Multifunctional Poro-Vascular Composites for UAV Performance Enhancement

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2nd Multifunctional Materials for Defense Workshop

July 31, 2012
# Multifunctional Poro-Vascular Composites for UAV Performance Enhancement

**1. REPORT DATE**
31 JUL 2012

**2. REPORT TYPE**

**3. DATES COVERED**
00-00-2012 to 00-00-2012

**4. TITLE AND SUBTITLE**
Multifunctional Poro-Vascular Composites for UAV Performance Enhancement

**5a. CONTRACT NUMBER**

**5b. GRANT NUMBER**

**5c. PROGRAM ELEMENT NUMBER**

**5d. PROJECT NUMBER**

**5e. TASK NUMBER**

**5f. WORK UNIT NUMBER**

**6. AUTHOR(S)**

**7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)**
U.S. Naval Research Laboratory, Multifunctional Materials Branch, Code 6350, Washington, DC, 20375

**8. PERFORMING ORGANIZATION REPORT NUMBER**

**9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)**

**10. SPONSOR/MONITOR’S ACRONYM(S)**

**11. SPONSOR/MONITOR’S REPORT NUMBER(S)**

**12. DISTRIBUTION/AVAILABILITY STATEMENT**
Approved for public release; distribution unlimited

**13. SUPPLEMENTARY NOTES**
Presented at the 2nd Multifunctional Materials for Defense Workshop in conjunction with the 2012 Annual Grantees’/Contractors’ Meeting for AFOSR Program on Mechanics of Multifunctional Materials & Microsystems Held 30 July - 3 August 2012 in Arlington, VA. Sponsored by AFRL, AFOSR, ARO, NRL, ONR, and ARL.

**14. ABSTRACT**

**15. SUBJECT TERMS**

**16. SECURITY CLASSIFICATION OF:**

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**17. LIMITATION OF ABSTRACT**
Same as Report (SAR)

**18. NUMBER OF PAGES**
20

**19a. NAME OF RESPONSIBLE PERSON**

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Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18
Outline

• Introduction & UAV Application
• Functional Overview
• Fluid-Phase Modeling
• Electro-Wetting Phenomena
• Fabrication & Vascular Flow Control
• Summary

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Acknowledgement: Office of Naval Research (NRL 6.1 Core Program)
Poro-Vascular Composites

Multifunctional structural “skin” materials with surface pores and internal vascular channels filled with an ionic-liquid whose height and shape at the pore exits is actively controlled.

Key Features
• Flexible structural skin laminate with $t \sim \text{mm}$.
• Surface-roughness control on sub-mm scale.
• Structure-roughness multifunctionality.

Fluid-Phase Surface Morphologies

$V = 0$

non-wetting

applied voltage

vascular pumping

wetting
UAV Applications

Structural skin layer with active surface roughness control for drag/heat transfer tuning → enhanced performance & energy efficiency.

<table>
<thead>
<tr>
<th>Surface Configuration</th>
<th>Normalized Heat Transfer, St/St₀</th>
<th>Normalized Skin Friction, C_f/C_f₀</th>
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<tr>
<td>Flat</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>Dimpled</td>
<td>1.3-1.6</td>
<td>1.2-2.2</td>
</tr>
<tr>
<td>Domed</td>
<td>1.4-2.5</td>
<td>2.5-3.3</td>
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Aerodynamic Notions

Skin-friction drag ($C_f$) versus Reynold's number ($Re_L$) for Flat Plates with Surface Roughness ($\varepsilon/L$)

Total Drag = (skin-friction + pressure) drag + induced drag

Surface Roughness Effects
Increased roughness ($\varepsilon/L$) →
- no effect on $C_f$ in laminar flow regime,
- significant increase in $C_f$ in turbulent regime,
- transitions to turbulent boundary-layer flow at lower $Re$. 

Reference: www.hpcnet.org/upload/directory/.../15698_20080506135629.ppt
Aerodynamics Notions (cont’d)

Pressure drag affected by boundary-layer flow separation!

Total Drag = (skin-friction + pressure) drag + induced drag

Airfoil Boundary-Layer Separation

Surface Roughness Effects

Increased roughness ($\varepsilon/L$) →
- induces transition to turbulent boundary-layer flow at lower $Re$,
- turbulent boundary-layer remains attached → lower pressure drag,
- laminar boundary-layer flow separates → higher pressure drag.
Functional Overview

- **Pore Fluid Meniscus Shape**
  - EWOD electroding
  - IL properties
  - Pore configuration

- **Fluid Height in Pore**
  - Channel configuration & surface properties
  - Pump characteristics
  - IL properties

**Structural Properties**
- Material properties, Laminate, pore array, channel configurations

**Surface Morphology Properties**
- Fluid shape and height control

**Integration into structure**

**Multifunctional Composite for System-Level Performance and New Capabilities**

**Thermal Control Applications:**
- heat-flow switching,
- enhanced thermal dissipation,
- enhanced “fin” efficiency

**UAV Applications:**
- new aero-control capability
- energy efficiency
- reduced weight

**Other Applications:**
- surface reflectivity
- surface damage sensing
- surface healing
Fluid-Phase Modeling

**Bond Number**

\[ B_0 = \frac{\Delta \rho g d}{\gamma / d} \]

- \( B_0 < 1 \) → gravity negligible
- \( B_0 \sim 0.1 \) PV composites

**Can ignore gravity!!**
Fluid-Phase Modeling

Laplace-Young: (capillary physics)

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

Young-Lippmann: (EWOD)

$$\cos \theta = \cos \theta_0 + \frac{\varepsilon_0 \varepsilon}{2t\gamma} V^2$$

Geometry:

$$r = -\frac{d}{2 \sec \theta}$$

Circular pores $\rightarrow$ spherical geometry

d = pore diameter
h = distance to meniscus top
$\theta$ = contact angle
r = radius of curvature
$\Delta P = p_f - p_a = \text{fluid “gauge” pressure}$

$$\Delta P = \frac{-4\gamma}{d} \cos \theta \quad & \quad h = \frac{d}{2} \left( \frac{\sin \theta - 1}{\cos \theta} \right)$$
### Modeling Results

#### Three Regimes

1. **A-B**: pore filling (constant \(r \& p\))
2. **B-C**: pore-surface transition (\(\theta \rightarrow \theta + \pi/2\))
3. **C-D**: fluid spreading (\(r \uparrow \& p \downarrow\))

#### Key Implications

- For stable behavior beyond peak pressure points (e.g., C or E):
  - displacement-pumping avoids uncontrolled spillage from pore,
  - hysteresis prevents siphon from pore with smallest contact angle.
- Large non-wetting contact angle not needed; anything >90 deg OK.
- Domed geometry natural \(\rightarrow\) others (flat or dimple) require polarization.
Electro-Wetting on Dielectric (EWOD)

Influence of applied potential on contact angle.

Lippmann-Young Equation:

\[ \cos \theta = \cos \theta_0 + \frac{1}{2\gamma} \left( \frac{\varepsilon_0 \varepsilon}{t} \right) V^2 \]

- Apparent contact angle
- Intrinsic contact angle (zero voltage)
- Permittivity of dielectric layer(s) over thickness
- Interfacial tension (IFT) of ionic liquid
- Applied potential
Electro-Wetting on Dielectric (EWOD)

Typical behavior

Contact Angle, $\theta$

Electric Potential, $V$

- non-wetting
- wetting
- advancing
- receding
- hysteresis
- saturation
- ideal (L-Y) behavior

Design Objectives:
- maximal $\Delta \theta$ with $V$
- minimal hysteresis
**EWOD and Meniscus Characterization**

*flat plates $\rightarrow$ single (capillary) pore $\rightarrow$ PV pore arrays*

**FTA 1000 Drop-Shape Characterization**
- Microscope lens: 0.5 to 12x magnification
- Side-, top-view cameras to 60 frames/sec

**EWOD Characterization Procedure**

- **Measurement Index, $n$**
  - Drop Width [mm]: 0.4, 0.8, 1.2, 1.6, 2.0
  - Contact Angle, $\theta$ [deg]: 90, 100, 110, 120, 130

- **Aqueous 0.1 M NaCl Solution**
- Conductive Kapton XC substrate
- Parylene-C (5.0 um) dielectric
- Teflon AF 1600 (200 nm) hydrophobic
- Applied potential: 0 ($\pm 50, 100, 150, 200$) volts
Flat Plate EWOD Characterization

Substrate Effects

Fluid Composition Effects

Key Implications

• Aqueous (0.1 M NaCl) fluids show larger $\Delta \theta$ versus applied potential,
• $\Delta \theta$ hysteresis due to variations in surface electrode layer properties.
Layer Deposition Effects

Kapton HN + Parylene HT + Teflon AF

Kapton RS200 + Parylene HT

$(\Delta h)_{\text{max}} \sim 600 \text{ nm}$
Fabrication

- **EWOD experiments:**
  - Flat specimens for electroding and IL shape control studies.
  - Glass capillary “single-pore analogs” for meniscus shape control studies.

- **PV composites experiments:**
  - Non-functional prototypes for fabrication technique assessment.
  - Functional PV composite prototypes for fluid control and pumping demonstrations.

Laser Micromachining System

Higher-speed possible via laser raster with stationary workpiece.
5-Layer Laminate Design

Processing Steps:

- Kapton RS bonded to Cirlex then laser micro-machined to create pores and channels,
- Glass capillary bonded to main channel for external-fluidic connection,
- Kapton HN bonded to seal channels,
- Assembly vapor-coated with Parylene-C and spin-coated with Teflon AF.
EWOD Electroding in PV Composites

Materials; thicknesses; and processing challenges

Pore Cross-Section

Key Challenges
- Require EWOD electroding on pore walls and surface at exit;
- Must avoid conductive paths between IL and solid-phase.
Fluid Height Control in Pores

- **Objective:** assess uniformity of fluid filling of pores.
- **Setup:** poro-vascular prototype without electroding layers:
  - 1000 μm diameter pores, 8 x 8 array,
  - external displacement pump control,
  - water, isopropyl alcohol fluids.
- **Measurements:**
  - qualitative video

**Results**
- Fluid constrictions at pore entries allowed uniform fluid delivery to all pores in array,
- Vascular designs with appropriate fluid curvatures needed via channel-pore geometry and surface coatings to assure uniform delivery.
Ongoing and Future Work

• Fluid shape-height control and characterization:
  o EWOD experimentation with glass capillaries (“single-pore”) and pore-array configurations,
  o Particle additives in fluid for enhanced EWOD performance,
  o Vascular network design for filling and fluid height control in pore,

• Structural characterization and interactions:
  o Mechanical properties,
  o Deformation interactions with fluid control,

• Application to airfoil aerodynamics:
  o Wind-tunnel experiments with “static” silicone PVC models on airfoil geometry for drag, lift, and transition characterization and proof-of-concept,
  o Computational simulation of surface morphology effects on boundary layer flow using airfoil models and direct numerical simulation,
  o Computational modeling/design to determine optimal surface morphologies for airfoil control applications.