Reconfigurable Optofluidic Barriers For 3D Particle Control Via Thermally Induced Flows

E. Ruiz-Reina[1], F. Schmidt[2], C. D. González-Gómez[3], M. Sulliger[2], R. A. Rica-Alarcón[4], J. Ortega-Arroyo[2], R. Quidant[2]

[1]Multiphysics Modeling School, Department of Applied Physics II, University of Málaga
[2]Department of Mechanical and Process Engineering, ETH Zurich
[3]Department of Applied Physics, University of Granada
[4]Research Unit 'Modeling Nature' (MNat), Department of Applied Physics, University of Granada

Abstract

Microfluidic systems traditionally rely on fixed physical barriers to manipulate fluids and particles. While effective, these static structures lack the flexibility required for dynamic or multifunctional applications. In this work, recently published in Nature Photonics [1], we present a reconfigurable optofluidic platform that uses structured light and photothermal conversion to generate virtual thermal barriers within microfluidic chambers. These barriers enable real-time, three-dimensional control over fluid flow and particle trajectories, offering a versatile alternative to traditional microfluidic architectures.
We used COMSOL Multiphysics to simulate the coupled heat transfer and fluid dynamics that arise from localized laser-induced heating. The simulations were essential to understand and optimize the interplay between thermo-osmosis, thermophoresis, and natural convection in the formation of virtual barriers. The Heat Transfer in Fluids and Laminar Flow physics interfaces were coupled via the Nonisothermal Flow multiphysics interface. Additionally, we employed the Particle Tracing for Fluid Flow interface to model the motion of colloidal particles under the influence of thermal gradients.
To replicate the experimental setup, we modeled a microfluidic chamber with gold nanorod-coated surfaces and introduced localized heat sources corresponding to laser foci. We implemented custom boundary conditions to simulate thermo-osmotic slip velocities and included thermophoretic forces in the particle tracing module. The simulations were validated against experimental data obtained via digital holographic microscopy and optical diffraction tomography.
Our results show that optofluidic barriers can be dynamically reconfigured to perform key microfluidic operations such as steering, splitting, merging, and trapping of particles. Furthermore, by arranging thermal pillars in periodic patterns, we demonstrated size-based particle sorting akin to deterministic lateral displacement (DLD) assays. The COMSOL simulations were instrumental in optimizing the spatial configuration and thermal input required for efficient sorting.
Applications and Impact: This technology opens new avenues for adaptive lab-on-chip devices, where multiple fluidic functions can be integrated and reconfigured in real time. Potential applications include:
- Chemical synthesis, where dynamic control over mixing and reaction zones enhances efficiency and selectivity.
- Biomedical diagnostics, enabling precise manipulation of cells and biomolecules without physical contact.
- Single-cell analysis, where reconfigurable traps allow long-term observation and isolation.
- Environmental sensing, through selective particle sorting and concentration.
- Soft robotics and programmable matter, where fluidic control can be embedded into responsive systems.

The ability to simulate complex thermal-fluid-particle interactions with COMSOL Multiphysics was key to engineering multifunctional microfluidic environments with high spatial and temporal resolution. This approach demonstrates how virtual barriers can surpass the limitations of physical structures, offering a flexible and scalable solution for next-generation microfluidic technologies.

Reference

1. F. Schmidt et al. Three-dimensional optofluidic control using reconfigurable thermal barriers. Nature Photonics, Accepted for publication (2025). DOI: https://doi.org/10.1038/s41566-025-01731-z (not been activated yet).
2. J. Nilsson et al. Review of cell and particle trapping in microfluidic systems. Anal. Chim. Acta 649, 141–157 (2009).
3. U. M. Attia et al. Micro-injection moulding of polymer microfluidic devices. Microfluid. Nanofluid. 7, 1–28 (2009).
4. K. Sugioka & Y. Cheng. Femtosecond laser three-dimensional micro- and nanofabrication. Appl. Phys. Rev. 1, 041303 (2014).
5. N. Bhattacharjee et al. The upcoming 3D-printing revolution in microfluidics. Lab Chip 16, 1720–1742 (2016).
6. T. Thorsen et al. Microfluidic large-scale integration. Science 298, 580–584 (2002).
7. R. B. Schasfoort et al. Field-effect flow control for microfabricated fluidic networks. Science 286, 942–945 (1999).
8. J. C. Ndukaife et al. Long-range and rapid transport of individual nano-objects by a hybrid electrothermoplasmonic nanotweezer. Nat. Nanotechnol. 11, 53–59 (2016).
9. H. H. Bau et al. A magneto-hydrodynamically controlled fluidic network. Sens. Actuators B Chem. 88, 205–216 (2003).
10. L. D'eramo et al. Microfluidic actuators based on temperature-responsive hydrogels. Microsyst. Nanoeng. 4, 17069 (2018).
11. H. Wada et al. Evaluation of the response characteristics of on-chip gel actuators for various single cell manipulations. IEEE Robot. Autom. Lett. 5, 5205–5212 (2020).
12. D. P. Taylor & G. V. Kaigala. Reconfigurable microfluidics: real-time shaping of virtual channels through hydrodynamic forces. Lab Chip 20, 1720–1728 (2020).
13. M. Krishnan & D. Erickson. Optically induced microfluidic reconfiguration. Lab Chip 12, 613–621 (2012).

14. F. Paratore et al. Reconfigurable microfluidics. Nat. Rev. Chem. 6, 70–80 (2022).
15. D. Baigl. Photo-actuation of liquids for light-driven microfluidics: state of the art and perspectives. Lab Chip 12, 3637–3653 (2012).
16. S. Duhr & D. Braun. Optothermal molecule trapping by opposing fluid flow with thermophoretic drift. Phys. Rev. Lett. 97, 038103 (2006).
17. N. Osterman & D. Braun. Thermooptical molecule sieve on the microscale. Appl. Phys. Lett. 106, 073508 (2015).
18. H. Ding et al. Programmable multimodal optothermal manipulation of synthetic particles and biological cells. ACS Nano 16, 10878–10889 (2022).
19. M. Fränzl & F. Cichos. Hydrodynamic manipulation of nano-objects by optically induced thermo-osmotic flows. Nat. Commun. 13, 656 (2022).
20. L. Lin et al. Thermophoretic tweezers for low-power and versatile manipulation of biological cells. ACS Nano 11, 3147–3154 (2017).
21. M. Mittasch et al. Non-invasive perturbations of intracellular flow reveal physical principles of cell organization. Nat. Cell Biol. 20, 344–351 (2018).
22. D. J. Simon et al. Thermoplasmonic manipulation for the study of single polymers and protein aggregates. Macromol. Chem. Phys. 224, 2300060 (2023).
23. D. J. Simon et al. Accumulation and stretching of DNA molecules in temperature-induced concentration gradients. J. Phys. Chem. B 127, 10861–10870 (2023).
24. R. Piazza & A. Parola. Thermophoresis in colloidal suspensions. J. Phys. Condens. Matter 20, 153102 (2008).
25. W. Kang et al. Coupled photothermal vortices for capture, sorting, and transportation of particles. Opt. Lett. 49, 3974–3977 (2024).
26. M. Watanabe et al. Micro-fluidic gate based on photo-rheological fluid. In Optical Imaging and Engineering (OIE) 2025.
27. K. Kobayashi & H. Onoe. Microfluidic-based flexible reflective multicolor display. Microsyst. Nanoeng. 4, 17 (2018).
28. A. B. Vasista et al. Non–steady state thermometry with optical diffraction tomography. Sci. Adv. 10, 5440 (2024).
29. B. Ciraulo et al. Long-range optofluidic control with plasmon heating. Nat. Commun. 12, 2001 (2021).
30. V. Ruzzi et al. Optothermal crystallization of hard spheres in an effective bidimensional geometry. J. Chem. Phys. 159, 154904 (2023).
31. K. Luckert. Handbuch der mechanischen Fest-Flüssig-Trennung (Vulkan-Verlag, 2004).
32. M. Krishnan et al. Geometry-induced electrostatic trapping of nanometric objects in a fluid. Nature 467, 692–695 (2010).
33. T. Takahashi et al. A microfluidic device for isolating intact chromosomes from single mammalian cells and probing their folding stability by controlling solution conditions. Sci. Rep. 8, 13684 (2018).
34. L. R. Huang et al. Continuous particle separation through deterministic lateral displacement. Science 304, 987–990 (2004).
35. M. Braibanti et al. Does thermophoretic mobility depend on particle size? Phys. Rev. Lett. 100, 108303 (2008).
36. X. Chen et al. Optothermally programmable liquids with spatiotemporal precision and functional complexity. Adv. Mater. 34, 2205563 (2022).
37. I. Thormählen et al. Refractive index of water and its dependence on wavelength, temperature, and density. J. Phys. Chem. Ref. Data 14, 933–945 (1985).
38. R. Parthasarathy. Rapid, accurate particle tracking by calculation of radial symmetry centers. Nat. Methods 9, 724–726 (2012).
39. J. Garcia-Guirado et al. Overcoming diffusion-limited biosensing by electrothermoplasmonics. ACS Photonics 5, 3673–3679 (2018).
40. F. Schmidt et al. 3D optofluidic control using reconfigurable thermal barriers. Zenodo https://doi.org/10.5281/zenodo.13990372 (2024).
41. T. Tsuji et al. Dynamic pattern formation of microparticles in a uniform flow by an on-chip thermophoretic separation device. Phys. Rev. Appl. 9, 024035 (2018).
42. A. Stollmann et al. Molecular fingerprinting of biological nanoparticles with a label-free optofluidic platform. Nat. Commun. 15, 4109 (2024).

Figures used in the abstract

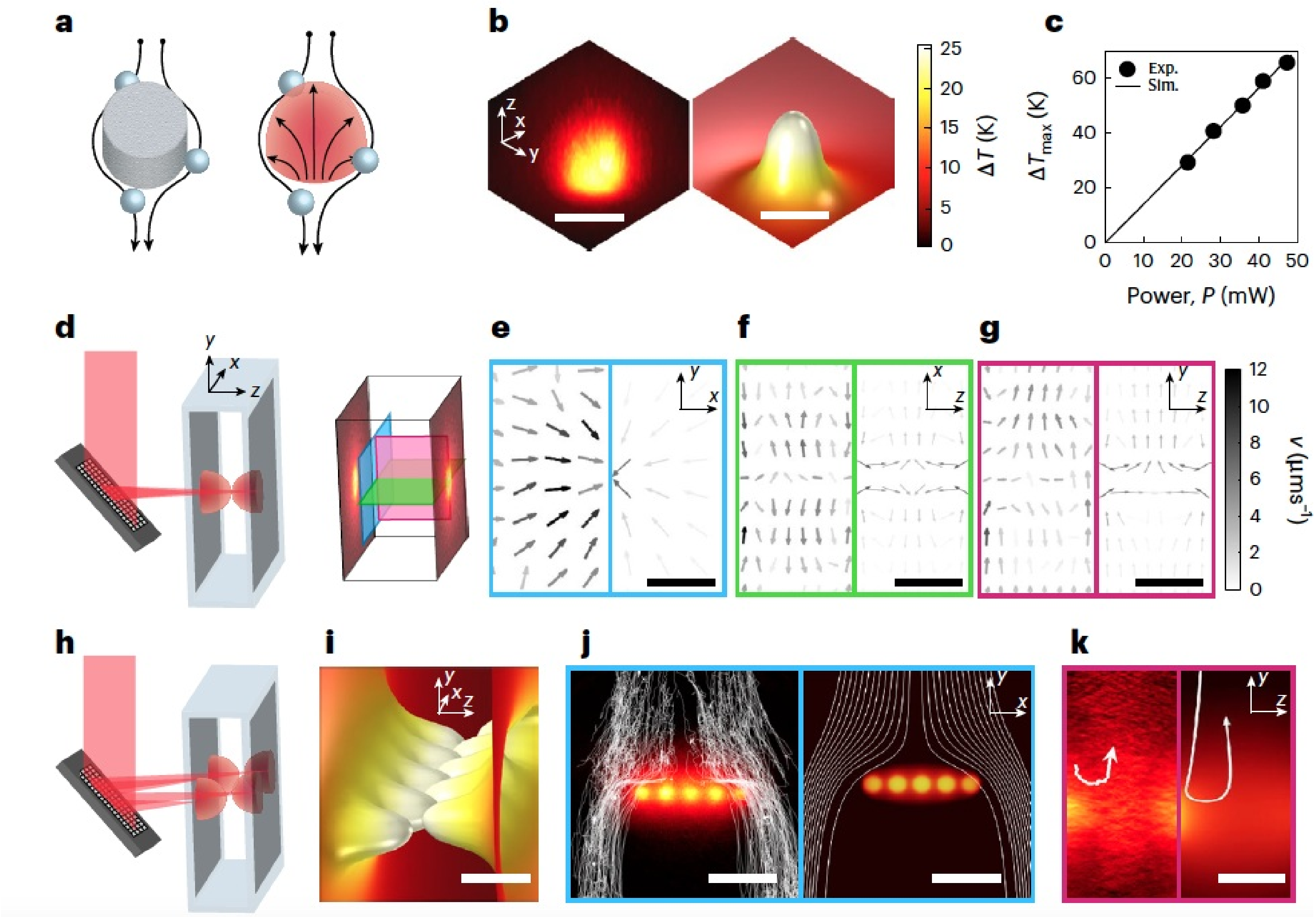

Figure 1 : Light-driven flows form reconfigurable barriers; experiments and simulations reveal 3D thermal control of particle trajectories.

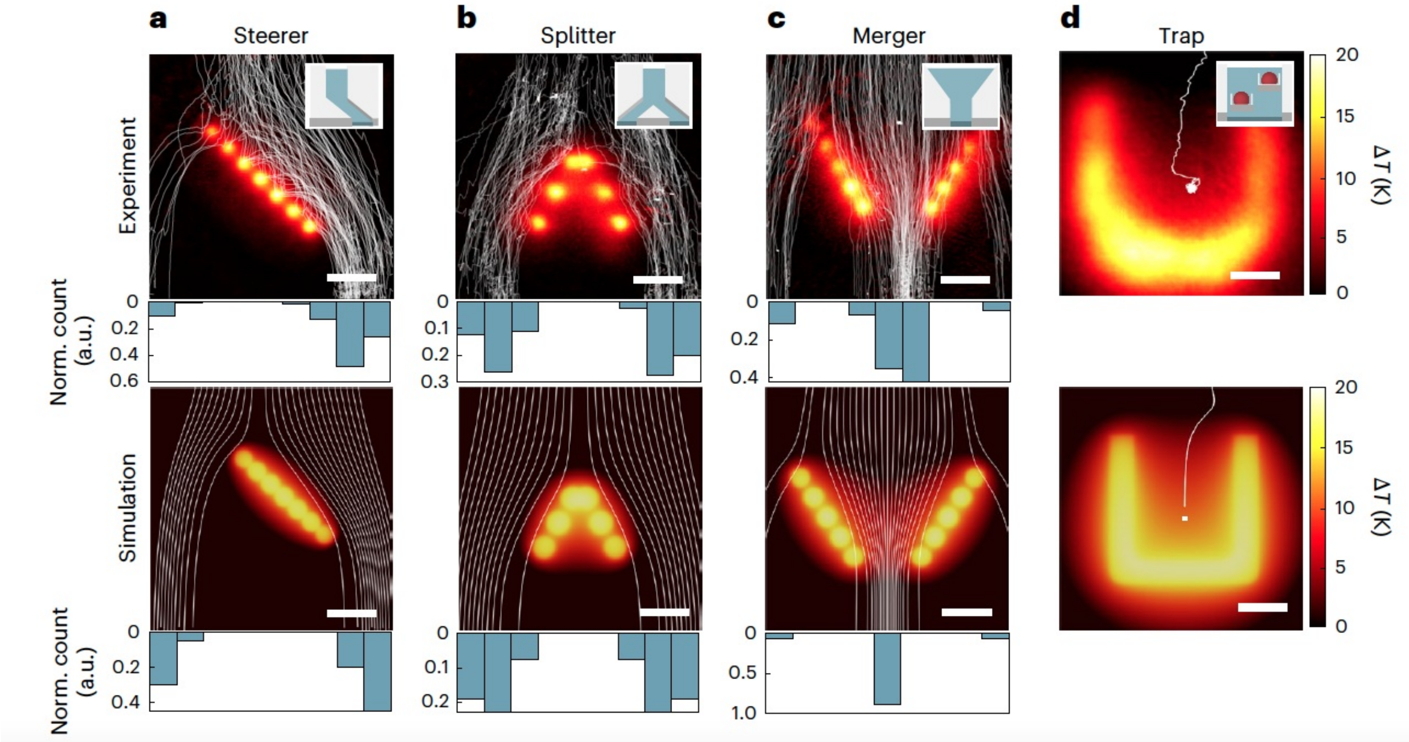

Figure 2 : Experimental and simulated optofluidic barriers steer, split, merge or trap particles via heat-induced flows and tailored thermal geometries.

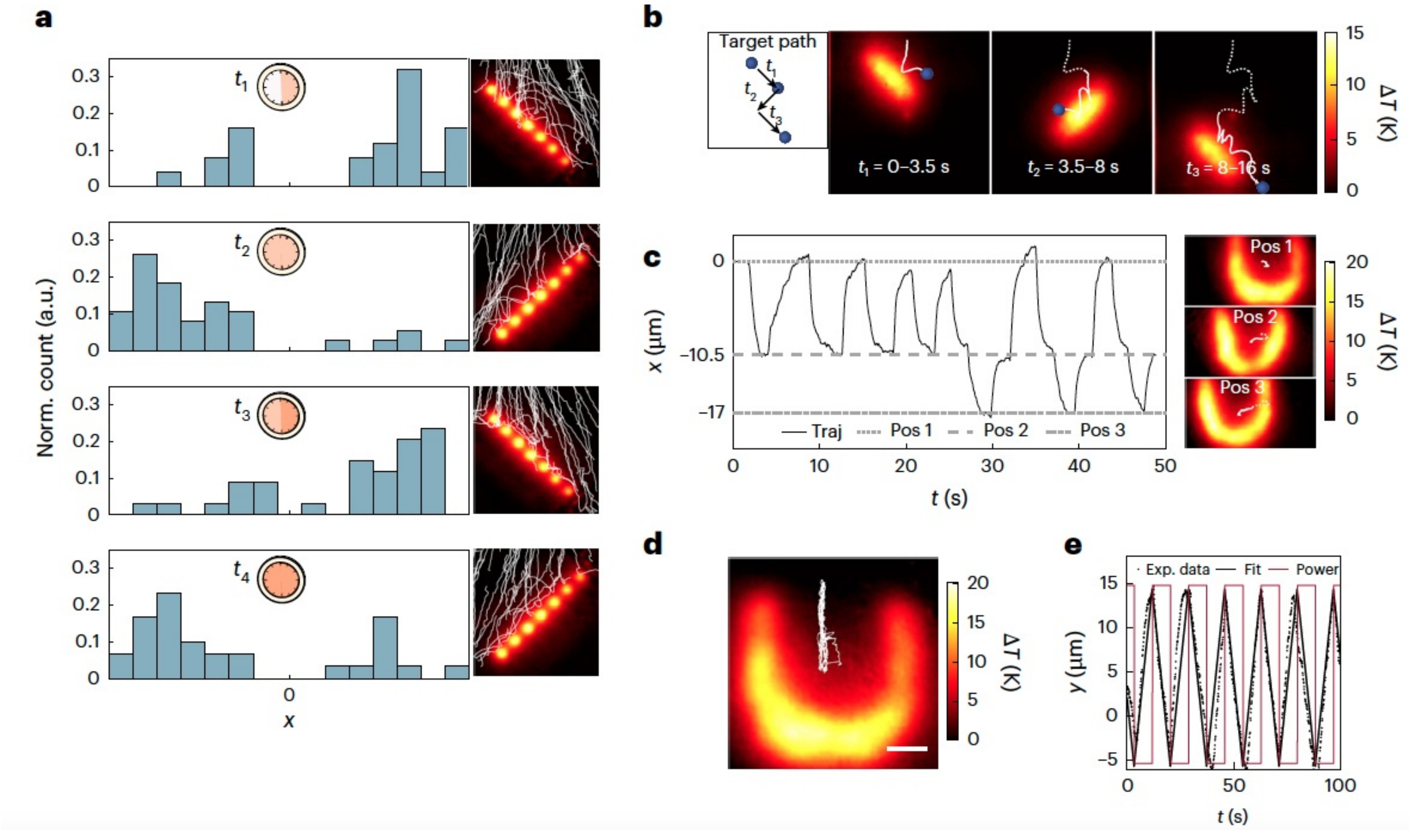

Figure 3 : Optofluidic barriers reconfigure in time and space to steer, trap, and shift particles; experiments and simulations show dynamic control.

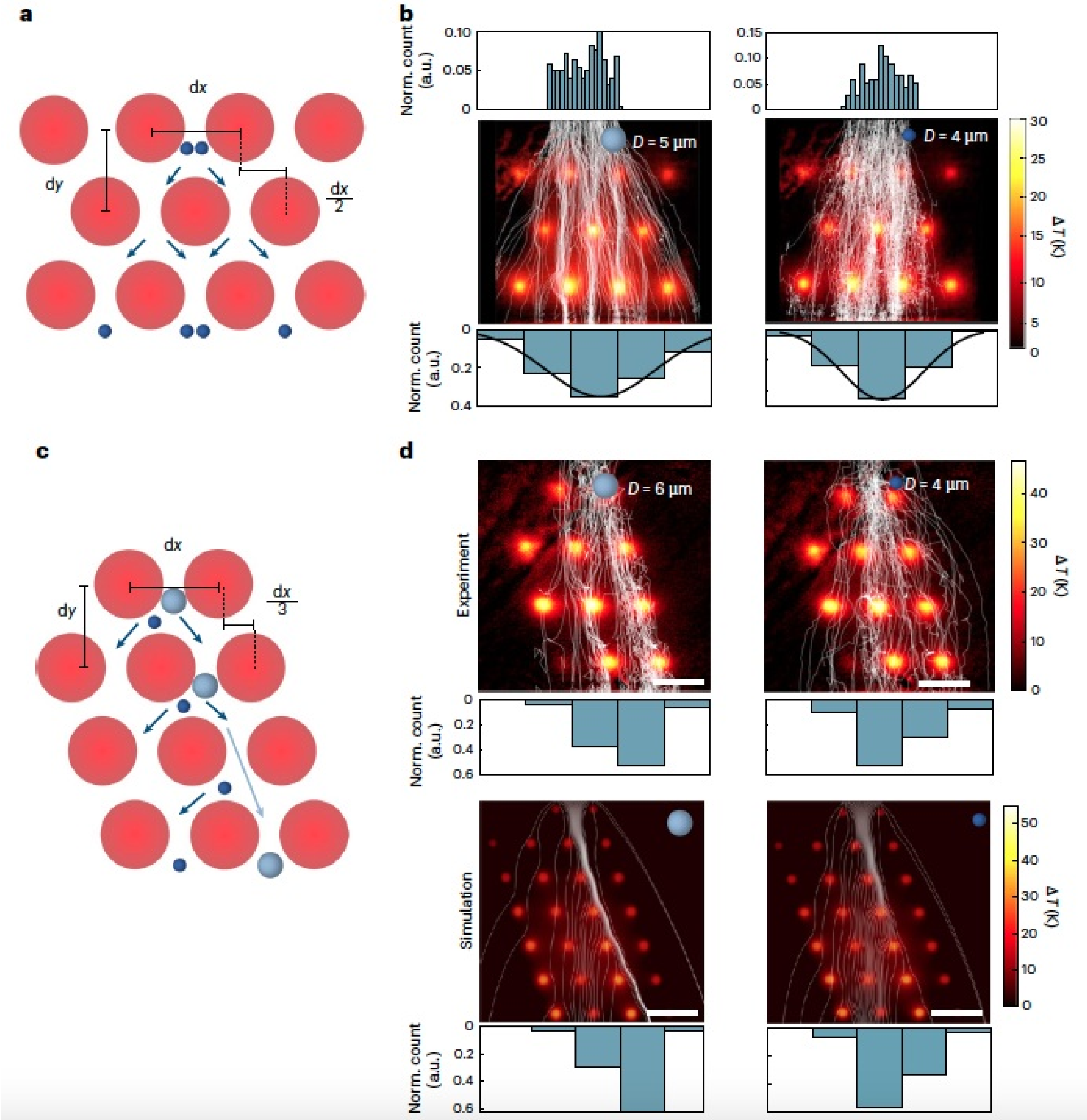

Figure 4 : Periodic optofluidic barriers steer particles into size-dependent paths; experiments and simulations show sorting via thermal flow patterns.