ICMA 2021
1st International Conference on Micromachines and Applications
15–30 APRIL 2021 | ONLINE
BARGATIN GROUP
micromachines
MDPI

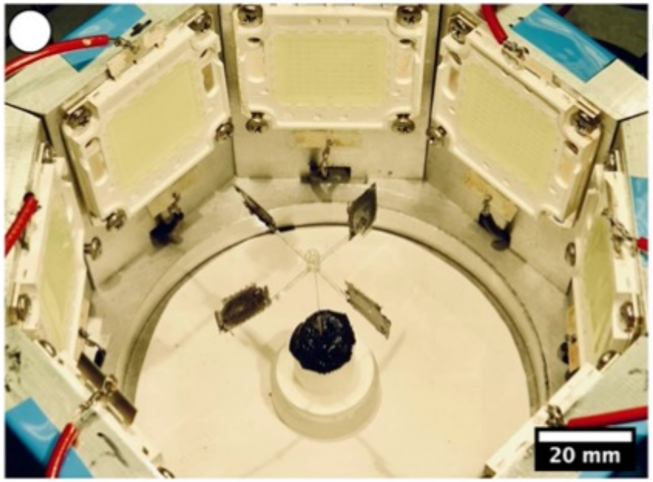
Demonstration of Atmospheric-Pressure Radiometer with Metamaterial Vanes

Zhipeng Lu[1], Mohsen Azadi[2], George A. Popov[2], Christopher Stanczak[2], Pratik Ponnarassery[2], Andy G. Eskenazi[2], John Cortes[3], Matthew F. Campbell[2], and Igor Bargatin[2*]

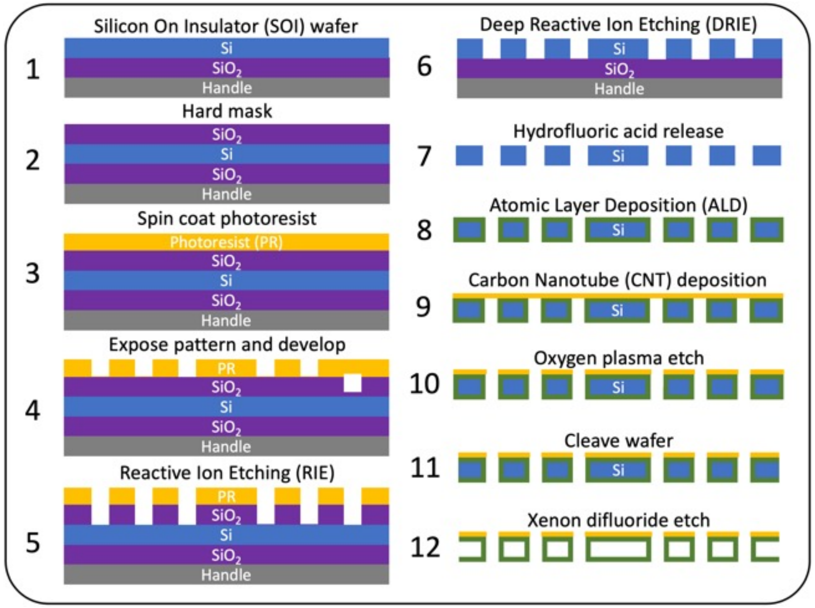
[1] Department of Chemistry, University of Pennsylvania, USA;
[2] Department of Mechanical Engineering and Applied Mechanics, University of Pennsylvania, USA;
[3] Lawrence Livermore National Laboratory, USA.

* Corresponding author: bargatin@seas.upenn.edu

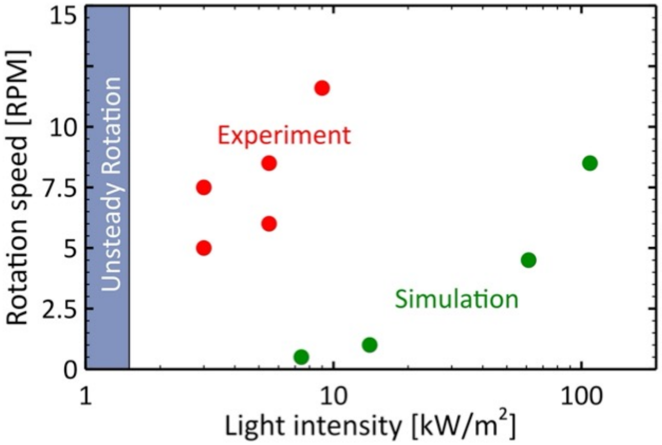
Demonstration of Atmospheric-Pressure Radiometer with Metamaterial Vanes



Photograph of radiometer inside test chamber.



Vane fabrication process.



Experimentally-measured and numerically-calculated rotation speeds as a function of light intensity incident on the vanes.

Azadi, Mohsen, et al. "Demonstration of Atmospheric-Pressure Radiometer With Nanocardboard Vanes." *Journal of Microelectromechanical Systems* 29.5 (2020): 811-817.

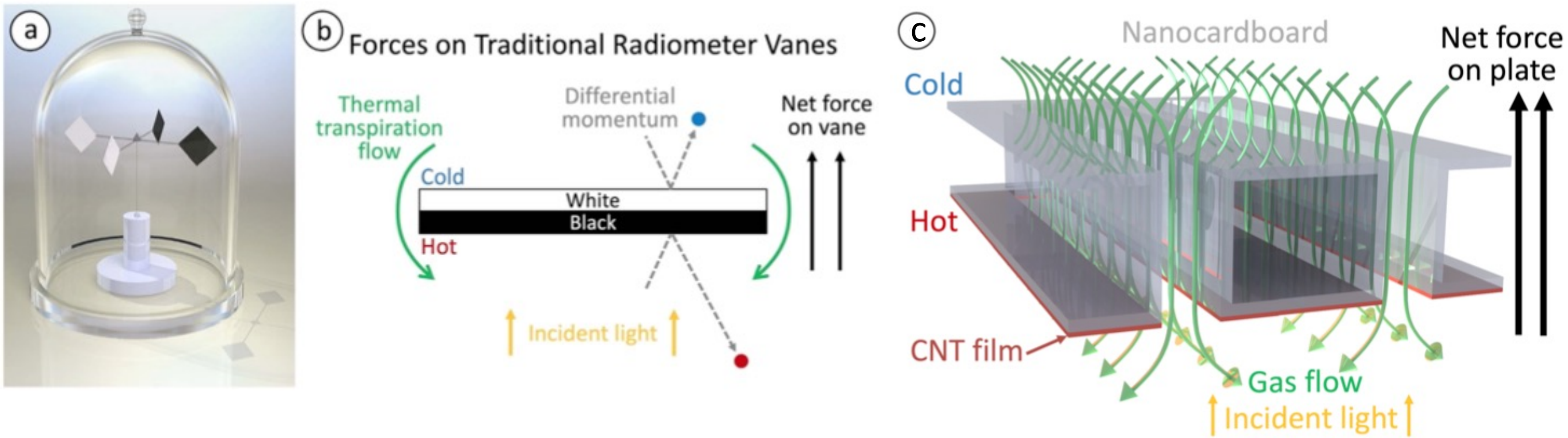
Abstract: We report a Crookes radiometer that rotates at atmospheric pressure using architected microporous dielectric plates, known as nanocardboard, as vanes [1,2]. The functionality at pressures three orders-of-magnitude larger results from the metamaterial vanes' unique features: (1) extremely low areal density (0.1 mg/cm^2) that reduces the vane mass and hub friction force by almost 100 times; (2) high thermal resistivity that increases the cross-vane temperature difference; and (3) micro-channels that enable through-vane thermal transpiration gas flows.

Each nanocardboard vane features a basketweave-style five-flow-channel pattern to amplify the thermal transpiration force. We manufactured these vanes using microfabrication techniques in four stages: (1) silicon mold creation using photolithography and reactive ion etching; (2) mold conformal coating using atomic layer deposition; (3) carbon nanotube drop-casting and oxygen plasma etching; and (4) mold cleaving and removing using XeF_2 isotropic etching [1, 5].

We measured the temperature and rotation speed of the radiometer using thermal and video cameras while illuminating it using an octagonal LED array. We found that our radiometer could operate at atmospheric pressure, and that its rotation rate increased with light intensity. To our knowledge, no other radiometers have achieved such functioning in ambient air. Lastly, we simulated the radiometer's fluid dynamics, obtaining similar trends between its rotation speed and light intensity and achieving order-of-magnitude agreement with our experiments.

Keywords: Crookes radiometer; microporous plate; photophoresis.

Introduction



(a) Photorealistic rendering of a traditional radiometer in a vacuum jar. (b) Schematic diagram showing forces on traditional radiometer vanes. (c) Schematic diagram showing thermal creep-induced gas flow though nanocardboard channels.

Adapted from Azadi, Mohsen, et al. "Demonstration of Atmospheric-Pressure Radiometer With Nanocardboard Vanes." *Journal of Microelectromechanical Systems* 29.5 (2020): 811-817.

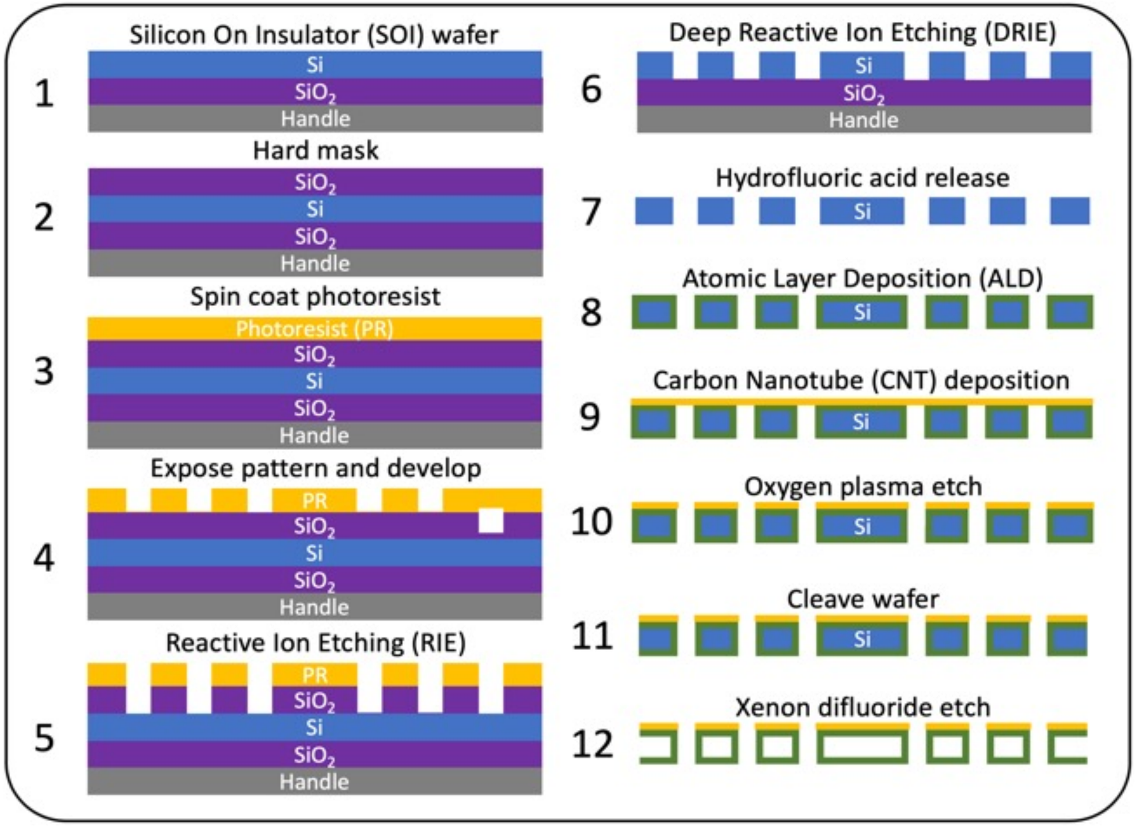
ICMA 2021

Results and Discussion: Video

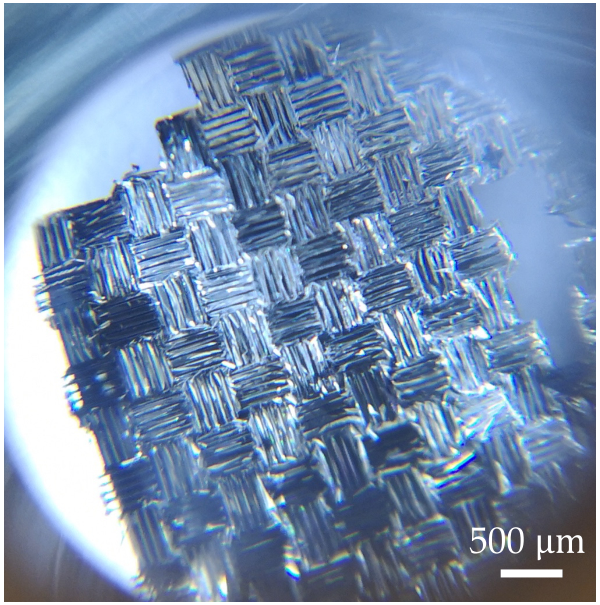
Video of radiometer operating under natural insolation (1 kW/m^2).

By courtesy of Mohsen Azadi.

Results and Discussion: Fabrication



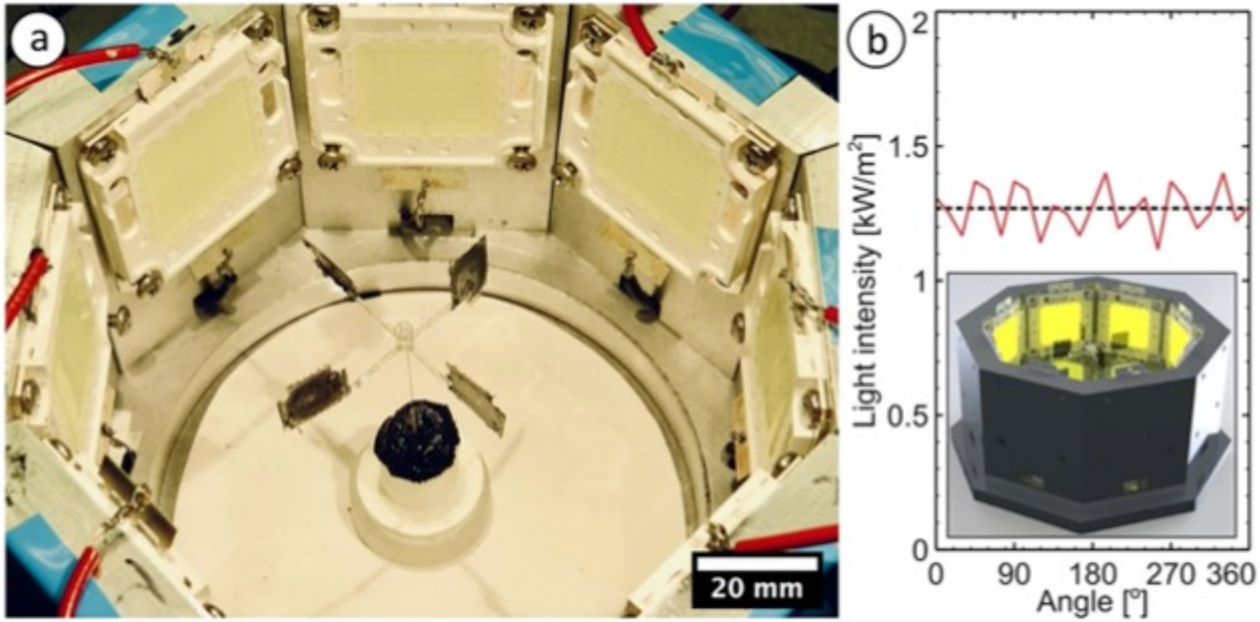
Vane fabrication process.



Magnified top-view photograph of the nanocardboard plate.

Azadi, Mohsen, et al. "Demonstration of Atmospheric-Pressure Radiometer With Nanocardboard Vanes." *Journal of Microelectromechanical Systems* 29.5 (2020): 811-817.

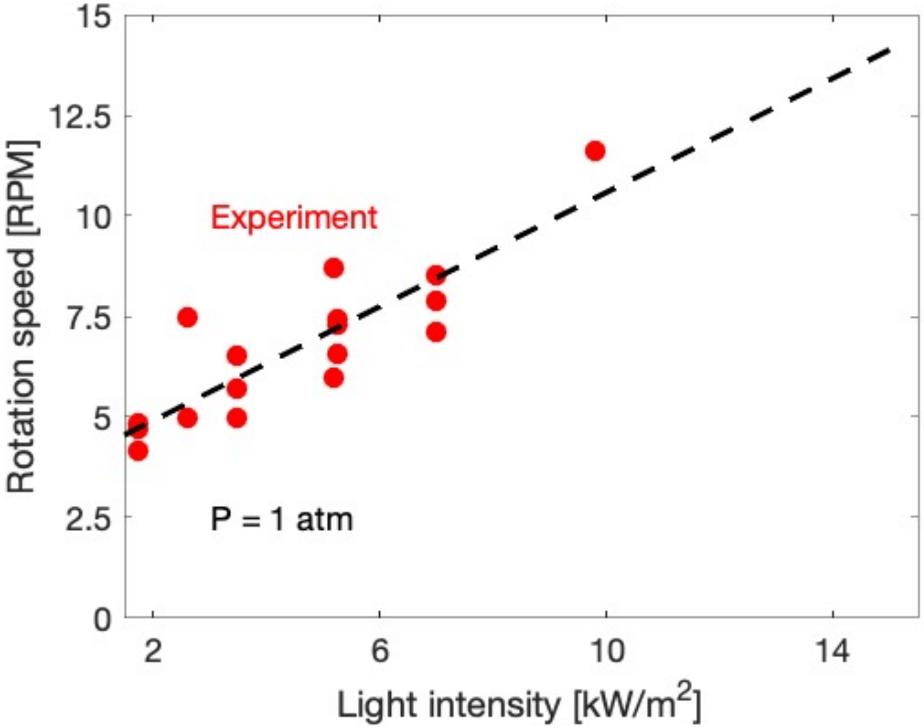
Results and Discussion: Setup



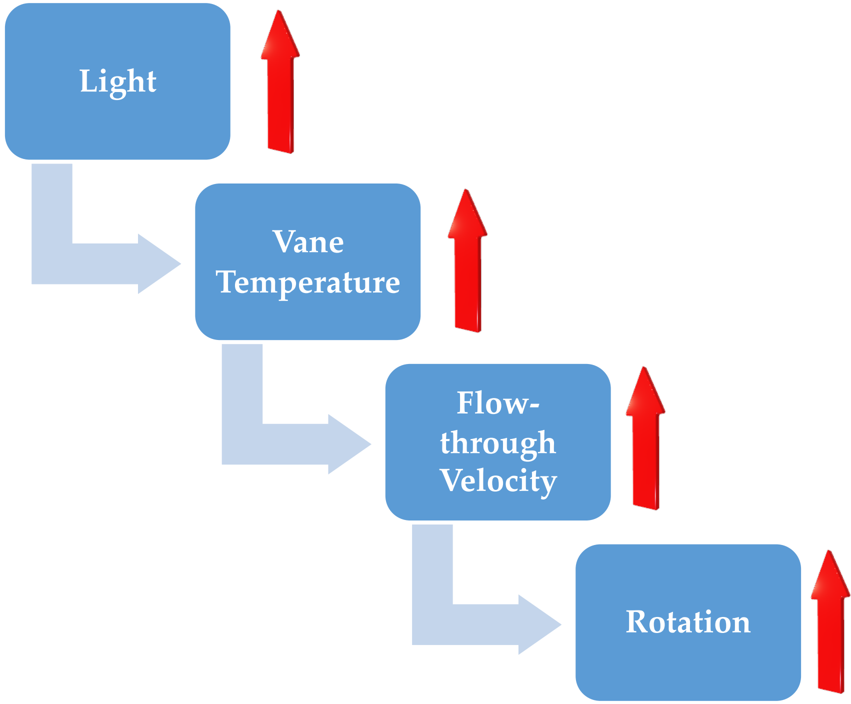
(a) Photograph of radiometer inside test chamber. (b) Light intensity as a function of angular position within the chamber at a radius of 13 mm. Inset: Computer rendering of chamber showing LED illumination.

Azadi, Mohsen, et al. "Demonstration of Atmospheric-Pressure Radiometer With Nanocardboard Vanes." *Journal of Microelectromechanical Systems* 29.5 (2020): 811-817.

Results and Discussion: Measurement



Experimentally-measured rotation speeds as a function of light intensity incident on the vanes.

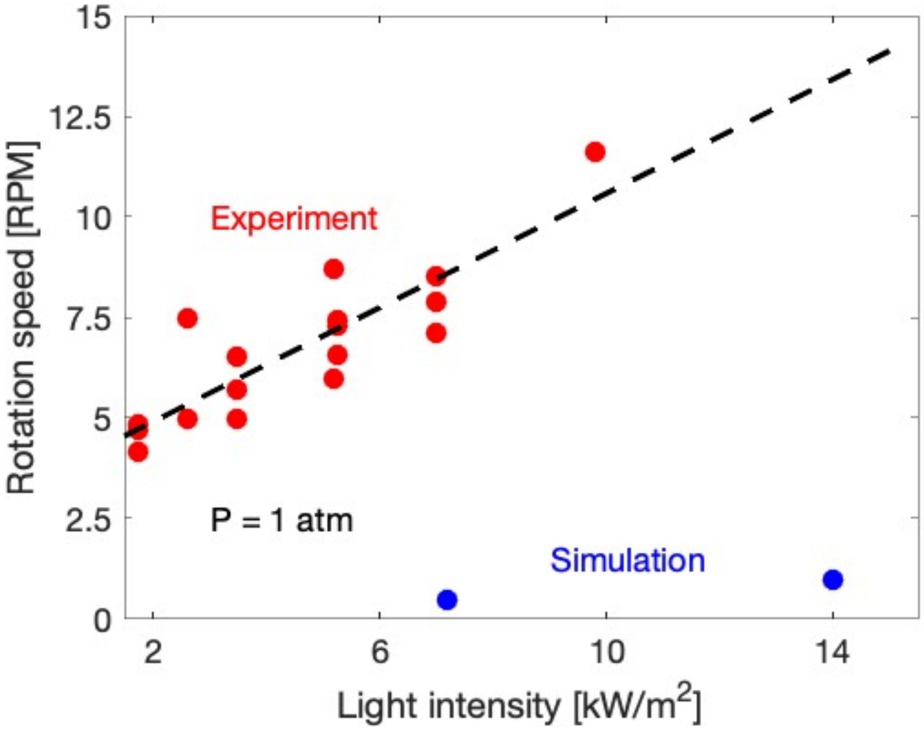


Explanation for the positive relationship between rotation speed and light intensity.

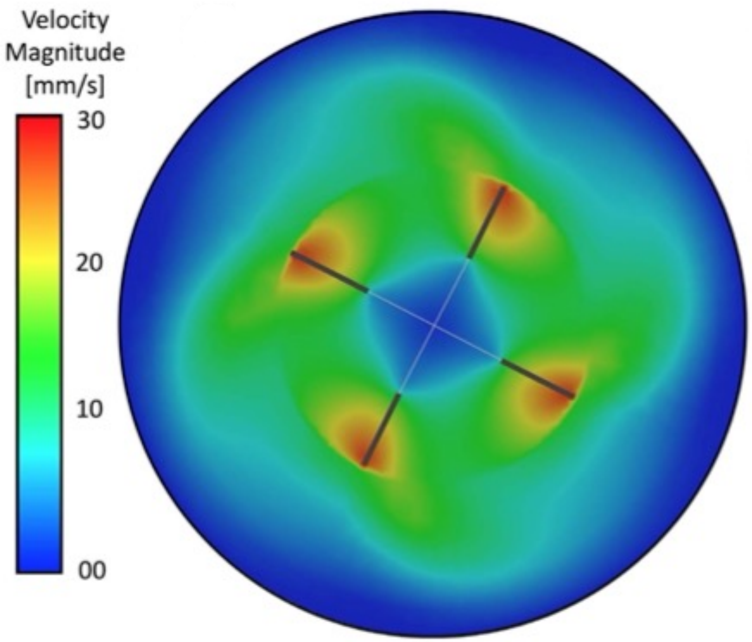
Adapted from Azadi, Mohsen, et al. "Demonstration of Atmospheric-Pressure Radiometer With Nanocardboard Vanes." *Journal of Microelectromechanical Systems* 29.5 (2020): 811-817.

ICMA 2021

Results and Discussion: Simulation



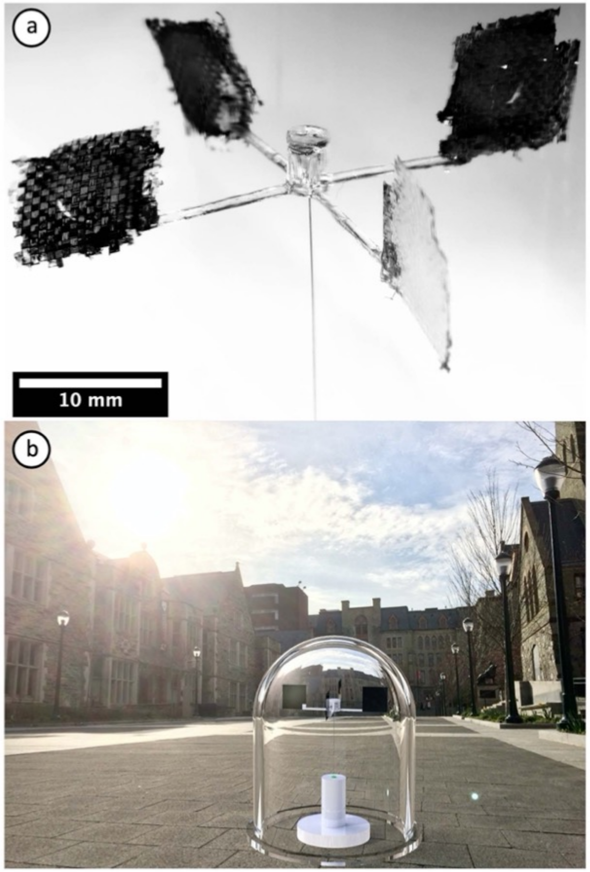
Experimentally-measured and simulated rotation speeds as a function of light intensity incident on the vanes.



Top view of the flow field in an atmospheric-pressure numerical simulation in which the 1.5-cm square vanes rotated at 10 RPM.

Adapted from Azadi, Mohsen, et al. "Demonstration of Atmospheric-Pressure Radiometer With Nanocardboard Vanes." *Journal of Microelectromechanical Systems* 29.5 (2020): 811-817.

Conclusions



(a) Photograph of vanes glued to the hub. The vanes are shown prior to the XeF_2 etch process. (b) Photorealistic rendering of the radiometer under sunlight on the University of Pennsylvania campus.

- First Crookes radiometer at 1 atm;
- Nanocardboard architecture;
- Qualitative agreement with theory;
- Applications: microflyers, photo-generators, etc.
- Next step: smaller, pattern.

Azadi, Mohsen, et al. "Demonstration of Atmospheric-Pressure Radiometer With Nanocardboard Vanes." *Journal of Microelectromechanical Systems* 29.5 (2020): 811-817.

Acknowledgments

The authors thank Prof. Howard Hu of the Department of Mechanical Engineering and Applied Mechanics, University of Pennsylvania, for his help with the simulations and the Staff of the Singh Center for Nanotechnology, Nanoscale Characterization Facility, and the Scanning and Local Probe facility at the same university.

Thanks for watching!

ICMA 2021

BARGATIN GROUP

Penn
UNIVERSITY of PENNSYLVANIA