的來做說明：

一、 設定取皮刀欲切出的厚度（圖 01）。
二、 取皮後，選取薄皮中間部分切成長條狀（圖 02）。
三、 立在金屬載物台上，以固定劑固定（圖 03），放進冷凍室中瞬間冰凍。
四、 用切片機切下厚度 1μm 的薄片放到載玻片上取其截面部份（圖 04）
五、 用染色劑染色。
六、 放到光學顯微鏡測量厚度（圖 05，圖 06）。

這種測量方式有 4 個缺點：

一、 在上述標本製作中，步驟 3 會出現圖裡右邊的情形，當標本沒有擺正時，量測的厚度直徑傾斜而非垂直截面，造成量測值過大。（圖 07）
二、 生物組織經過冷凍後，從活細胞變成死細胞會有形變的情況。
三、 測量麻煩費時費力，需要運用多項昂貴儀器，成本高。

伍、 探討測具之不準確度

理論上，對物體施力測量時，會造成形變量 t，t 可分為正常施力時使物體形變的量 t1，和控制對物體施力時的誤差量 t2，而 t1 和 t2 都可寫成力除以物體的彈性係數，於是公式如下

$$t = t_1 + t_2 = \frac{F}{k} + \frac{\Delta F}{k}$$

t	測量物體時的誤差值
t1	正常施力時物體的形變量
t2	控制對物體施力時的誤差量
F	正常施力
ΔF	控制對物體施力時的誤差
k	物體的彈性係數

陸、 儀器原理

一、本研究有關非破壞性量測原理

1. 針頭接近物體的情況（圖 08）

氣體由幫浦供應流至兩側端針頭送出，中間物體爲待測物。當兩側針頭非常靠近物體時（並沒有碰到），所流出的氣體會受到阻礙而產生反壓（圖 09），產生的原因在於氣體從針頭流出呈輻射狀，當針頭越靠近待測物，待測物表面單位面積所承受的力量越大，相對於氣體而言，越靠近待測物所造成的反向壓力也越大，所以反壓上升使針頭的出口堵塞，後續氣流因此相對流向另一 Y 型管路到氣泡指示計，使沒入水中的管口壓出氣泡，當氣泡爲半顆球時視爲達到平衡狀態，此時即爲指示針頭與被測物間的適當位置。

二、儀器的校正與測量

1. 儀器的校正（圖 10）

用已知厚度的標準片(A)做爲待測物讓針頭夾擊趨近，使氣泡指示計中的管口產生半顆氣泡。將螺旋測微器的讀值(C)扣除標準片的厚度，即爲校正值(2B)（空隙的距離）。之後測量未知厚度時，將螺旋測微器的讀值扣除校正值(2B)，即物體不受破壞時的厚度。

2. 如何確定半顆氣泡（圖 11）

圖 12，爲管口出現氣泡的情形，符合數學公式

$$\Delta P = \frac{2\gamma \cos\theta}{r}$$

當 θ 爲 0 時，即管口產生爲半顆氣泡，ΔP 達到最大值。由於管線內部氣體是持續供應的，壓力會隨針頭與物體距離變化，當內壓的力量大於管外水壓的力量加上水的表面張力，造成失去平衡狀態，因此當氣泡處於留在管口與即將脫離管口之臨界點時，我們可以確定它是理論上的半顆氣泡。

三、 物體的置中機制

1. 圖 12 中，在兩針頭距離相同下，物體的位置偏向一邊，會使較靠近物體的針頭所受的反壓較強，使產生的氣泡大小比在正中央時來得大，造成半顆氣泡形成時可能代表多種不同針間與測物距離情形，因此物體需要維持在兩針頭的正中央，以減少測量變異與誤差。
2. 在區域三中（圖 13），於放置待測物的平移台兩側加上相同的彈簧，再利用螺旋測微器推動連接針頭的基座向中間擠壓，平移台會因彈簧的靜力平衡而置中。

3. 最後由平移台（圖 15）上的 X 軸調整物體位置，當物體在正中央時，針頭兩邊所受的反壓相同，同時因為氣泡大小正好在兩針頭距離最短時，因此我們在針頭後端各加上壓力感測器做被測物置中調整校正之用（圖 14），以增加精確度。

柒、 實驗過程

一、 求壓力感測器的特性直線（圖 16）

1. 接好壓力感測器的電路，外接電錶以方便觀察感測器輸出的電壓。
2. 將壓力感測器外接 60cc 針筒和一個 500cc 緩衝瓶，緩衝瓶的用意在於避免壓縮體積的比例（壓縮體積相對於總體積）太大而毀損感測器。
3. 每次壓縮 1cc，等待電壓不再跳動後記錄電壓（因為要等待壓縮體積所造成的上升溫度降下來）。
4. 紀錄當時的大氣壓力 P 和對應到的電壓，以及管路中的總體積 V，利用 PV=P’V’，算出不同體積 V’對應到氣壓 P’，再將氣壓 P’對照電壓繪出關係圖，再繪出體積的倒數與氣壓的關係圖。

二、 針頭至物體距離與反壓大小關係（連接氣泡指示計）（圖 17）

1. 以金屬片為假想待測物，同時用針頭與蜂鳴器串聯成一個迴路，以辨識物體與針頭間的距離是否為 0，當針頭接觸到待測物時，會發出蜂鳴聲。
2. 以針閥調整幫浦的氣體流量，使氣泡指示計出現半顆氣泡，此時針頭與物體的距離恆為 0.02mm。
3. 紀錄距離與氣壓的關係，每間距 0.005mm 紀錄一次。
4. 將數據輸入到電腦，使用 Origin7 程式擬合(fitting)，找出距離和壓力的函數關係。
5. 將函數用 Graph 程式，對 0.02mm 量測距離的點作切線，求靈敏度。

三、 針頭至物體距離與壓力大小關係（沒有連接氣泡指示計）

1. 實驗裝置同步驟二「針頭至物體距離與壓力大小（連接氣泡指示計）」，但將氣泡指示計的管口封住（變因）。
2. 紀錄距離與氣壓的關係，每間距 0.005mm 紀錄一次。
3. 將數據輸入到電腦，以 Origin7 程式擬合(fitting)，找出距離和壓力的函數關係。

四、 反壓增加大小與單位時間流量關係

1. 實驗裝置同步驟三「針頭與物體距離與壓力大小關係（沒有連接氣泡指示計）」，但用管線將針頭延伸至水中，針頭與集氣瓶外的水面同高，並在中間裝上節流閥。
2. 控制不同的壓力大小，以排水集氣法收集單位時間的流量大小。
3. 將壓力值扣除針頭與物體距離為無限遠時的壓力值。

4. 將數據輸入到電腦，以 Origin7 程式擬合(fitting)，找出距離和壓力的函數關係。

五、 測量蓋玻片

1. 目的在於求出校正值（如圖 10 的距離 2B），及測量剛性物質的精準度。
2. 校正時使用蓋玻片作爲已知物，厚度爲 0.150mm，將蓋玻片一片一片的累加，看是否片數與氣流式薄膜測厚儀量所測到的厚度呈線性關係。
3. 估計值部分用數位相機拍下後，送到電腦裡計算

六、 測量保鮮膜（圖 18）

1. 目的在於證明測量軟性物質時也和測量剛性物質時一樣準確。
2. 由於保鮮膜的厚度均勻且極薄，厚度爲 0.0127mm（0.0005inch），我們擬將實驗測得的數據與廠製保鮮膜厚度標準值（0.0127mm）比較。
3. 另外用螺旋測微器量測同一保鮮膜樣品並做比較。

七、 測量氣流和螺旋測微器對物體的施力大小

1. 測量彈簧（壓縮式）接受 400 克重時的形變量，算出該彈簧的彈力係數。
2. 將該彈簧放至到螺旋測微器下，轉到不能再壓縮時，紀錄該彈簧的形變量。
3. 算出螺旋測微器對於物體的施力
4. 將實驗「針頭至物體距離壓力大小」中的裝置直接拿到電子秤測量氣流接觸到物體的施力。

八、 測量皮膚

1. 實際測量皮膚厚度，本研究使用豬皮爲樣品。
2. 將豬皮用取皮刀取下六種厚度，分別爲 0.005inch、0.010inch、0.015inch、0.020inch、0.025inch、0.030inch，並進行測量，最後將同一批樣品用醫學測厚的方法測定，比較兩邊的結果。

捌、 實驗結果

一、 求壓力感測器的特性直線

1. 見圖 20

二、 針頭至物體距離與反壓大小關係（連接氣泡指示計）（圖 21）

1. 界定半顆氣泡：針頭逐漸接近被測物時，氣泡開始產生。氣泡產生的範圍，從針頭至被測物 0.075mm 開始，到 0.020mm 爲半顆氣泡（成泡點），當針頭與被測物距離更接近時，氣泡就脫離指示器管端而浮上水面。
2. 將切線中的斜率倒數後，氣泡指示計在成泡點爲 0.02mm 時，靈敏度爲 5×10^{-5}mm/Pa

三、 針頭至物體距離與壓力大小關係（沒有連接氣泡指示計）（圖 22）

1. 當距離範圍在 0.000mm 到 0.150mm 時，圖形符合 First Order Exponential Decay
2. 距離越接近，壓力變化越大，其靈敏度越高，故在選擇針頭與物體時的距離越短，造成的施力誤差越小

四、 反壓增加大小與單位時間流量關係

1. 圖 23 中的藍色曲線方程式，由於 3 次和 2 次項的係數太小故可忽略，所以當反壓範圍在 0 到 2000Pa 之間，大致呈線性遞減。
2. 圖 24 爲圖 22 與圖 23 之合併結果，當距離範圍在 0.000mm 到 0.150mm 時，圖形符合 Exponential Growth。
3. 變化幅度在 1.66 至 1.75cc/sec 之間，從流量可推出中的雷諾數約爲 200，屬於穩流的情形。顯示針頭接近物體與反壓增加的相對關係中，有固定的曲線。

五、 測量蓋玻片（圖 24）

1. 比較本研究儀器與螺旋測微器所測厚度的差異，結果顯示相差誤差爲±0.001mm，在螺旋測微器的解析度 0.01mm 內，表示本儀器的準確度以螺旋測微器爲基礎，結合氣動測量原理，同時保持螺旋測微器的在測量剛體時的準確度。
2. 本實驗的數據中 R 趨近於 1，顯示出本儀器測量厚度有很高的準確性。

六、 測量保鮮膜（圖 25）

1. 本研究儀器所測得的厚度，介於保鮮膜真實厚度範圍±0.001mm。
2. 螺旋測微器測得的厚度，都低於保鮮膜真實厚度範圍，顯示出保鮮膜的確會受螺旋測微器的施力而變薄。

3. 證實本研究的儀器可以在尚未形變被測物前，準確測量軟性物質的厚度。

七、 測量氣流和螺旋測微器對物體的施力大小

1. 氣體對於物體的施力爲 0.2 到 0.3gw，螺旋測微器的施力爲 600 到 700gw，氣體施力只有螺旋測微器的的千分之一

八、 測量皮膚（圖 26）

1. 與 Dermatome setting 的設定值比較，Microscopy 的最小絕對誤差爲 0.030mm，最大誤差爲 0.122mm，Our Apparatus 的最小絕對誤差 0.005mm，最大 0.086mm。
2. 比較 Microscopy 和本研究儀器的測量步驟，所需要的方法、時間、材料、資源、成本都優於 Microscopy，達到本研究的目標。

玖、討論

一、 爲什麼儀器設計上沒有使用緩衝瓶來穩定氣流？

雖然增加緩衝瓶可穩定氣流，但對於儀器而言，需要氣泡指示計快速反應來顯示針頭與物體的相對位置，加了緩衝瓶反而會因體積增加使儀器操作遲鈍，更容易破壞待測物體。因此我們以增長管線，縮小管徑，減少雷諾數，來解決氣流穩定的問題。

二、 如何決定針頭的孔徑大小？

從趨勢性探討，根據連續方程式和白努力定律，在相同距離之下，孔徑越大，流速差越小，單位距離的壓力變化就越小；反之，則單位距離的壓力變化就越大。但孔徑越小，所需接近物體的距離越短，操作時相對的越容易觸碰到待測物體。故針頭的孔徑大小由待測物所需的安全距離和靈敏度而定。

三、 爲什麼採用懸吊式雙針頭測量物體？

如果採用單邊測量物體，當貼在一平面上時，可能因爲有細毛的支撐而測到多餘的空隙。

四、 爲什麼要用氣泡指示計而不用壓力感測器？

由於壓力感測器本身會受溫度的影響而改變其壓力與電壓的特性關係，因此相同氣壓下，電壓値會不停的下降，所以每隔一段時間就要重新抓取半顆氣泡時的電壓値。氣泡指示計在半氣泡狀態時的靈敏度約爲 1E-5mm/Pa，相當於 0.1mV/Pa，而壓力感測器只有 1mV/Pa，表示半氣泡說明出半顆氣泡指示的能力優於我們使用的壓力感測器。氣泡指示計的靈敏度會隨著幫浦流量縮減和使用表面張力較小的液體而

提升，可視測量需求而改變之，這又是另一項優點。

壹拾、　結論

一、在針頭至物體距離與壓力變化的關係中，當距離在 0.000mm 到 0.150mm 時，圖形符合 first order exponential decay。所以針頭與物體的距離越短，靈敏度越高。
二、針頭與物體距離與壓力增加大小的關係中，成泡點在 0.02mm 時，靈敏度爲 10-5mm/Pa。
三、使用氣體接觸被測物的施力，比螺旋測微器的施力少 1000 倍。
四、對於測量同一物體，氣體施力比螺旋測微器小，加上氣泡指示計的高靈敏度，和物體置中的機制，可以準確控制針頭與物體的位置，所以正常施力降低，施力的誤差程度得以控制，於是測量時的精準度提高。
五、由反壓增加與單位時間流量的關係得知管路中的雷諾數爲 200，屬於穩流，所以可確定針頭至物體距離與壓力增加有固定的曲線關係。
六、由測量蓋玻片的實驗中，顯示可以以氣動原理精確測量剛性物質。
七、在測量保鮮膜的實驗中，證實本研究儀器可以在尚未破壞被測物前，準確的測到軟性物質的厚度。
八、在測量皮膚的實驗中，本研究儀器的測量步驟，所需要的方法、時間、材料、資源、成本都優於 Microscopy，達到本研究的目標。

壹拾壹、　未來與展望

一、將本儀器的功用延伸至其他領域，並開發新的用途。
二、繼續研發改良本儀器的機械設計，朝構造簡單化，平價化的方向前進。

壹拾貳、　參考資料

三、G E Gale; 1995; A thickness measuring device using pneumatic gauging to detect the sample; Silsoe Research Institute,UK; Meas. Sci. Technol
四、林明瑞；高中物質科學物理篇下冊；再版；台南市安平工業區新義路 6 號；南一書局企業股份有限公司；pg.114~pg.115
五、鄭雨軒；毛細管內液體流速之探討及黏度測量方法之創新
六、Anonymous: Feb 2000: Noncontacting measurement system: Manufacturing Engineering : 124, 2: pg. 34
七、Anonymous; Feb 2000; Manufacturing Engineering; 124, 2; Proquest Computing INFAS Sociedad Responsabilidad Limitatda, Repu’blica Argentina.
八、Anonymous; Oct 2003; Noncontacting measurement system; Manufacturing Engineering; 131, 4
九、Diehl K C, van Gelder M F and Byler R K: 1990: Automated dimension measurement system for soft biological materials
十、G E Gale and P Griffiths: An automatic micrometer for measuring soft electrically conductive materials

十一、 Jim Destegani; Oct 2003; Air gagging; Manufacturing Engineering; 131, 4; pg. 69
十二、 “PNEUMATIC CONTROL; An Introduction to the Principles”, Werner Deppert/Kurt Stoll
十三、 Fang, P. MD *; Engrav, L.H. MD *; Gibran, N.S. MD *; Honari, S. RN, BSN *; Kiriluk, D.B. RN *; Cole, J.K. MD *; Fleckman, Philip MD ++; Heimbach, D. M. MD *; Bauer, G.J. MD *; Matsumura, H. MD +; Warner, P. MD *; 2002; Dermatome Setting for Autografts to Cover INTEGRA(R); Journal of Burn Care & Rehabilitation. 23(5):327-332, September/October
十四、 http://www.pep.com.cn/
十五、 www.sme.org/manufacturingengineering

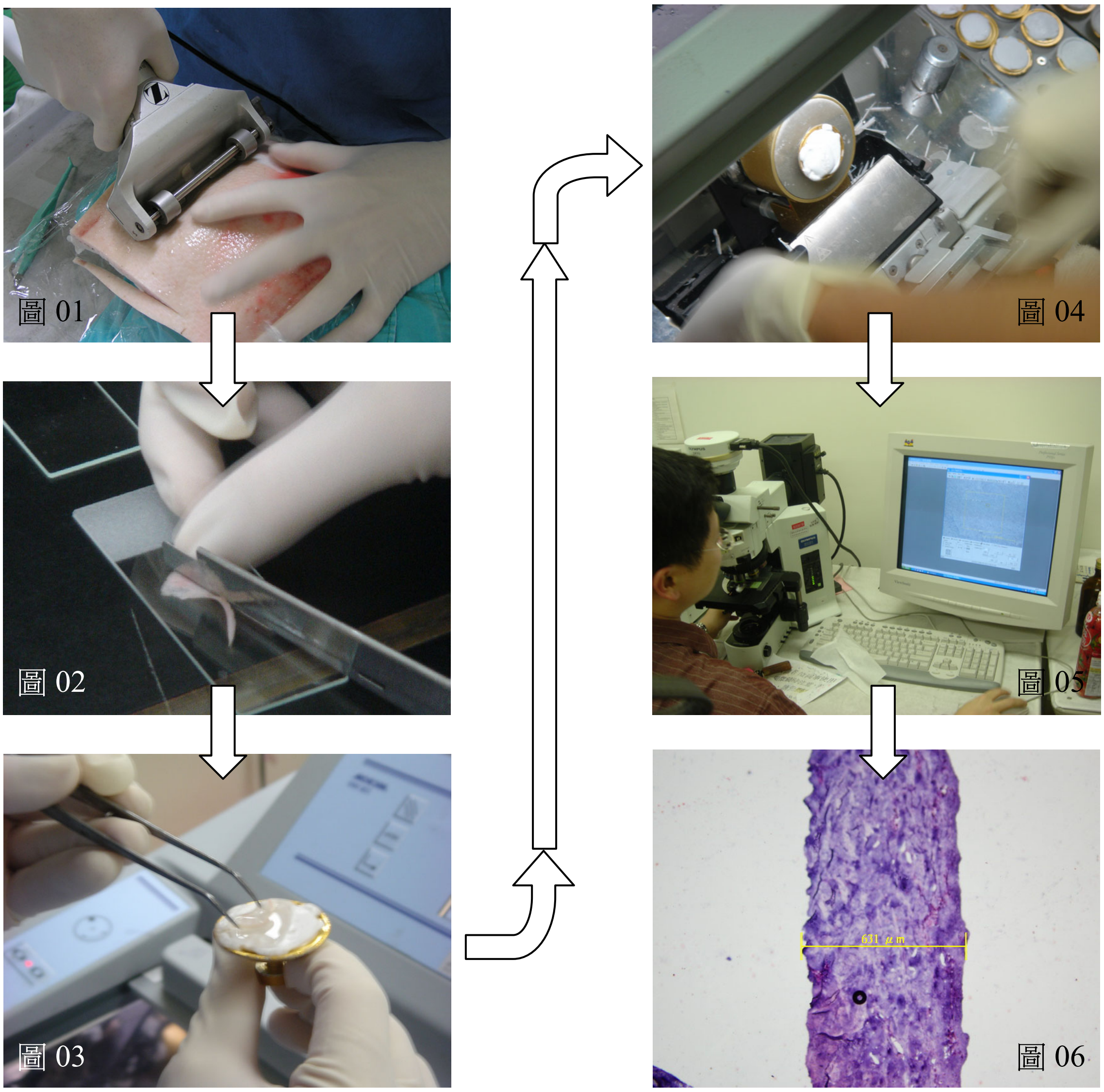


圖 01
圖 02
圖 03
圖 04
圖 05
圖 06

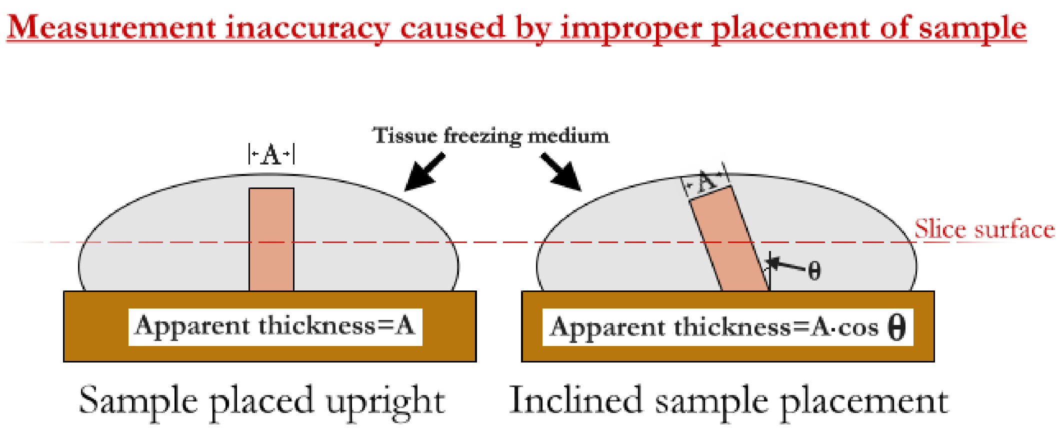


圖 07 醫學上的測量，可能會因為皮膚樣本沒放正而有誤差

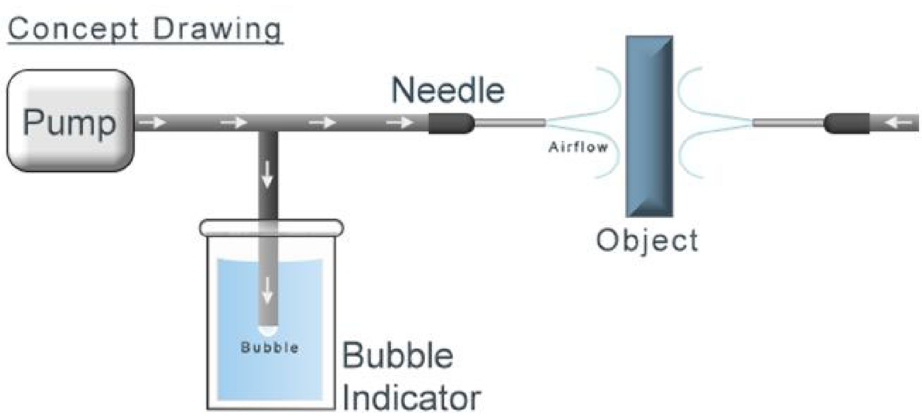


圖 08 儀器運作原理簡圖

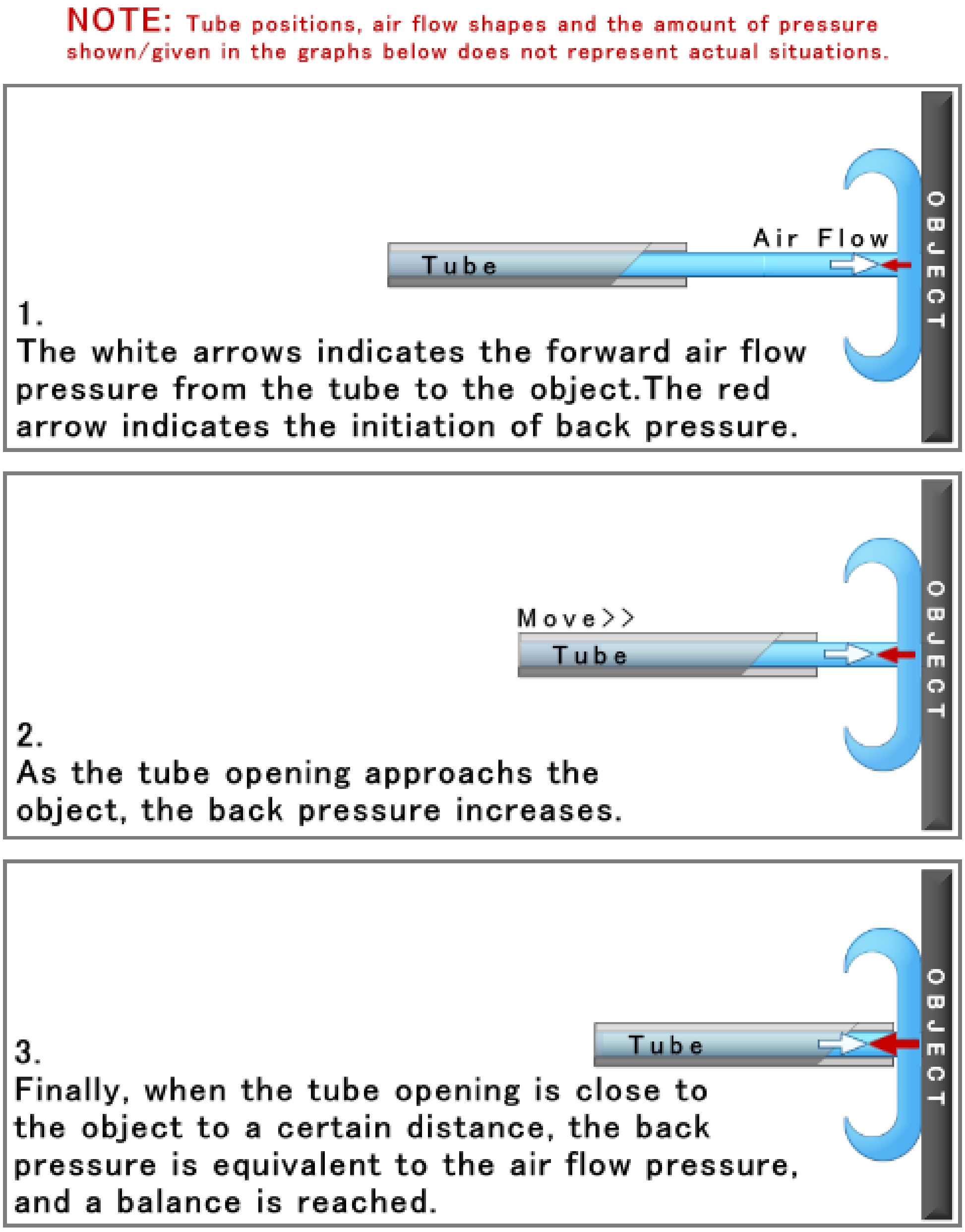


圖 09 物體越接近針頭，反壓越大

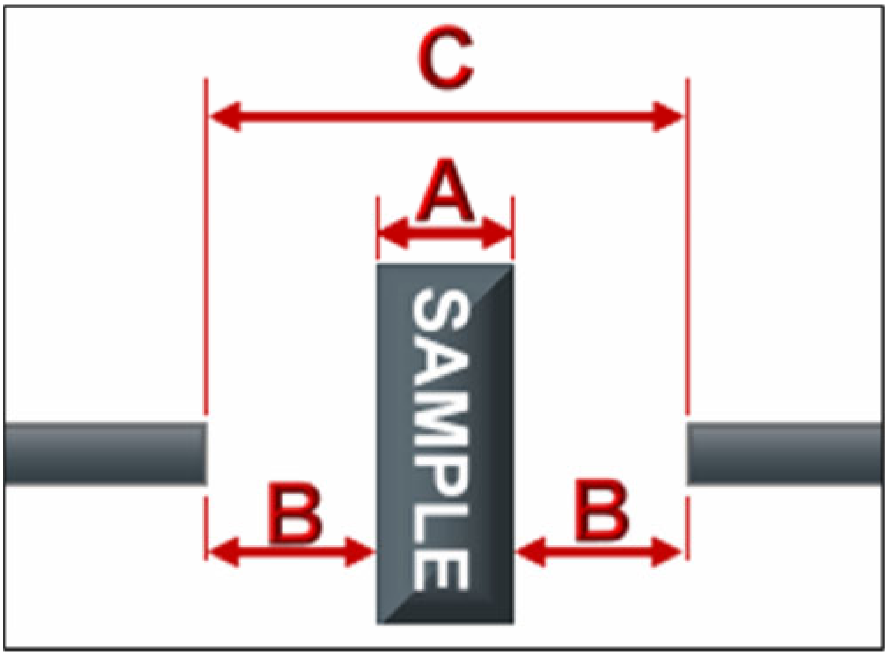


圖 10 將兩針頭的距離 C，扣除空隙距離 2B〈校正常數〉，即為物體厚度

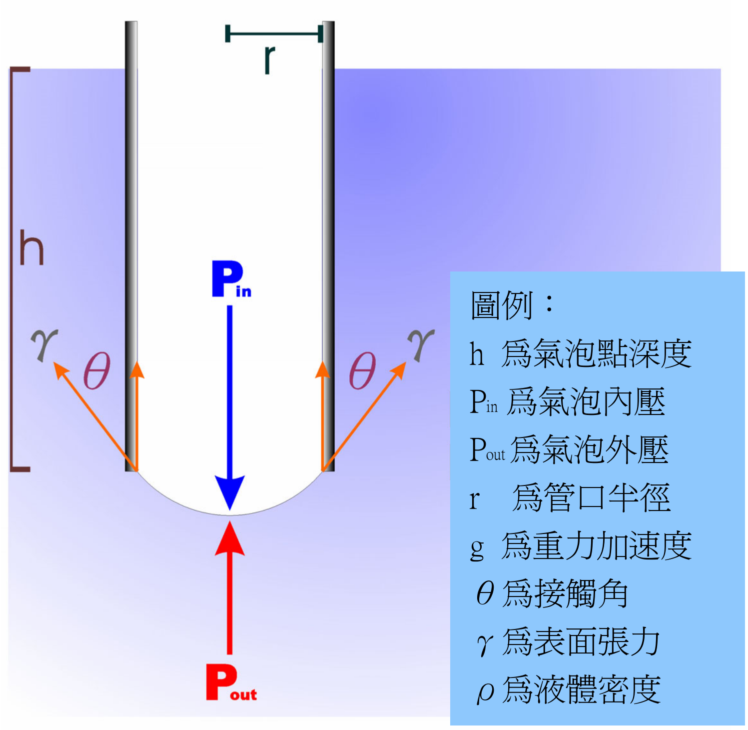


圖 11 氣泡在水裡產生的情形

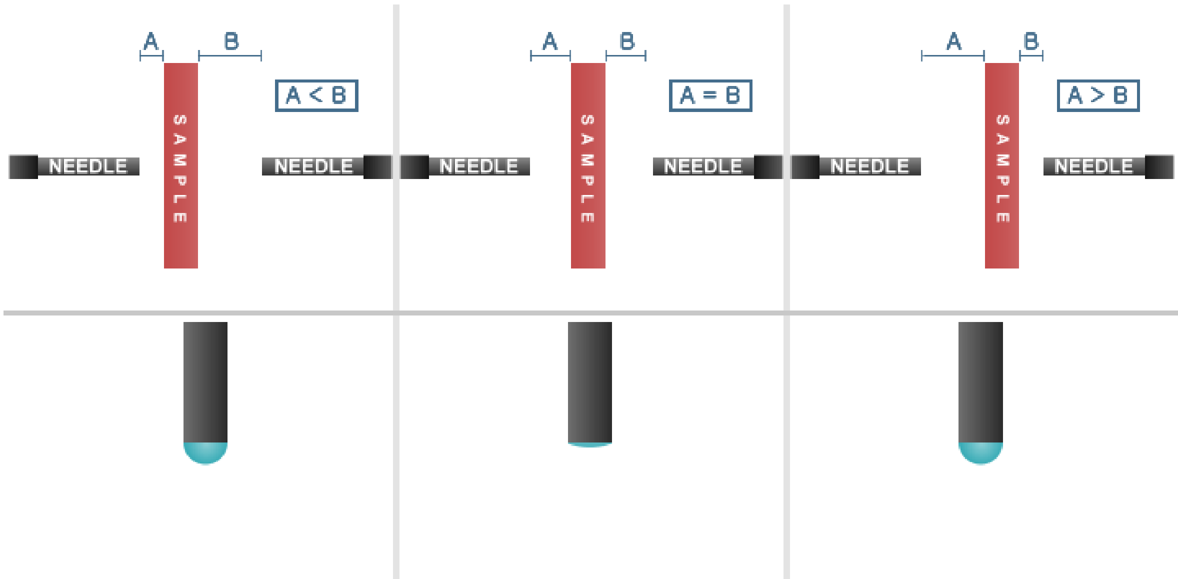


圖 12 當物體在置中與不置中時，氣泡產生的狀況

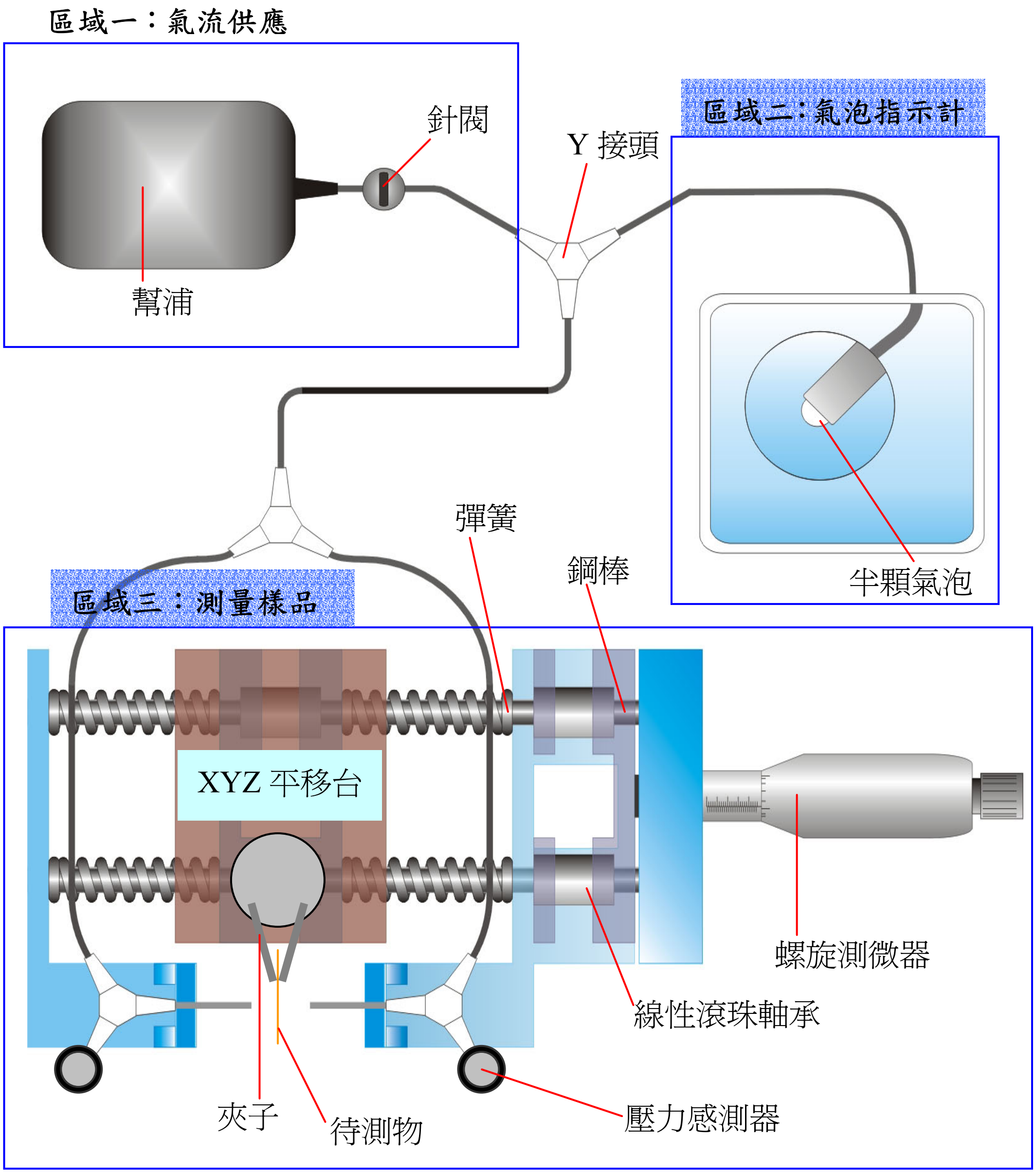


圖 13 儀器簡圖

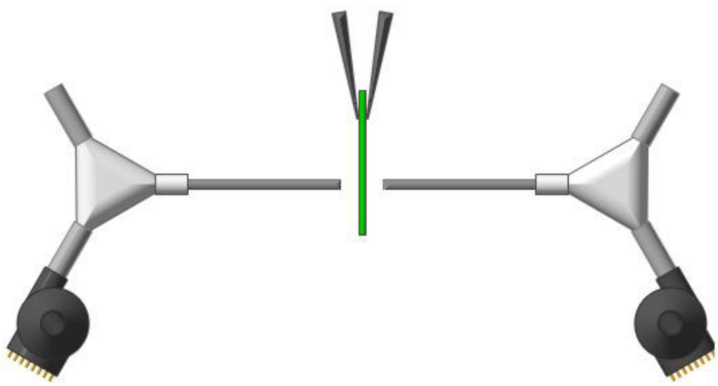


圖 14 由壓力感測器輔助物體置中

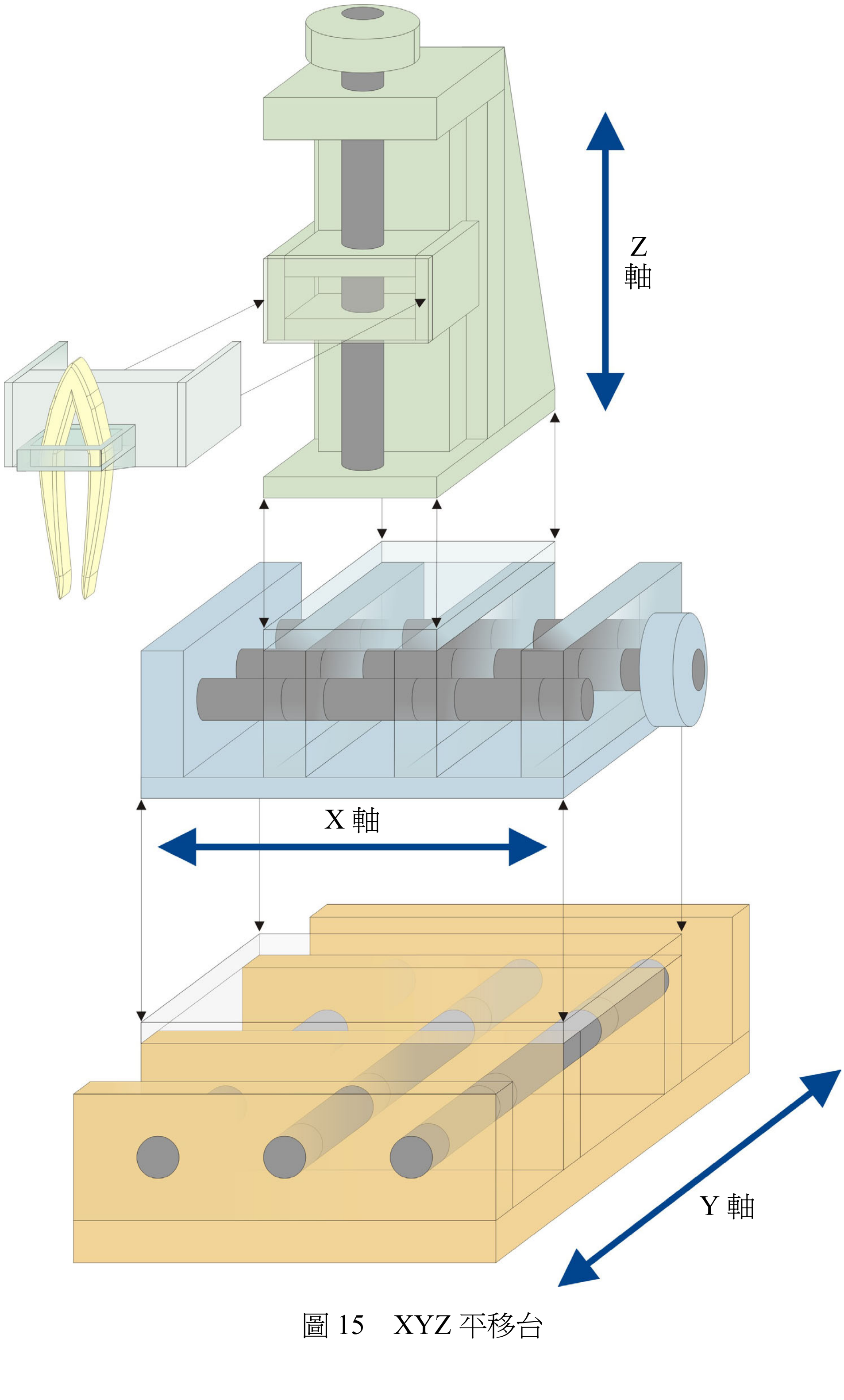


圖 15　XYZ 平移台

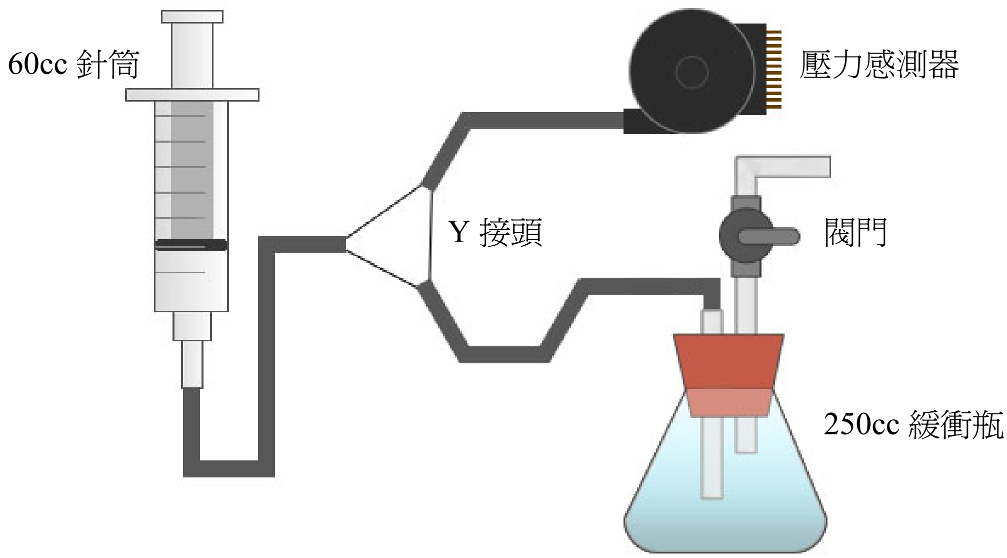


圖 16 求壓力感測器的特性直線

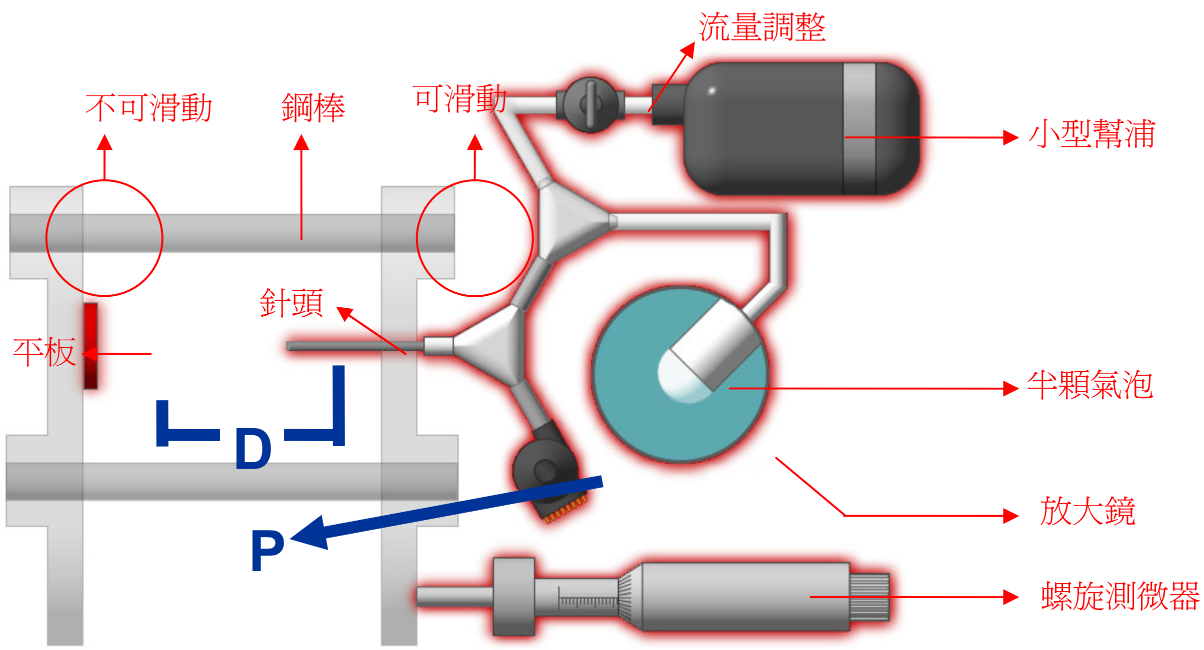


圖 17 測量針頭與物體距離與壓力增加的關係的實驗裝置

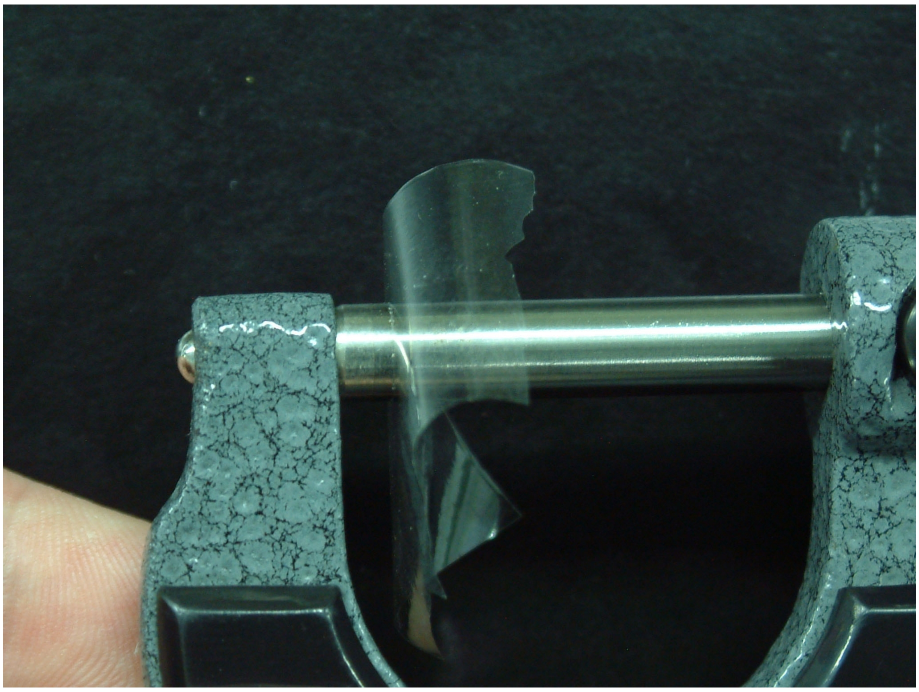


圖 18 夾擊保鮮膜

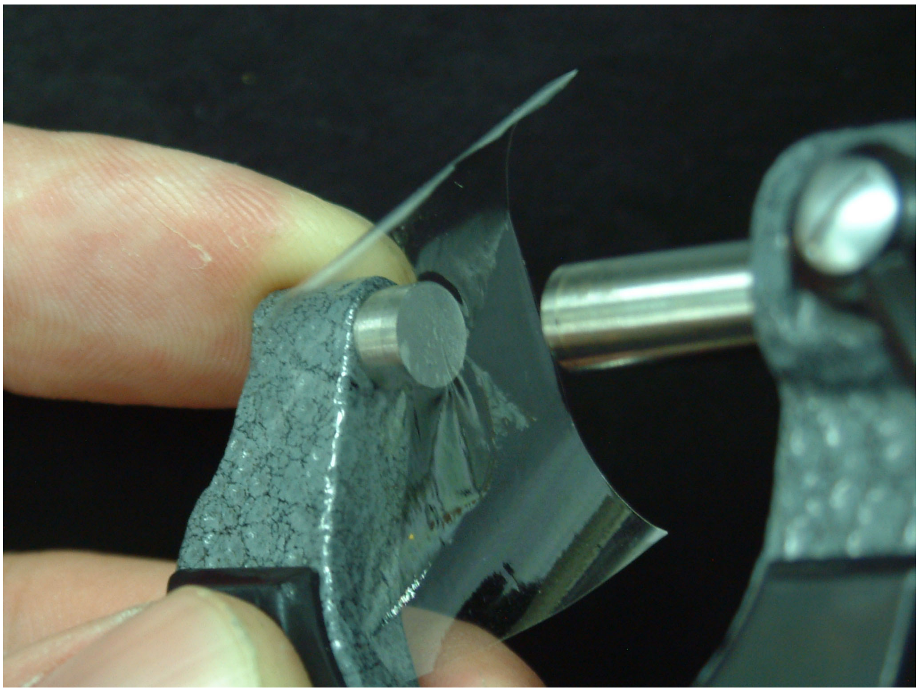


圖 19 保鮮膜形變

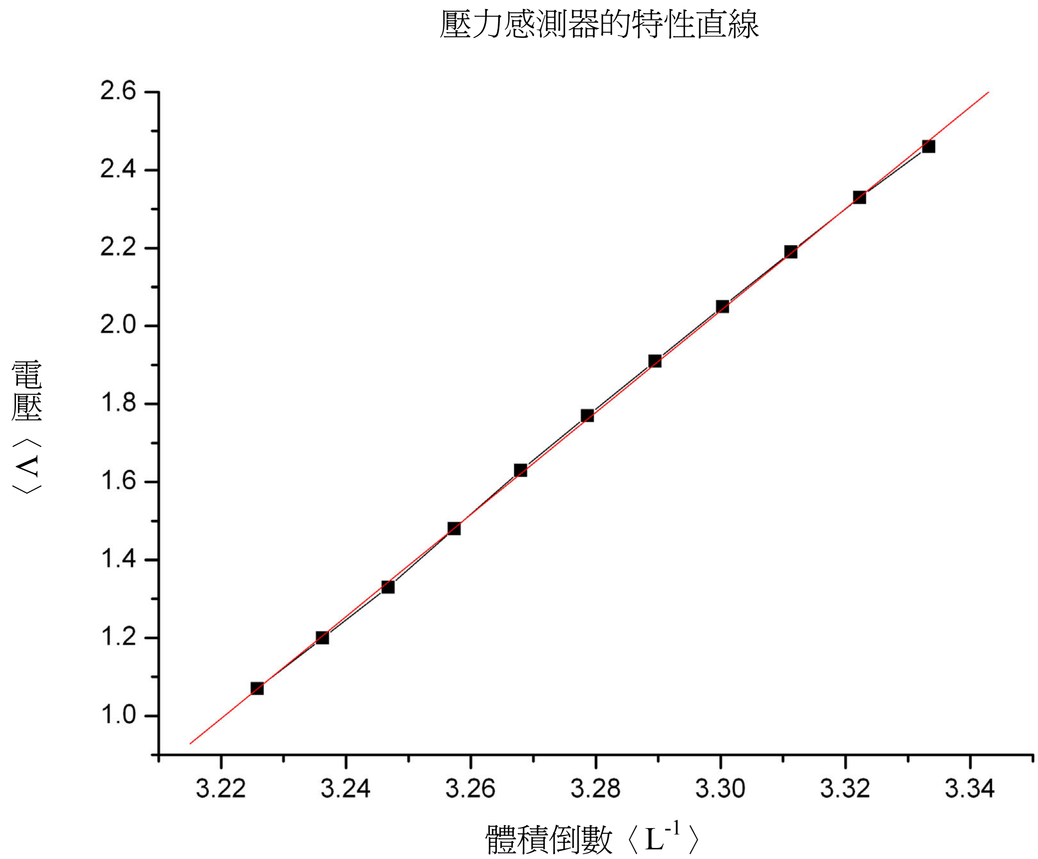

壓力感測器的特性直線
2.6
2.4
2.2
2.0
1.8
1.6
1.4
1.2
1.0
3.22
3.24
3.26
3.28
3.30
3.32
3.34
電壓〈V〉
體積倒數〈L^{-1}〉

圖 20

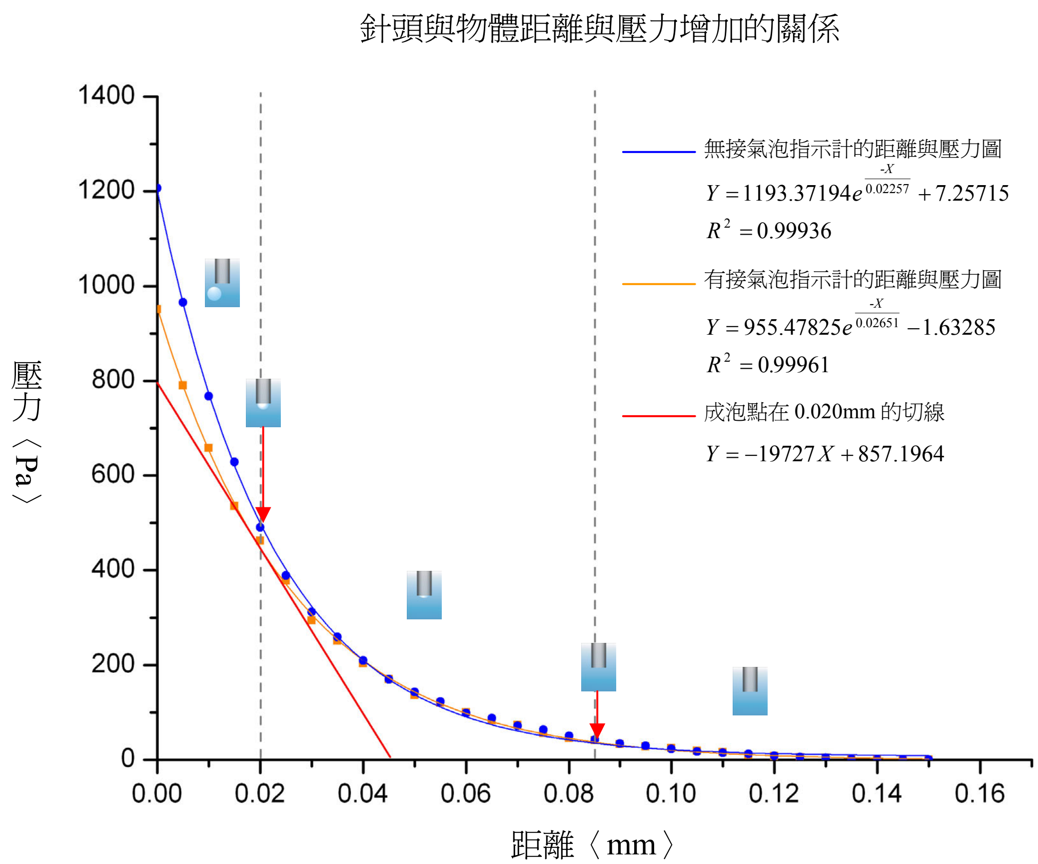

針頭與物體距離與壓力增加的關係
無接氣泡指示計的距離與壓力圖
$Y = 1193.37194e^{\frac{-X}{0.02257}} + 7.25715$
$R^2 = 0.99936$
有接氣泡指示計的距離與壓力圖
$Y = 955.47825e^{\frac{-X}{0.02651}} - 1.63285$
$R^2 = 0.99961$
成泡點在 0.020mm 的切線
$Y = -19727X + 857.1964$
1400
1200
1000
800
600
400
200
0
0.00
0.02
0.04
0.06
0.08
0.10
0.12
0.14
0.16
壓力〈Pa〉
距離〈mm〉

圖 21

反壓增加與單位時間的流量關係

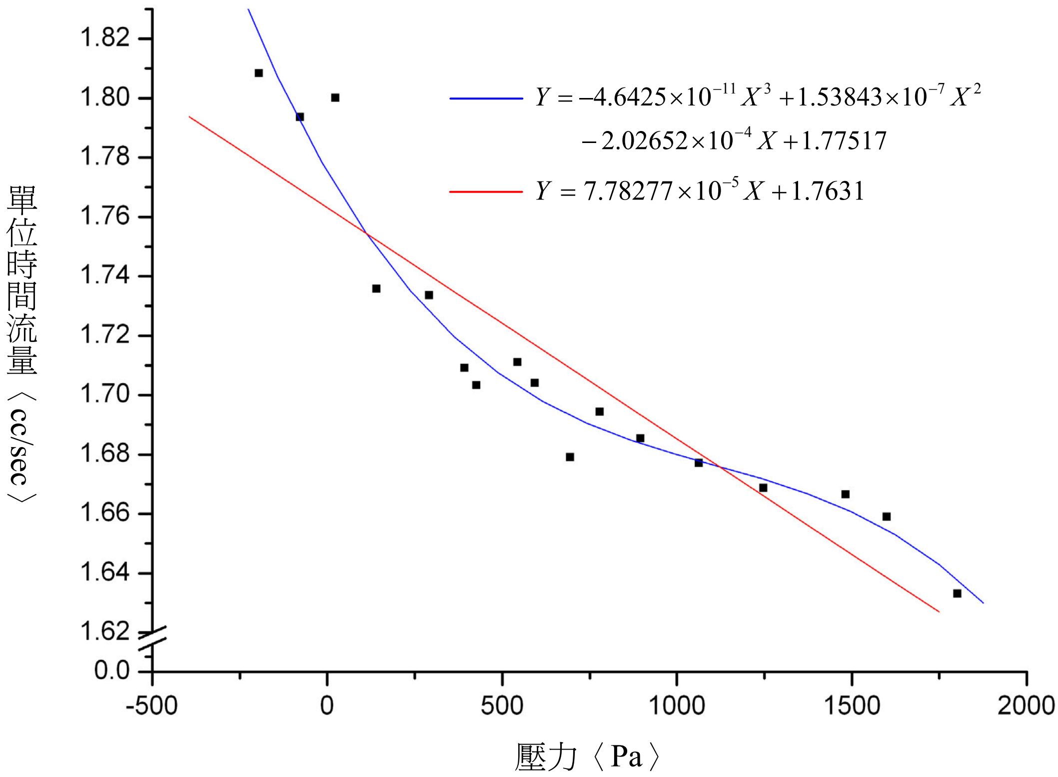


圖 22

針頭與物體距離與單位時間的流量關係

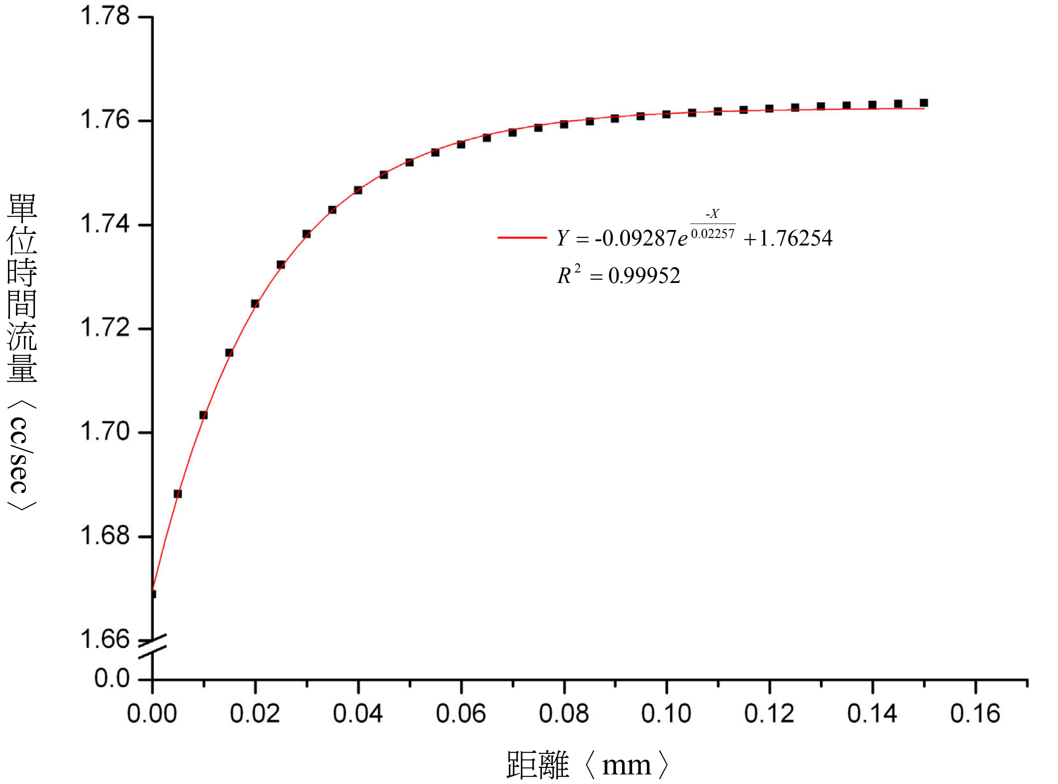


圖 23

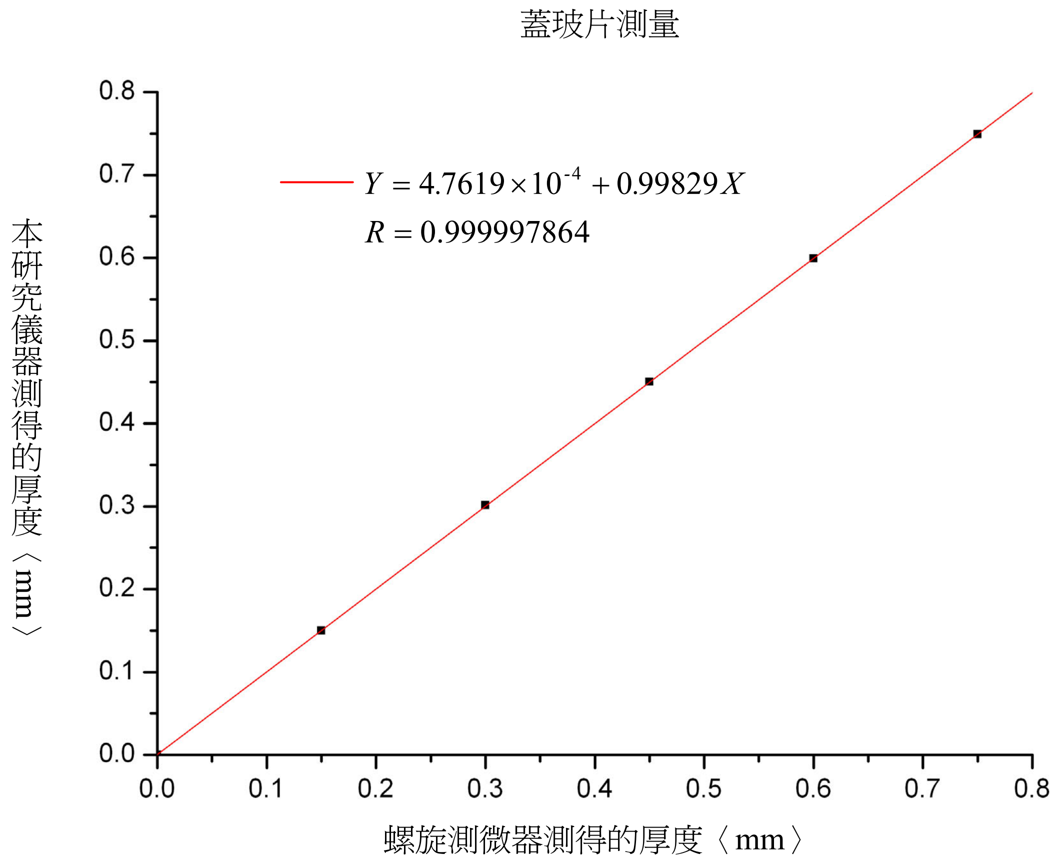

蓋玻片測量
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
$Y = 4.7619\times10^{-4} + 0.99829X$
$R = 0.999997864$
本研究儀器測得的厚度〈mm〉
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
螺旋測微器測得的厚度〈mm〉

圖 24

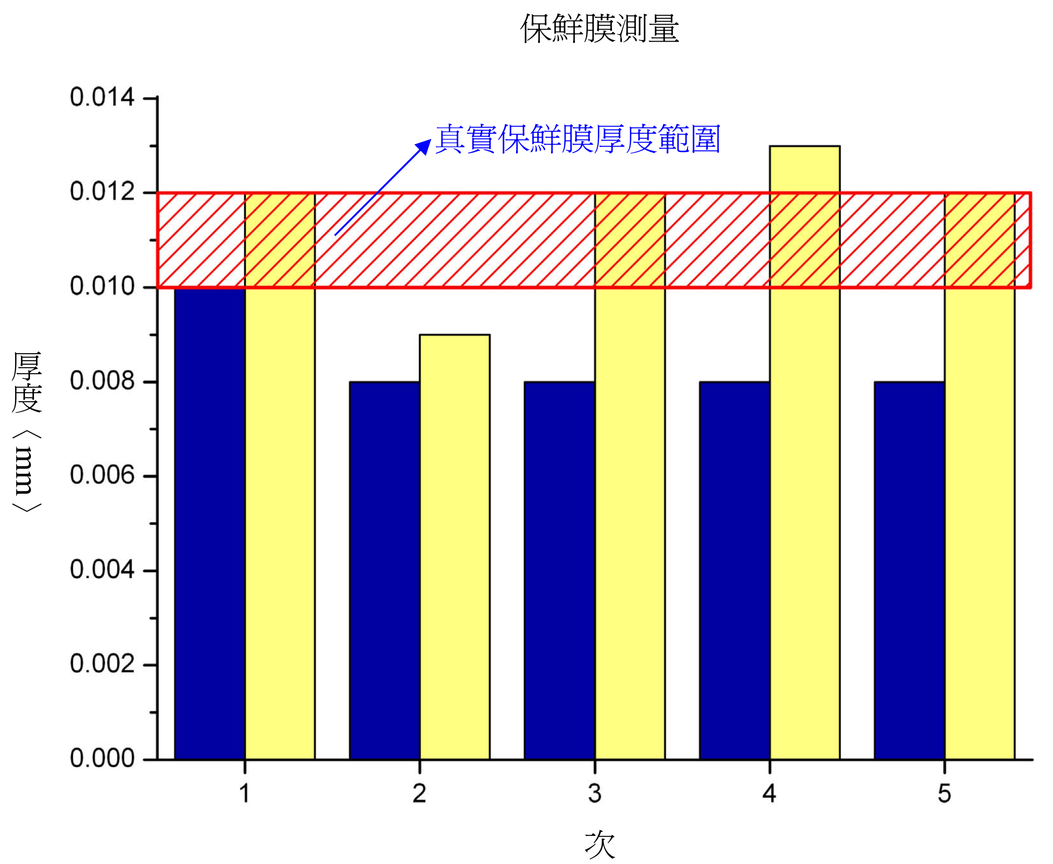

保鮮膜測量
0.014
0.012
0.010
0.008
0.006
0.004
0.002
0.000
真實保鮮膜厚度範圍
厚度〈mm〉
1
2
3
4
5
次

圖 25

測量皮膚厚度

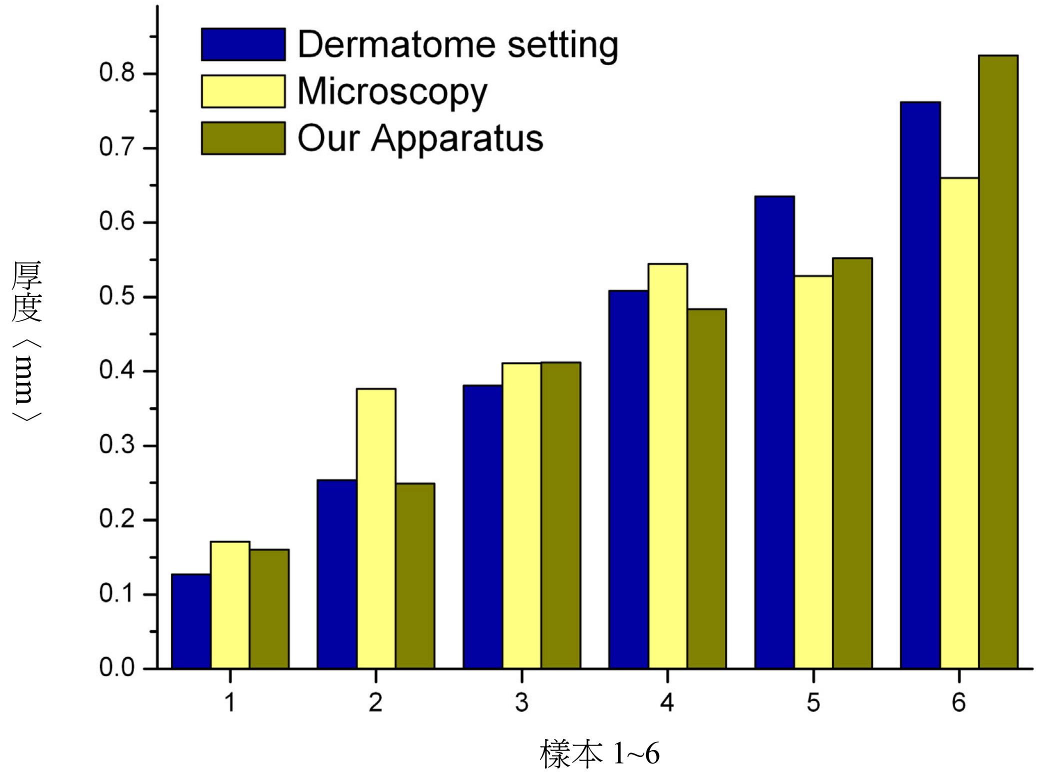

Dermatome setting
Microscopy
Our Apparatus
厚度〈mm〉
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
1
2
3
4
5
6
樣本 1~6

圖 26

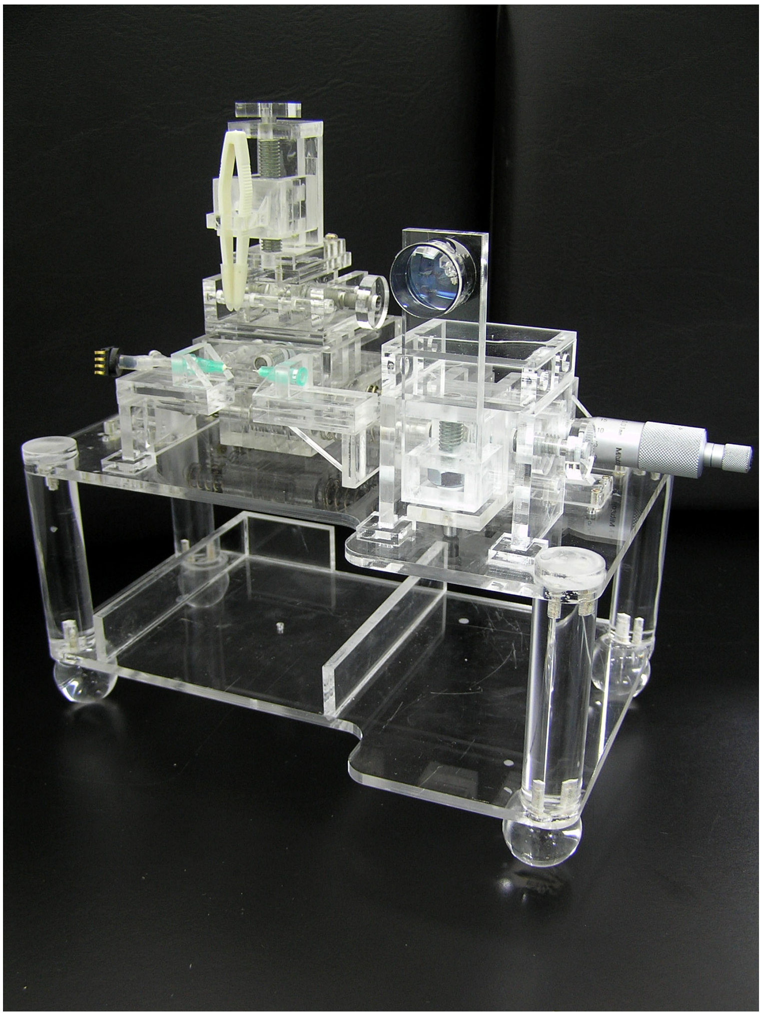


圖 27 儀器全圖

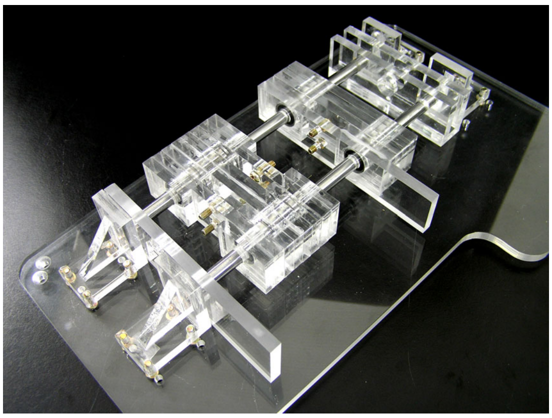


圖 28 使平移台置中的機構

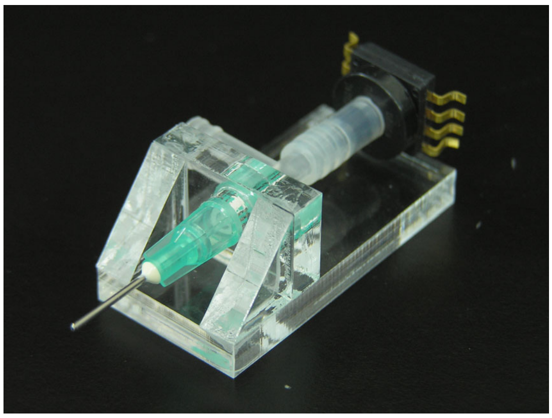


圖 29 針頭後面連接壓力感測器

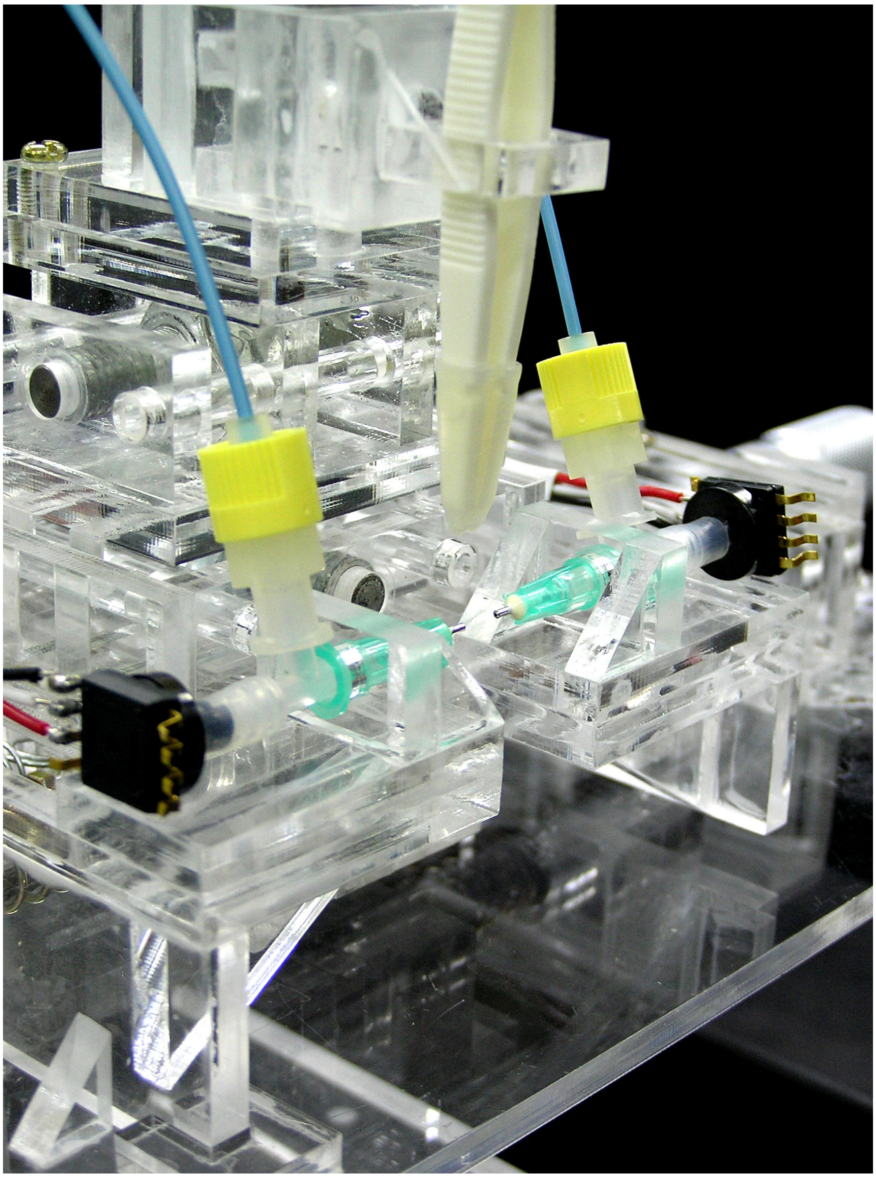


圖 30 測量區圖，針頭後面有連接壓力感測器

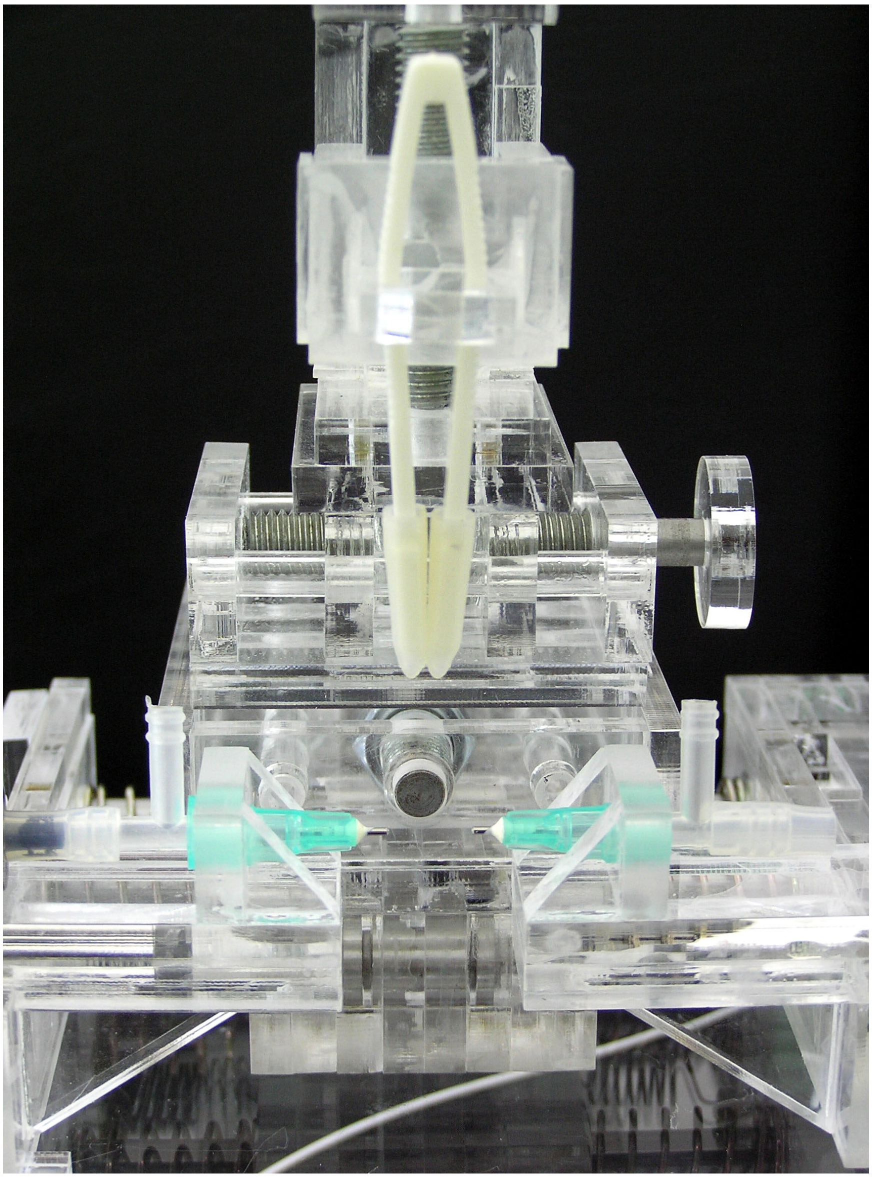


圖31 上部為XYZ軸平移台，夾子的部份帶有保護樣品的矽膠套

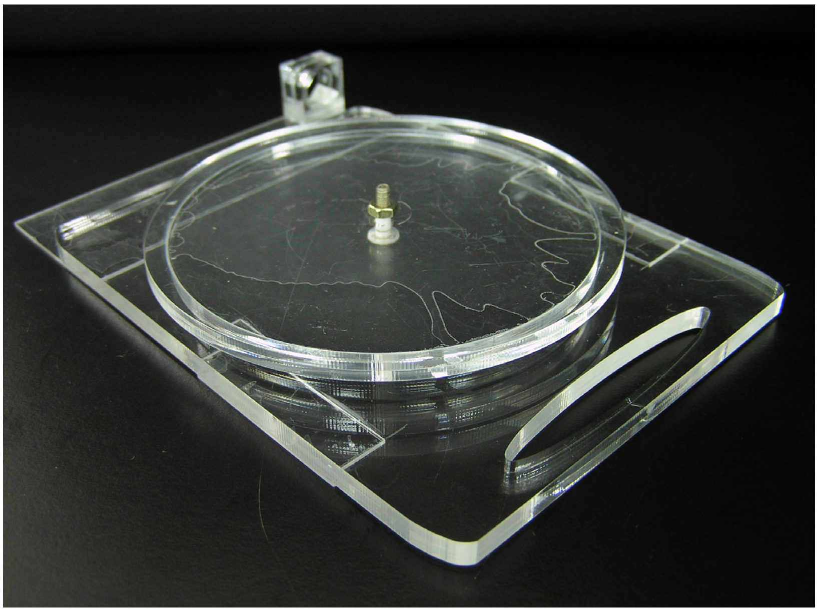


圖 32 保護連接到氣泡指示計細管的裝置

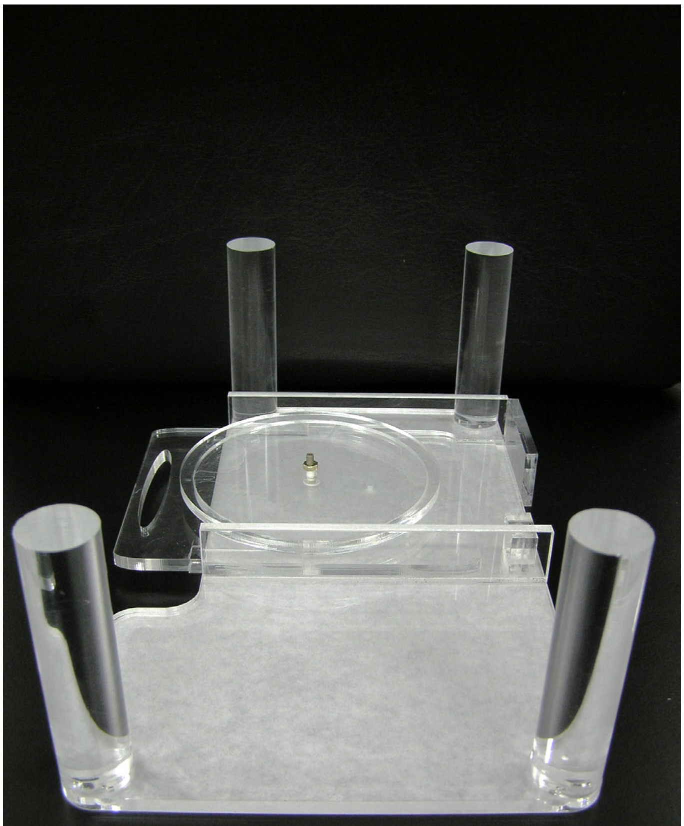


圖33 氣流式薄膜測厚儀的架子

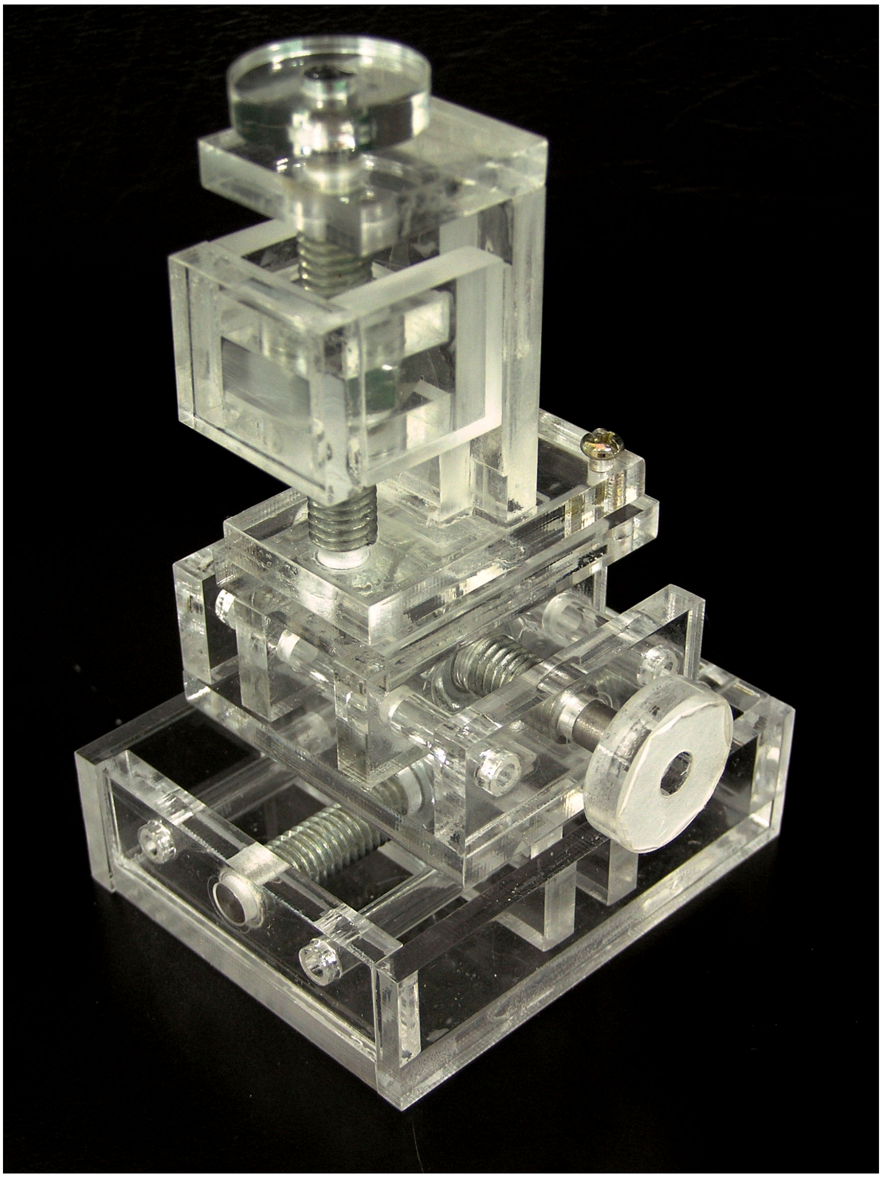


圖34 XYZ平移台，移動待測物的位置

圖 35 放大鏡的架子

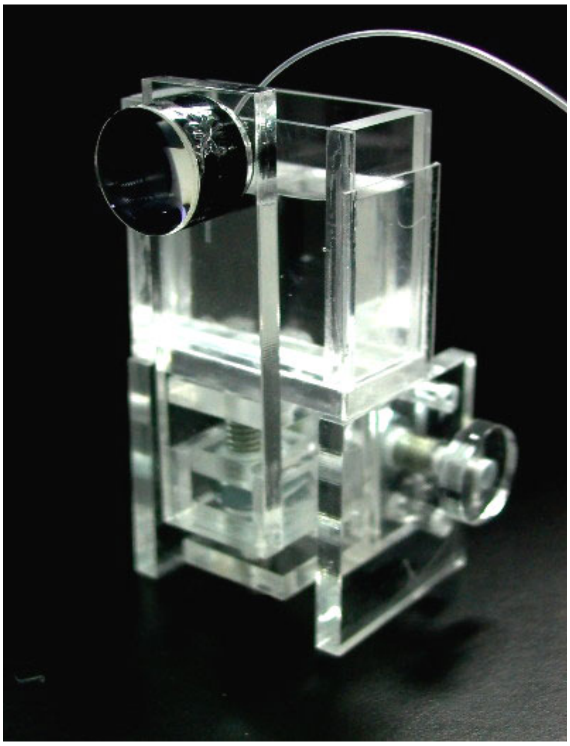


圖36 氣泡指示計的完整照片

圖37 氣泡指示計的完整照片

Innovative Thickness Measurement of Biological Tissue by Using Maximum Bubble Pressure Method

C. H. Lee & Y. C. Chen

Introduction

Our project is about an innovative thickness measurement system that we devised to solve the problem of biological tissue thickness metrology.

Skin grafting is a type of graft surgery that replaces a patient's damaged or lost skin with healthy ones from either the patient himself or a donor. It is mostly applied to patients with extensive wounds, burns or those in need of cosmetic reconstruction. The thickness of skin graft can have great influences on the cosmetic success of graft surgery, depending on the condition of the wound. Currently, thickness measurement of skin graft is done by direct microscopy, but we found this method to be inadequate as it can cause serious damage to the skin sample. Applying photonic sensors to such measurement have been considered as well, since it has the great advantage of non-contact measurement with high accuracy. But due to skin graft's irregularity in color and its translucent feature, this method is not suitable.

What we did was devise a new practicable measurement system that possessed the same key advantages of the photonic sensor, yet able to obviate the measurement difficulties that photonic sensors faced. We integrated the concept of maximum bubble pressure method and pneumatic gauging, and together with our mechanical designs, we are able to measure thickness without causing distortion and destruction of the sample, plus it can be reused after the measurement.

Theory

As we all know, photonic sensors (Fig. 1) work by emitting photons onto the sample through fiber optics, and then determine how close the target is by the amount of photons reflected back, which is detected by the photo-sensor. As you can see here, when the distance between the photonic sensor and the target varies, the reception rate changes and creates a curve effect (Fig. 2), giving us three measurement regions: the forward region, optical peak, and the backward region. You can then choose to operate the photonic sensor within a certain region, pertaining to your measurement criteria, plus fine-tune its dynamic range and sensitivity by adopting different fiber formations as shown here.

Our system (Fig. 3), which we call it the flownic sensor, functions in a similar way. We changed the measurement media from light to air, and utilize the similar curve characteristics derived from the maximum bubble pressure method, which is now used for pressure indication, an entirely new concept and application for an effect originally used in tensiometers. We use the bubble to indicate the pressure climb within our flownic sensor's catheter system when the sensor approaches the target. As you can see, the pressure change creates an interesting twin-curve effect; we call it the flownic sensor curve (Fig. 4). Like the one from the photonic sensor, the flownic sensor curve also provides us with three measurement regions: the static bubble region, maximum bubble pressure point, and the dynamic bubble region, but because the latter is impractical for use, we only adopt the prior two regions. This project currently focuses on utilizing the maximum bubble pressure point for safe thickness measurement. In other word, we operate our flownic sensor in the h mode (Fig. 5). In addition, the flownic sensor curve can also be fine-tuned, but unlike the photonic sensor, we accomplish this by altering the system design.

Device Design

We have a schematic drawing of "Model-3" (Fig. 6-1), which is divided into four subsystems: A, the air flow supply system; B, the pressure indication system; C, the catheter system, and D, the measurement system, which is made up of three positioning mechanisms. On the top right-hand corner is a decomposed diagram of our triple axes adjustment mechanism (Fig. 6-2), which is positioned on top of our sample centering mechanism, and together with the pressure sensors, they integrate into our pressure balance centering mechanism.

In addition, the resolution of the micrometer will be enhanced into micron level by the computer vision with the pixel- evaluated scales.

Following is the operation of our flownic sensor (Fig. 6-3). The figure is a twin-needle design, whose distance is controlled by the micrometer. The sample is positioned between the needles, carefully done by our pressure balance centering mechanism, so that it will remain in the center during the operation.

On top right-hand corner is the magnification of the bubble indicator capillary opening, where we obverse the formation of the bubble. Then we can calculate the thickness of the sample by subtracting twice the bubble indicated distance, D, from the distance between the needles, X, which is derived from the micrometer, then we get the thickness of the sample, a.

System Characterization

The following characterizations of our flownic sensor are based upon experimental datum we obtained from the performances of Model-3. Here we have a simple depiction of our flownic sensor. As you can see (Fig. 7 and fig. 8), each circle represents a subsystem, and is linked together by our catheter system. By combining the relations between different physical effects of every subsystem, we can then establish the theory circle and the characteristics of our flownic sensor.

As you already know, we use the maximum bubble to indicate the pressure change within our catheter system, as the needle approaches the sample, the pressure within the catheter system rises. This relation is shown here (Fig. 9), and indicated in the theory circle by this arrow. This flownic sensor curve was done using an air flow rate of 1.1 cubic centimeters per second, and as you can see, the bubble reaches hemispherical shape at the distance of 34 microns. Now because the static hemispherical bubble will be replaced by a stream of bubbles once the distance is shorter than 34 microns, which will extend the curve into the dynamic bubble region, we only adopt the flownic sensor curve in the static bubble region, which includes the maximum bubble pressure point (Fig. 10). By fitting the adopted curve with a corresponding function and calculate the gradient of the maximum bubble pressure point, we can obtain the sensitivity of the bubble. In this case, at the air flow rate of 1.1 cubic centimeters per second, the bubble sensitivity derived was six times 10 to the minus second power microns per pascal plus minus 0.16%, and the resulting distance indication deviation was plus minus 0.034 microns. With such amazing datum, we believe that using the maximum bubble to indicate distance is feasible.

Of course, different flownic sensor curve derive different sensitivity. As you can see in the theory circle by this arrow pointing to the right, the smaller the air flow rate, the greater the gradient of the maximum bubble pressure point (Fig11), leading to higher sensitivity and minor distance indication deviation, for instance, the bubble sensitivity of the flownic sensor curve at the air flow rate of 0.5 c.c. /sec. is ten to the minus second power micron per pascal, with a distance indication deviation too small to cause any significant affect. We also discovered something interesting from this diagram, as you can see when we fit the maximum bubble pressure points with a corresponding function, it turns out to be an exponential decay curve, which we call it the maximum bubble pressure curve. Why does it resemble a decaying pressure curve instead of constant pressure points? We believe this is because of the pressure drop caused by friction loss in the capillaries, the stronger the air flow, the greater the friction loss.

You can understand more of the maximum bubble pressure point from the diagram (Fig. 12), indicated in the theory circle by this arrow pointing to the left. As you can see, the smaller the air flow rate, the shorter the distance indicated by the maximum bubble pressure point. In addition, the reynold number calculated within our system was 700 to the maximum, indicating stable laminar flow; one of the important factors that promise our flownic sensor's proper functioning. So, by utilizing the two curves, the flownic sensor curve and the maximum bubble pressure curve, our flownic sensor can accurately measure thickness.

Prototype Evolution

In this project, we devised several prototypes (Fig. 13-1, fig.13-2 and fig.13-3); each played an important role in the evolution of our flownic sensor. Among the prototype setups, the catheter system was the most challenging part of the sensor configurations. Not only was it an integral connection unit between subsystems, but also the key to strengthening the bonds between factors and the establishment of our flownic sensor's operation theory. As of today, we've developed ten generations of catheter systems; each made progressive improvements towards the stability and the versatility of our flownic sensor.

Results

In order to verify our design's practicability, we preformed a series of thickness validation tests, covering solid (Fig. 14) and soft samples (Fig.15). We began with measuring the thickness of solid subjects: cover slides, which we pre-measured its thickness with a micrometer, and then had them run over with a stylus Instrument and being given precise thickness. The results here shows the high correlation between the thicknesses derived from Flownic three and the actual thicknesses of the cover slides.

So, solid subjects pass, time to measure soft subjects. For this experiment, we used plastic wrap, which we obtained its thickness range from its manufacturer in advance.

In addition to our measurement results, we also added those derived from a micrometer. As you can see, the thickness derived from Flownic Three almost fit in the thickness range every time, while the results from micrometer, are constantly lower. This not only implies that our flownic sensor design is feasible, but also the importance of such measurement systems due to the fact that metrology like our flownic sensor, does not distort nor destruct the sample, yet able to accurately measure its thickness.

After we confirmed the fact that we can measure the thickness of soft and transparent film, we then moved on and performed a comparison test with microscopy (Fig.16).

As you can see, the thickness derived from Flownic Three varies with the thicknesses set by the dermatome and those measured by microscopy. So what do the results tell us? We think that there is a serious problem with the dermatome. The thickness of the skin samples sliced did not match the thickness settings from the dermatome. If this speculation is true, surgeons won't know how thick the graft they'll get!! We believe that our flownic sensor has the potential of calibrating the dermatome settings so that they will tell the truth.

Future Work

Finally, I would like to invite you to revisit our project process and what we plan to pursue in the future. We can proudly state that the roadmap of our project has been successfully developed. More specifically, the vision of our project is now clear. We devised a new solution, one that no one has thought of before. Our design leads us to integrate many wonderful design developed in other fields. As you can see that, we attempted many designs. With our design evolves along the way, our current design not only serves our design goal but also leaves many routes for further development.

We learned that engineering is an endless evolution. The many new possibilities revealed in our design roadmap testify this thought. To further improve our measurement resolution in the h mode, we are to replace the micrometer. To use our system in the delta h mode, we will operate our flownic sensor in the static bubble region and observes the bubble size change.

Conclusion

We developed the flownic sensor applicable to thin-film thickness metrology without harming the sample. It has the advantage of high accuracy, high sensitivity and high versatility to suit the different measurement criteria.

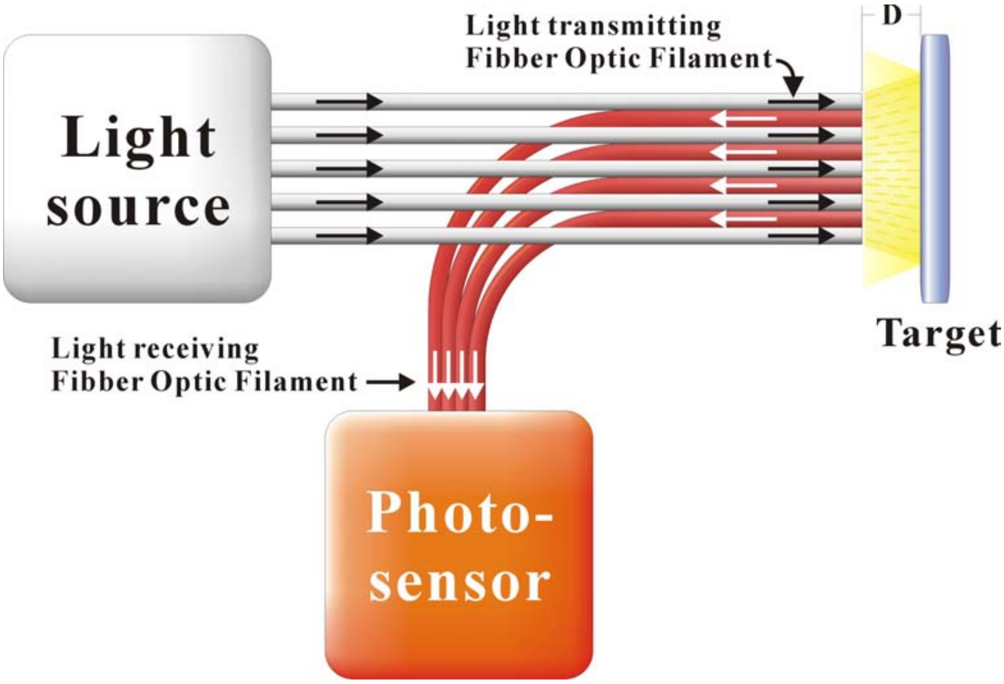


Fig. 1 Key components of the photonic sensor

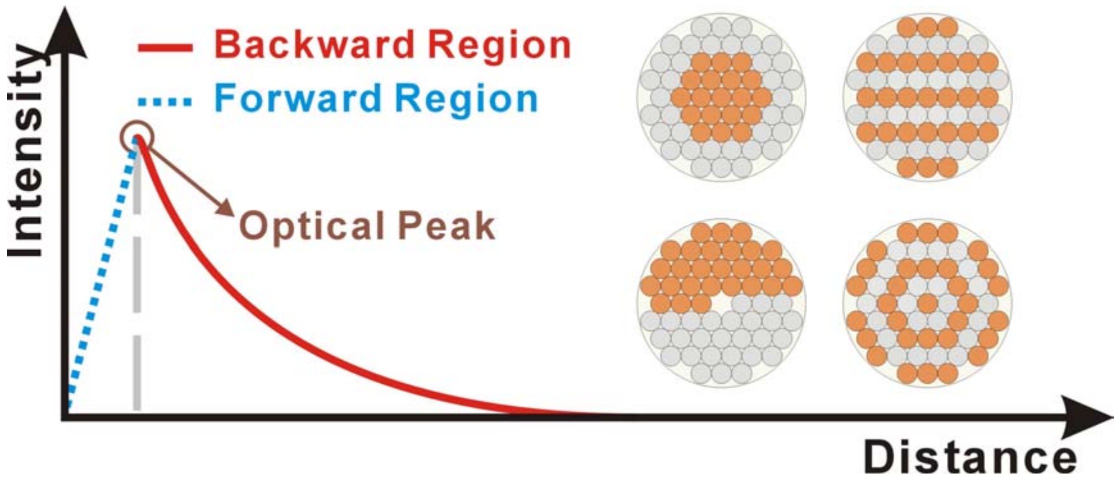


Fig. 2 Photonic sensor curve

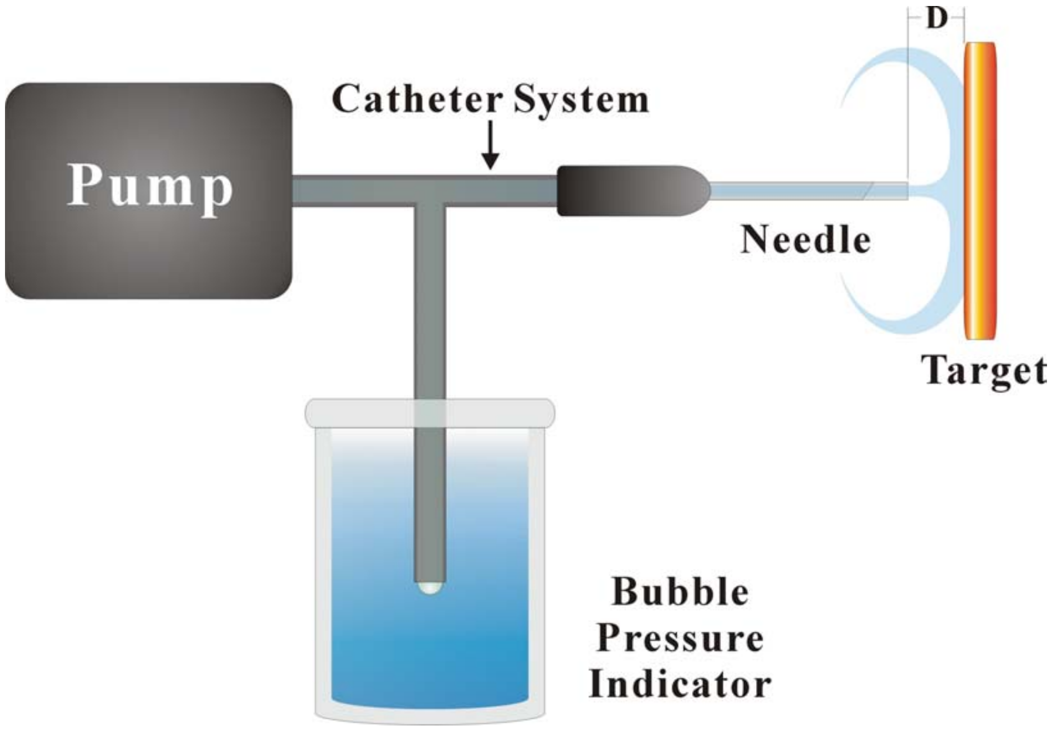


Fig. 3 Key components of the flownic sensor

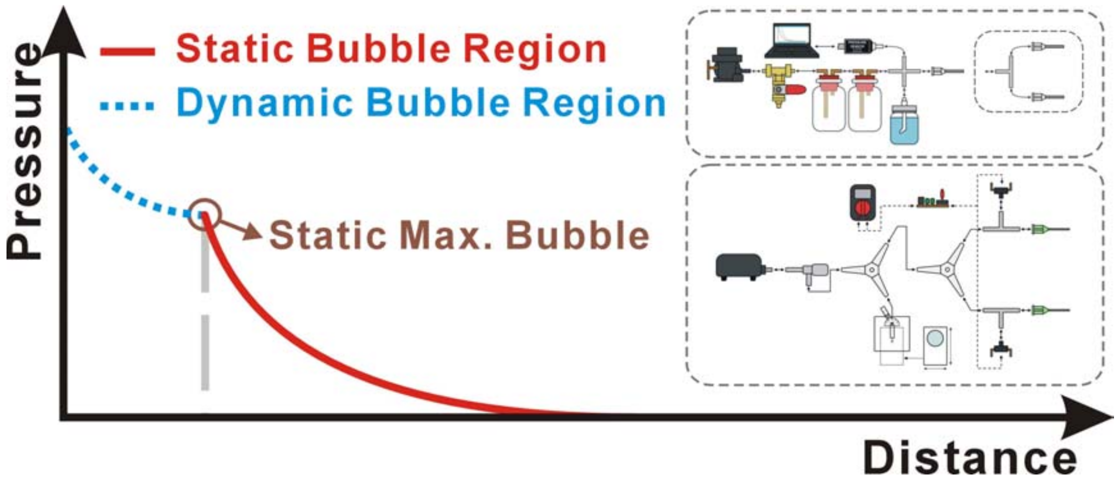


Fig. 4 Flownic sensor curve

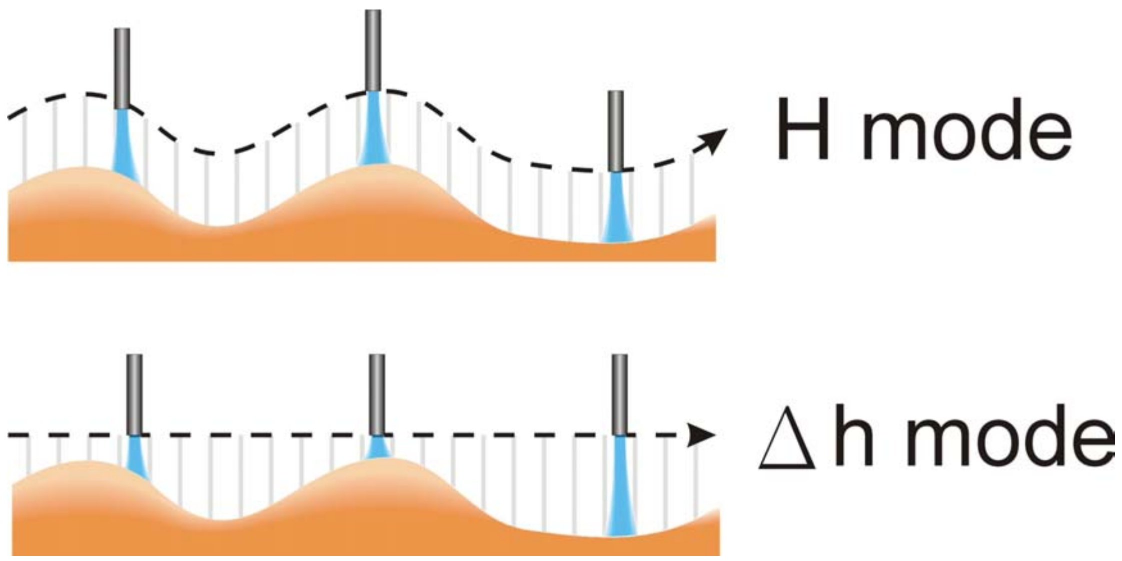


Fig. 5 H mode and ΔH mode

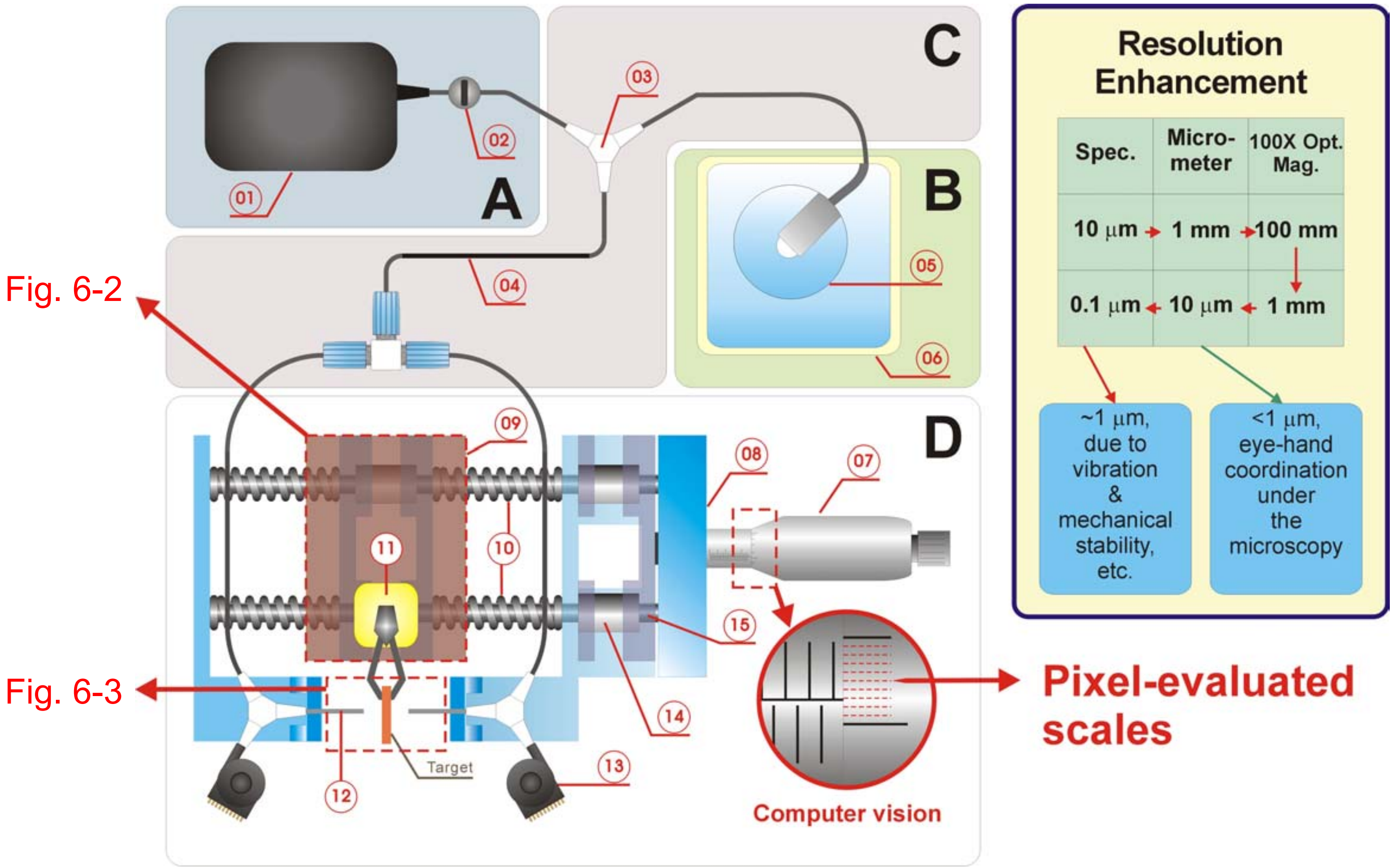


Fig. 6-1 Schematic drawing of Model-3

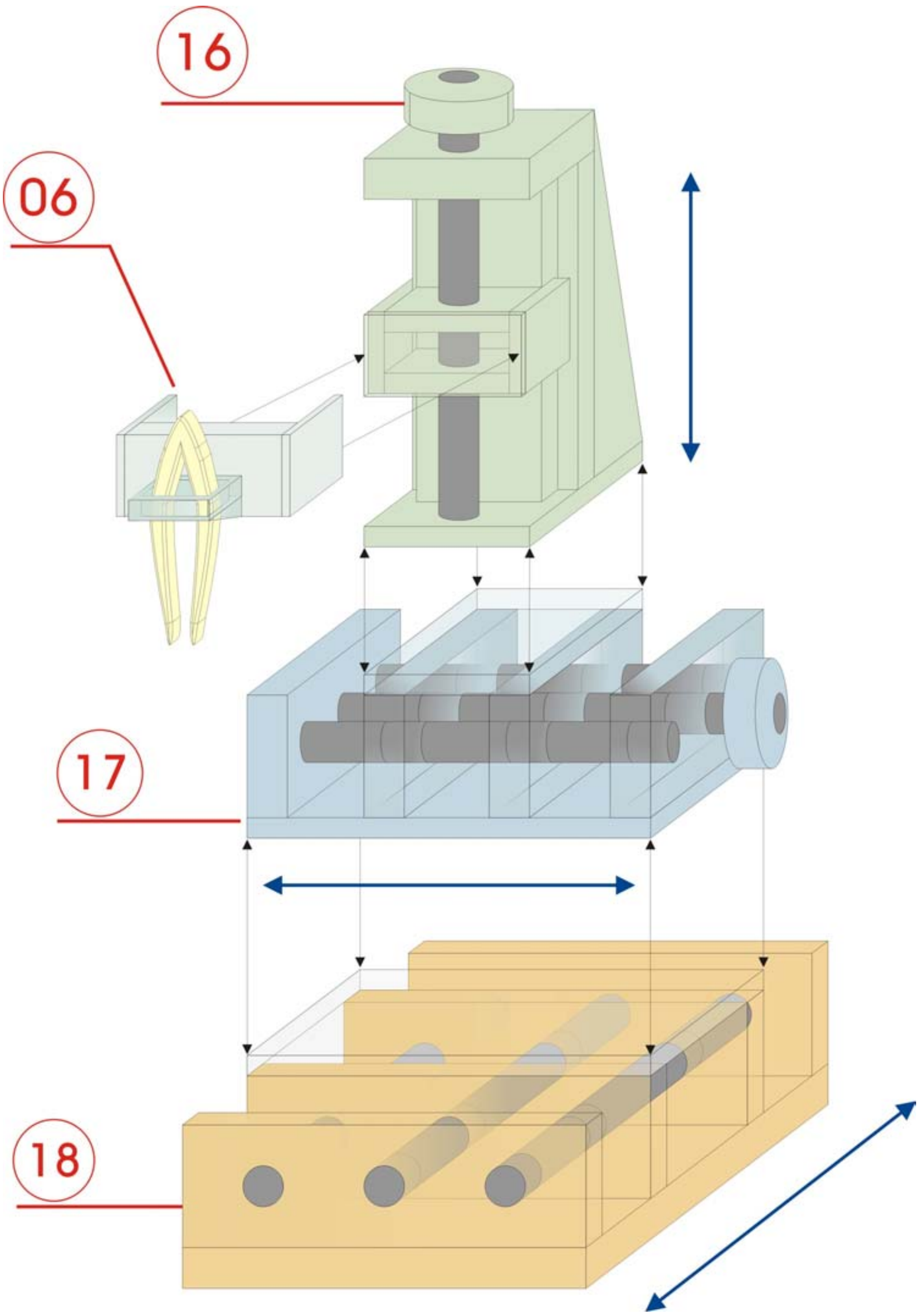


Fig. 6-2 Blow up diagram of the 3D adjustment

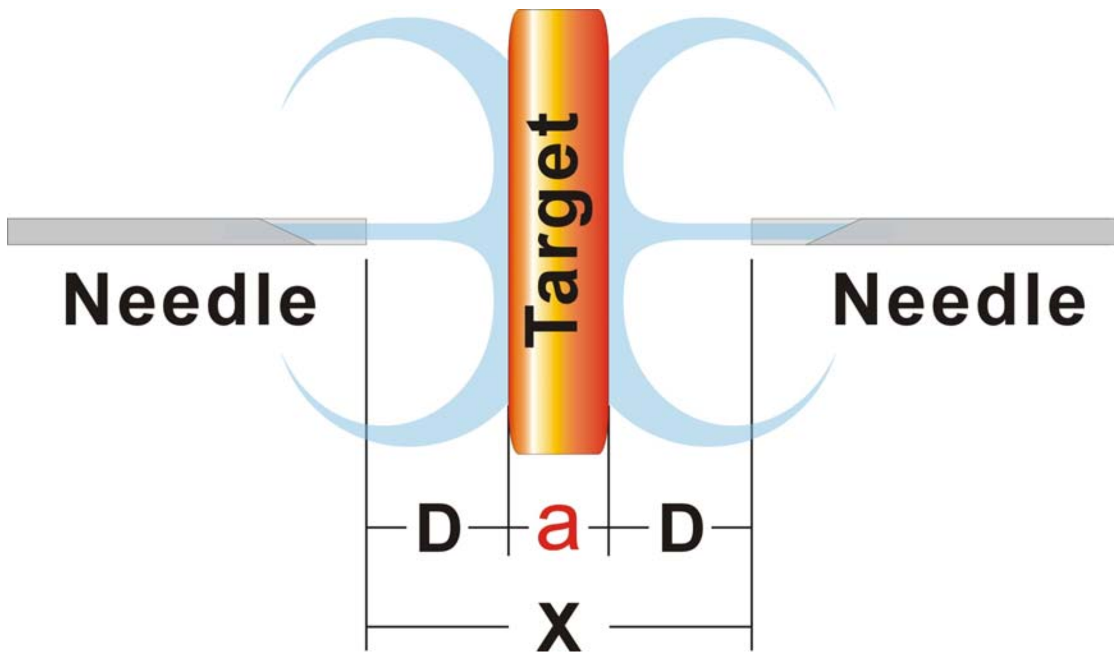


Fig. 6-3 Operation of our Model-3

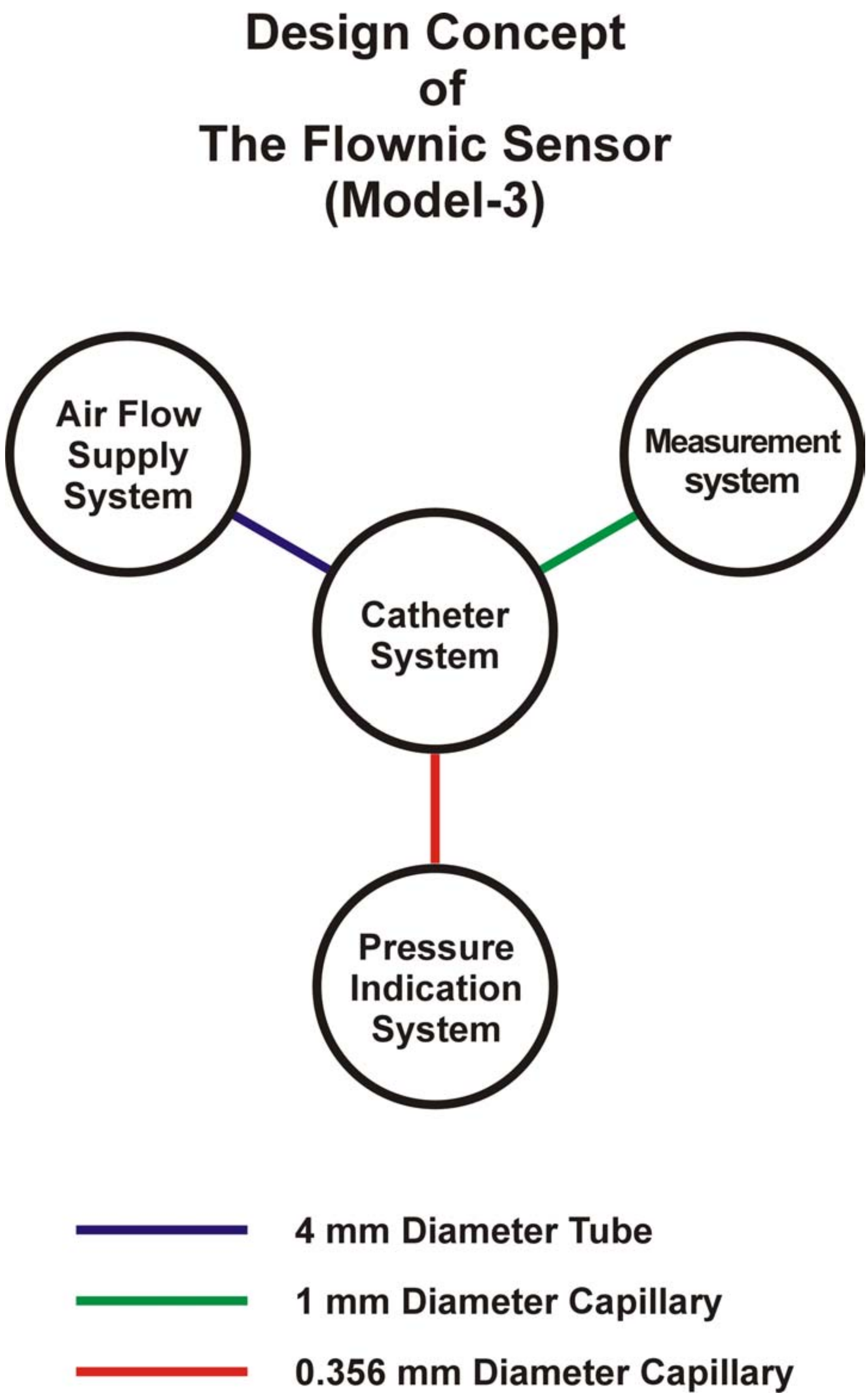


Fig. 7 Design concept of the flownic sensor (Model-3)

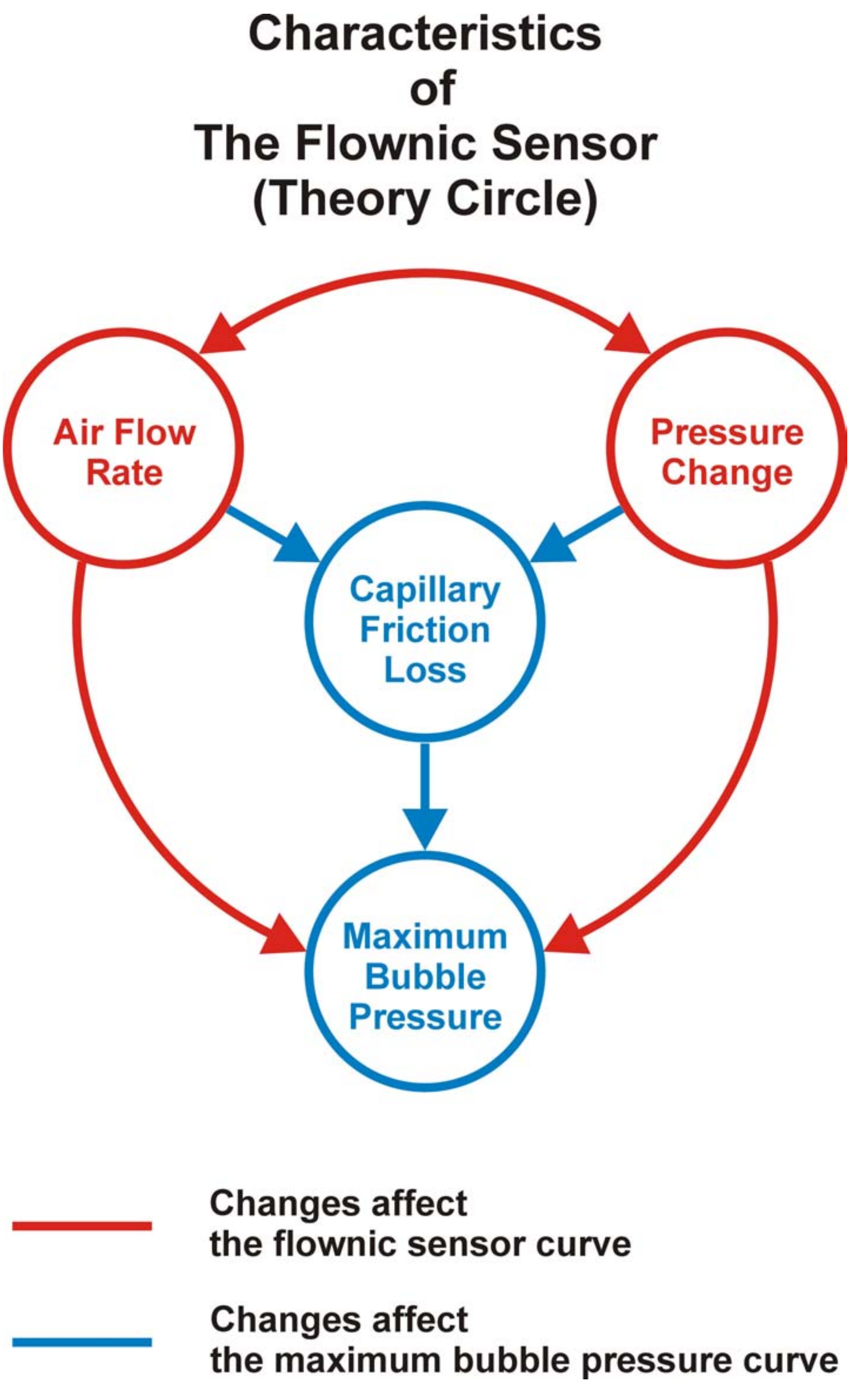


Fig. 8 Characteristics of the flownic sensor (Theory Circle)

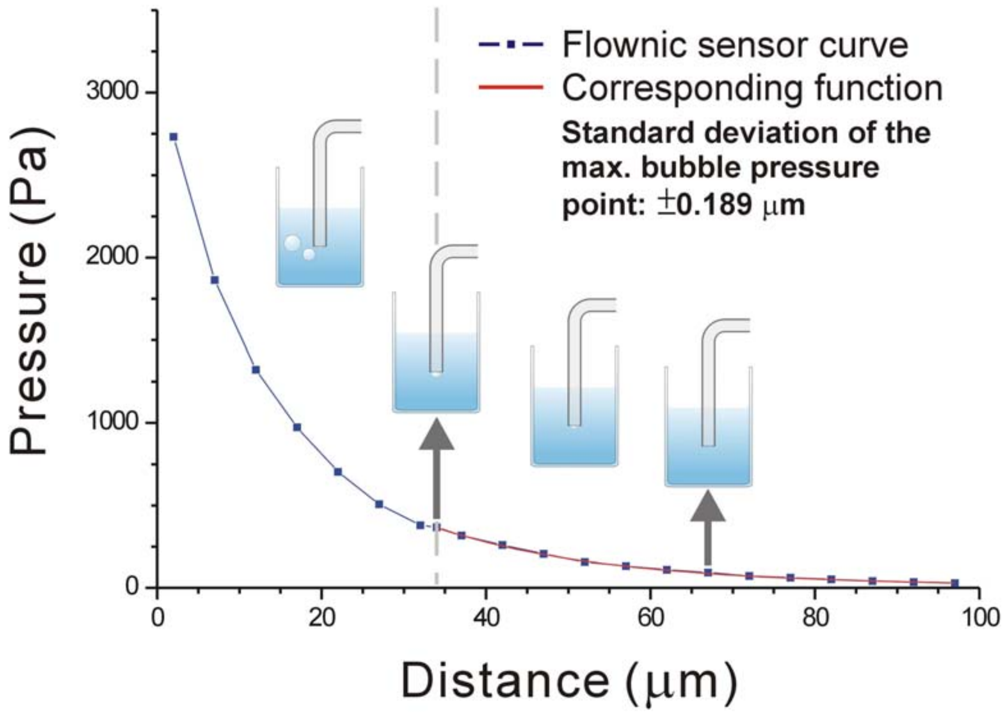


Fig. 9 Relation between maximum bubble pressure and distance of needle tip to sample (at air flow rate 1.1 c.c./sec.)

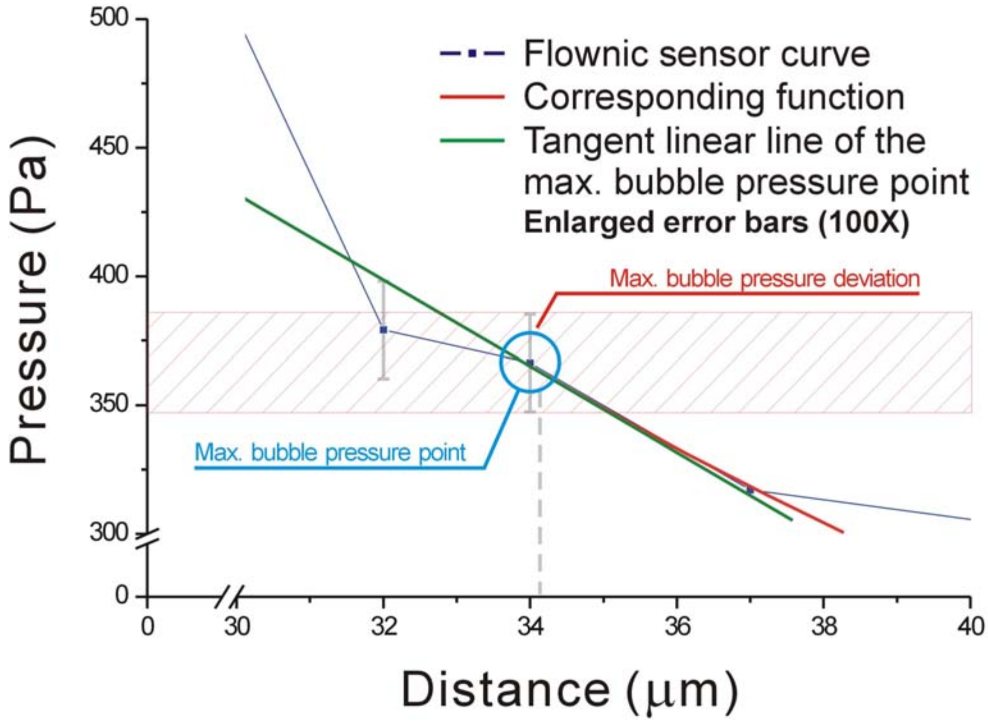


Fig. 10 Enlarged view of the maximum bubble pressure point

(at air flow rate 1.1 c.c./sec.)

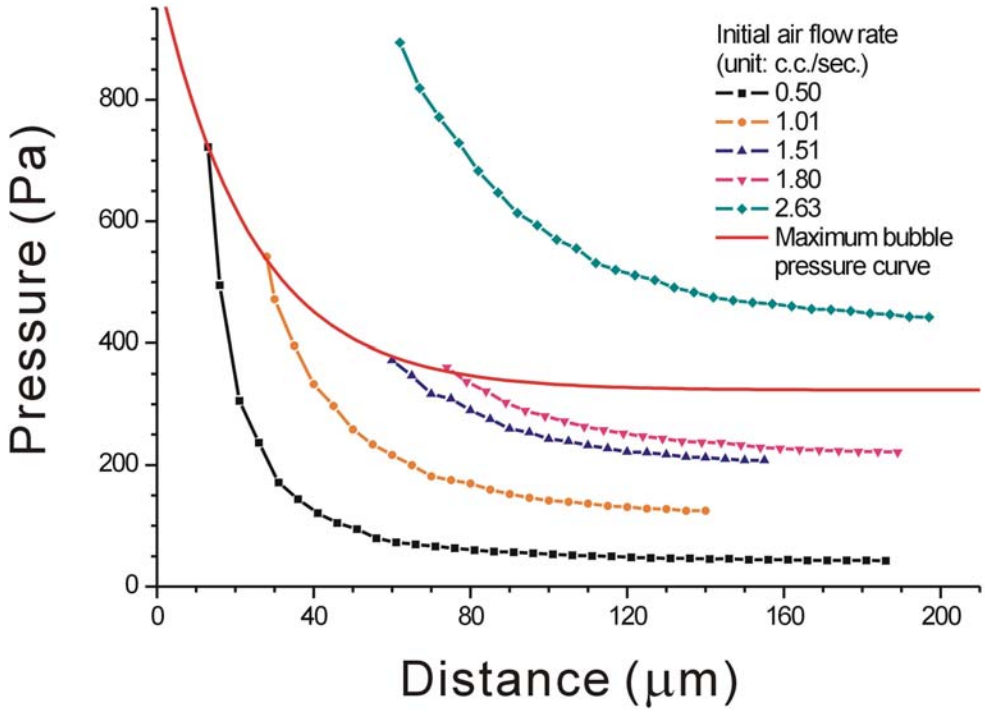


Fig. 11 Relation between air flow rate

and maximum bubble pressure

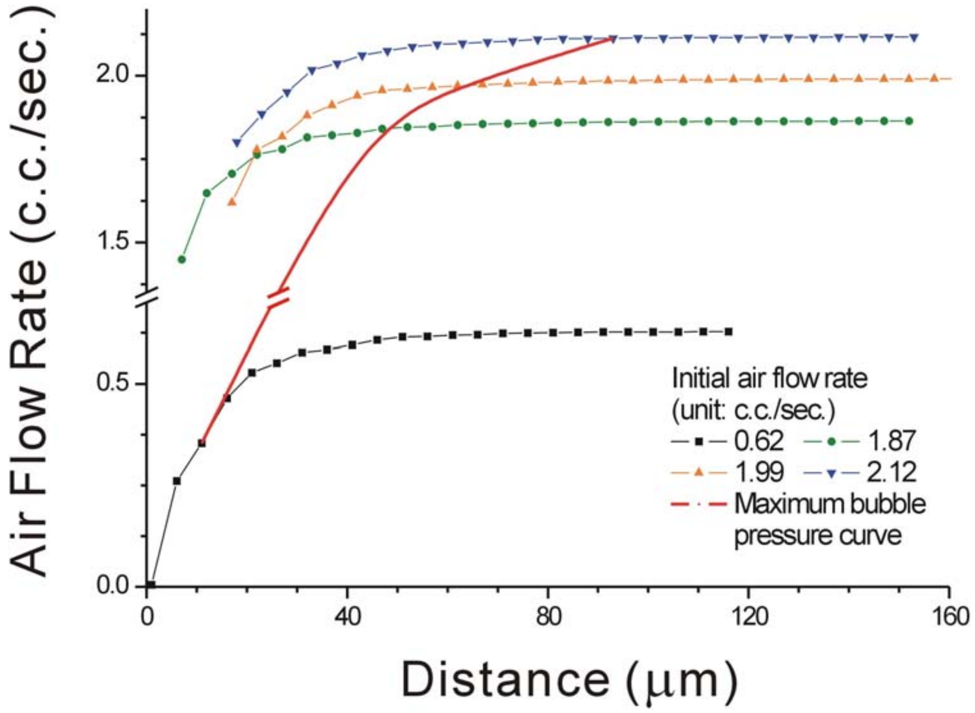


Fig. 12 Relation between air flow rate and distance of needle tip to sample

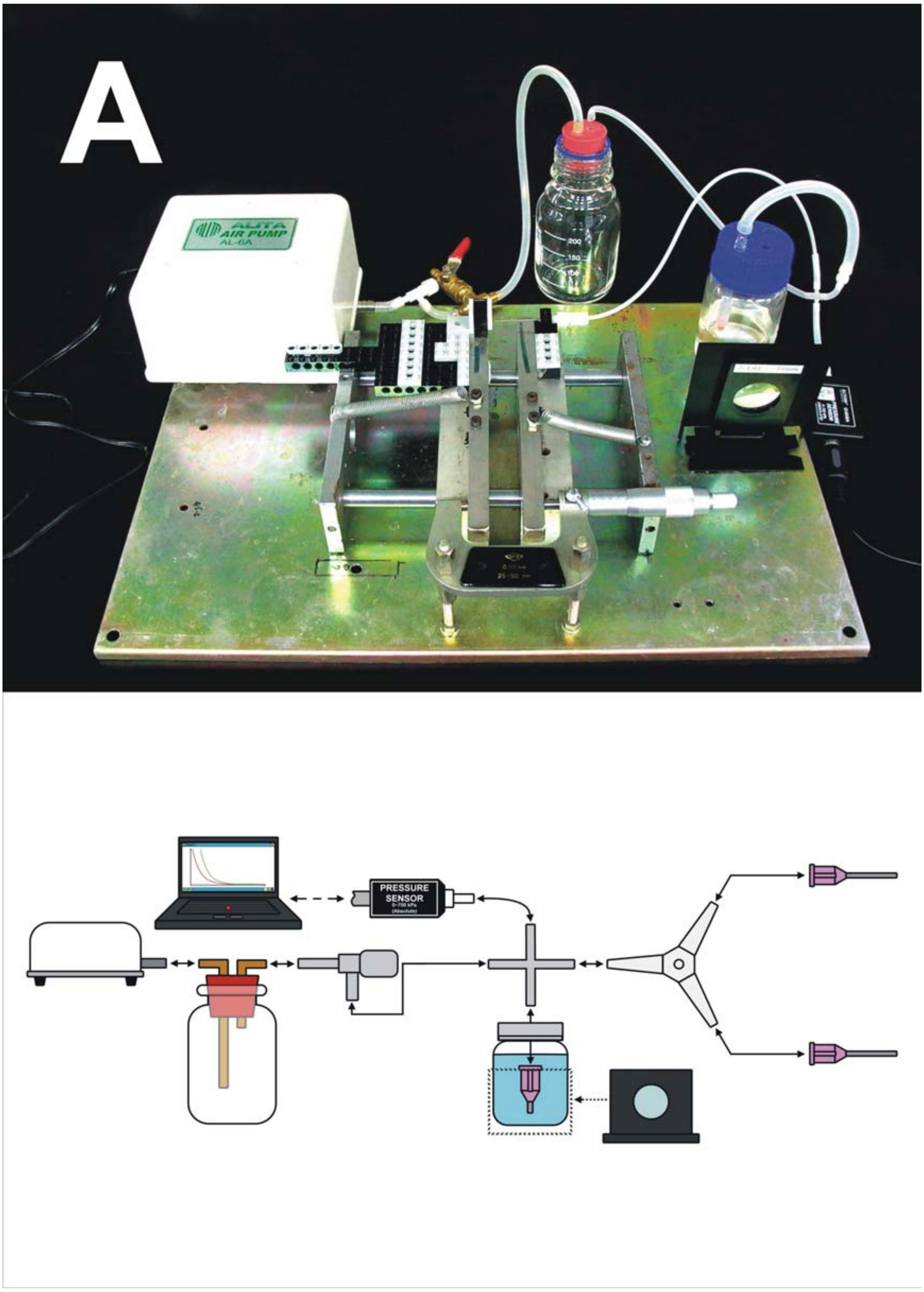


Fig. 13-1 Model-1

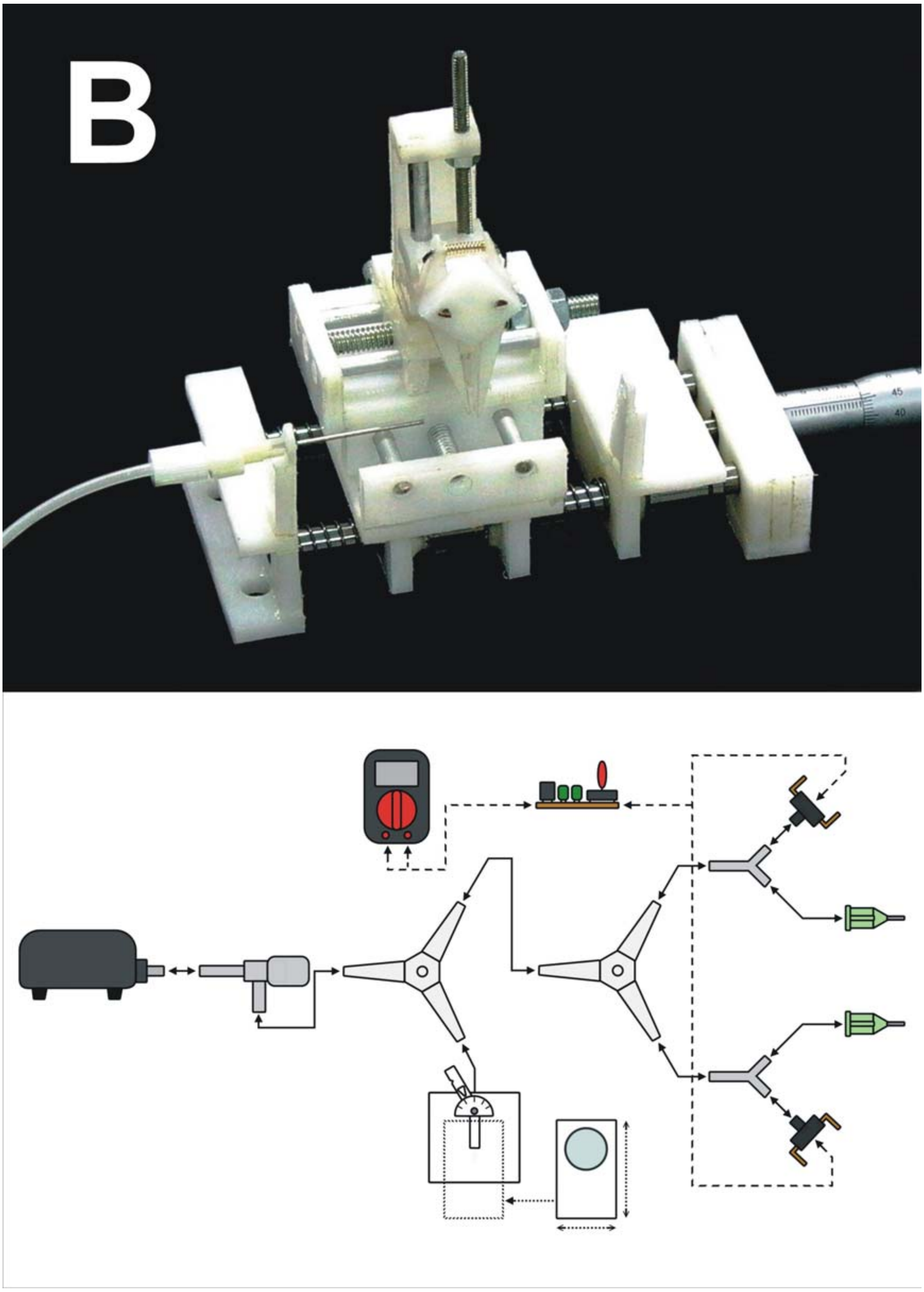


Fig. 13-2 Model-2

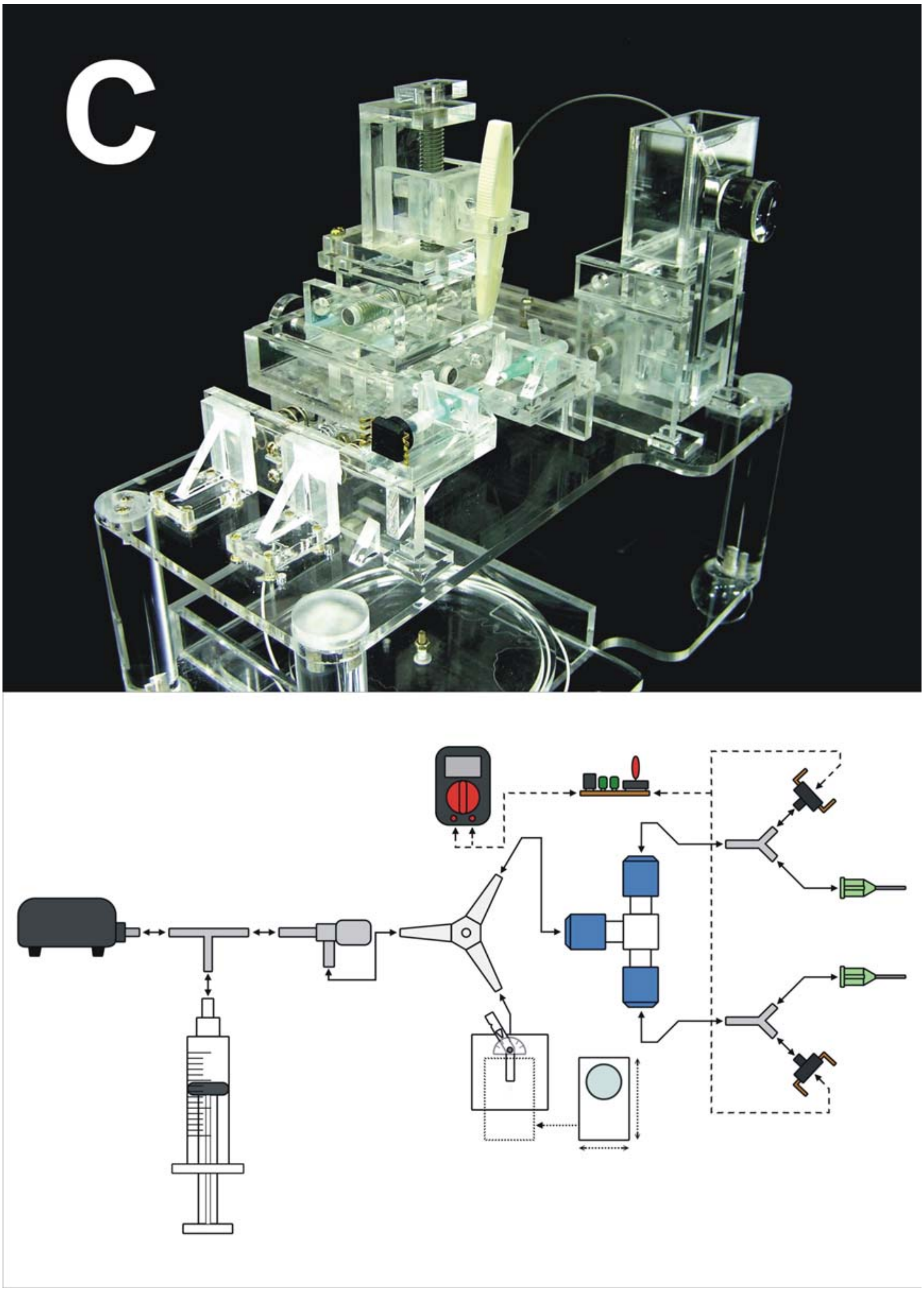


Fig. 13-3 Model-3

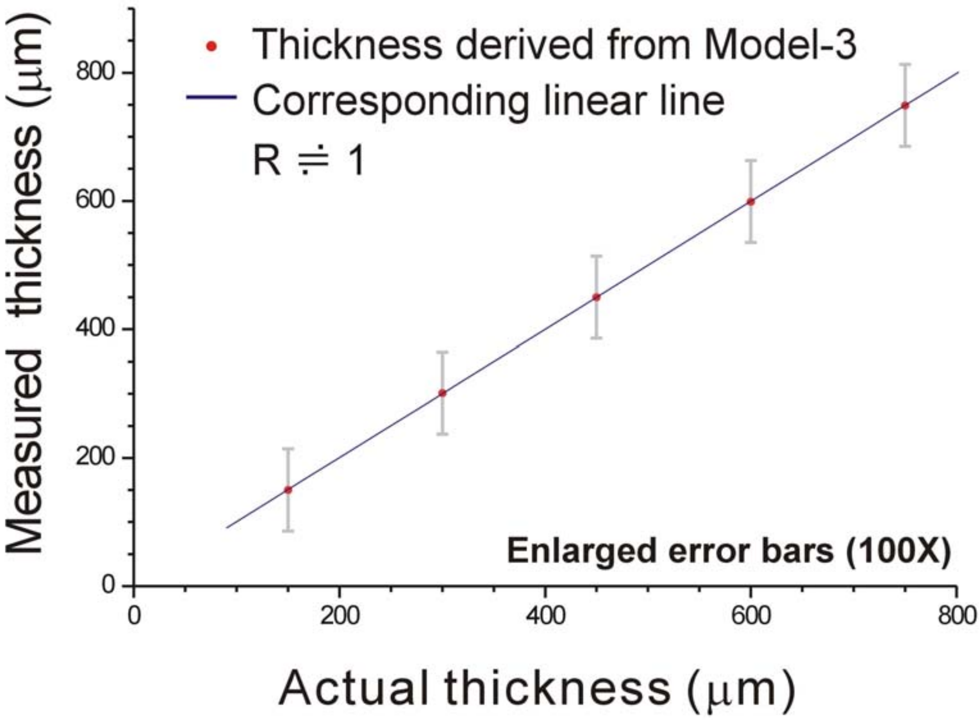


Fig. 14 Measurement of cover slides (solid sample) thickness

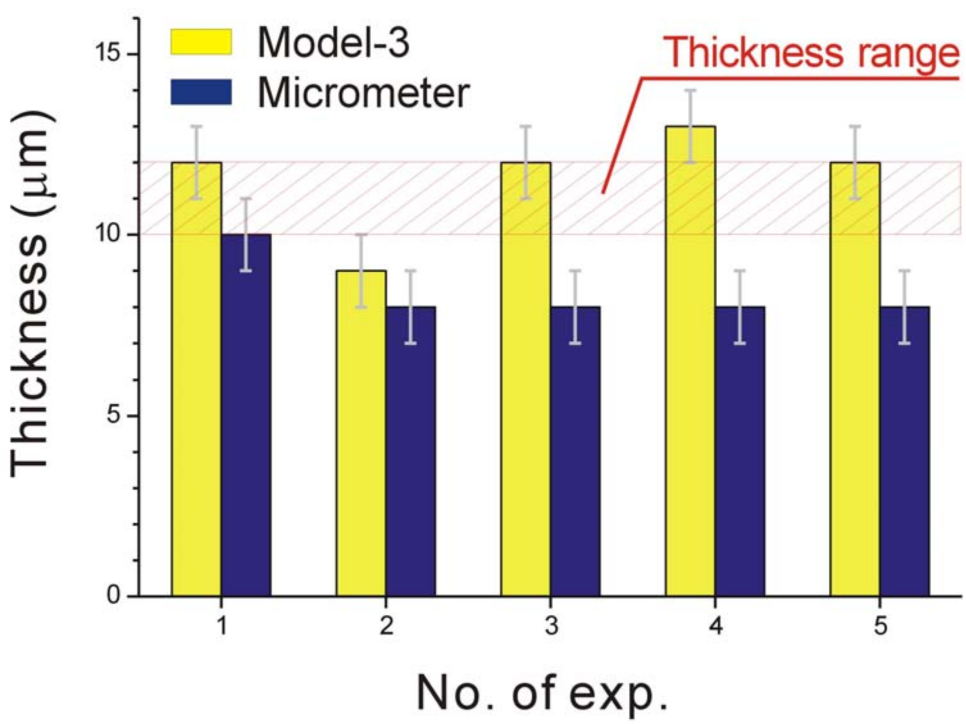


Fig. 15 Measurement of plastic wrap (Soft sample) thickness

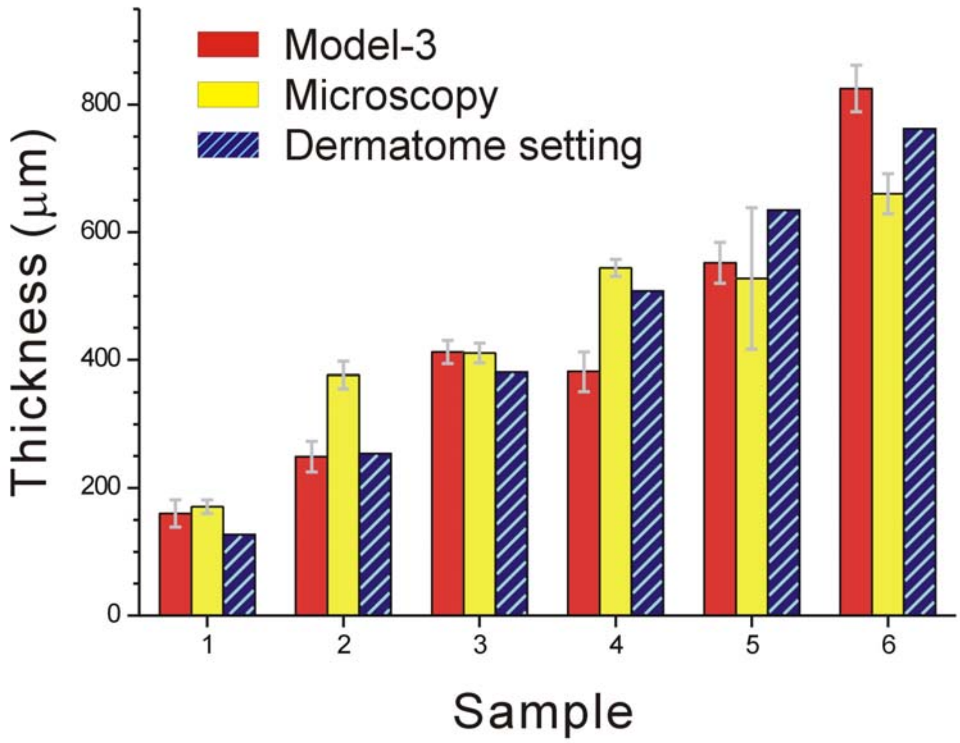


Fig. 16 Comparison of thickness measured by microscopy, dermatome setting and Model-3

評語

利用氣體在管路內的流動特性會受噴出口附近環境阻礙影響而有背壓現象出現的原理做為量測基準點的依據，配合精密微尺的量測能力及精巧的實驗裝置，得以量測薄膜的厚度。本作品的應用原理具創新性而研究方法亦具科學性，是一優秀作品。