FROM ELECTROSPINNING TO THERMAL MANAGEMENT IN MICROELECTRONICS, FROM CO-ELECTROSPINNING TO NANOFLOWIDICS

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Outline

1. Electrospinning of nanofiber mats
2. Drops on nanofiber mats: static superhydrophobicity
3. Drop impact on nanofiber mats: dynamic wettability
4. Cooling of micro- and opto-electronics, and radiological devices; UAVs, UGVs and server racks
5. Carbon nanotubes via co-electrospinning
6. Carbon nanotubes from a single nozzle
7. Pressure-driven nanofluidics in macroscopically long carbon nanotubes
8. Template approach: nanotube strips
9. Beyond Poiseuille
Process Initiation: Taylor Cone

Electrospinning of Polymer Solutions


Electrospinning of Polymer Solutions

Reneker, Yarin, Fong, Koombhogse
Electrospinning of Polymer Solutions

Reneker, Yarin, Fong, Koombhongse
a- Syringe drop generator for direct impact of 2-3 mm or 100 micron drops at velocities of about 2 m/s.
b- Syringe drop generator produces primary drop, which impact on liquid film and produce corona splash to generate 0.4-1.4 mm drops for oblique impact.
Electrospun Nanofiber Mat and a Droplet Softly Deposited on it

Static superhydrophobicity: Cassie-Baxter state due to 90-95% of air in the mat

### Drop Impact on a Dry Solid Wall

<table>
<thead>
<tr>
<th>Deposition</th>
<th>Prompt splash</th>
<th>Corona splash</th>
<th>Receding break-up</th>
<th>Partial rebound</th>
<th>Complete rebound</th>
</tr>
</thead>
</table>

Drop Impact on a Dry Nanofiber Mat

Contact line is pinned: no receding, no bouncing; Dynamically imposed Wenzel state
Drop Impact on Prewetted Nanofiber Mat:
Back to Corona Splash

<table>
<thead>
<tr>
<th></th>
<th>0s</th>
<th>0.003s</th>
<th>0.007s</th>
<th>0.014s</th>
<th>0.03s</th>
</tr>
</thead>
<tbody>
<tr>
<td>a)</td>
<td><img src="image1.jpg" alt="Image" /></td>
<td><img src="image2.jpg" alt="Image" /></td>
<td><img src="image3.jpg" alt="Image" /></td>
<td><img src="image4.jpg" alt="Image" /></td>
<td><img src="image5.jpg" alt="Image" /></td>
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<tr>
<td>b)</td>
<td><img src="image6.jpg" alt="Image" /></td>
<td><img src="image7.jpg" alt="Image" /></td>
<td><img src="image8.jpg" alt="Image" /></td>
<td><img src="image9.jpg" alt="Image" /></td>
<td><img src="image10.jpg" alt="Image" /></td>
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<tr>
<td>c)</td>
<td><img src="image11.jpg" alt="Image" /></td>
<td><img src="image12.jpg" alt="Image" /></td>
<td><img src="image13.jpg" alt="Image" /></td>
<td><img src="image14.jpg" alt="Image" /></td>
<td><img src="image15.jpg" alt="Image" /></td>
</tr>
<tr>
<td>d)</td>
<td><img src="image16.jpg" alt="Image" /></td>
<td><img src="image17.jpg" alt="Image" /></td>
<td><img src="image18.jpg" alt="Image" /></td>
<td><img src="image19.jpg" alt="Image" /></td>
<td><img src="image20.jpg" alt="Image" /></td>
</tr>
</tbody>
</table>
Pressure impulse and potential

\[ \Pi = \lim_{t \to 0} \int_0^t \Delta p \, dt; \quad \varphi = -\Pi / \rho \]

Potential \( \varphi \) is a harmonic function

Evaluating pressure impulse

Compressible impact:
The convective part of the force:
\[ F_c = \rho V_0 c D^2 \]

The "water hammer"-like part of the force:
\[ F_{wh} = -\rho D^3 A = -\rho D^3 \left(-V_0 c / D \right) = \rho V_0 c D^2. \]

Therefore,
\[ \Delta p = F / D^2 = \rho V_0 c; \quad \tau = D / c, \text{ and} \]
\[ \Pi = \rho V_0 D; \quad \varphi_0 = -V_0 D \]
Evaluating pressure impulse

Incompressible impact:
The convective part of the force:

\[ F_c = \rho V_0^2 D^2 \]

The "water hammer"—like part of the force:

\[ F_{\text{wh}} = -\rho D^3 A = -\rho D^3 \left( -\frac{V_0 V_0}{D} \right) = \rho V_0^2 D^2. \]

Therefore,

\[ \Delta p = F / D^2 = \rho V_0^2; \quad \tau = D / V_0, \text{ and} \]

\[ \Pi = \rho V_0 D; \quad \phi_0 = -V_0 D \quad \text{as in the compressible case} \]
Accumulation and Channeling of Kinetic Energy in Drop Impact on a Pore

Liquid drop at the "moment of impact"
The boundary condition for the harmonic potential: Planar case

Over \(-\infty \leq X \leq -a, \ y = 0\);
and over \(a \leq X \leq \infty, \ y = 0\) (2D wall):
\[
\varphi(X) = \varphi_0 = -V_0 D
\]
Over \(-a < X < a, \ y = 0\) (2D pore):
\[
\varphi(X) = 0.
\]
The harmonic potential in the liquid drop in the upper half-plane is given by the Cauchy formula, which reduces to Poisson’s integral formula for the upper half-plane

\[
\varphi(x, y) = \frac{1}{\pi} \int_{-\infty}^{\infty} \frac{\varphi(X, 0)y}{(x-X)+y^2} dX = -\frac{\varphi_0}{\pi} \arctan \left( \frac{2ay}{x^2+y^2-a^2} \right)
\]

Therefore,

\[
V_{\text{opening}}(x) = \left. \frac{\partial \varphi}{\partial y} \right|_{y=0} = \frac{V_0 D}{\pi} \frac{2a}{x^2-a^2};
\]

\[
|V_{\text{opening}}(0)| = \frac{V_0}{\pi a} \frac{2 D}{a} = \frac{d}{2}
\]
The Reasons of Filling Non-wettable Nanofiber Mats

Predicted penetration speed: accumulation and channeling of kinetic energy (a la shaped-charge jets!)

\[ U = \frac{4}{\pi} \frac{D}{d} V_0 \]

Impregnation: Lucas-Washburn speed

\[ U_{LW} = \frac{\sigma d \cos \theta}{8 \mu H} \]

\[ \frac{D}{d} \gg 1, \quad U \gg U_{LW} \]

Wettability plays practically no role: it is possible to fill non-wettable pores!!!
The boundary condition for the harmonic potential: Cylindrical case-Solved by the Fourier method as a problem with a continuous spectrum

Over \( a \leq r \leq \infty, z = 0 \) (2D wall):
\[
\varphi(X) = \varphi_0 = -V_0D
\]
Over \( 0 \leq t < a, y = 0 \) (2D pore):
\[
\varphi(X) = 0.
\]

The harmonic potential in the liquid drop in the upper semi-space: Cylindrical case-solution as the Fourier-Bessel integral

\[ \varphi(r, z) = V_0 Da \int_0^\infty J_0(r)J_1(va)\exp(-vz)dv \]

Therefore,

\[ v_z(r) \bigg|_{z=0} = \frac{\partial \varphi}{\partial z} \bigg|_{z=0} = -V_0D \int_a^\infty \xi J_0 \left( \frac{r}{a} \right) J_1(\xi) d\xi; \]

\[ \left| v_z(r=0) \right|_{z=0} = V_0 \frac{2D}{d}; \quad a = d / 2 \]
The Reasons of Filling Non-wettable Nanofiber Mats

Predicted penetration speed: Predicted in the cylindrical case

\[ U = \frac{2D}{d} V_0 \]

Even higher than in the planar case!

Wettability plays practically no role: it is possible to fill non-wettable pores!!!
Observations of Water Spreading inside Nanofiber Mats

Setup for observations of nanomat impregnation
Water Spreading inside Nanofiber Mat: Experimental Results

Matching of refractive indexes of wet nanofibers and water makes the copper substrate visible
Water Spreading inside Nanofiber Mat:
1D Axisymmetric Theory

The moisture transport equation:
\[
\frac{\partial u}{\partial t} = a_m \frac{1}{r} \frac{\partial}{\partial r} \left( r \frac{\partial u}{\partial r} \right)
\]

The initial and boundary conditions:
\[ t = 0: \quad u = \chi(r); \quad t \geq 0: \quad u < \infty, \quad r = 0 \quad \text{and} \quad u = 0, \quad r = \infty \]

The solution:
\[
u(r, t) = \frac{1}{2a_m t} \exp \left( -\frac{r^2}{4a_m t} \right) \int_0^{\xi} \exp \left( -\frac{\xi^2}{4a_m t} \right) I_0 \left( \frac{r\xi}{2a_m t} \right) \xi \, d\xi
\]
Water Spreading inside Nanofiber Mat: 1D Axisymmetric Theory
Water Spreading inside Nanofiber Mat: Experiments vs. Theory

\[ R_f = 1.492 \sqrt{a_m t} + \text{const} \]

The moisture transport coefficient:

\[ a_m = 8 \times 10^{-4} \, \text{cm}^2 / \text{s} \]
The images were downloaded from internet
Drop/Spray Cooling through Nanofiber Mats: Thermal Stability? PCL Easily Shrinks

Drop/Spray Cooling through Nanofiber Mats: PAN Does Not Shrink Even at 250°C
Temperature Field

Bare metal

Metal covered by nanofiber mat

$t=0.0042\ s$

$t=0.004\ s$

$t=100\ s$

$t=13\ s$

$t=280\ s$

$t=46\ s$
An attractive way for cooling high-heat flux components in microelectronics (e.g. on board of UAVs), as well as server rooms
Bare Surface: The Leidenfrost Effect

(a) 60°C, (b) 220°C, and (c) 300°C
Nano-Textured Surface: The Anti-Leidenfrost Effect

(a) 60°C, (b) 220°C, and (c) 300°C
Australian Thorny Devil Lizard
Thorny Devil Copper Nanofibers
Thorny Devil Nanofibers: Fractal Surfaces?
Silver Nanofibers: Dendrite-Like
Nickel Nanofibers: Rough and Smooth Domains
Gold Nanofibers: Rather Smooth
Experimental Setup
Drop Impact from Height of 3.55 cm at Copper Thorny Devil Nanofibers at 150 C

(a) at t = 0

(b) at t = 32.5 ms

(c) at t = 70 ms

Bubbling of water

Cessation of activity
The Anti-Leidenfrost Effect on Copper Thorny Devil Nanofibers at 172.2°C
Drop Impact at Thorny Devil Nanofibers at 125°C

<table>
<thead>
<tr>
<th>Time (ms)</th>
<th>Copper fibers</th>
<th>Bare copper</th>
<th>Silver fibers</th>
<th>Nickel fibers</th>
<th>Gold fibers</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 ms</td>
<td>(a)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>33 ms</td>
<td>(b)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>66 ms</td>
<td>(c)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>132 ms</td>
<td>(d)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Thermal diffusivities:
Cu-1.12; Ag-1.66; Ni-0.155; Au-1.27 (sq.cm/s);
Water evaporation on copper and silver fibers is the fastest but on gold—the slowest! Thorny devils win!
Drop Impact at Thorny Devil Nanofibers at 150 C

- Copper fibers
- Bare copper fibers
- Silver fibers
- Nickel fibers
- Gold fibers

0 ms (a)
33 ms (b)
66 ms (c)
132 ms (d)
Drop Impact at Thorny Devil Nanofibers at 200 C

![Image showing drop impact at different times and materials: Copper fibers, Bare copper, Silver fibers, Nickel fibers, Gold fibers.](image)
Mass Losses due to “Atomization” during Evaporative Cooling Through Copper Nanofibers

Copper fibers:
a-125 C,
b-150 C,
c-200 C

(a)

(b)

(c)
Mass Losses due to “Atomization” during Evaporative Cooling on Bare Copper
Mass Losses due to “Atomization” during Evaporative Cooling on Silver Nanofibers

Silver fibers:
- 150°C
- 200°C

(a)  
(b)
Mass Losses due to “Atomization” during Evaporative Cooling on Nickel Nanofibers

Silver fibers:
a- 125 C
b- 150 C
c- 200 C
The Resulting Spreading Factor and Cooling Rate for Copper Nanofibers at Different Impact Speeds

<table>
<thead>
<tr>
<th>h (cm)</th>
<th>V (cm/s)</th>
<th>Δt (ms)</th>
<th>ξ</th>
<th>p</th>
<th>J-evap. (kW/cm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.55</td>
<td>83.46</td>
<td>70</td>
<td>2.6</td>
<td>0</td>
<td>0.607</td>
</tr>
<tr>
<td>6.15</td>
<td>109.85</td>
<td>58</td>
<td>2.85</td>
<td>0</td>
<td>0.575</td>
</tr>
<tr>
<td>8.75</td>
<td>131.02</td>
<td>53.5</td>
<td>3.02</td>
<td>0</td>
<td>0.555</td>
</tr>
<tr>
<td>11.15</td>
<td>147.91</td>
<td>52.5</td>
<td>3.15</td>
<td>0</td>
<td>0.521</td>
</tr>
<tr>
<td>13.75</td>
<td>164.25</td>
<td>47</td>
<td>3.41</td>
<td>0</td>
<td>0.543</td>
</tr>
</tbody>
</table>
The Resulting Spreading Factor and Cooling Rate for Metal-Plated Nanofibers at Different Impact Speeds and the Non-Zero “Atomization” Ratio p

<table>
<thead>
<tr>
<th>Material</th>
<th>Temperature (°C)</th>
<th>Δt (ms)</th>
<th>p</th>
<th>J-evap. (kW/ cm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bare copper</td>
<td>125</td>
<td>264</td>
<td>0.32</td>
<td>0.256</td>
</tr>
<tr>
<td></td>
<td>150</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td></td>
<td>200</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Copper nanofibers</td>
<td>125</td>
<td>172.5</td>
<td>0.09</td>
<td>0.136</td>
</tr>
<tr>
<td></td>
<td>150</td>
<td>53</td>
<td>0.16</td>
<td>0.392</td>
</tr>
<tr>
<td></td>
<td>200</td>
<td>52</td>
<td>0.13</td>
<td>0.408</td>
</tr>
<tr>
<td>Silver nanofibers</td>
<td>125</td>
<td>170</td>
<td>0.05</td>
<td>0.138</td>
</tr>
<tr>
<td></td>
<td>150</td>
<td>128.5</td>
<td>0.056</td>
<td>0.181</td>
</tr>
<tr>
<td></td>
<td>200</td>
<td>55.5</td>
<td>0.08</td>
<td>0.407</td>
</tr>
<tr>
<td>Nickel nanofibers</td>
<td>125</td>
<td>355</td>
<td>0.124</td>
<td>0.061</td>
</tr>
<tr>
<td></td>
<td>150</td>
<td>600</td>
<td>0.25</td>
<td>0.031</td>
</tr>
<tr>
<td></td>
<td>200</td>
<td>388</td>
<td>0.15</td>
<td>0.054</td>
</tr>
<tr>
<td>Gold nanofiber</td>
<td>125</td>
<td>495</td>
<td>0.05</td>
<td>0.047</td>
</tr>
<tr>
<td></td>
<td>150</td>
<td>633.5</td>
<td>0.05</td>
<td>0.037</td>
</tr>
<tr>
<td></td>
<td>200</td>
<td>468</td>
<td>0.05</td>
<td>0.049</td>
</tr>
</tbody>
</table>
Co-electrospinning: Compound Nanofibers and Nanotubes

Solution: PEO (1e6) 1% in ethanol/water
Inner solution contains 2% bromophenol
Outer solution contains 0.2% bromophenol

Co-electrospinning

Core: PMMA

Shell: PAN


Experimental setup

Plot of the electric field strength in the region of the wheel

Theron A, Zussman E, Yarin A L, *Nanotechnology* 12, 2001
Nanoropes

5μm

2μm
Turbostratic Carbon Nanotubes

Core: PMMA
Shell: PAN
Optical appearance of a PMMA/PAN emulsion about 1 day after mixing of a homogeneous blend containing 6 wt% PMMA + 6% PAN in DMF

A.V. Bazilevsky, A.L. Yarin, C.M. Megaridis
Experimental set-up and hollow carbon tubes
Pressure-driven Nanofluidics in Macroscopically Long Carbon Nanotubes

Experimental Setup

[Diagram of experimental setup with labeled parts: Pressure gauge, Stopcock, Air chamber, Three way stopcock, Glass capillary, CCD, PC]

[Image of micrograph showing Epoxy, CNT bundle, Water, Bubble, scale bar 1mm]
Release Observation

- N-decane
- Gas bubble
- Epoxy plug
- Water
- N-decane droplet
- Bubble
- 1mm

Mechanical & Industrial Engineering
N-decane Flow Rate; Recovering the Flow-carrying Inner Tube Diameter Distribution

\[ Q = \left( \pi a^4 \frac{N}{8\mu L} \right) \Delta p \]
Amendment to Poiseuille’s Law

\[ Q \propto a_{\text{max}}^4 + a_{\text{max}-1}^4 \Delta p \]

\[ \Delta p_* = \frac{2\sigma}{a_{\text{max}}} \]

\[ \frac{2\sigma}{a_{\text{max}-1}} \]
Template Approach: Nanotube Strips

Entrapped Bubbles: Two-phase Flows

(a)

(b)

- Air
- N-decane
- Nanotubes
- Epoxy
- Glass Capillary
Modeling of Entrapped Air in n-Decane

Four possible situations describing air-liquid flow

1. Capillary instability

2. Air-liquid flow with dispersed bubbles

3. Capillary instability

4. Dispersed bubbles cannot appear due to relatively low pressure available; would contradict the observations (reducing liquid flow rate)!
Theoretical Model

\[ \frac{d^2 u_i}{dy^2} = \frac{1}{\mu_i} \frac{dp}{dx}, \quad i = 1, 2, \quad \ldots \ldots (1) \]

The boundary conditions are:

\[ y = 0 \quad u_1 = 0; \quad y = H \quad u_2 = 0, \quad \ldots \ldots (2) \]

\[ y = h \quad u_1 = u_2, \quad \mu_1 \frac{du_1}{dy} = \mu_2 \frac{du_2}{dy}, \quad \ldots \ldots (3) \]

where \( i = 1 \) and 2 correspond to liquid and gas
The Outcome is Amazing!!! Beyond Poiseuille

\[ R = \frac{Q_l}{Q_{l,\text{pure}}} = -2\bar{h}^3 + 3\frac{\bar{h}^2 - \bar{h}^4(1 - \mu_2 / \mu_1)}{1 - \bar{h}(1 - \mu_2 / \mu_1)} \]

\[ \bar{h} = \frac{h}{H} \]

\[ Q_{l,\text{pure}} = -\frac{H^3}{12\mu_1} \frac{dp}{dx}, \]

Explanation

Velocity profile in n-decane/air flow ($\mu_2/\mu_1=0.0196$), $h/H=0.8$. 

$0.8 \leq y/H \leq 1$
Experiments: Observations

(a) at 1.143 bar

(b) at 1.133 bar

Same nanotubes at the same pressure
Experiments: Measurements
Results

Volumetric flow rates of bi-layer n-decane/air flow ($Q_1$, triangles) and pure n-decane ($Q_{1,pure}$, squares) through the same carbon nanotube bundle.

The average $Q_1/Q_{1,pure} = 2.188$

Reverse Osmosis for Water Desalination!
Conclusions

(i) Electrospun nanofiber mats and their metallized or carbonized counterparts (monolithic and hollow) can be used for significant enhancement of heat removal in drop/spray high-heat-flux microelectronics. It is possible to reach heat removal rates of the order of 1 kW/sq.cm with water, which might result in breakthrough in further miniatutrition in microelectroncs devices and computers.

(ii) Coelectrospun nanofluidics of layered gas/liquid flows demonstrated how significant benefits for reverse osmosis in water desalination can be achieved.