# **Nanofluidic Energy Conversion**

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# **Advantage of Nanoporous Materials**

#### Nanoporous materials:

- Zeolites, nanoporous silicas, aluminas, TiO<sub>2</sub>, Au, Cu, PMMA, carbon nanotube ...) are solids containing large volume fractions (30-90%) of nanometer-sized pores
- They are usually synthesized by templating or nanocasting techniques, and used for selective sorption or catalysis. Cost is relatively low.
- Pore size from <1nm to about 100nm.
- The specific surface area is ~  $100-2000 \text{ m}^2/\text{g}$ .





### Ultralarge Surface of Nanoporous Materials: Ideal Platform for Energy Conversion



The area of an entire Olympic stadium in several gram of nanoporous material



The very large inner surface of a nanoporous material (~10,000,000 times larger than its bulk counterparts) provides an ideal platform for surface energy conversion processes: And nanoporous solid and liquid can make seamless coupling to become an attractive **multifunctional nanocomposite**.

(Total Converted Energy) = (Surface Energy Density) (Total Surface Area)

Adjustable → Variable performance



# **Nanofluidic Energy Conversion**



# **Nanofluidic Energy Absorption**



# **Nanofluidic Energy Absorption**

**Energy Absorption**: Conversion of Mechanical Energy to Other Forms



- Adjustable interface properties  $\rightarrow$  variable performance
- Fundamental behaviors of molecules in confined nanoenvironment

# Nanoporous Energy Absorption System (NEAS)



Suspension of hydrophobic nanoporous particles in a nonwetting liquid.

A nanocomposite which seamlessly integrates the nanoporous solid "matrix" with liquid "filler"

#### **Example of NEAS Sorption Isotherm**



Hydrophobic <u>nanoporous silica</u> particles immersed in <u>water</u>. Average pore size: 10 nm. Specific pore volume: 0.6 cm<sup>3</sup>/g. Specific surface area is ~500 m<sup>2</sup>/g.

Energy absorption: 150 J/g (orders-of-magnitude higher w.r.t. conventional energy absorption systems, 0.1 J/g of Ti-Ni alloy, 1-10 J/g of textile composites, etc.)

#### **Example of Adjust Energy Absorption Performance**



 $\mathbf{E} = \Delta \boldsymbol{\gamma} \cdot \mathbf{A}$ 

Both  $P_{in}$  and  $dP/dV \sim \Delta\gamma$ Adjustable system and materials parameters  $\rightarrow$ variable performance



# **Nanofluidic Energy Actuation**



# **Nanofluidic Energy Actuation**

<u>Actuation</u>: Conversion of other forms of energy (e.g. thermal energy or electric energy) to mechanical motion

Electro-capillary effect: As an electric potential is applied across a solid-liquid interface, the interface tension varies, which may cause liquid motions (electric to mechanical energy conversion)

Thermo-capillary effect: As temperature changes, the solid-liquid interfacial tension varies accordingly, which may cause liquid motions (thermal to mechanical energy conversion)

 $E = \delta \gamma A$ 



 Interface energy ~ electrical field or temperature
Electrical/thermal fields can cause hydrophobic hydrophilic transition which leads to liquid motions

### **Actuation based on Thermo-capillary Effect**



 $E = \delta \gamma \cdot A$ 

Output energy density  $E = \delta \gamma \cdot A \sim 1-100 \text{ J/g}$  $\delta \gamma \sim 1-100 \text{ mJ/m}^2; A \sim 100-1000 \text{ m}^2/\text{g}$ 

(compared with 1-100mJ/g for piezoelectrics, shape memory alloys, etc.)



### **Electro-capillary effect and Actuation**



With constant volume, pressure increases as the system becomes more hydrophobic (which is controllable by the potential difference, voltage)



The thermo-/electro- capillary effect, which is "trivial" in conventional materials, becomes significant in nanoporous materials.

# **Nanofluidic Energy Harvesting**



# **Nanofluidic Energy Harvesting**

**Energy Harvesting**: Conversion of other forms of energy (e.g. thermal energy or mechanical energy) to electricity



As an electrolyte solution enters a nanopore, since ions at the solid-liquid interface are subjected to unbalanced forces from the solid and the bulk liquid phase, the ion structure becomes anisotropic, forming a double layer. That is, an solid electrode nanochannel can spontaneously absorb ions.

The double layer structure causes zeta potential difference across the solid-liquid interface.

- The surface ion density and zeta potential ~ temperature and mechanical motions.
- Thermal/mechanical field  $\rightarrow$  electricity
- Relatively high efficiency for harvesting lowgrade heat (waste heat recovery)

$$E = \mathbf{d} \boldsymbol{\gamma} \mathbf{A}$$

## Thermoelectric Energy Harvesting using Nanoporous Materials



- At higher temperature, more solvated ions diffuse away from an electrode surface. If connected with a lowtemperature electrode, a current is generated.
- The effect is amplified significantly by the ultrahigh surface area.





## **Mechano-electric Energy Harvesting**



- By conducting a flow of electrolyte solution across a nanoporous electrode, significant output electric power was measured.
- The energy conversion is achieved by mechanically disturbing the surface ion structure at the large inner surfaces of nanopores.
- The energy conversion is semi-continuous, based on the capacitive effect
- The voltage is independent of the electrode distance and the flow rate

# **Nanofluidic Energy Conversion**



# Nanofluidic Energy Conversion System underpins the Building Blocks of the Next-Generation Multifunctional Structures & Systems





#### Self-protective

Absorb harmful vibration/noise, protect from impact/blast

#### Self-powered

Wasted/harmful mechanical/thermal/solar energy  $\rightarrow$  electricity Wireless powering sensors for smart infrastructure

#### Self-actuated

Thermo-electric actuation for volume memory/optimization



## Science of Nanofluidics vs. Energy Conversion

#### **Nanofluidic Behaviors**



Performance of Nanoporous System



For Thermal Actuation: Max  $\partial P_{in} / \partial T$ 

For Electro Actuation: Max  $\partial P_{in}/\partial E$ 

For Thermal Harvesting: Max  $\partial \rho / \partial T$ 

For Mechanical harvesting: Max  $\partial \rho / \partial v$ 

Materials Variables Pore Size Pore Geometry Liquid Phase Solid Phase Surface Modification

> System Variables Temperature Electrical Field Mechanical Load

> > . . .

Surface Energy Density

Surface Area

Transport

Infiltration

**Energy Output** 

# **Conclusion: Nanofluidic Energy Conversion**

- Nanoporous materials provide an ideal platform to amplify beneficial surface energy conversion effects, to effectively address grand challenges in energy efficiency and sustainability & next generation materials
- By using lyophobic nanoporous materials, high performance energy absorption systems can be developed
- By controlling the effective wettability thermally or electrically, high energy density and high displacement actuation liquid can be developed
- By controlling surface ion density in nanopores thermally or mechanically, useful electric energy can be harvested with high efficiency
- The design and optimization of the nanocomposite relies on the science of nanofluids, where solid mechanics and fluid mechanics meet at nanoscale, which leads to the unique behaviors of the confined liquid molecules and ions (a wide open scientific area).