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EDITORIAL

Flow and transport in micro- and nano-scale devices

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1. Introduction

Flow and transport phenomena in micro- and nano-scale devices occupy a distinctive position in fluid mechanics. At these length scales, confinement, interfaces, surface charge, wetting, slip, diffusion and particle dynamics often dominate over the mechanisms familiar at larger scales. Micro- and nanofluidic systems therefore serve a dual role: they are both compact platforms for chemical, biological and materials analysis and synthesis, and also well-controlled settings in which fundamental questions about interfacial dynamics, electrokinetic transport, multiphase flow, mixing, diffusion and the particulate dynamics can be examined with unusual precision.

The field is inherently interdisciplinary. Progress often requires the joint use of theory, computation, microfabrication, advanced imaging, data-driven analysis and carefully designed experiments. The same physical mechanisms that raise fundamental questions also create opportunities for practical technologies, including lab-on-a-chip diagnostics, nanopore sensing, desalination and energy harvesting, microreactors, soft-material manufacturing, microrobotic propulsion and control of complex suspensions. This dual character is closely aligned with the founding purpose of *Flow*: to show how the principles and tools of fluid mechanics can be used to address concrete problems, enable new technologies and deepen our understanding of nature (Santiago 2021). In this sense, applications are often most compelling when they are built on clear physical understanding, and fundamental analysis is often most powerful when it remains connected to the problems it can help solve.

This Special Issue, "Flow and Transport in Micro- and Nano-Scale Devices", brings together 14 research articles that reflect the breadth and diversity of contemporary research in the field. The contributions span electroosmotic instabilities in bipolar nanochannels, electroosmotic flow in nanopores, wall-slip measurement and characterisation, slip-flow analysis and prediction, particle diffusometry, thermally driven mixing, cell manipulation and viability in microstreaming flows, droplet and jet formation in ternary fluid systems, droplet breakup in confined flow-focusing geometries, microbubble coalescence and bubble-driven propulsion, nanofibril assembly, dense suspension hopper flows and wetting on microstructured surfaces. Although the topics are diverse, they share a common aim: to connect micro- and nano-scale flow physics with measurement, modelling, design and application.

In the following section, we summarise the contributions in alphabetical order by the first author's family name, consistent with the format of the references. Rather than simply reviewing individual papers, we organise the discussion around the scientific questions that motivate the work, the approaches used to address those questions and the insights that emerge from the findings. In keeping with *Flow*'s

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emphasis on accessible, application-aware fluid mechanics, our aim is not only to summarise the Special Issue, but also to illuminate the broader scientific challenges, opportunities and implications that connect these studies. We then conclude by identifying several common themes and future directions for the field.

2. Overview of the contributions

Ion-selective nanochannels and membranes are central to desalination, energy harvesting, biosensing and fluidic circuits, but their behaviour is not only determined by average charge or applied voltage. A particularly important question is how electroosmotic instabilities change ion transport when two oppositely charged permselective regions are placed in series. In their two-part study, Abu-Rjal & Green (2024*a*,*b*) examine this problem using systematic numerical simulations of bipolar nanochannels. Part 1 focuses on the steady-state current–voltage response and shows that internally symmetric bipolar systems can suppress overlimiting currents, whereas asymmetric systems display voltage-dependent signatures. Part 2 follows the transient evolution and clarifies when instabilities appear, persist or decay at the two charged interfaces. The broader lesson is that bipolar systems are not simple extensions of unipolar systems; their response depends on geometry, charge layout and the history by which steady state is reached. The practical implication is a more reliable interpretation of electrical signatures in fabricated bipolar devices, especially when geometry and surface-charge layout are used as design variables.

Wall slip is often a small boundary effect, but in micro- and nano-scale flows it can influence drag, lubrication, dynamic wetting and flow resistance. The difficulty is that slip lengths are hard to measure reliably on technically relevant rough surfaces, especially because many existing wall-slip measurement techniques operate at small characteristic length scales, often of the order of 10 μm, which can be comparable to the surface roughness. This motivates the question of whether a larger-scale plate–plate slip-length tribometer with a 10-mm-diameter plate can infer the slip length from torque and gap-height measurements without being compromised by inlet and outlet effects. To address this question, Asghar *et al.* (2024) validate their tribometer model using OpenFOAM simulations with a Navier-slip boundary condition. The numerical results agree closely with the simplified analytical model and show that inlet effects are negligible for the device geometry. The significance of this work is methodological: it strengthens the basis for measuring wall slip at varying temperature (–30 to 100 °C) and roughness (10 nm to 1 μm), relevant to engineered surfaces. Such capability is important for lubrication, sealing, coating and wetting technologies where boundary conditions cannot simply be assumed.

Mixing remains one of the persistent limitations in some microfluidic applications because low-Reynolds-number flows lack turbulence and molecular diffusion is often too slow. A useful mixer should therefore generate transverse transport without excessive complexity, moving parts or harsh operating conditions. The question addressed here is whether modest thermal gradients can drive three-dimensional swirling motion through mixed convection, and over what range of channel dimensions and Reynolds numbers this effect is useful. Azzini *et al.* (2025) combine general defocusing particle tracking in a square glass capillary with numerical simulations over an extended parameter space, measuring the three-dimensional flow fields in different operating conditions. They show that thermally driven swirlers have an optimal operating range, particularly for hydraulic diameters of roughly 400–1600 μm and Reynolds numbers near unity, where the mixing efficiency reaches up to 60% above that achieved by pure diffusion. The work is valuable because it identifies both the promises and the limits of this active mixing strategy. Because the device needs no moving parts and operates with moderate temperature differences, the work provides a practical basis for low-cost active mixing in microreactors and lab-on-a-chip platforms, while also defining the limits of this approach.

Precise manipulation of cells in microfluidic devices is useful only if the cells remain viable and functionally intact. This creates a demanding scientific and engineering problem: actuation must be strong enough to position, sort or remove cells, yet gentle enough to avoid mechanical damage. The central question is whether ultrasound-driven microbubble streaming can meet this requirement for human cells. Bakhtiari *et al.* (2025) address this issue by quantifying the shear-stress field around actuated

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microbubbles using high-frequency micro-particle tracking velocimetry and by testing cell viability during microbubble-based detection, positioning and sorting. The highest stresses ($\tau = 1 \times 10^{-6}$ N m^{-2}) are localised near the bubble and, under the tested conditions, remain below the levels expected to damage most biological cells. This study therefore advances microbubble streaming from a particle-manipulation method toward a cell-compatible microfluidic tool. The application implications are clear but should remain specific: the method may support lab-on-a-chip diagnostics, automated removal of compromised cells and selective positioning of rare cells, provided that exposure time, cell type and device geometry are controlled.

Engineered wetting surfaces are designed to guide droplet spreading, but the usual descriptors of surface roughness, pillar density or symmetry do not always distinguish surfaces that produce different moving contact-line morphologies. The scientific need is therefore a descriptor that captures the configurational complexity of pillar-arrayed microstructures and relates it to droplet behaviour. Chen *et al.* (2024) introduce configurational entropy as such a measure and apply it to periodic and quasiperiodic pillar arrays. By comparing the calculated entropy with reported wetting morphologies, they show that surfaces with non-zero configurational entropy can produce more complex contact-line morphologies than surfaces with zero configurational entropy. The significance is not that configurational entropy alone replaces detailed wetting models, but that it provides a way to connect microstructure design with contact-line morphology. This perspective may help guiding the design of surfaces for microfluidic patterning, printing, water harvesting and self-cleaning, where the desired function often depends on controlling how a droplet spreads rather than only how strongly it wets.

Electroosmotic flow, i.e. the motion of fluid due to an external electric field, is one of the most common electrohydrodynamic phenomena. Electroosmotic flow in nanopores strongly affects nanopore sensing, membrane separations and nanofluidic energy conversion, but direct flow measurements at nanometre scales are extremely difficult. For this reason, approximate expressions are often used to infer electroosmotic flow from more accessible electrical measurements such as ion selectivity and ionic current. The scientific question is when such approximations are physically justified and when they become misleading. Di Muccio *et al.* (2025) examine this issue using theoretical scaling arguments, continuum electrohydrodynamic simulations and molecular dynamics simulations of biological nanopores. They show that some popular estimates violate basic fluid-dynamic scaling, although they may still capture the order of magnitude for very narrow pores. They also identify situations in which ion selectivity does not correlate simply with electroosmotic flow, especially for non-cylindrical pores and localised charge changes. The work provides a cautionary but useful framework for nanopore engineering: convenient estimates can be valuable, but they must be checked against pore geometry, charge pattern and molecular-scale physics.

Droplet-based microfluidic technology depends on controlled droplet generation and, in many applications, controlled downstream splitting. Yet breakup in confined channels is highly sensitive to geometry, capillary number and three-dimensional interface curvature. The key question is how the channel aspect ratio modifies droplet deformation and breakup at flow-focusing junctions. He *et al.* (2025) study this problem using devices with two flow-focusing junctions and aspect ratios of 1, 1/2 and 1/3, combining experiments with numerical simulations. They identify no-breakup, single-breakup and multiple-breakup regimes, quantify the dependence of droplet length on flow parameters and aspect ratio and analyse neck thinning together with interfacial curvature. A notable result is that the scaling of mean curvature differs between square and rectangular channels. The broader implication is that droplet breakup should be designed with the full three-dimensional interface in mind. This mechanistic understanding can not only advance our knowledge of the fluid interface dynamics, but also support microfluidic systems for chemical assays, cell analysis, pharmaceutical processing and materials synthesis, where droplet size and splitting reliability matter.

Ternary fluid systems containing water, oil and a mutually miscible solvent are common in extraction, emulsification, pharmaceutical processing and soft-material synthesis, but their short-time, out-of-equilibrium microfluidic behaviour is difficult to predict. Solvent transfer can alter interfacial tension, viscosity contrast, wetting and phase behaviour while the flow is still evolving. The central

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question is how solvent concentration reorganises droplet and jet formation when an aqueous phase is injected into a solvent-rich oil phase. Joseph & Cubaud (2025) address this question in coaxial square microchannels by varying flow rates and solvent concentration. They map dripping, jetting, phase inversion, dynamic wetting and conjugate-jet regimes, and develop functional relations for droplet length, spacing and jet morphology. The authors show how solvent concentration changes interfacial tension, viscosity contrast, mass transfer and wetting in ways that reorganise flow patterns. The study shows that microfluidics can be used, not only for droplet production, but also for probing out-of-equilibrium phase behaviour in complex liquid mixtures. Its implications are relevant to microreactors, separations and the processing of time-evolving soft materials, where mass transfer and hydrodynamic stability must be controlled together.

Particle discharge through constrictions is familiar in dry grains, suspensions, blood flow, printing and industrial transport, yet clogging remains difficult to predict because many particle properties are hard to vary independently in conventional set-ups. A useful model system should allow controlled changes in particle size, shape and deformability while retaining a well-defined flow geometry. Kool *et al.* (2025) develop such a platform by combining *in situ* photolithographic particle fabrication with a microfluidic model system featuring a two-dimensional hopper channel and a Quake valve for particle compaction at the constriction. For dense suspensions of hard monodisperse disks, they show constant discharge rates under imposed pressure and imposed flow rate, a Beverloo-like scaling under imposed flow rate and stochastic clogging statistics consistent with other hopper systems. Although this study focuses only on densely packed, hard, disk-shaped particles, particle shape can be readily controlled in their experimental set-up by changing the design of the UV mask used during particle fabrication. It provides a bridge between granular physics and wet suspension transport, and it opens a route to systematic studies of more complex particles. Such studies are relevant to microfluidic clogging, biomedical flows and manufacturing processes involving dense particulate suspensions.

Slip at a solid boundary can be small in absolute magnitude but still change measurable quantities such as drag, torque and pressure loss in micro- and nano-scale Stokes flows. The challenge is to predict these first-order effects without solving a full slip-flow problem for every new geometry. Lockerby (2025) addresses this challenge by generalising a reciprocal-theorem approach to surface moments of the traction force, such as drag and torque. The method converts known no-slip solutions into first-order estimates for Navier- or Maxwell-slip effects and is verified numerically across several cases. Applications include translating particles, a micro-journal bearing, a self-propelled squirmer and pressure-driven channel flow. The analysis also yields useful general results: within the low-slip Stokes-flow limit, positive slip reduces drag on translating particles and reduces pressure loss in straight channels. The contribution is valuable because it turns existing no-slip solutions into practical estimates for slip corrections. Such results can guide the design of microchannels, particle-based devices and low-friction surfaces before more detailed simulations are required.

Sustainable high-performance materials increasingly rely on controlling structure across scales, including the alignment of nanoscale building blocks during processing. For cellulose nanofibrils, alignment can strongly influence the stiffness and properties of the resulting filament, but the relation between microfluidic geometry and fibril orientation is not straightforward. The question is how flow-focusing channel design can be used to tune both thread formation and nanofibril alignment. Osawa *et al.* (2025) combine experiments, X-ray scattering and simulations of flow and fibril orientation to examine the effects of confluence angle, channel aspect ratio and contractions in the core and sheath flows. The work aims to understand and control the assembly of nanostructured material in micrometre- and millimetre-sized flow systems. The results show that the confluence angle has a smaller influence on alignment than channel contractions; sheath-flow contractions help detaching the core from channel walls, whereas core-flow contractions increase and homogenise alignment. The strength of the work lies in linking device geometry to alignment and filament shape through a validated modelling framework. The practical implication is direct: microfluidic design can become a route for manufacturing aligned bio-based filaments and other hierarchical materials with improved performance and lower energy demand.

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Quantitative diffusometry is important for disease detection, nanoparticle characterisation and microfluidic property measurement, among others, but real particle images are rarely ideal. Flow, image noise, high particle concentration and defocussing can all degrade conventional and deep learning-based particle diffusometry (DPD) algorithms. The question is how to estimate diffusion coefficients robustly across such experimental variability. Sardana & Wereley (2025) develop DPD-v2, a generalised deep particle diffusometry method based on redesigned convolutional neural networks. Instead of relying on temporal averaging, the method uses stacks of image frames, allowing the network to retain temporal information more effectively. The authors train and test the models on synthetic Gaussian and defocused-particle datasets, benchmark them against conventional algorithms and evaluate them on experimental no-flow data. The DPD-v2 method gives lower errors than other methods and is more robust to particle shape and imaging conditions. The broader value is methodological: improved diffusometry can support point-of-care diagnostics, nanoparticle characterisation and microfluidic property measurement. The same data-driven framework may also be adapted to infer velocity fields in flows where diffusion and advection are coupled.

Bubble-powered micromotors convert rapid interfacial events into motion, but the propulsion mechanism can be difficult to isolate when bubble growth, coalescence, detachment, viscosity and confinement act together. A key question is how two coalescing microbubbles near a Janus micromotor generate displacement. Wang *et al.* (2025) investigate this question using high-speed microscopy of microbubbles produced on a platinum–silica Janus microsphere over a range of Ohnesorge numbers. They identify a universal coalescence scaling with a transition from an inertially limited viscous regime to an inertial regime, observe asymmetric neck growth due to the nearby solid boundary and separate two contributions to micromotor displacement: liquid counteraction during bubble deformation and momentum transfer during bubble detachment. The study clarifies how surface tension, viscosity, confinement and detachment combine to propel a micromotor. Its application relevance lies in the design of bubble-powered microrobots and microrockets, where propulsion efficiency depends on controlling not only bubble production but also bubble interaction and release.

3. Common threads and future directions

Several common threads emerge from this Special Issue. First, micro- and nano-scale flow systems are governed by mechanisms that are often interfacial, coupled and geometry-dependent: electroosmotic instabilities depend on charge layout; droplet breakup depends on confinement and curvature; wetting morphology depends on surface architecture; and bubble propulsion depends on coalescence near boundaries. Second, reliable progress often requires methods that connect scales. Analytical models, continuum simulations, molecular simulations, data-driven algorithms, advanced imaging and microfabricated model systems all appear in this Special Issue, often in combination. Third, application-oriented work is strongest when it remains anchored in physical fundamentals. This is the guiding balance emphasised by *Flow*: fundamental concepts of fluid mechanics should be used to reach concrete applications, and practical applications should in turn sharpen the questions asked on the side of fundamentals.

At the same time, several open questions remain. Many of the phenomena discussed here involve non-equilibrium interfaces, heterogeneous surfaces, complex fluids or biological materials, for which general predictive models are still limited. Boundary conditions such as slip, surface charge and wetting remain difficult to measure and to transfer across scales. Data-driven methods are promising, but their reliability depends on training data, physical constraints and validation against experiments outside idealised conditions. For biological and biomedical applications, device performance must be evaluated together with biocompatibility, robustness and repeatability. For materials and energy applications, laboratory demonstrations must eventually be connected to throughput, durability, as well as manufacturability and operating constraints.

Future work should therefore move in three directions. The first is quantitative characterisation: improved *in situ* measurements of velocity, stress, concentration, temperature, charge, interface shape

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and material structure will remain essential. The second is predictive modelling: simplified, physically grounded models, high-fidelity simulations and machine-learning tools should be developed in ways that are mutually testable and physically interpretable. The third is design translation: micro- and nano-scale devices should be optimised not only for isolated performance metrics, but also for stability, fabrication tolerance, cost, scalability and integration into larger systems. These directions are closely aligned with the mission of *Flow*, which is to connect fundamental fluid mechanics with applications in engineering, biology, materials science and technology.

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Declaration of interests. The authors report no conflicts of interest.

References

Abu-Rjal, R., & Green, Y. (2024*a*). Bipolar nanochannels: The effects of an electroosmotic instability. Part 1. Steady-state response. *Flow*, *4*, E28.

Abu-Rjal, R., & Green, Y. (2024*b*). Bipolar nanochannels: the effects of an electroosmotic instability. Part 2. Time-transient response. *Flow*, *4*, E29.

Asghar, M. H., Marić, T., Gozlen, H. B., Raju, S., Fricke, M., Kuhr, M.M.G., Pelz, P. F., & Bothe, D. (2024). Analytical and numerical validation of a plate-plate tribometer for measuring wall slip. *Flow*, *4*, E31.

Azzini, F., M'hadbi, A., Ganaoui, M. E., Pulvirenti, B., Morini, G. L., Rojas-Cárdenas, M., & Rossi, M. (2025). Assessment of mixing efficiency of thermally driven microfluidic swirlers. *Flow*, *5*, E21.

Bakhtiari, A., Schumm, B., Schönfelder, M., & Kähler, C. J. (2025). Investigating cell viability under shear stress in complex microstreaming flows generated by ultrasound-driven actuated microbubbles. *Flow*, *5*, E7.

Chen, E., Huang, X., & Zhao, Y.-P. (2024). The configurational entropy of pillar-arrayed microstructured surfaces with spreading droplets. *Flow*, *4*, E12.

Di Muccio, G., Gargano, S., Iacoviello, D. F., Rocca, B. M., & Chinappi, M. (2025). Validity of approximated expressions for electro-osmotic flow in nanopores evaluated by continuum electrohydrodynamics and atomistic simulations. *Flow*, *5*, E28.

He, L., Wang, B., Liu, Q., & Chen, X. (2025). Interface evolution of microdroplets in flow-focusing channels with varying aspect ratios. *Flow*, *5*, E19.

Joseph, V., & Cubaud, T. (2025). Formation of microfluidic droplets and jets in a solvent-rich oil phase. *Flow*, *5*, E24.

Kool, L., Tampier, J., Bourrianne, P., & Lindner, A. (2025). Hopper flows of dense suspensions: a 2D microfluidic model system. *Flow*, *5*, E26.

Lockerby, D. A. (2025). First-order analysis of slip flow for micro and nanoscale applications. *Flow*, *5*, E3.

Osawa, K., Gowda, V. K., Rosén, T., Roth, S. V., Söderberg, L. D., Shiomi, J., & Lundell, F. (2025). Regulating nanofibril assembly using diverse flow-focusing channels. *Flow*, *5*, E12.

Santiago, J. G. (2021). Flow forth. *Flow*, *1*, E1.

Sardana, P., & Wereley, S. T. (2025). DPD-v2: Generalised deep particle diffusometry for varied particle shapes and experimental conditions. *Flow*, *5*, E6.

Wang, L., Yang, F., Wang, L., Chen, L., Huang, M., Guan, D., Cui, H., & Zheng, X. (2025). Coalescence of microbubbles for the double-bubble-powered micromotor in viscous liquids near a confinement boundary. *Flow*, *5*, E15.

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