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作品名稱

水滴在高溫鋸齒上爬坡之物理機制探討

得獎獎項

大會獎：二等獎

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關鍵字：水滴、鋸齒、爬坡

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大家好，我是張芳瑤。

國中三年充滿了變化，不變的就是每四十五分鐘固定敲一次的鐘聲和讀書、考試……。但是，除此之外我還能大聲的說：我過的很充實。當別人課餘時間在打電動、逛街，我就是拿著滴管作實驗，樂此不疲。

在實驗過程中，失敗、挫折是在所難免的，還好有一群關心我的師長、朋友，他們告訴我：Never give up!

這個年紀的小孩常被問到：你未來想當什麼？

有人說他想當下一個牛頓，下一個愛因斯坦，下一個哥倫布，但我只告訴自己：做一個熱衷自己所愛的人。

摘要

本研究主要探討水滴在高溫鋸齒面上之爬坡現象。實驗中發現在高達四百度的鋸齒面上能形成懸浮水滴，且水滴可持續一段時間而不會立即蒸發，在水平之鋸齒面沿特定方向移動，特別的是，水滴甚至沿著傾斜之鋸齒面向上運動。首先，水滴因受熱在周圍形成一層蒸氣層，阻隔熱的傳遞，使其不會立即蒸發。實驗中改變鋸齒齒廓之兩斜邊的比例，可以驅動水滴往長斜邊所面對的方向運動。進一步實驗顯示，水滴內部的流動趨勢分別為：水滴前端呈順時針方向流動，而水滴後端則呈逆時針方向流動。此外，爬坡中的水滴，其後半部具有較高之蒸發速率，經由設計一個類比的實驗，我們發現，在高溫金屬平面上，透過其平面上的一個凹槽，可以控制水滴前後部位蒸發速率的差異性，也造成水滴向上爬坡的結果。由實驗結果證明，蒸氣壓力與氣體運動對水滴造成的摩擦力為驅動水滴爬坡的力量來源。

Abstract

Droplets climbing up an asymmetrical saw tooth surface heated up to 400 degrees Celsius is investigated. The moving direction of water droplets is always against the long segment of the saw tooth. An analogous experiment shows that a gradient of evaporation rate along the droplet does affect motion of droplets and can be regarded as a driving mechanism.

As the droplet touches the hot surface, a thin vapor layer is formed around it, slowing down heat transfer. This provides sufficient time for the droplet. By experiments done, two models are proposed to explain the climbing phenomenon. One is force due to vapor pressure exerted by vapors under the droplet. The other is friction due to vapors' flowing under the droplet. Basically, the vapors are driven by a gradient of vapor pressure resulted from a gradient of evaporation rate along the droplet. By observing the internal flowing of water droplets, the second model is confirmed. In particular, when the two models go with the asymmetrical saw tooth surface, droplets are able to climb against gravity.

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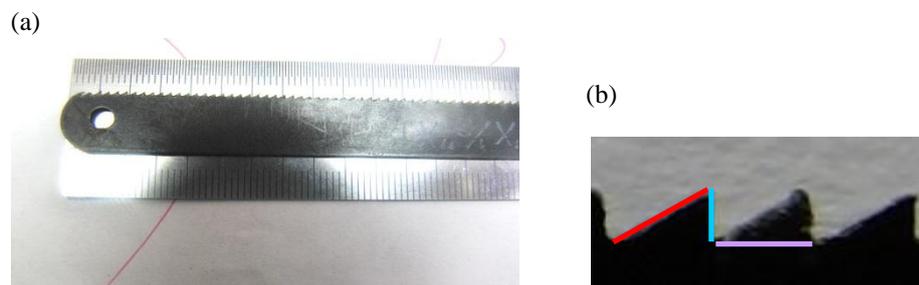
壹、研究動機

起初，我們發現水滴在高溫並排的鋸齒面上會沿著固定方向移動，於是把它擺放一個傾斜角度，卻發現水滴在上方可以向上運動。

得到如此有趣的結果，我們進一步思考：在什麼條件下可驅使水滴爬坡？、水滴爬坡速率受到什麼變因影響？又有什麼力量驅動水滴爬坡呢？

貳、實驗架設

- 一、將約 15 條相同鋸片(如圖一)並排，形成水滴可滾動的表面，如圖二。
- 二、再用兩個角鐵將 15 條鋸片固定住，如圖三。
- 三、將鋸齒組放至瓦斯爐上加熱。
- 四、以熱電偶式溫度計測量溫度，達到特定溫度，滴下水滴並進行拍攝。



圖一：(a)鋸齒片，
(b)鋸齒片放大圖 \longleftrightarrow 鋸齒長邊：1.27mm、 \longleftrightarrow 鋸齒間距：1.09mm、
 \longleftrightarrow 鋸齒短邊：0.64mm。



圖二：實驗全圖



圖三：實驗架設側視圖

參、研究結果與討論

本研究中，我們作了以下實驗，最後，我們分別討論此四項實驗的重要結果。

- 一、鋸齒表面溫度對水滴運動的影響；
- 二、水滴爬坡之受力情形分析；
- 三、鋸齒齒廓對水滴運動方向的影響；
- 四、水滴爬坡之物理機制探討。(其中包括：1.水滴內部流動、2.水滴各部位蒸發速率差異對其運動的影響。)

實驗一：鋸齒表面溫度對水滴運動的影響

溫度	100~300°C	300°C	400°C 以上
現象	水滴快速蒸發	水珠炸開	水滴爬坡

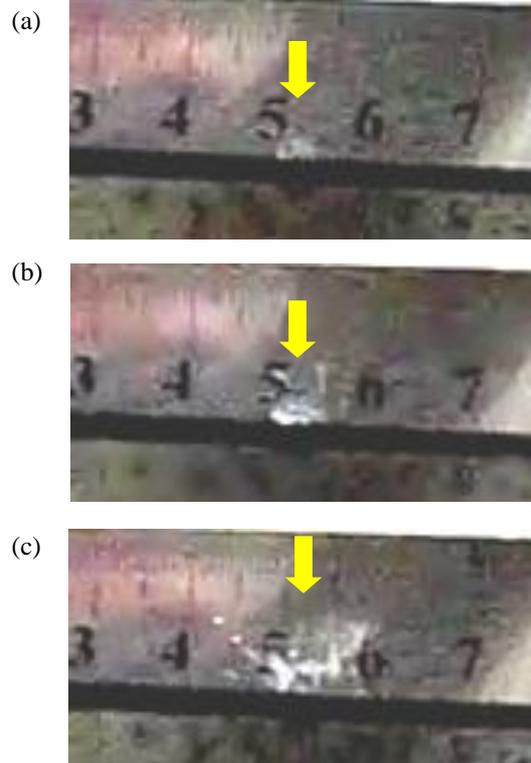
1、目標：了解水滴在鋸齒上能形成珠狀，且不會馬上蒸發的溫度。

2、結果：此實驗之重要結果如下表格，圖片見圖四、圖五。

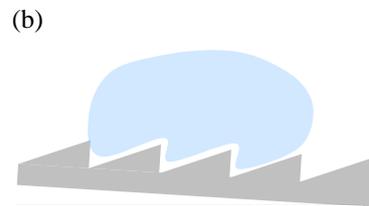
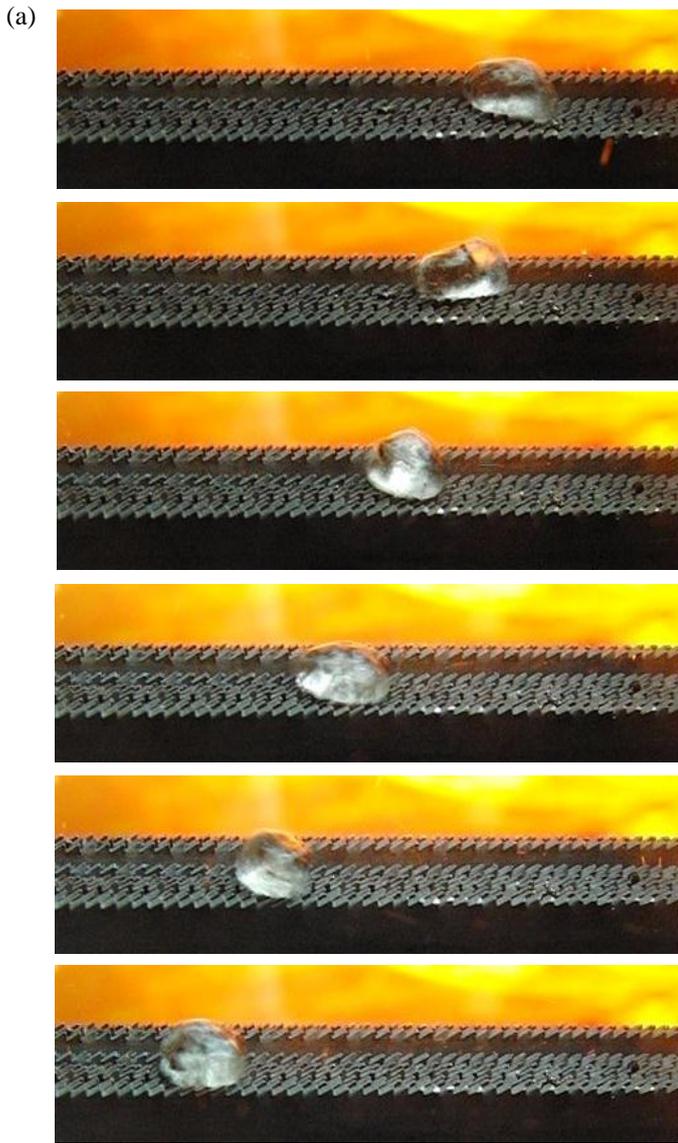
(1)、當鋸齒狀金屬溫度在 100~300°C 左右會造成水滴快速的蒸發。

(2)、當鋸齒狀金屬溫度大約為 300°C，會造成液滴產生炸開的現象，如圖四：

(3)、金屬表面上達到 400 度時，水滴結成珠狀，不會馬上蒸發，且會向上爬坡，

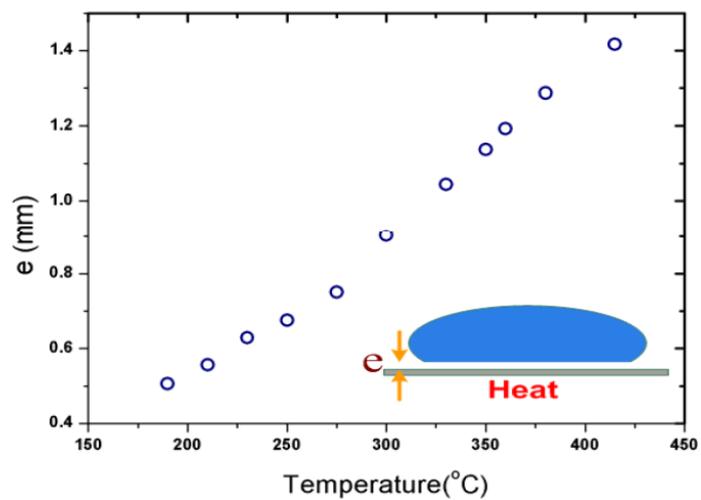


圖四:(a)水滴剛滴落至鋸齒表面，(b)水滴周圍碎出小水滴，(c)水滴整個碎裂開來。



圖五：(a)水滴爬坡俯視圖，(b)鋸齒實際傾斜狀況。

3、討論：鋸齒表面溫度如何影響水滴形成？



圖六：水滴下方的蒸氣層厚度與金屬面溫度趨勢圖
 摘自〈見微知「駐」-水珠律動與圓駐波〉科展作品

在一高溫金屬面上，水珠因受熱產生一蒸氣層，並且隨著金屬面溫度提高，蒸氣層的厚度越厚，如圖六。

當鋸齒表面的溫度大約是 300°C 時，水滴反而會有碎裂開來的情形，參考圖六，可知當鋸齒表面約為 300°C 時，水滴下方的蒸氣層厚度較 400°C 時來的薄，而水蒸氣是不好的導熱體，當水蒸氣的厚度較薄則代表其阻隔熱傳遞的效果變差，因此整顆水滴會劇烈的蒸發，類似沸騰的狀態。這導致水滴劇烈振盪，甚至水滴會被蒸氣炸開。

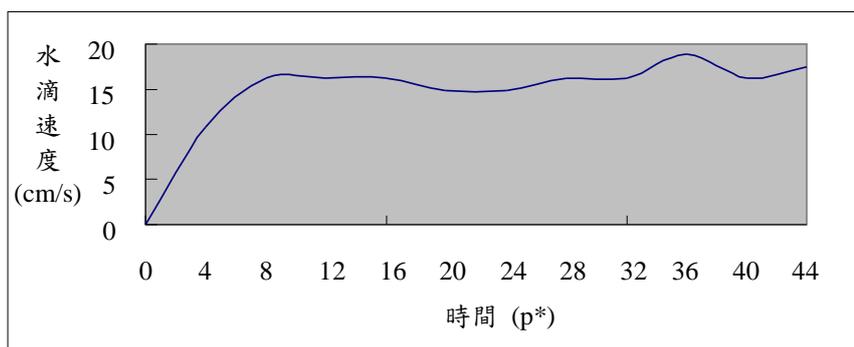
而當鋸齒表面達到 400°C 時，水滴下方存有足夠的蒸氣以阻隔熱的傳遞，使水滴不致於蒸發太快，並且才能懸浮於鋸齒上方而不會立即蒸發。

接下來，我們有個疑問是：水滴既然會爬坡，那麼水滴爬坡過程的速率分布是如何變化呢？如果我們得到<速率>與<時間>的關係圖，則我們就會知道水滴在爬坡過程的受力分布情形。因此我們緊接著進行實驗二-水滴爬坡過程的受力情形。

實驗二：水滴爬坡之受力情形分析

1、目標：探討水滴在鋸齒上的爬坡速率分布狀況。

2、結果：如以下圖。



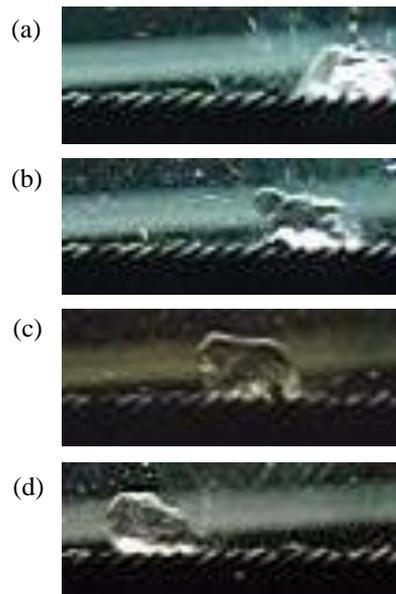
圖七：水滴爬坡速率對時間關係圖 *p 為兩張照片之間的時間間隔， $1p=1s/216\approx 0.005s$

3、分析與討論：

由圖七可知，水滴一開始加速，而後漸趨穩定、波動幅度較小。當水滴剛滴落到鋸齒表面時，水滴下方尚未存在有蒸氣層，因此，水滴會快速蒸發，產

生蒸氣壓力，使水滴加速，同時，蒸氣層在水滴下方產生，隔絕了水滴和鋸齒直接接觸，故水滴蒸發速度變慢，以致蒸發所產生的力量減少，且與萬有引力達平衡，水滴速度呈小幅度波動。

圖八中顯示，水滴在爬坡的過程中呈現不同的樣貌，可見其蒸發速率不同，而導致水滴有不同的速度變化。

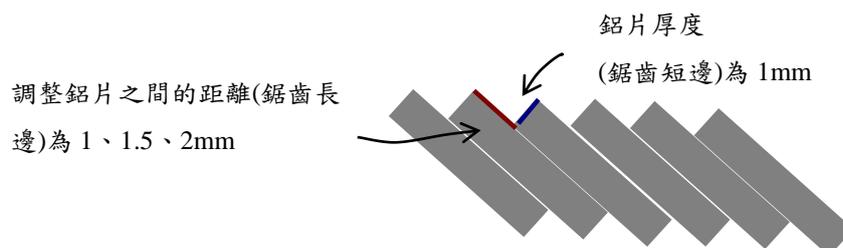


圖八：(a)~(b)水滴剛滴落鋸齒表面時，劇烈地蒸發，其周圍碎裂出小水滴。(c)~(d) 水滴下方形成蒸氣層，使其蒸發速率降低並形成珠狀。

在研究過程中，我們發現鋸齒形狀對水滴的運動方向有決定性的影響，但如何影響？於是進行實驗三來回答我們的疑問。

實驗三：鋸齒齒廓對水滴運動方向的影響

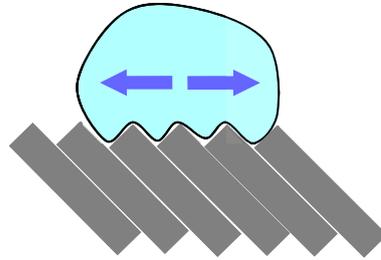
- 1、目標：了解水滴移動方向與鋸齒兩斜邊長度比例的關係。
- 2、架設：將鋁片排列並調整之間的距離，示意圖如下。



圖九：鋁片的排列方法。

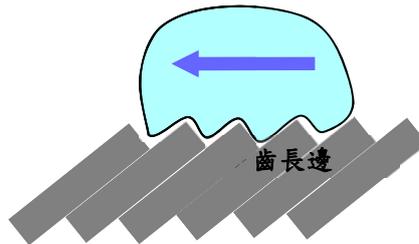
3、結果：

(1)、當兩斜面比例為 1:1，並擺放水平時，水滴沒有特定的移動方向，若是擺放傾斜，水滴向低處流，示意圖如下。



圖十：水滴在 1:1 階梯上的運動

(2)、當兩斜面之一較大時，水滴會朝向「鋸齒長邊」所面向的方向移動，且在一定角度之內，不論階梯擺放「左邊高」、「右邊高」亦或「水平」，都有相同的現象



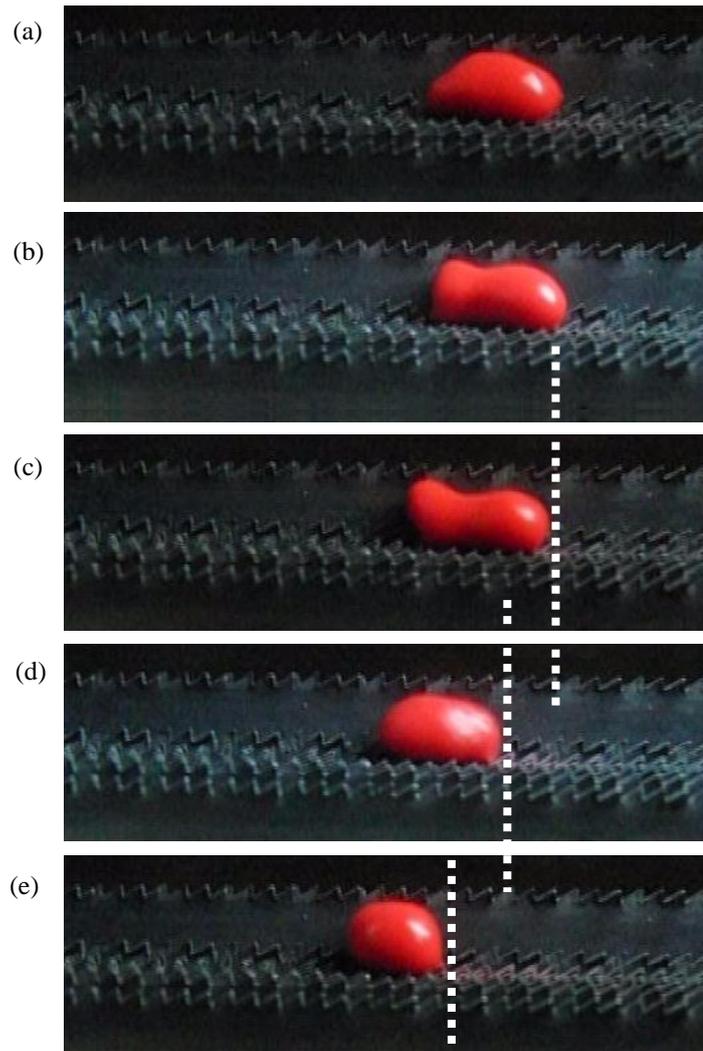
圖十一：水滴在 1:2 階梯上的運動

4、討論：水滴蒸發及鋸齒齒廓如何驅使水滴爬坡？

在諸多爬坡影像的支持下，我們得知**水滴蒸發**為爬坡現象的驅動力之一，並且配合鋸齒兩斜邊不等長的特性，我們推論出蒸發的力量為---蒸氣壓力所形成之正向力，詳細內容分述於(1).蒸發帶動水滴爬坡之過程及(2).蒸氣壓力驅動水滴爬坡：

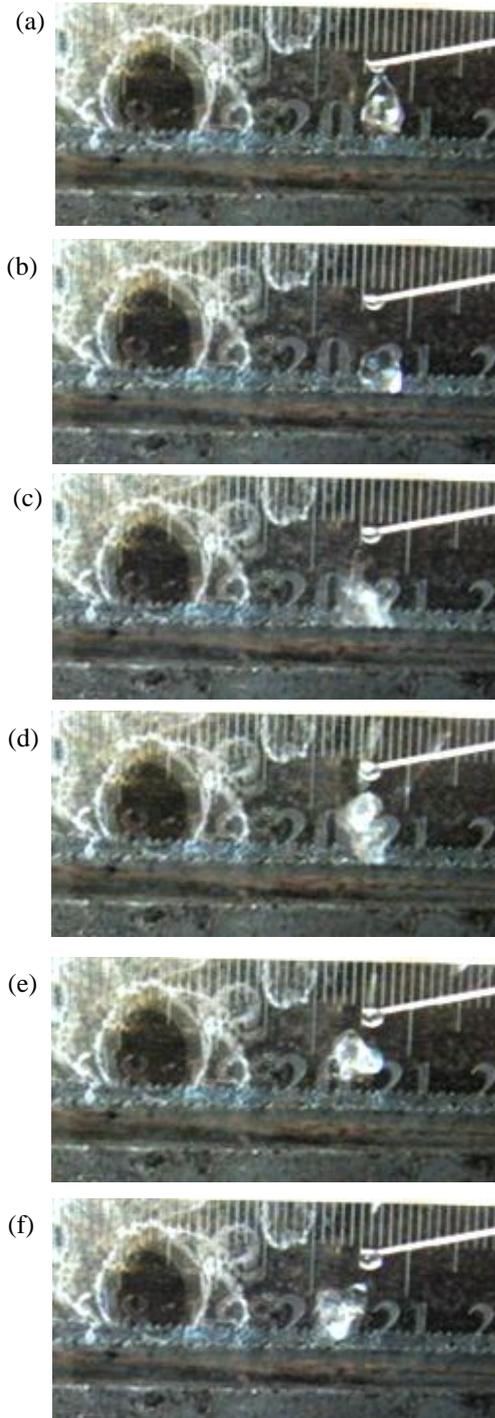
(1).蒸發帶動水滴爬坡之過程：

圖十二中，我們使用摻入紅色顏料的液滴以便觀察，其中，在液滴向左凸出之前，我們觀察到液滴劇烈地晃動，並且出現模糊的形狀，由此可知液滴受熱、蒸發快速。之後水滴往左上方凸出，如圖(a)~(c)，並且往前加速，如圖(c)~(e)，此現象顯示**蒸發會產生一驅動力**。



圖十二、紅顏料液滴在鋸齒上的運動情形

另一項觀察如圖十三所示，我們一直對鐵片加熱 4 小時，鋸齒表面大約 480 °C。圖(c)中，水滴剛接觸高溫鋸齒面時，形狀瞬間模糊，可見水滴蒸發得非常劇烈，圖(d)~(f)之間水滴甚至往左上方彈跳。如同上頁描述，藉由水滴一連串的形狀、運動變化，我們可知：水滴劇烈蒸發會產生一驅動力，且此力方向偏向左上方。



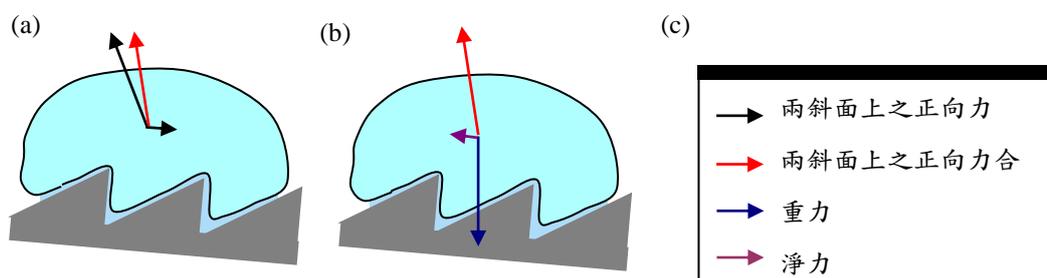
圖十三，水滴在 480°C 鋸齒表面上的彈跳圖片。

(2). 蒸氣壓力驅動水滴爬坡：

A. 原理：水滴因受熱，在其周圍形成一蒸氣層，蒸氣具有動能，會施加給水滴一正向力，在單位面積上所受的正向力，即為壓力。

B. 水滴在鋸齒面上所受的正向力如圖十四所示。

在兩斜面上的力量大小:根據 $P=F/A$ 可知，在相同壓力之下，受面積越大，則其所受的力量也越大。在水滴爬坡的系統中，我們視在兩斜邊上的壓力相同，且根據兩斜邊比例為 1:2.2，即可推知，在兩斜邊上蒸氣推動的力量亦為 1:2.2(圖十四中黑色箭頭)，將兩力相加會產生一偏向左上方的淨力(圖中紅色箭頭)，最後再加上重力(圖中藍色箭頭)，便是一沿著斜坡向上的淨力(圖中紫色箭頭)。藉此分析，我們對於所有的研究結果最大的共同點「水滴總是沿著鋸齒長邊所面向的方向前進」，可以得到一個合理的解釋。



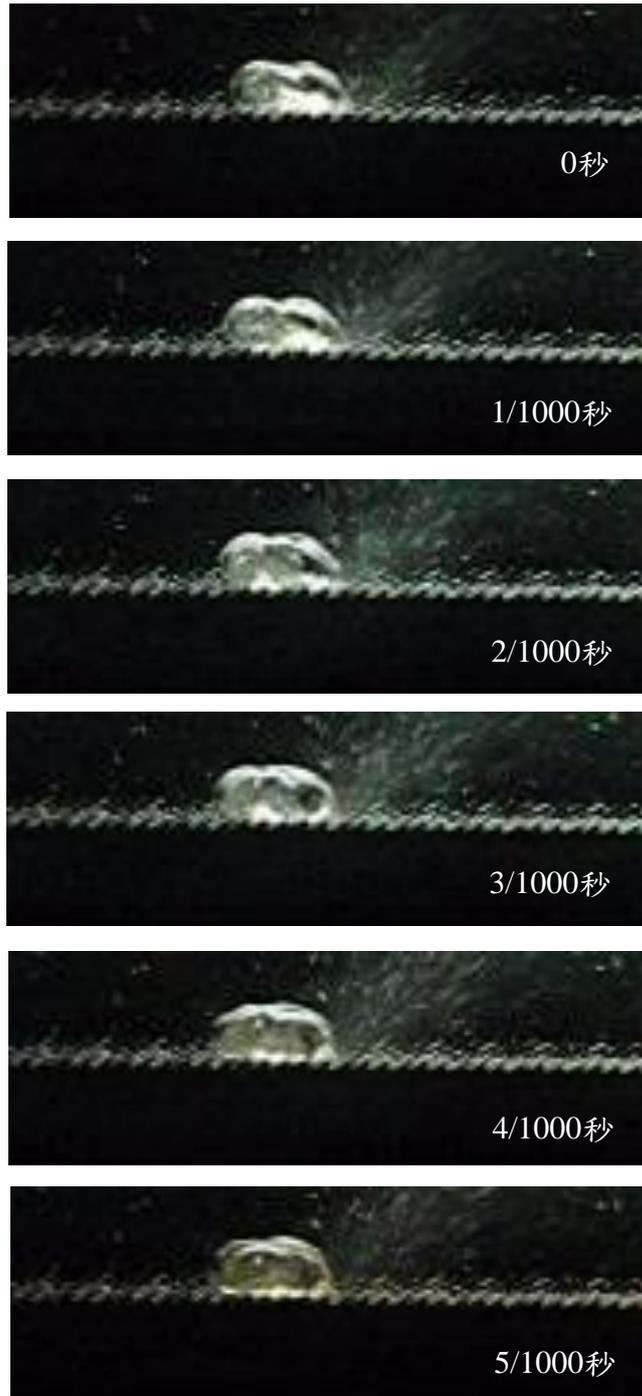
圖十四-(a)~(b)水滴受力圖，(c)圖例。

從實驗一~三中，我們了解到，水滴受熱後將產生水蒸氣，此蒸氣是造成水滴爬坡的主要原因。但我們不了解水滴在受熱之後，其內部如何流動。再者，實驗三告訴我們，由於水滴在鋸齒上的不對稱蒸發而造成水滴往固定方向移動，但似乎需要更多的證據來反覆驗證。因此，我們進行實驗四的實驗探究，包括：1.水滴內部流動、2.水滴各部位蒸發速率差異對其運動的影響。

實驗四：水滴各部位蒸發速率差異對其運動的影響

1、動機：

在實驗過程中，我們發現水滴後方會噴發出許多小水滴，而前端卻少有此種現象，藉此發現可知水滴前後受熱程度不同，以致蒸發速率不一，為探討此一現象對水滴內部流動、爬升過程的影響，我們試著在接下來的實驗中(p.13)模擬此一現象，進行探討。實際影像見下圖。



圖十五：水滴後端不斷噴出小水珠，而前端卻不然。

2、架設：

- (1)、在一鋁條上刻出凹槽(格式見圖十六)。
- (2)、將鋁條以加熱板加熱至 500°C ，並將其擺放傾斜(左邊高)。

(3)、將水滴落上方並使其由左向右滑落至凹槽。

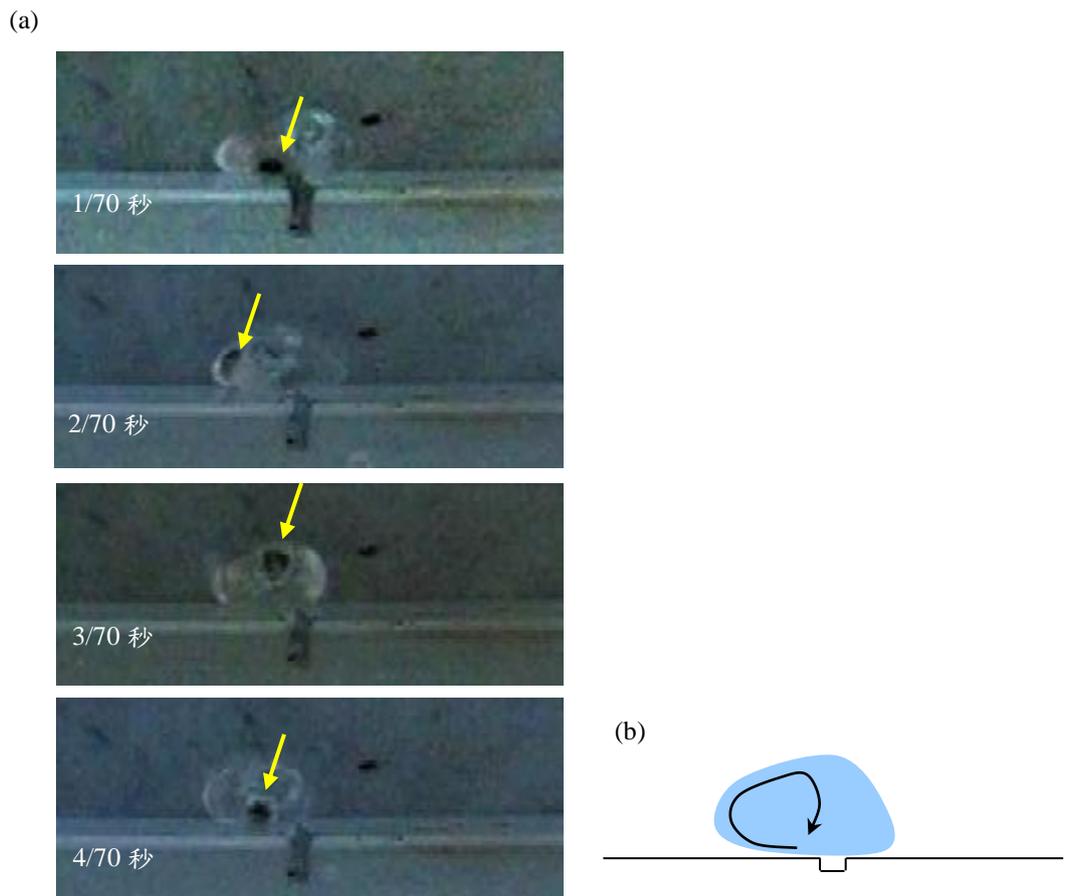
此架設的目的在於：當水滴右側碰觸到凹槽時，水滴下方的氣體*大量流泄，蒸氣層變薄、隔熱的效果變差，以致於凹槽周圍的水滴蒸發的較快，藉此比擬鋸齒上的現象。



圖十六：(a)金屬側視圖，銀色為鋁條(長:8.9;寬:1.5;高:0.7)，黑色為凹槽(長:1.5;寬:0.1;深:0.25)，單位:cm，(b).金屬俯視圖，圖中藍色部份為水珠。

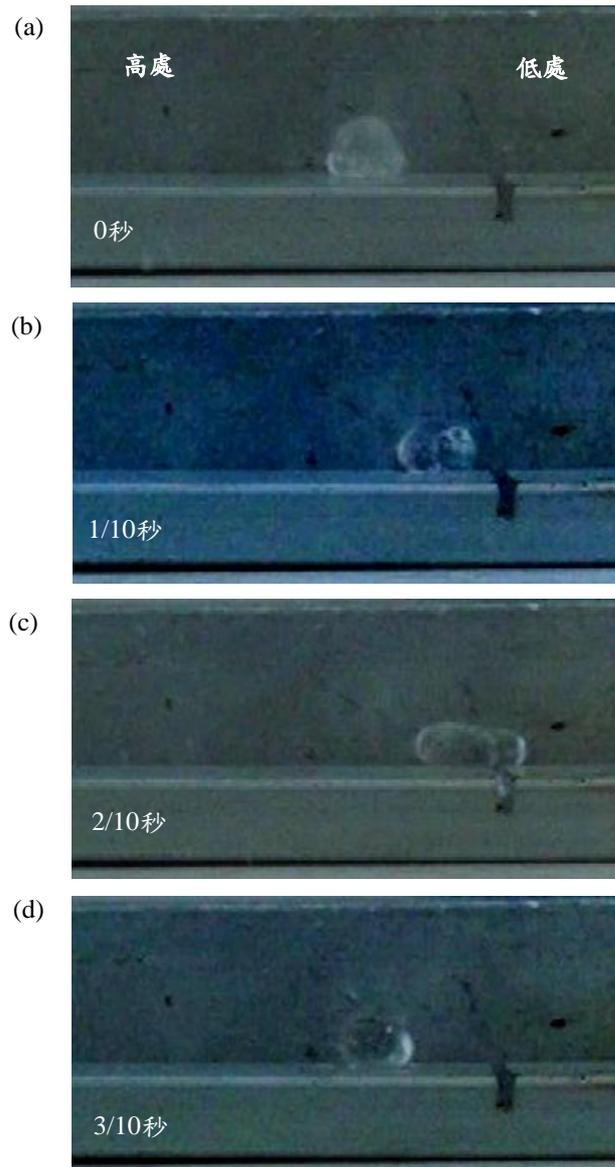
3、結果：

(1)、水滴內部呈現順時針流動，如圖十七所示：



圖十七：(a)水滴內部流動影像，(b)水滴內部流動示意圖。

(2)、水滴碰觸到凹槽後，往高處彈回，如圖十八所示：



圖十八：(a)~(b)水滴由高處滑落至右方。

(c)~(d)水滴接觸洞口後，往左方拉長，又移動到高處。

4、結論：

(1)、當水滴碰觸到凹槽時，水滴內部出現許多小氣泡，可見接觸凹槽水滴劇烈蒸發，顯示此架設達到先前預設目的:使水滴各部位具有不同的蒸發速率。

(2)、當系統的條件被控制，而使得水滴前、後端蒸發效果不一時，水滴出現特定的流動模式。反觀鋸齒上的水滴，亦是前、後端蒸發速率不一，

並且出現類似的流動模式。

在此二種方式的實驗觀察可知：水滴各部位蒸發速率的差異是影響水滴內部流動的重要機制，並且會產生一驅動力使水滴前進。

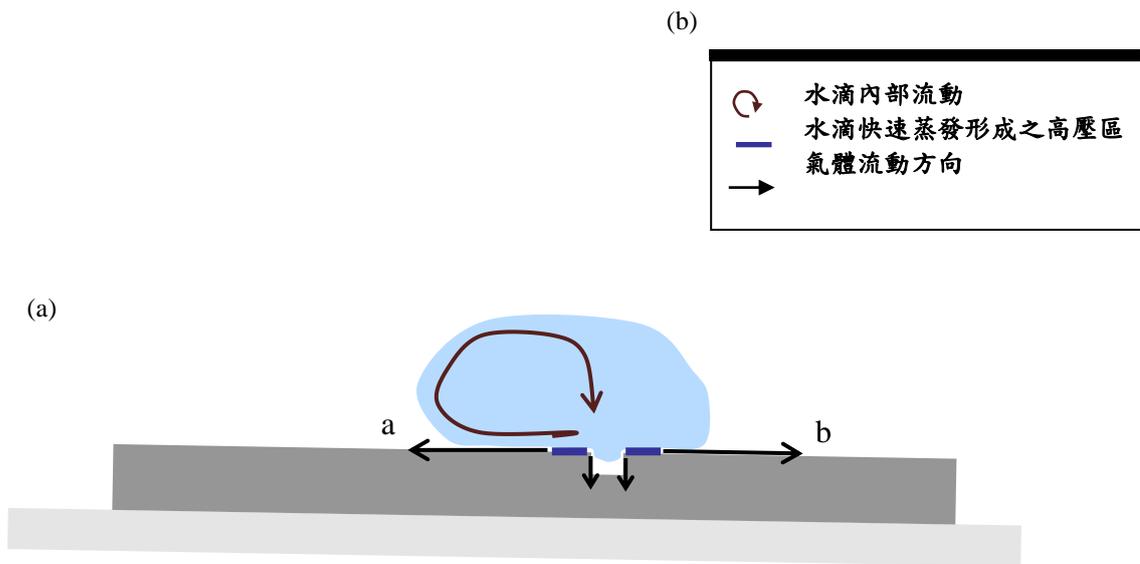
5、分析與討論：水滴蒸發速率差異如何影響水滴運動？

此部份分述在凹槽金屬上及鋸齒上的水滴之行為如何受到其蒸發速率影響，內容如下：

(1).凹槽金屬上的水滴：

當水滴碰觸到凹槽時，其下方的氣體會往外流泄，使得凹槽周圍的蒸氣層較薄、隔熱效果較差，因此，接近凹槽的水分子會蒸發的較快，進而在凹槽周圍形成較大的氣壓(如圖十九中的深藍區塊)，此部份氣體會流至相對低壓的區域，圖中黑色箭頭即為氣體流向。

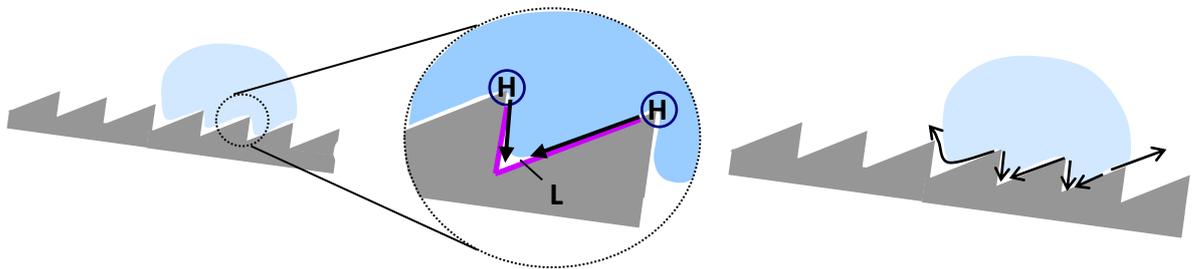
當氣體從水滴下方通過時，它們會對水分子產生一個與其運動方向相同之摩擦力，即圖十九中往 a 方向移動的氣體會將水分子帶往左方；反之亦然。由於大部份的水分子在凹槽左方，故往 a 方向的氣體影響範圍較 b 大，以致水滴最後克服重力往左。根據上述理論，凹槽左方氣體會往左流動，此機制亦可解釋水滴內部順時針的流動模式。



圖十九：(a)水滴下方氣體移動及水滴內部流動示意圖，(b)為圖例。

(2).鋸齒上的水滴：

藉由上述分析可知：水滴各部位蒸發速率差異會影響水滴下方的氣體運動，進而影響水滴內部流動及其運動，反觀鋸齒上的水珠，其各部位的蒸發速率亦是不同的，若將水滴接觸鋸齒的部份分為二：平面和尖銳處(見圖二十)，則尖銳處較易深入水滴內部，我們推測此部份的水分子受熱較快、蒸發較快，因而具有較大的氣體壓力，進而往兩旁的低壓處流動，同樣地，氣體在水滴下方運動會對水滴產生摩擦，由於鋸齒長邊上的水分子較多，即往左下方移動之氣體的影響力較大，故水滴朝著左方運動。



圖二十：水滴下方氣體流動示意圖：○尖銳處 — 平面處 ← 氣體流動方向，
H 高壓處，L 低壓處。

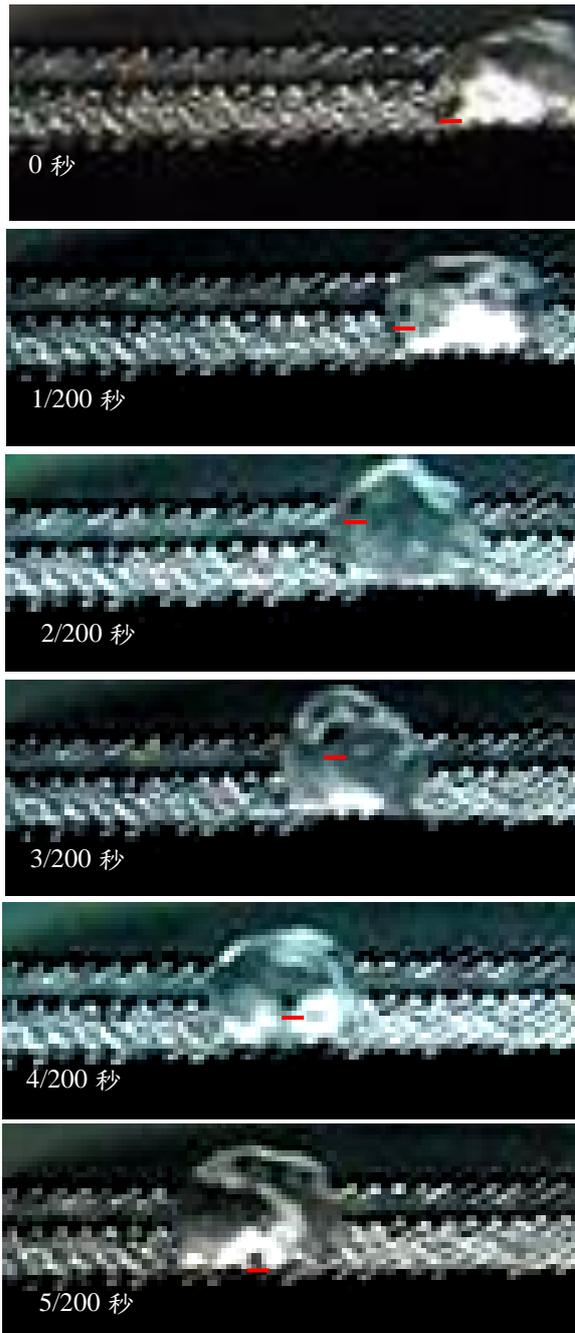
實驗五：觀察水滴內部流動：

1、動機：為檢驗上述氣體流動模型是否影響水滴運動，我們在水滴內部放置胡椒顆粒，以觀察水滴內部流動。

2、結果：

整體而言，水滴前、後兩端的流動有明顯的特徵，可簡單歸納為二：

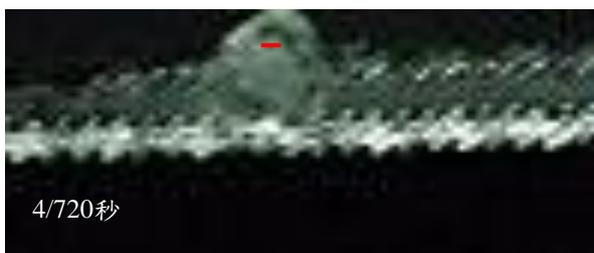
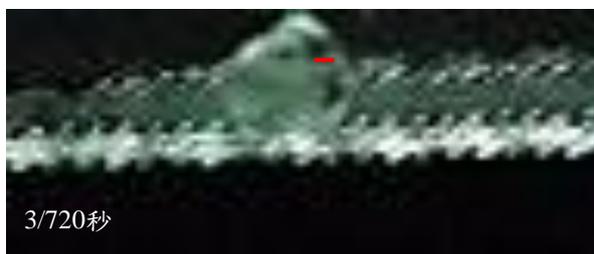
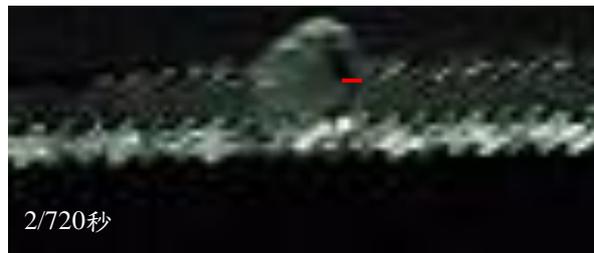
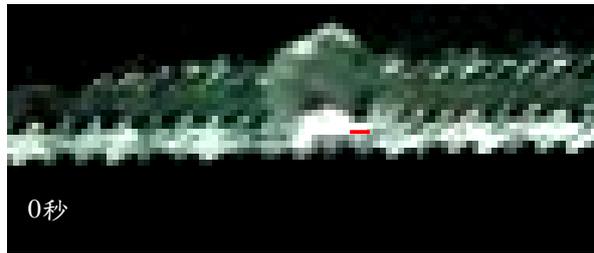
(1).前端水滴—順時針方向流動(紅色指標上方即為胡椒顆粒)



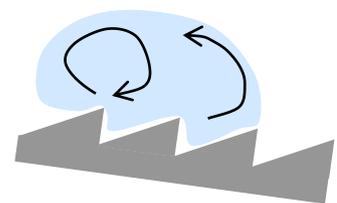
圖二十一、水滴前端流動影像。

(2).後端水滴—逆時針方向流動：

(a)



(b)



圖二十二：(a)水滴後端流動影像(b)水滴內部流動模型。

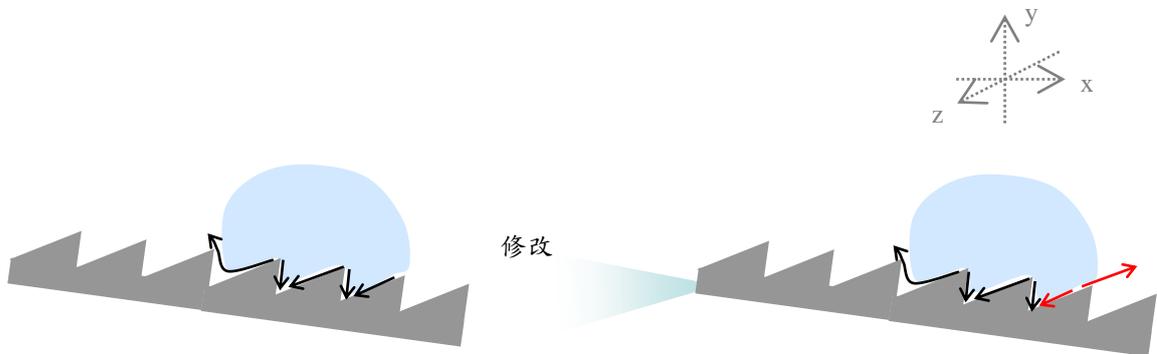
3、討論:

由於水滴下方的氣體流動，水滴獲得一個偏向左方的合力，此推論可由水滴內部順時針的流動得到驗證，但是:為何水滴後端會出現逆時針的循環呢?

為了解釋此現象，我們修改原先的模型(見圖二十三):

在原先理論當中，外在氣體壓力並未納入考量。事實上，外在壓力要比水滴下方低，以致於後端的氣體大多往右上方跑，而此部分水滴所受的合力往右上方，才會導致逆時針循環。

透過這項實驗，氣體流動之模型得以確認。



圖二十三:水滴下方氣體流動模型(修改前、修改後)。

肆、結論

一、水滴爬坡的因素包括：

- 1、鋸齒表面達 400°C ，水滴下方產生一蒸氣層，可阻隔熱量傳遞，使水滴不立刻蒸發。
- 2、蒸發所產生的驅動力，包含蒸氣壓力及水滴下方氣體流動對水滴的摩擦力。

二、水滴內部流動模式可分為：

- 1、前端水滴呈順時針方向流動；
- 2、後端水滴呈逆時針方向流動，且此二模式皆是水滴下方氣體特定的流動方向所致。

三、水滴運動方向受到以下因素控制：

- 1、鋸齒長邊與短邊的比例，當兩斜邊不等長時，水滴會往鋸齒長邊所面向的方向前進。
- 2、當水滴各部位蒸發程度不同，會使得水滴下方產生壓力差，驅使蒸氣往特定方向流動，並對水滴產生摩擦力，經適當的實驗設計，水滴甚至可以在鋸齒以外的系統中向上運動。

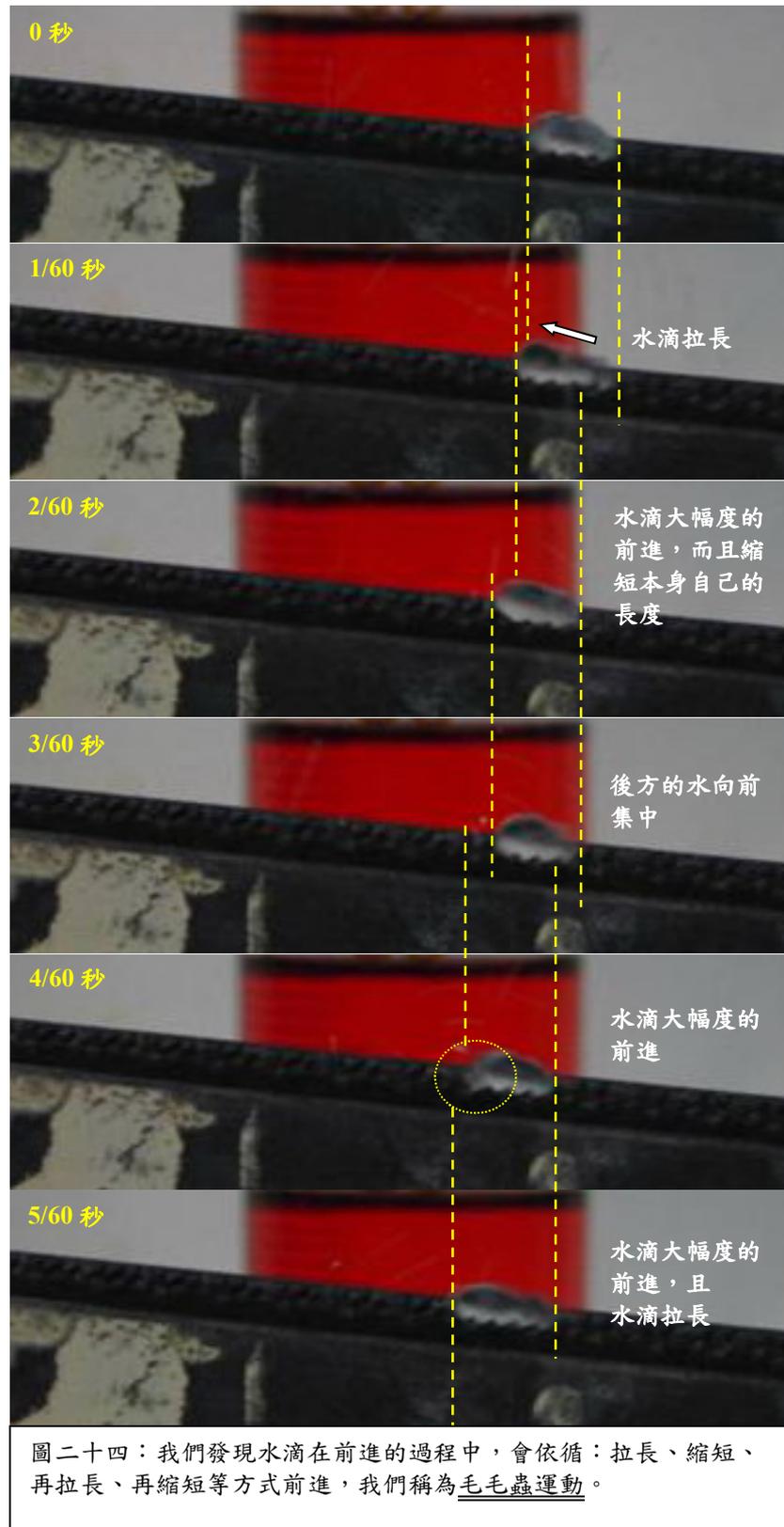
伍、參考資料

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- 【2】Anne-Laure Biance、Christophe Clanet and David Que´re´，2003，Leidenfrost drops，PHYSICS OF FLUIDS。
- 【3】見微知「駐」-水珠律動與圓駐波，2008 年美國 Intel 國際科學展覽會，作者：崔德昕。
- 【4】膜沸騰、萊氏現象 http://www.nsc.gov.tw/files/popsc/2005_57/64-67.pdf
- 【5】原著者：REESE，編譯者：駱劍秋、李金連、林世穆、陳堯輝、李世格、曾世杰、蔡淑雲，普通物理，高立圖書有限公司，P.346~352，2006.7.10 出版。

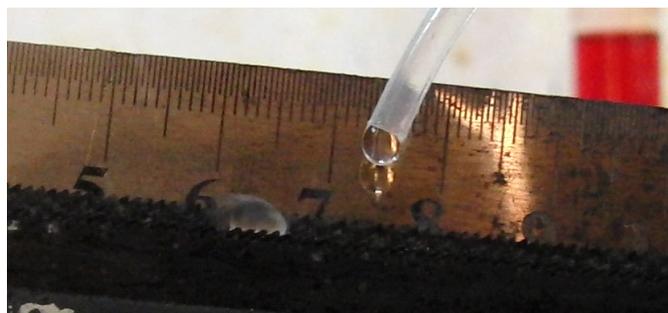
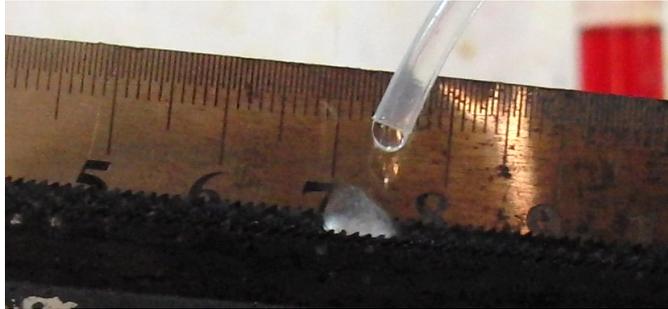
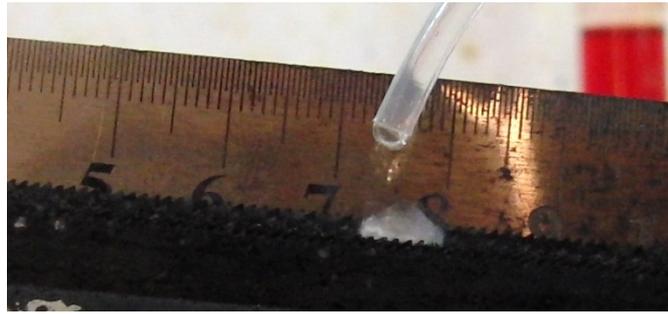
陸、附錄

附錄一：水滴爬坡圖片

1、水滴爬坡條件：蒸餾液大小為 40 ul. 、鋸齒片傾斜 5 度



2、水滴爬坡條件：蒸餾水、液滴大小為 40ul、鋸齒片傾斜 7.5 度角。



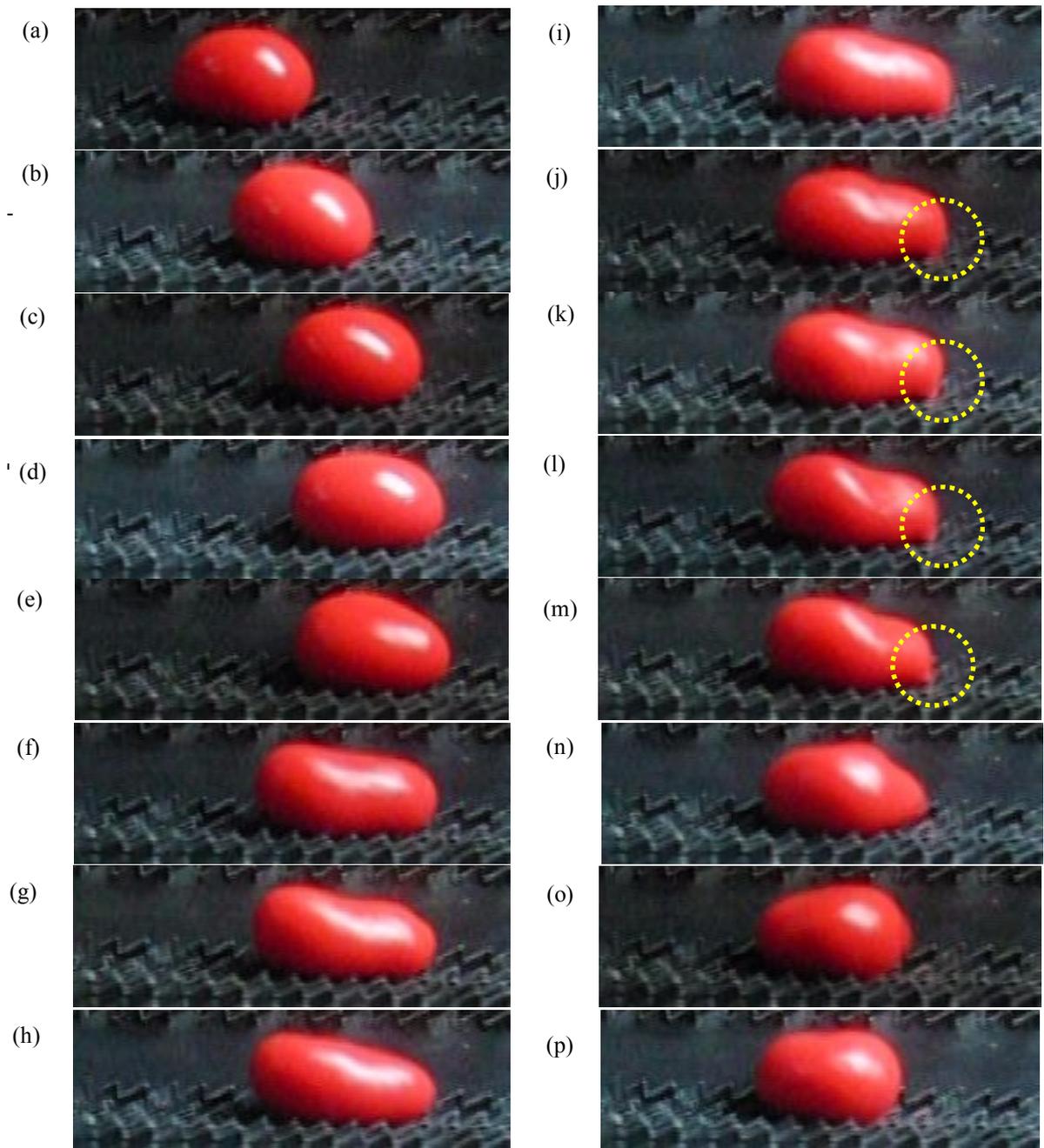
圖二十五：我們發現水滴在前進的過程中，水滴的前端會向上、向前凸起，顯示蒸發淨力朝向左上。

3. 液滴爬坡條件：液滴摻入紅色顏料，鋸齒表面溫度為 400°C，水滴大小為 40ul，

鋸齒傾斜五度角。

相較於其它液滴，紅顏料液滴的爬坡現象較不穩定，如圖(a)~(c)，液滴

下滑，但是到了圖(d)~(h)液滴開始向前拉長，之後，水滴後端黏滯在鋸齒上，如圖(j)~(m)的黃色區塊，此現象導致水滴後端停滯不前但是前端卻不斷拉長。照理來說，液滴下方的蒸氣層應隔絕液滴與鋸齒直接接觸，則液滴將懸浮於鋸齒上方，故圖中的現象顯示水滴後方的蒸氣層較薄，以致於水滴後端黏滯在鋸齒上方。影片當中更可明顯地看到水滴後端劇烈震動，顯示水滴受熱快速，之後液滴再往前縮短，此乃液滴表面張力亦或蒸發的驅動力造成的結果。



圖二十六：紅顏料液滴在鋸齒面上的爬坡過程。

附錄二：水滴爬坡速率與水滴大小、鋸齒傾斜角度(β)的關係

1、變因：

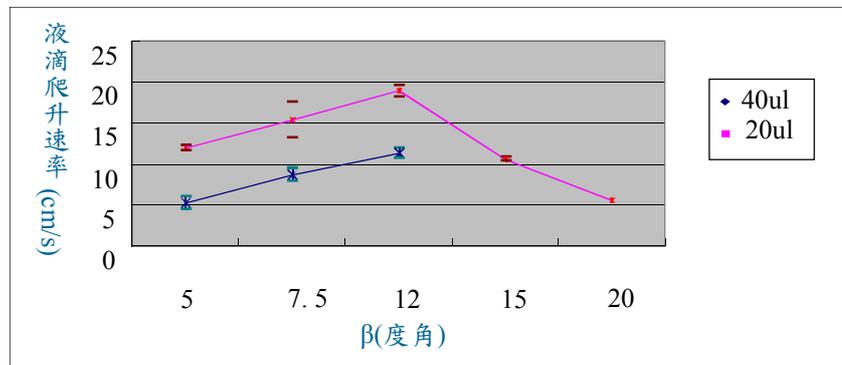
(1)、操縱變因：改變鋸齒傾斜角度，分別為：5、7.5、12、15、20 度。

(2)、控制變因：

第一組實驗：水滴大小為 40ul、使用蒸餾水；

第二組實驗：水滴大小為 20ul、使用蒸餾水。

2、結果： β 和水滴速率之關係圖：



3、結論：

a、當 $\beta < 12$ ，角度越大，水滴爬坡速度越快，且 20ul 水滴的爬坡速率較 40ul 水滴快。

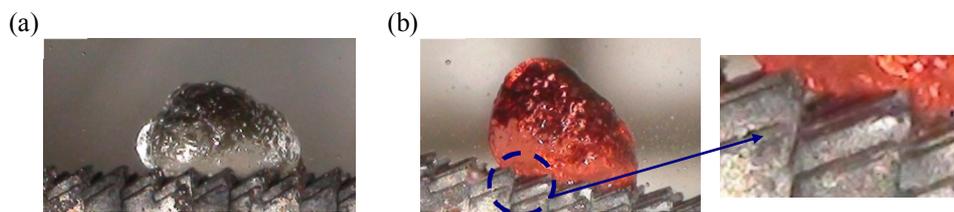
b、當 $\beta > 12$ ，角度越大，20ul 水滴的爬坡速度變慢，40ul 水滴則不能爬坡。

照理來說，水滴停留在越傾斜的鋸齒上，會因為斜面上的下滑力較大的緣故，而使得水滴爬的較慢，甚至不會爬升。但根據我們的實驗，當鋸齒傾斜 12 度角以內，水滴的爬升速率會隨著角度越大而越快。

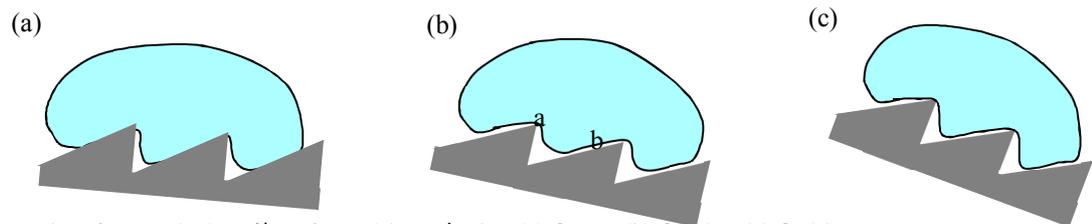
我們試著繪出 $\beta=5$ 、12、20 時水滴在鋸齒上的附著情形(如下頁圖二十七~二十八):當 $\beta=5$ 時，水珠緊黏於鋸齒上方，且在水滴下方的兩個斜面上，壓力是差不多的，此時水珠在鋸齒面上所受的力量與其所接觸的兩斜面面積比例有關;但當 β 提高至 12 時，水珠與鋸齒短邊脫離，造成水滴在兩斜面的蒸發量不平均，如圖二

十八-(b)中，a、b 兩處存在一壓力差，水滴直接與鋸齒長邊接觸，蒸發量較多，造成b處的壓力較大；而水珠脫離鋸齒短邊的動作，使得水滴與鋸齒短邊存在空隙，因此水蒸氣較容易散逸，此處的蒸氣壓較小。相較於 $\beta=5$ ，所形成的阻力也較小。上述的現象是「 $\beta < 12$ ，角度越大，水滴爬升速率會較快」的原因。

當角度持續提高，如圖二十八-(c)， $\beta=20$ ，水滴依然是脫離鋸齒短邊的，也就是當角度從 12 度提高至 20 度，鋸齒短邊對水滴的阻力已變動不大，反倒是在斜面上的下滑力越大，造成「 $\beta > 12$ ，角度越大，水滴爬升速率會越慢」。



圖二十七：水滴實際影像，(a). $\beta=5$ ，(b). $\beta=12$



圖二十八：水滴附蓋鋸齒之形狀示意圖，(a) $\beta=5$ ，(b) $\beta=12$ ，(c) $\beta=20$ 。

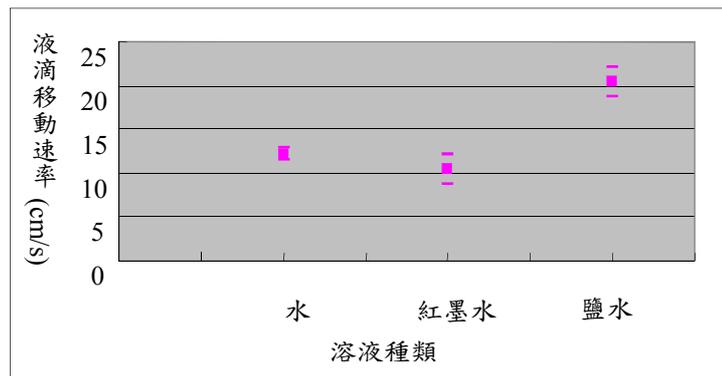
附錄三：水滴爬坡速率與液滴種類的關係

1. 實驗變因：

操縱變因：液滴種類分為水、鹽水、紅墨水

控制變因：液滴大小為 20ul， $\beta=5$ 。

2. 實驗數據如下所示：



3. 結論：

表面張力大小依序為：鹽水 > 水 > 紅墨水，而液滴移動速率亦是：鹽水 > 水 > 紅墨水，可見：表面張力越大，液滴移動速率越快。

4. 分析：

實驗當中，我們發現液體會有拉長、往前縮短的運動情形(參考 P.20，附錄一-第 1 項)，其中液滴之所以會往前縮短，與其本身的表面張力有關，當液體的表面張力較大，代表向液體內部的垂直拉力越大，會使其運動時的伸長、縮短的時間差較小，故造成爬升速率會較快，所以液滴的爬升速率會受到表面張力的影響。

Self-propelled Energy Resource from Geometrical Symmetry Breaking

Abstract

A thin vapor layer that has a critical thickness can be used to insulate a droplet of liquid from a hot surface underneath, significantly reducing the evaporation rate of the droplet and providing an opportunity to study the flow of the liquid inside the droplet. In the case of a water droplet, the critical thickness can be as thin as 0.1 mm to insulate the droplet from a 400-°C hot plate. A self-propelled engine, which consumes the atomic binding energy of the molecules, can be manufactured by breaking the geometrical symmetry of the droplet. This self-propelled engine is demonstrated by setting the droplet to climb against gravity on an inclined plate with an asymmetrical saw-tooth surface. An edge can also trigger the self-propelled machinery to generate damped oscillations of a liquid droplet that is moving on the inclined hot plate. The driving force behind the self-propulsion effect is identified to be based on the circulating liquid that creates vortices. Creating an uneven distribution of dynamical liquid vortices in the droplet is the key to triggering the self-propulsion.

Introduction

It is known that a liquid droplet can stand on an extremely hot plate for a long period of time, after a vapor layer forms underneath. This layer limits heat transfer between the droplet and the hot plate [1-3]. A self-propelled engine that consumes the atomic binding energy can be manufactured by breaking the geometrical symmetry of the droplet. In this study, a self-propelled engine of this type is demonstrated by setting the droplet to climb against gravity on an asymmetrical saw-tooth surface. The same self-propelled machinery can also be triggered by edges to generate damped oscillations of a droplet on a hot smooth plate.

Motivation

I was first aware of the Leidenfrost effect from my initial internet research and became more and more interested as I continued to gather more information. As it turns out, numerous scientists have studied this effect. Indeed, a preferred direction of movement of a droplet that is placed on a ratchet-like surface has already been discovered by scientists Linke etc [1]. To test for this effect, I came up with the idea of binding saw blades together to form the mentioned kind of surface. Fortunately, this method works, thus allowing for further study.

Materials and Methods

In this study, several systems are designed, including saw blades and an aluminum bar with single notch. First, I am going to describe how the saw blade systems are set-up and then how the aluminum bars are used.

I Saw blade systems

Based on the requirements of different experiments (Fig. 1), the saw-tooth profiles are made using different methods, as shown below:

Types of experiments	Devices
Test study	bound saw blades
Initial/Quantitative study about how the profile of the saw-tooth affects droplet motion	bound aluminum chips/processed saw-tooth surfaces

Fig. 1 A table shows devices used in different types of experiments.

1 Bound saw blades

To form a saw-tooth surface profile for the droplets to stay on, fifteen saw blades (Fig. 2a) are bound together (Fig. 2b). Subsequently, the system is heated up with a gas stove (Fig. 2c) and the motion of droplets is recorded using a high-speed camera.

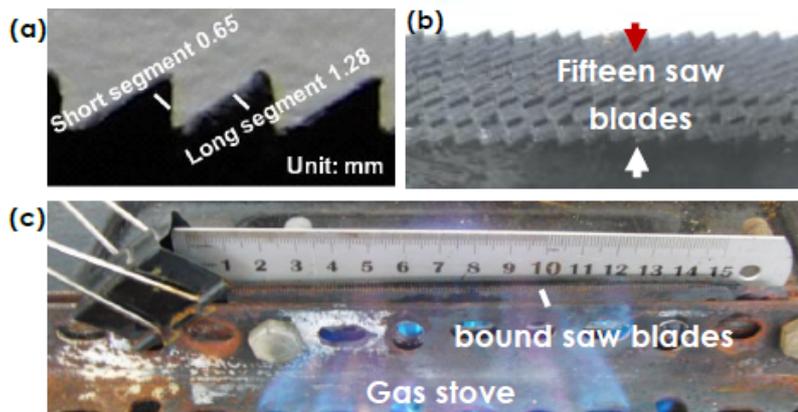


Fig. 2 (a) A side view of a single saw blade, (b) a top view of saw blades bound together and (c) the whole apparatus

2 Bound aluminum chips

To initially check if the asymmetrical saw-tooth profile plays a big role in droplet motion, several aluminum chips are bound together (Fig. 3). By controlling the distance between any two aluminum chips, the ratio of the two segments is then manipulated to be 1, 1.5 and 2.



Fig. 3 Side views of the bound aluminum chips

3 Processed saw-tooth surfaces

For further study, several aluminum bars are milled by a machinist (Fig. 4). Based on the profile I have in Fig. 2a (dark section in Fig. 4), the short segments are fixed at 0.65 mm while the long ones are each fixed at different lengths of 1.2, 1.4, 1.6 and 1.9 mm (dotted line in Fig. 4).

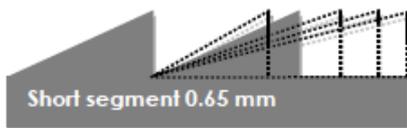


Fig. 4 A schematic drawing shows the milled-saw blades with dotted lines to indicate the saw-tooth surfaces with various profiles.

II An aluminum bar with single notch

To study how the gradient of evaporation rate along a droplet affects its motion, a notch is milled on to an aluminum bar (Fig. 5) by a machinist. In this study, the bar is then heated up by a hot plate.



Fig. 5 Side views of an aluminum bar which has a notch with arrows to define the width and the depth of the notch

Overall, the plate temperature is measured by a thermocouple. For data analysis, several software programs are used, including Tracker-the video analysis and modeling tool, Corel VideoStudio and Ulead GIF Animator.

Results and Discussion

The contents below contain: I Phenomena at a glance, II Critical parameters, III Self-propelled engine, and IV Damped bound state.

I Phenomena at a glance

Two interesting phenomena are found in this study, as shown below:

1 Climbing against gravity

First, a preferred movement of droplets is observed on the saw blade which is heated to $\sim 300\text{ }^{\circ}\text{C}$ (Fig. 6). Furthermore, droplets can climb spontaneously on the inclined surface with speeds of up to 20 cm/sec.

In addition, as the droplet moves into the colder region of the blade, it blows up. This indicates that the temperature of the surface is critical for the climbing phenomenon.

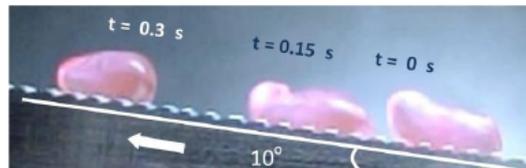


Fig. 6 Superimposed photos of a droplet that is climbing against gravity

2 Deformation and oscillation

Pulled by gravity, a droplet placed on the aluminum bar first slides down. Surprisingly, as the droplet touches the notch on the bar, it bounces back to where it was first placed instead of sliding down (Fig. 7). Amazingly, the oscillations last around 30 seconds.

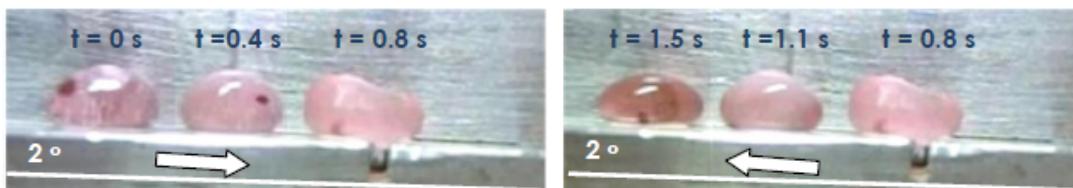


Fig. 7 Superimposed photos of a droplet that is oscillating on a hot, smooth surface with arrows to indicate the sequence

II Critical parameters

To create the conditions that make the anti-gravitational effect possible, several parameters listed below are needed, including heat shielding as well as uneven vortices within the droplet.

1 Heat shielding

Based on the Leidenfrost effect (also called a film boiling effect) [2], a critical plate temperature is crucial for a vapor layer formation (Fig. 8b). This layer insulates heat transfer from the hot surface, thus providing sufficient time for the droplets to avoid boiling off.

Normally, the temperature at which an operative layer forms is defined as the Leidenfrost point. Actually, this point varies a lot (Fig. 8a) depending on the liquid boiling point and the quality of the surface (e.g. heat transfer coefficient, roughness etc).

It is known that the thickness of the vapor layer is positively correlated with the plate temperature within a state called transition boiling [3]. As the droplet moves into the colder region of the plate, a thinner vapor layer may not protect the droplet as operatively, thus leading to an unstable droplet conformation (Fig. 8c).

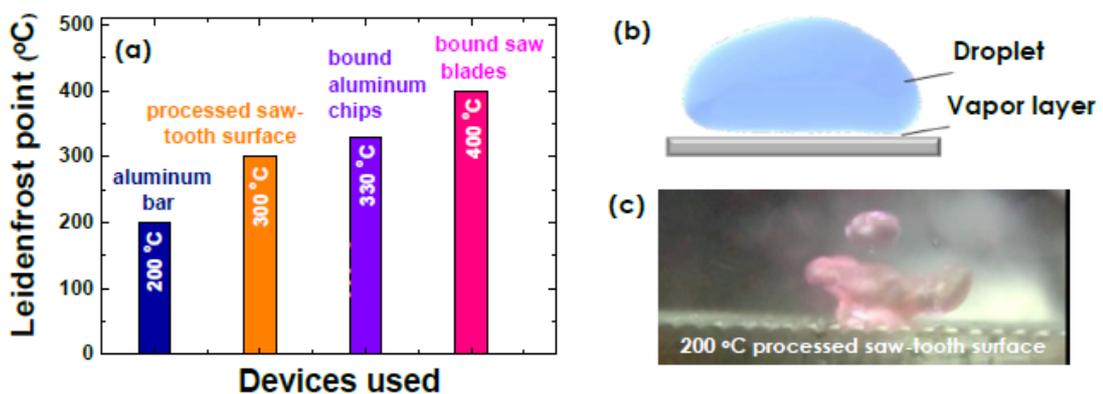


Fig. 8 (a) The Leidenfrost points found for a 25 oC-water droplet placed on various devices, (b) the vapor layer underneath a droplet and (c) an unstable conformation of a droplet on a 200 oC processed saw blade

2 Uneven vortices

By controlling the ratios of the two segments to be 1, 1.5 and 2, I found that the droplets on a symmetrical saw-tooth surface move in a random direction (Fig. 9a) while the ones on the asymmetrical surface move against the long segments (Fig. 9b).

Interestingly, an uneven dumb-bell shape of circulating liquid droplets is observed on the asymmetrical surface (Fig. 9c). This shows that the symmetry of the droplet is broken, which is that kindles my interest to study the flow dynamics of droplets in later experiments.

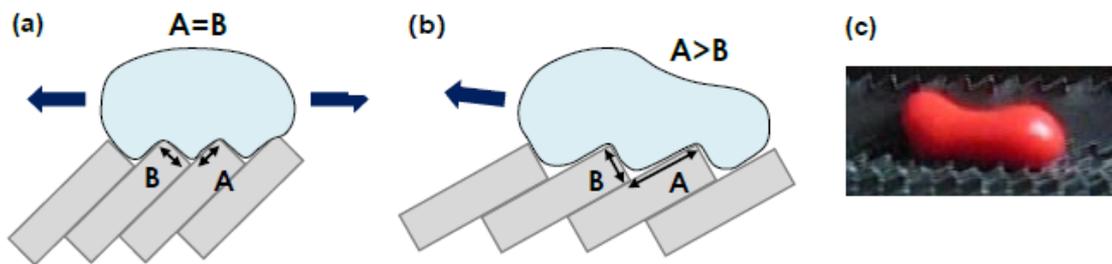


Fig. 9 (a), (b) The conformations of droplets on symmetrical and asymmetrical saw-tooth surfaces as well as (c) a red ink droplet with an uneven dumb-bell shape on asymmetrical saw-tooth surface

III Self-propelled engine

In this section, I aim to study the dynamical vortices within the droplets.

1 Dynamical vortices

To observe the dynamics, pepper particles were introduced into the droplets as a tracer. Surprisingly, liquids in the two bells are circulating separately, each along a horizontal axis but in opposite directions (Fig. 10a, b). In addition, the angular speeds of the large and small vortices are typically $\omega_l = 20.1$ and $\omega_s = 22.5 \pi$ rad/s, respectively.

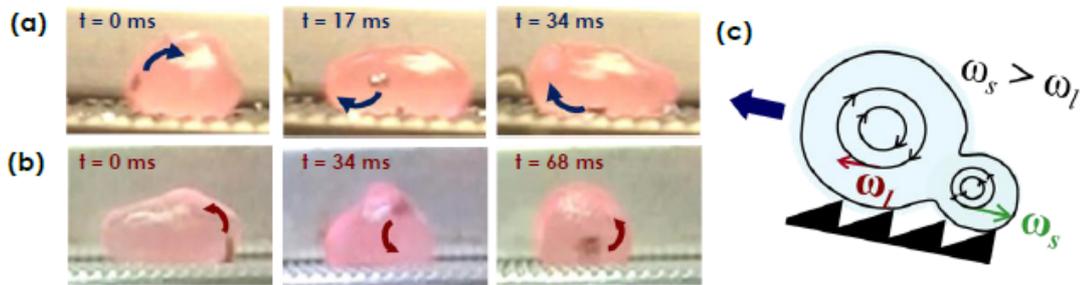


Fig. 10 (a)(b) Internal flows of the large and the small vortices of a droplet as well as (c) the uneven vortices formed within a droplet

Further, the uneven vortices are inferred to be based on an imbalance of forces on the two segments that results from the vapor pressure underneath the droplet. As the liquids flow through the interface between the droplet and the saw-tooth surface, a tangential force triggers the vortex as a whole. Since the two vortices flow in opposite directions, they orderly provide a driving and a drag momentum for the droplet. That is to say, according to the speed and volume differential between the two vortices (Fig. 10c), a net driving momentum is generated for the droplets to roll towards the larger vortex side. On the contrary, vortices that have the similar speed and volume cannot generate a large enough driving momentum, thus causing movement in a random direction.

2 Dynamical competition

For further confirmation, I captured the climbing speed V as well as the circulating speed of the large vortex ω_l during the climbing effect that occurs on saw-tooth surfaces with various A/B ratios (Fig. 11). The climbing speed is first increased whereas it is saturated as the angular speed is increased further. Moreover, by fitting the data, the saturation follows the Langevin profile and the equations below:

$$V = V_0 \left(\coth(x) - \frac{1}{x} \right) ; \quad x = \left(\omega_l / \omega_{l0} \right)^\beta$$

Where V is the climbing speed of a droplet, V_0 is the highest climbing speed obtained from the data fitting, ω_l is the angular speed of the large vortex, ω_{l0} is a dragging parameter of $\sim 5.7\pi$ rad/s and β is a fitted exponent of ~ 3.7 .

This shows that the phenomenon can be described by a driving parameter ω_l from the large vortex and a dragging parameter ω_{l0} from the small vortex and friction. By inference, it is the kinetic energy associated with the vortices that drives the motion of the droplet.

In general, the kinetic energy for a rigid rotator is known to be proportioned to $I\omega^2$. Based on an exponent of $\beta = 3.7$ obtained from the data fitting, the circulation of the liquid vortex can be described by an effective moment-of-inertia of $I \propto \omega^{1.7}$.

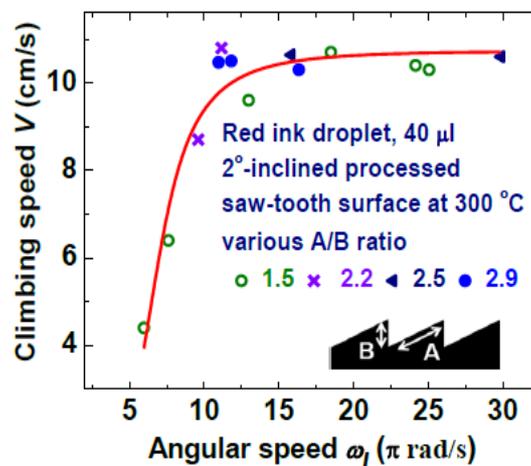


Fig. 7 Variations of the climbing speed with the angular speed of the large vortex.

3 Thermal perturbation

In this experiment, the climbing speeds of water droplets at various initial temperatures are recorded. As results shown in Fig. 12, the climbing speed reaches equilibrium at ~ 0.04 s and is found to be significantly reduced as the temperature of the droplets approaches the boiling point, which indicates that the boiling effect thoroughly disturbs the vortices.

In particular, for droplets of temperatures ranging from 20 to 80 °C, a great reduction of speed appears before it stabilizes. This shows that the drag momentum from the smaller vortex stabilizes later.

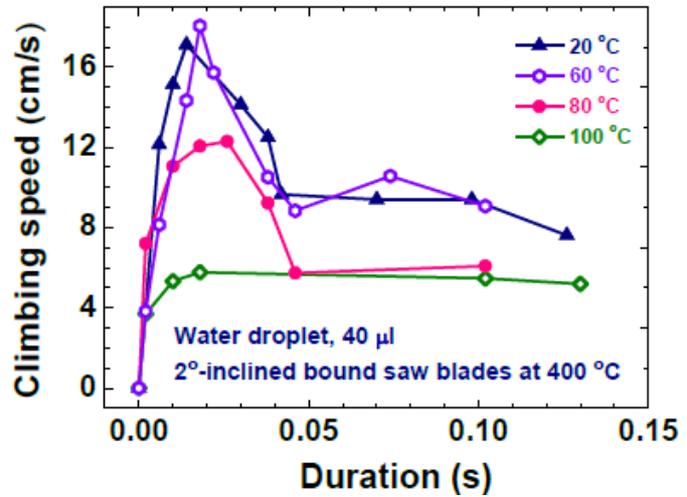


Fig. 12 A chart shows the climbing speed of water droplets at various initial temperatures.

IV Damped bound state

The interactions between the edges on the bar and droplets of various sizes are the focus of this section, as shown below:

1 Single trigger

Wonderfully, as the droplet touches an edge of the bar, it deforms and evaporates more violently than sliding on the smooth surface. This effect is realized in the form of a sizzling sound as well as a visible puff of steam surrounding. After that, the motion of the droplet reverses, which is triggered by an observed clockwise vortex (Fig.13).

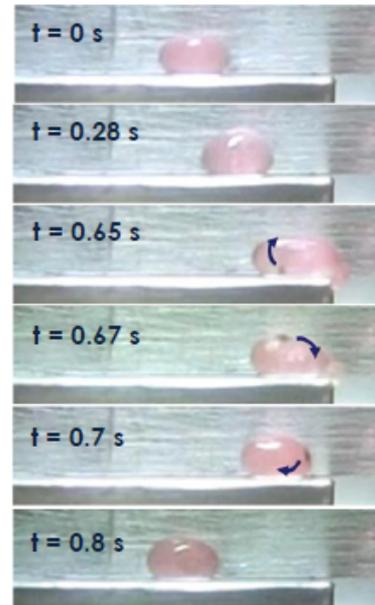


Fig. 13 Photos indicate a small droplet which is triggered by a sharp edge.

2 Double trigger

Based on a larger degree of deformation needed, droplets larger than 50 μl require two edges on the bar to be triggered. Furthermore, pepper particles are placed into the red ink droplets again. Surprisingly, the pattern of flowing liquids (Fig. 14) is observed to be very similar to the one in the saw blade system. Based on the driving momentum from the large vortex, the oscillations are then explained.

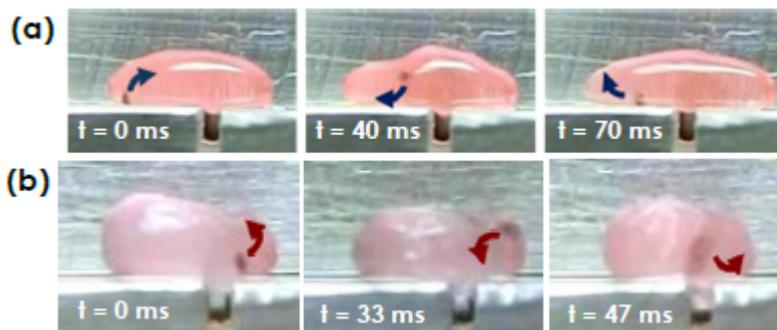


Fig. 14 Internal flows of (a) the larger and (b) the smaller vortices of a red ink droplet on a 2°- inclined hot smooth surface at 200 °C

3 Energy resources

In this section, I analyzed the droplet oscillations on the notched-aluminum bar and observed that the oscillator damps simultaneously with a reduction in its own mass (Fig. 15). This damping may be due to the capability-reducing vortices within the droplets that accompany the mass reduction. In addition, this reduction could also be regarded as an energy resource for triggering the droplets because the atomic binding energy is released as the liquid droplet evaporates into vapor.

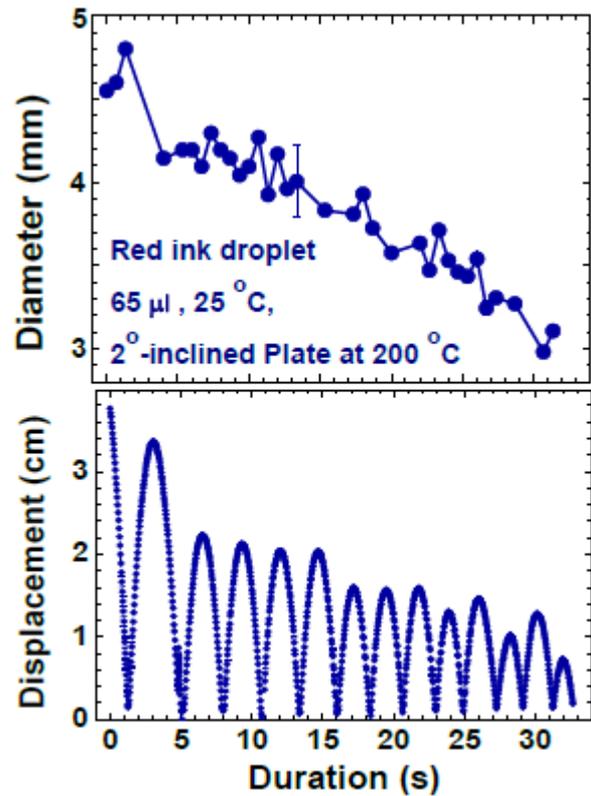


Fig. 15 Charts showing (a) a mass reduction and (b) damped oscillations of a red ink droplet

Conclusions

- 1 A supporting vapor layer underneath a droplet protects it from being violently evaporated for a self-propelled engine of water droplets on a hot surface.
- 2 The key is to produce two uneven liquid vortices that are circulating about horizontal axes in opposite directions and at different speeds.
- 3 It's the chemical energy released from evaporation that provides the energy for vortex circulation and droplet motion.
- 4 Vortices instability from local turbulence can significantly reduce the self-propulsion capability.

Potential Application

This engine can be applied in the real world to deliver cold liquids into the remote or hard-to-reach cores of hot sources for temperature control or emergency cooling of the cores at specific spots.

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評語

- 1、 本作品研究水滴在高溫不對稱鋸齒面上爬坡現象之機制，並研究水滴內水流特性與水滴運動的關係，此外並在高溫平面上之凹槽反射水滴，有非常高的創意。
- 2、 作者若能控制鋸齒的幾何特徵，例如斜度、尖端特性等，再做更多的定量分析，更能釐清水滴運動的物理機制。