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Enhancing Lift Force at Low Reynold's Numbers with Photophoretic Levitation of Porous 3D Structures

micromachines

MDPI

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LEGES SINE MORIBUS VANAE

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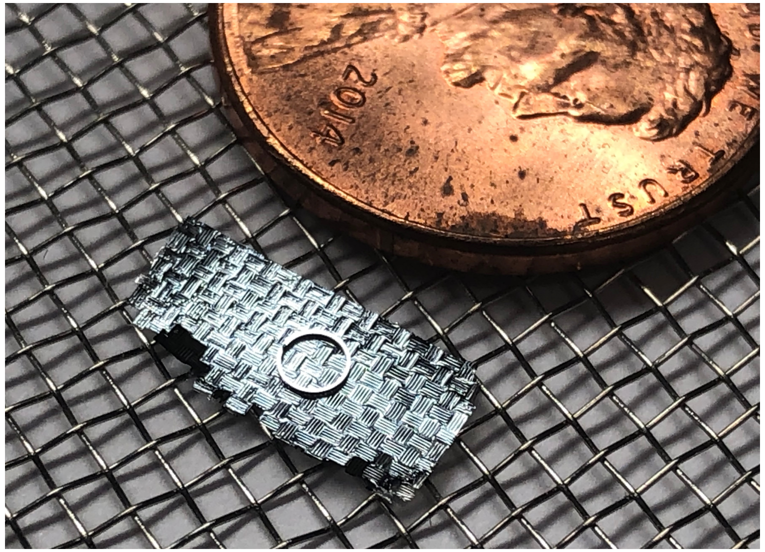
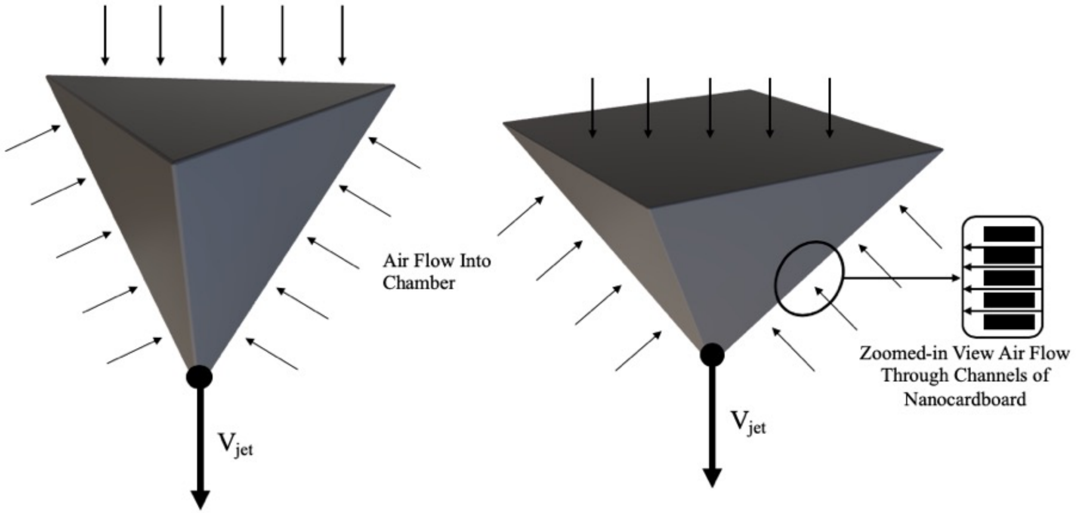
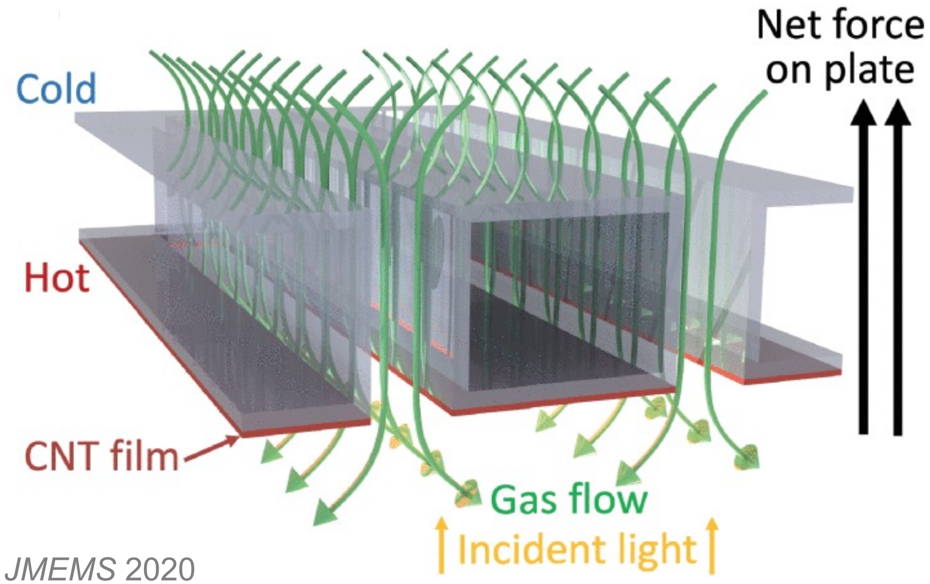


Nanocardboard metamaterial

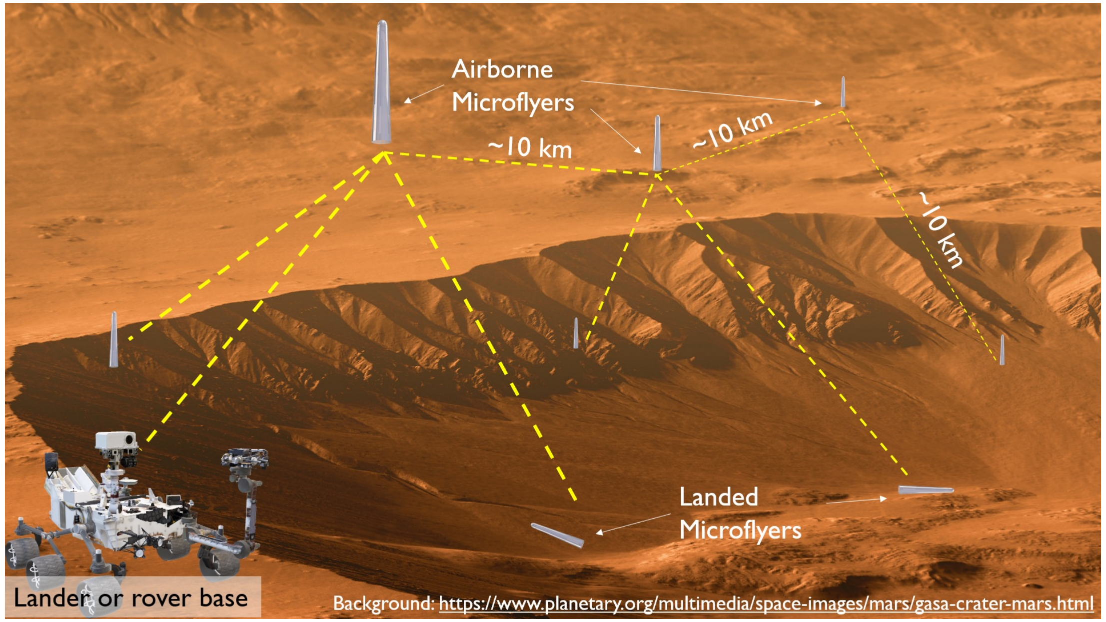


3D structures with porous materials

Photophoretic levitation



Martian Applications



Azadi *JMEMS* 2020

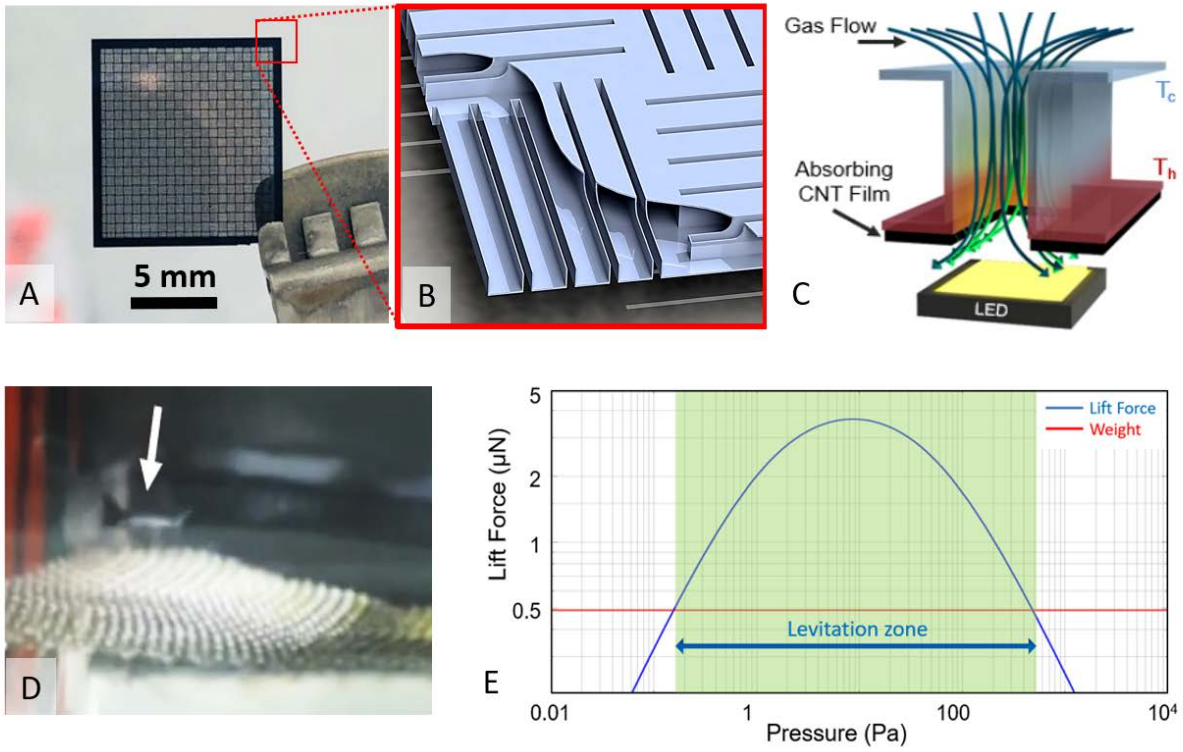
Abstract

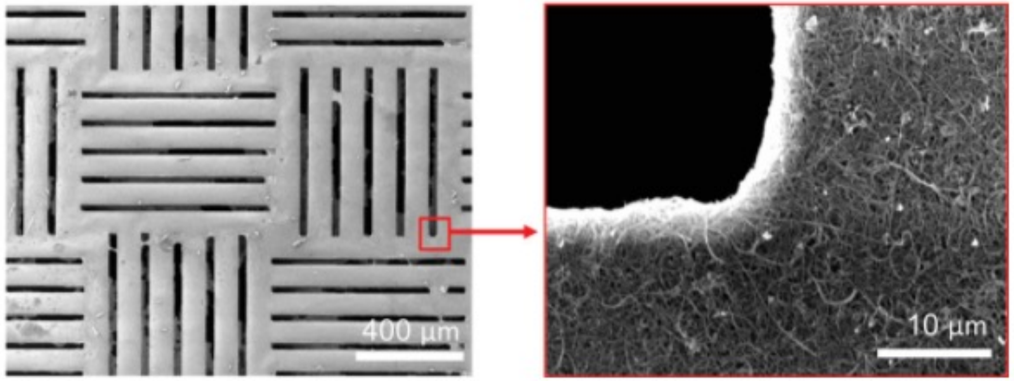
It is well documented that the lift force of hovering micro aerial vehicles can be enhanced by increasing their air-flow velocities. This is commonly accomplished using nozzles and other flow-manipulating geometries with Reynolds numbers above the order of 100s. However, the effect of geometries, like a nozzle, are not well characterized for below Reynolds numbers within the Stoke's regime. Fig. 2 shows near-zero enhancement of lift for nozzles within this regime. In general, controlled flight in low-Reynolds number conditions using conventional propulsion methods such as propellers is difficult. Instead, levitation at ultra-low Reynolds number conditions has been accomplished through other means, including photophoretically as demonstrated recently by Cortes et al. and Azadi et al. These works levitated planar materials without macroscale geometric enhancements and relied strictly on the lift force created through a temperature or accommodation coefficient difference across the planar structure. In the current work, we numerically explored the feasibility of multiscale structures operating at low-to-moderate Reynolds numbers that pair microscale photophoretic gas pumping with macroscale jet-inducing nozzles.

We used ANSYS Fluent to simulate the lift forces in centimeter-scale porous membrane discs (no macroscale enhancements) and in conical nozzles created from porous membranes. Our results reveal a lift enhancements due to porous nozzle geometries occur within Stoke's Reynolds number regime. In addition, we developed a semi-analytical flow model and found good agreement with the simulations. We are currently fabricating mylar structures analogous to the simulation geometries, laser machined to create porosity and adhered to lightweight frames to maintain shape. The multiscale structures we create will be of critical importance for exploring low-pressure environments such as Earth's mesosphere and the Martian atmosphere.

Benedict *MAV* 2015, Seddon 2011, Cortes *Adv. Mater.* 2020, Azadi *Sci. Adv.* 2021

Photophoretic levitation - Nanocardboard





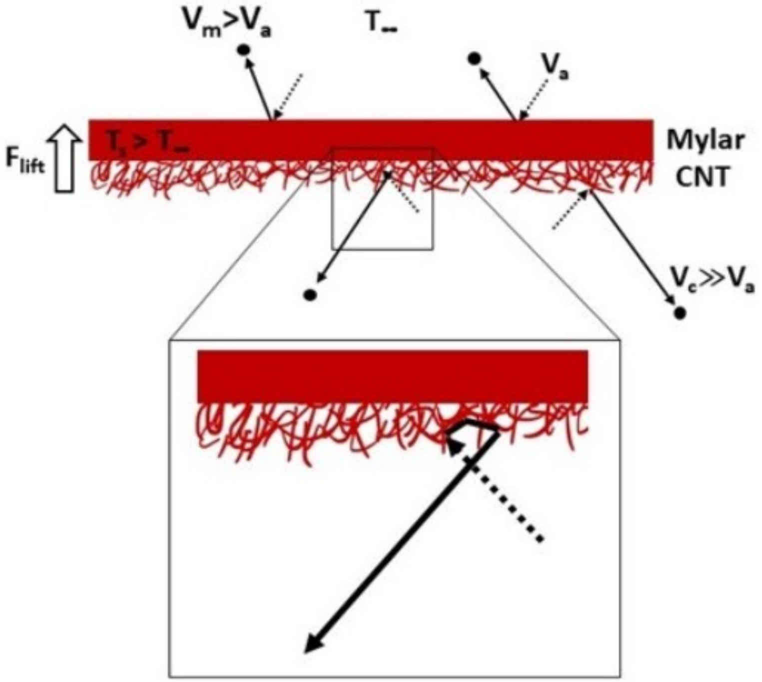
a) Naked-eye view of nanocardboard
b) Zoomed-in view of channels
c) Levitation mechanism
d) Experimental levitation
e) Ideal pressure range for levitation

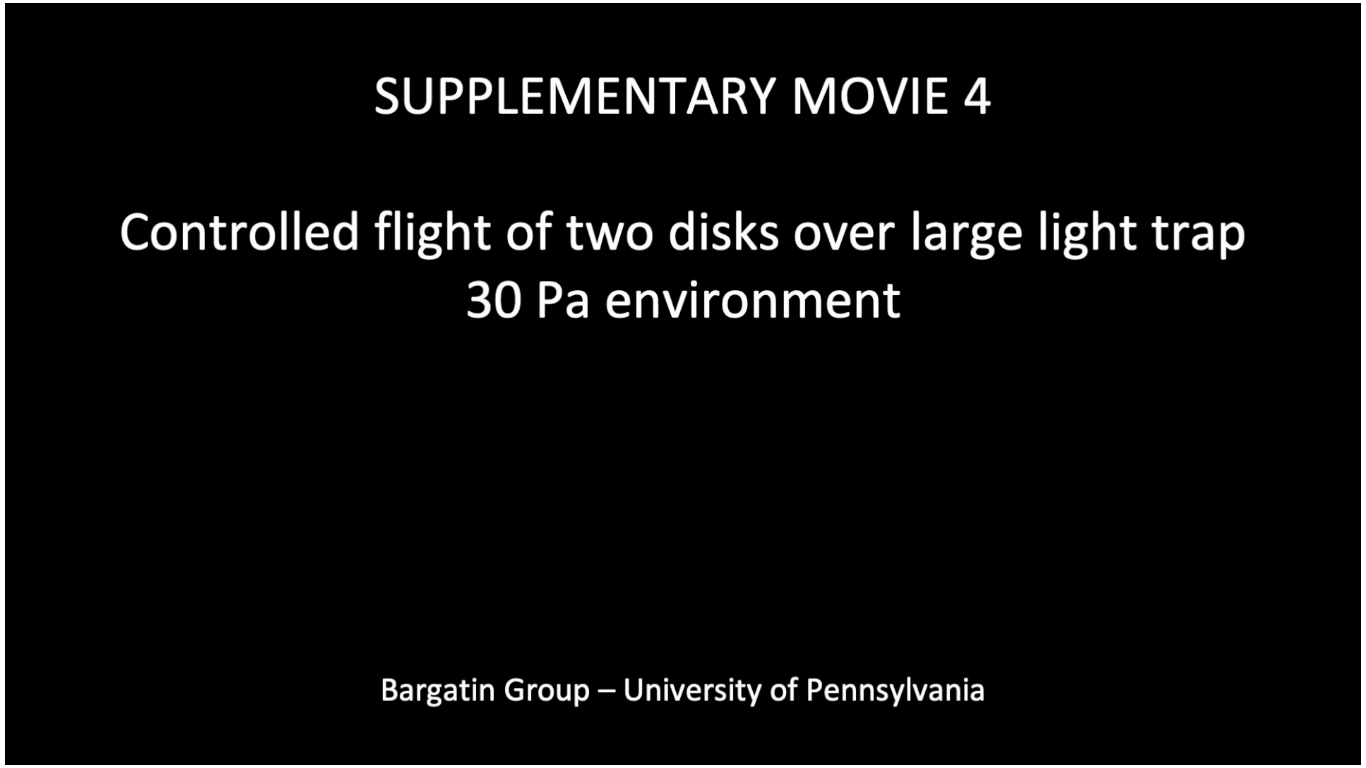
- 2D material with microscale thickness, macroscale area
- Increased plate stiffness and ultralight weight (4 orders of magnitude stiffer, 1 g/m^2)
  - Difficult to fold, bend, adhere
- Achieve levitation through one version of photophoretic forces
  - Light heats up a layer of carbon nanotubes
  - Air flows through channels along temperature gradient

Cortes *Adv. Mater.* 2020, Lin *Nat. Comm.* 2018

Photophoretic levitation - Mylar

- Light heats up one side coated with carbon nanotubes creating a temperature gradient
- Induces gas flow and increases speed of reflected gas molecules
- Creates a lift force to create levitation at low pressures

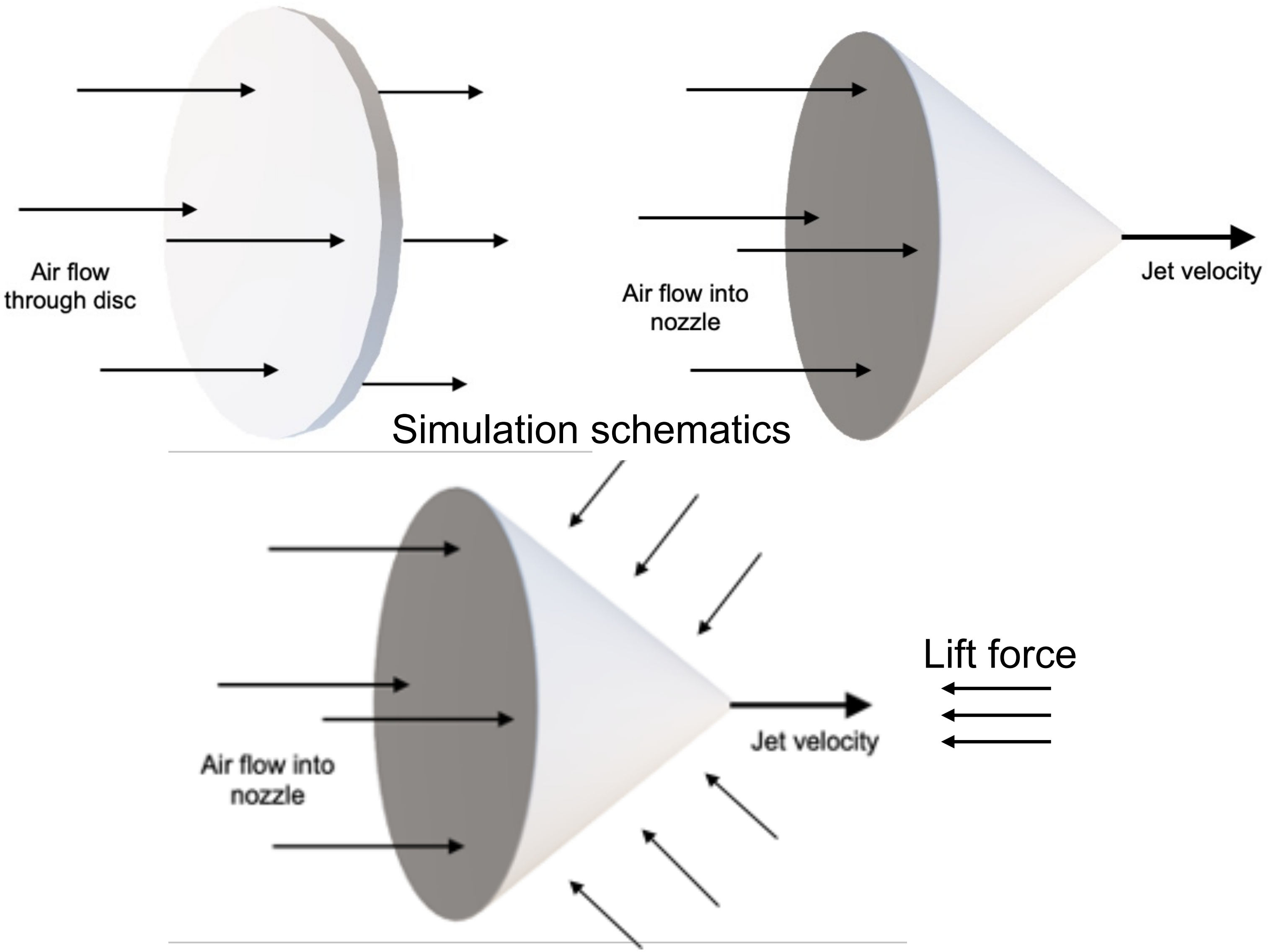




Azadi *Sci. Adv.* 2021

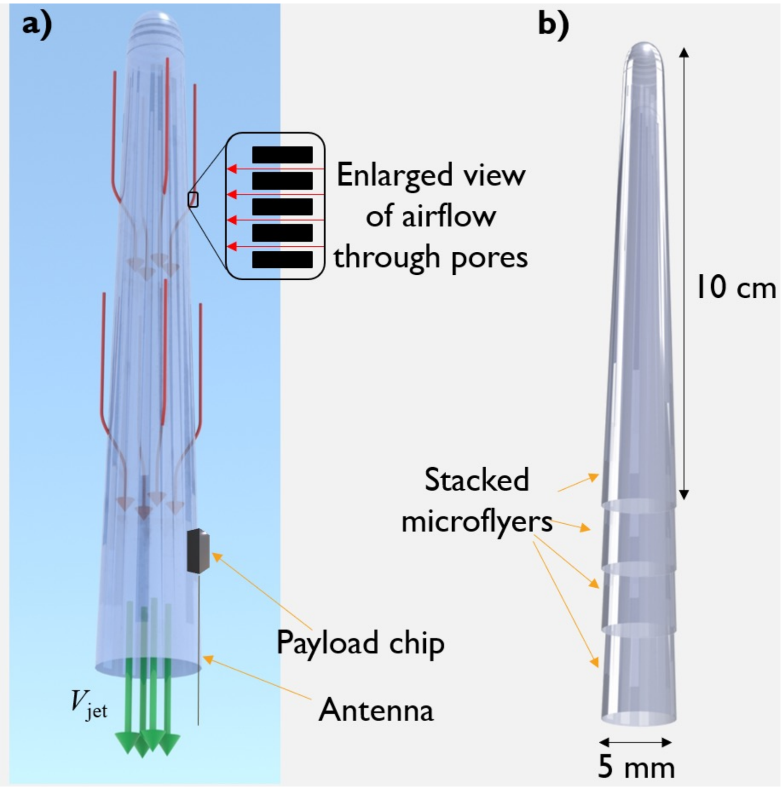
Methodology

- Start with simple disk simulations and move to more complex geometries
- Simulates 3D version of the planar photophoretic levitation
    - Carbon nanotube layer is on the inside
- Approximations of flow-through effect



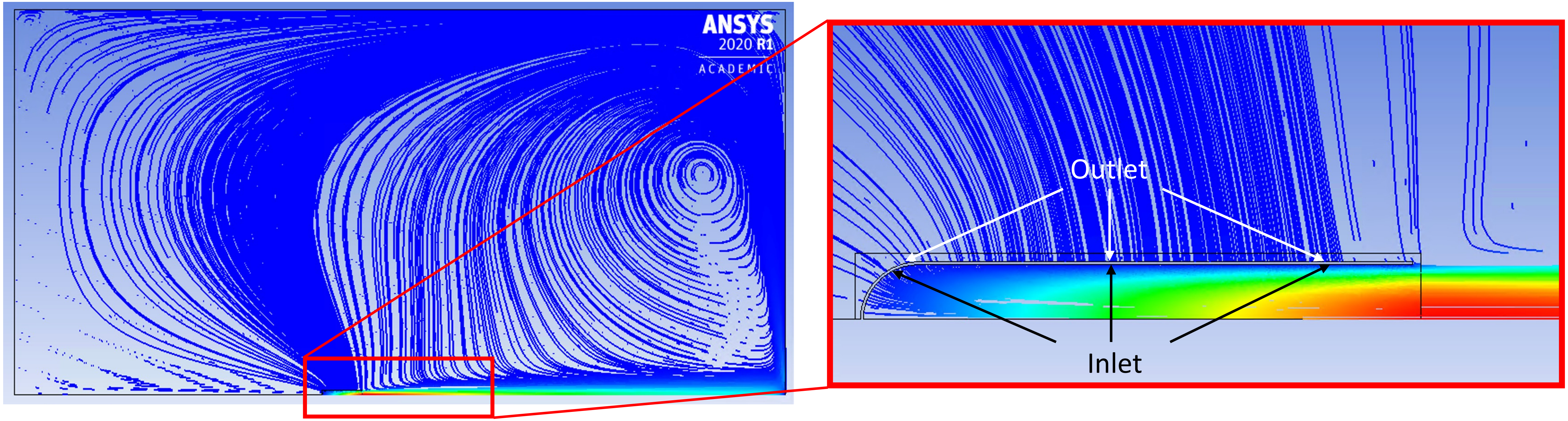
Simulation schematics

Final render of microflyers



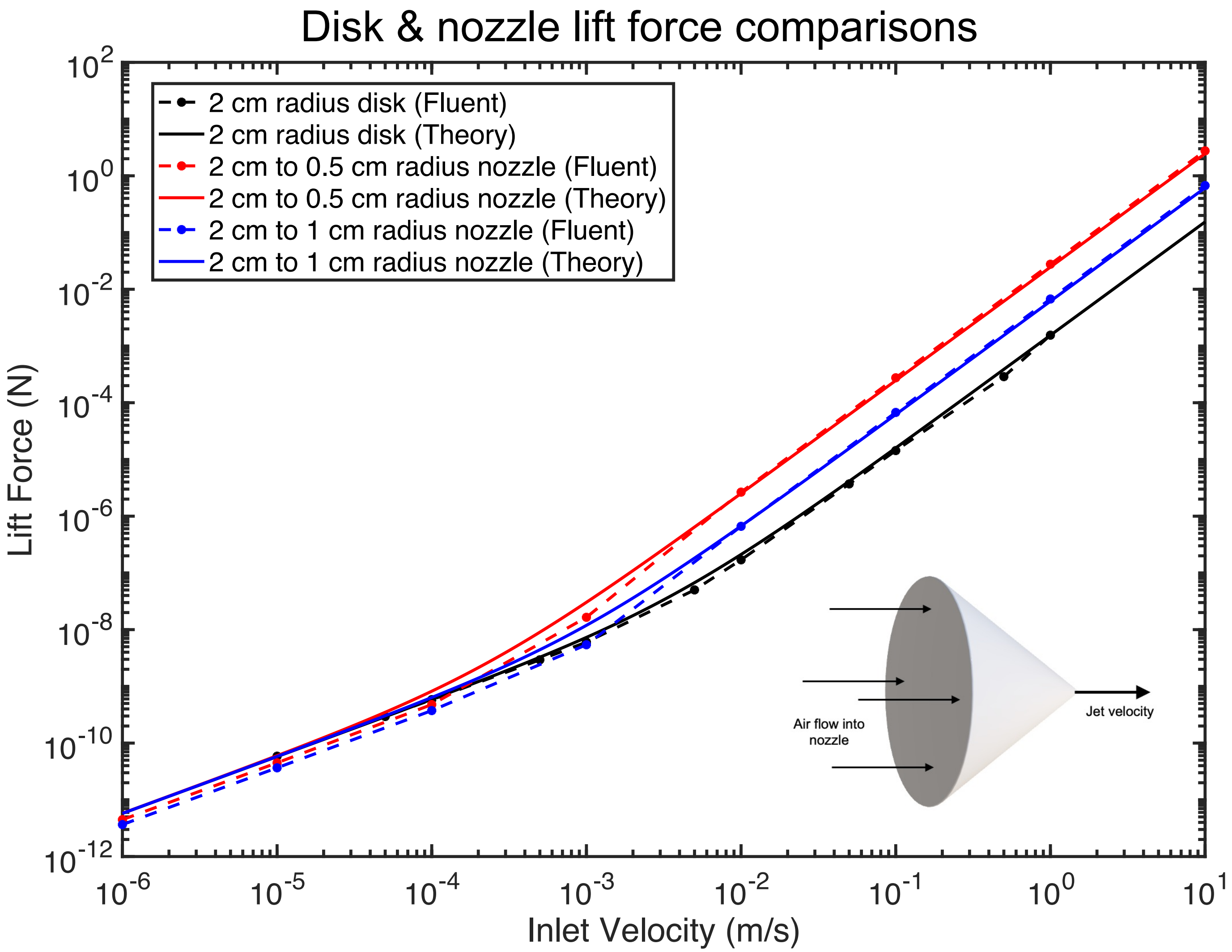
Axisymmetric ANSYS Fluent Simulations

Streamlines of rocket-shape inside an air box



- Inlet is inner side, outlet is outer side - highlight
  - Creates air flow into microflyers
- Vary geometry and size with same setup
- Lift force taken as reaction force along walls

Disk and nozzle results



Reynold's Number

$$Re = \frac{\rho v L}{\mu}$$

Disk

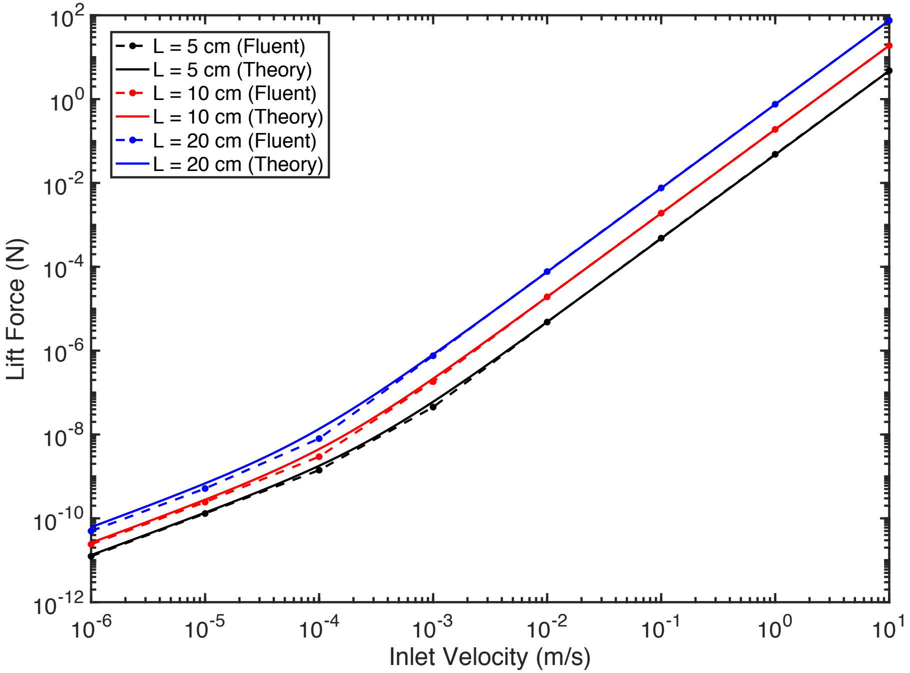
$$F = \rho A v^2 + 16 \mu R v$$

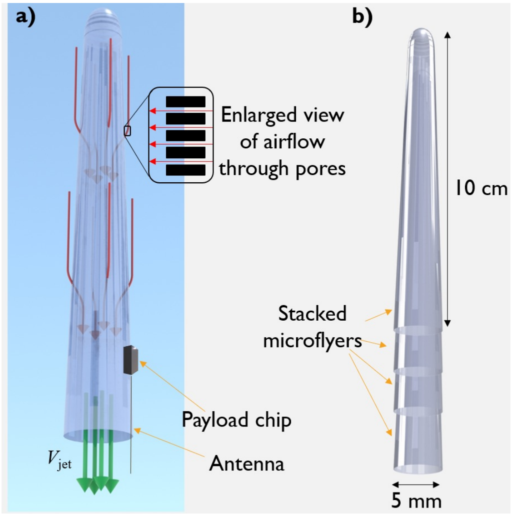
Nozzle

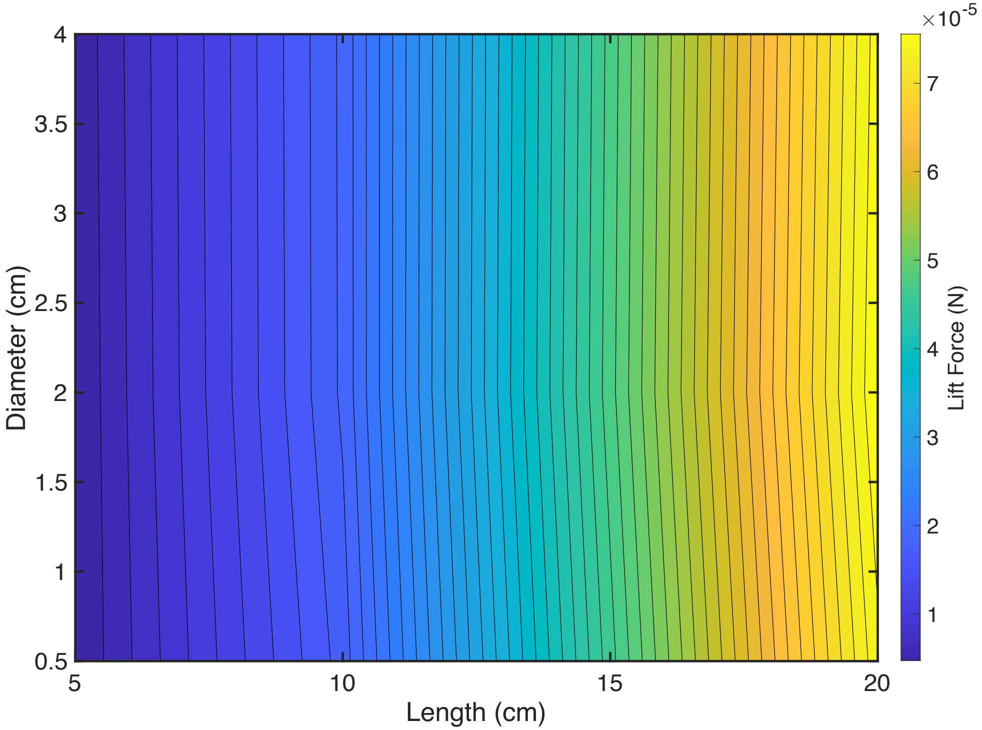
$$F = \rho A_{out} {v_{out}}^2 + 16 \mu R_{in} v_{in}$$

ρ = density
A = cross-sectional area
μ = viscosity
v = velocity
R = radius
L = characteristic linear dimension

Rocket shape results





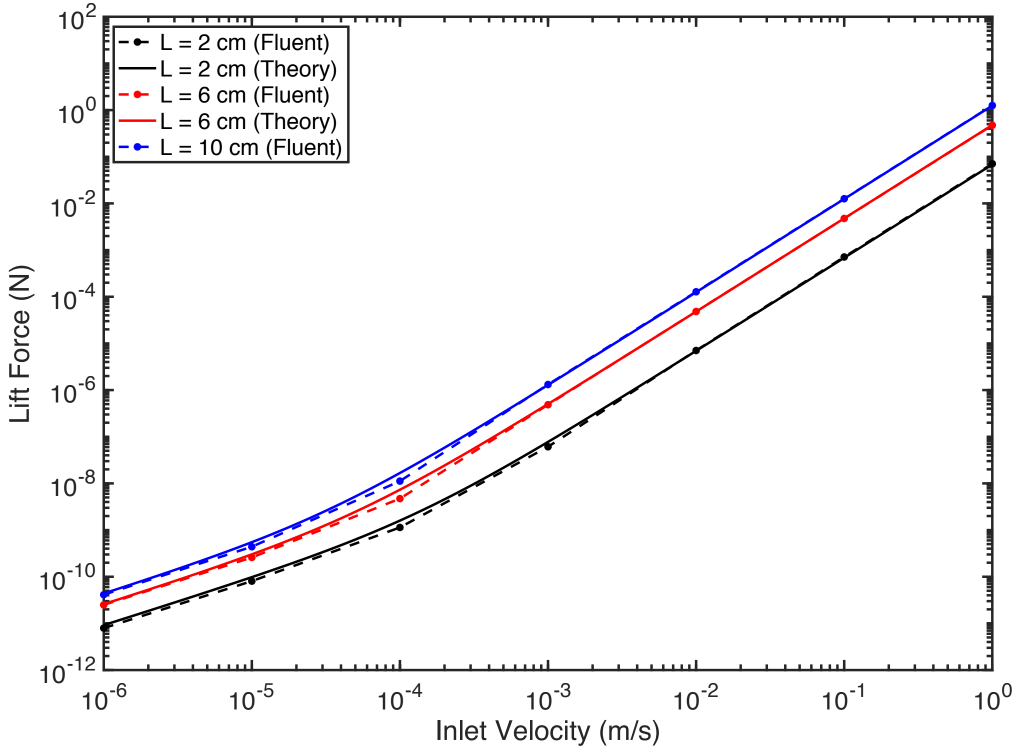


$$F = C_1 16 \mu R v_{out} + C_2 \rho A_{out} {v_{out}}^2$$

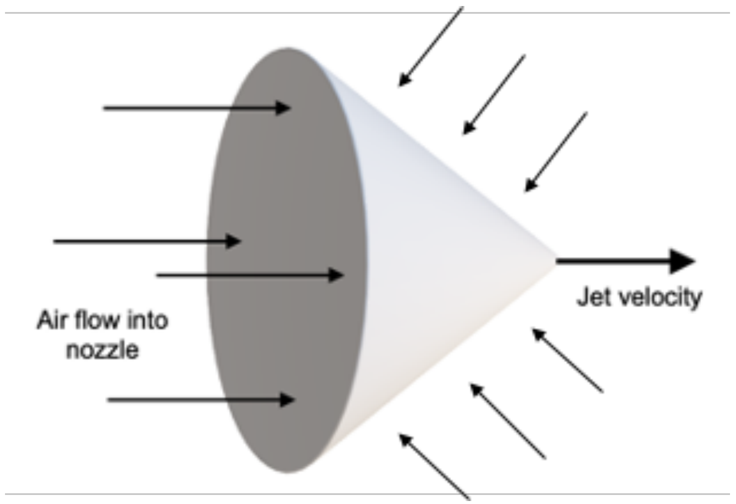
$$v_{out} = \left({A_{in}}/{A_{out}} \right) v_{in}$$

C_1 and C_2 are fitting parameters

Porous cone results



R_{in} = 2 cm, R_{out} = 5 mm



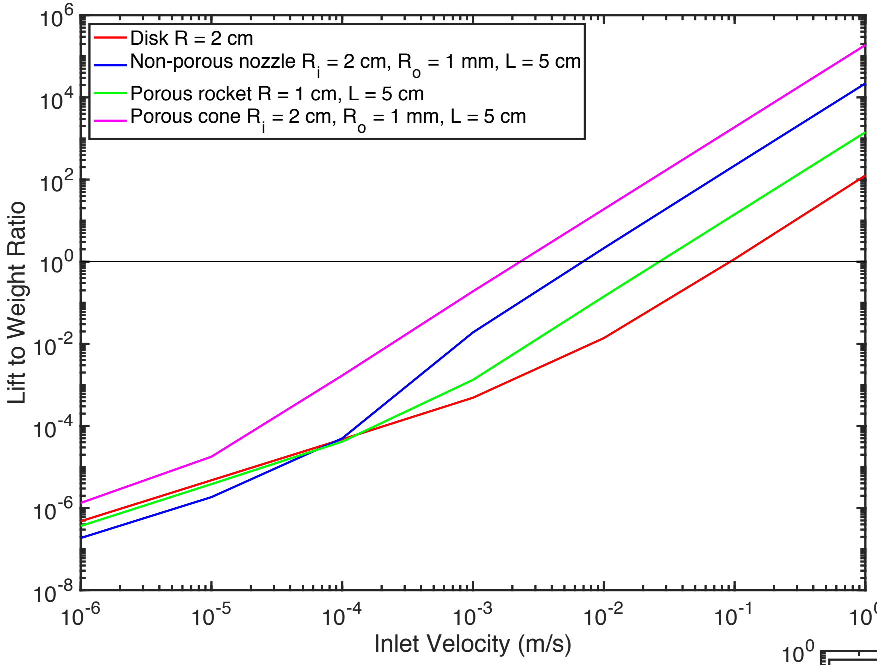
Porous cone analytical equation

$$F = C_1 16 \mu R_{in} v_{in} + C_2 \rho A_{out} {v_{out}}^2$$

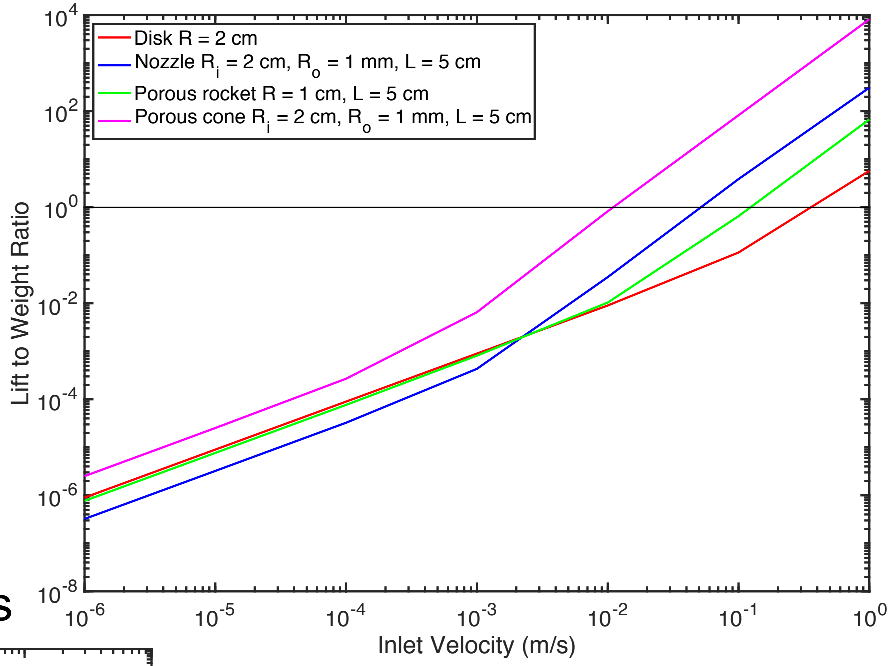
	Earth (Higher pressure)		Mars (Lower pressure)	
Geometry	C1	C2	C1	C2
Disc	1.028	1.011	1.000	1.057
Nozzle	1.606	1.088	1.373	0.612
Rocket	0.376	0.821	0.433	1.224
Cone	0.167	0.976	10.92	0.997

Lift-to-weight ratios

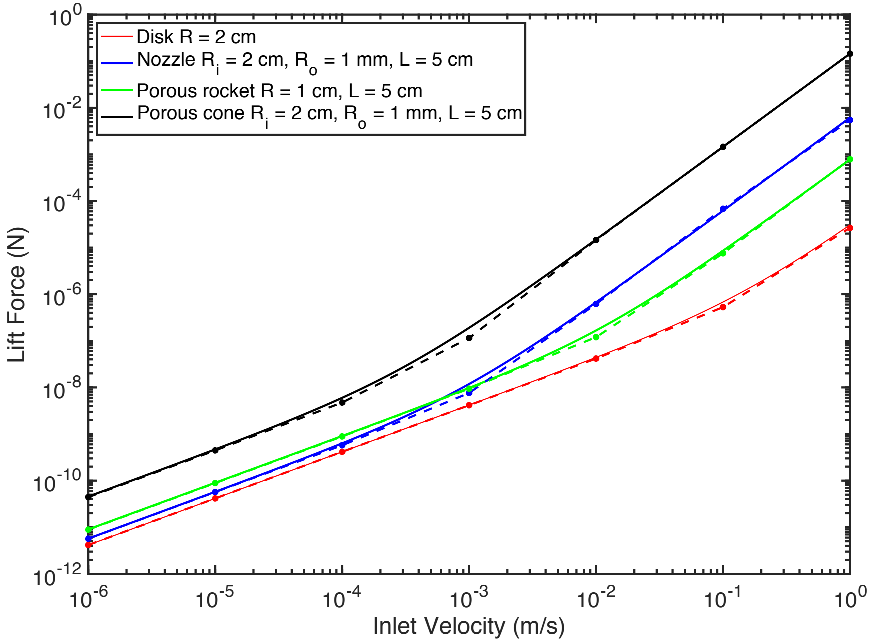
Earth, sea level conditions



Mars conditions, 610 Pa

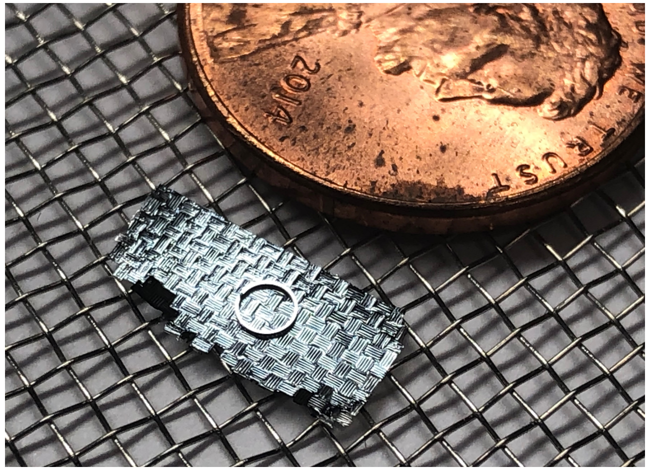


Mars fitting parameters

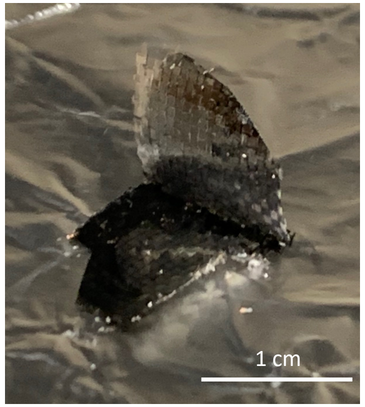


What's next?

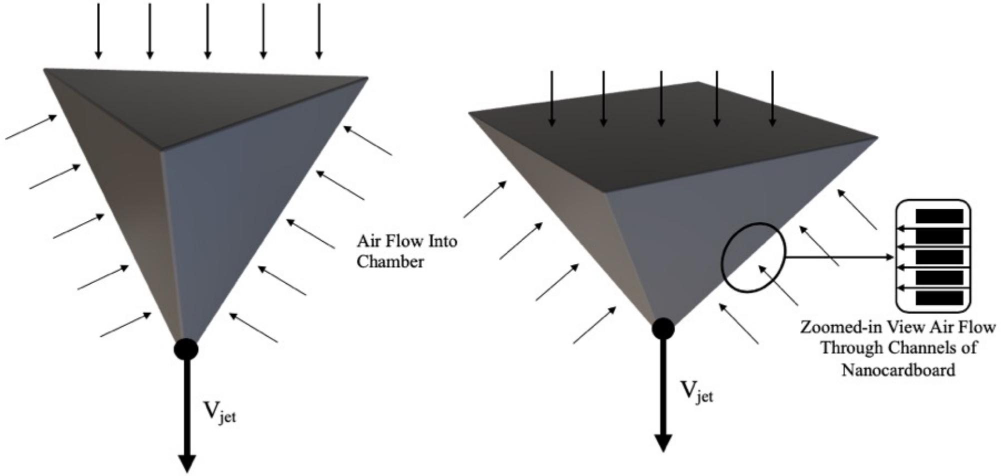
- Lift-to-weight ratios show promise for Martian flight
- Pressure range for flight increased with 3D geometries
- New simulations will include spheres
- Applications will include atmospheric sensing in the mesosphere and on Mars
- Experimental work has begun on constructing the geometries



Nanocardboard metamaterial



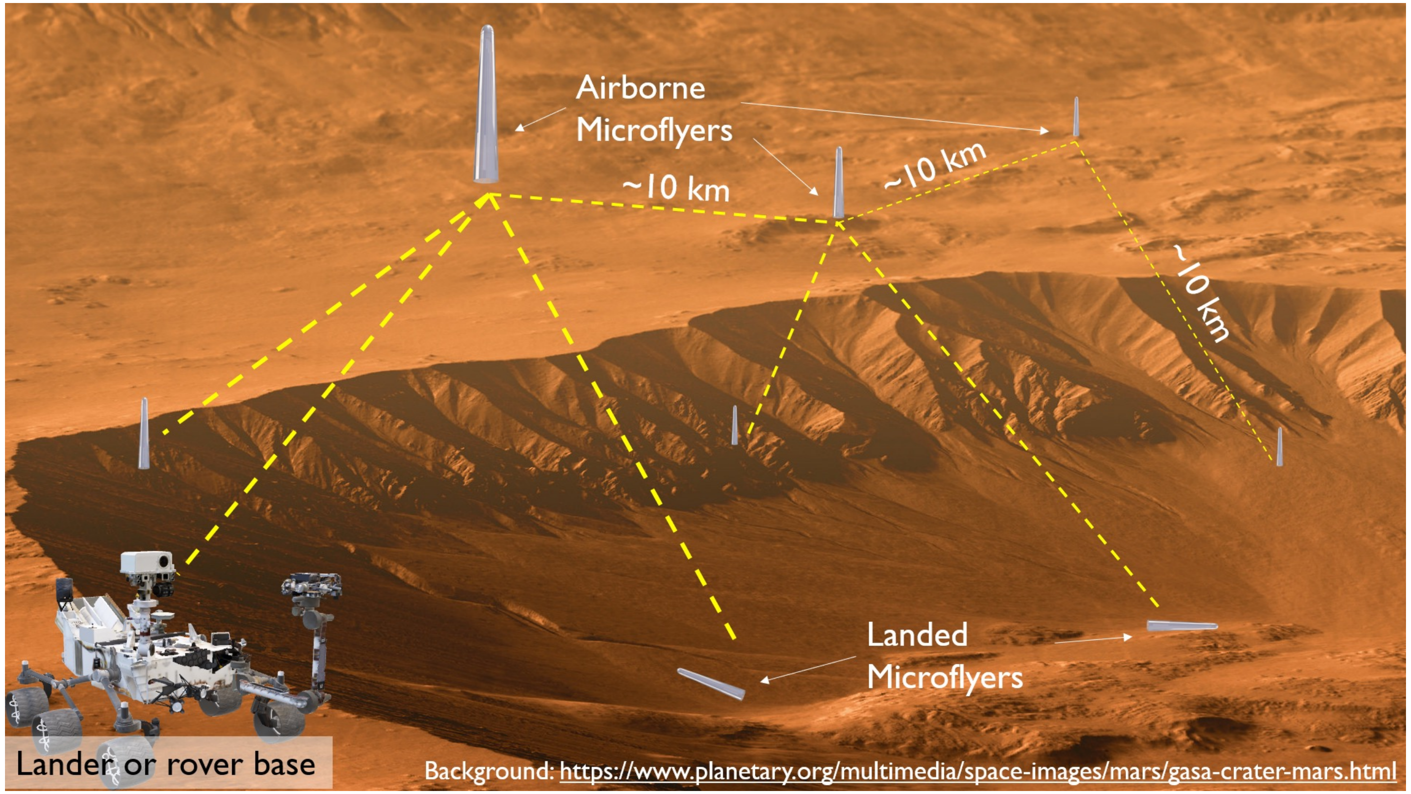
Adhered nanocardboard



3D structures with porous materials

Conclusion

- Photophoretic levitation of planar structures achieved by Bargatin group
- COVID-19 halted experimental work
- Simulations meant to research expanding to 3D geometries for increased pressure range of levitation
- Next: fabrication of 3D geometries with experimental levitation tests
- Future goal: Martian and mesosphere exploration



Thank you!

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3) Seddon, John M., and Simon Newman. *Basic helicopter aerodynamics*. Vol. 40. John Wiley & Sons, 2011.
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6) Lin, Chen, et al. "Nanocardboard as a nanoscale analog of hollow sandwich plates." *Nature communications* 9.1 (2018): 1-8.