

Nanofluidic Channels in Photopolymer Materials: Fabrication, Surface Charge, Wetting, Fouling and Transport

Qualification of printed nanochannels where geometry, interfacial chemistry and confinement jointly determine transport

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Abstract

Nanofluidic channels in photopolymer materials operate in a regime where channel dimensions, wall chemistry and electrical double layers jointly control transport. This review focuses on fabrication, surface charge, wetting, fouling and ionic/molecular transport rather than treating a nanochannel as a scaled microchannel. General printed-microfluidics literature defines additive fabrication constraints, while dedicated nanofluidic work shows that surface charge and electroosmotic flow become primary state variables under strong confinement. Qualification therefore requires channel-size and continuity metrology, wall-surface characterisation, ionic conductance or electroosmotic measurements, wetting/adsorption controls and stability under the intended electrolyte. The framework distinguishes geometric occlusion from charge-driven transport changes and from fouling, because all three can reduce flow or conductance. A transport model should be tested against measured channel and surface state rather than fitted to an unknown effective geometry.

Keywords: nanofluidics; photopolymer; two-photon polymerisation; nanochannel; surface charge; wetting; fouling; electrokinetics; transport

1. Significance and scope

When one channel dimension approaches the scale at which interfacial layers occupy a substantial fraction of the cross-section, the wall becomes part of the transport law. Surface charge, ionic strength, pH, wetting and adsorption can alter conductance and electroosmotic flow even when nominal geometry is unchanged. Manufacturing qualification must therefore include surface-state measurements alongside dimensional metrology.

1.1 Corpus boundary

ER-340 owns confined transport in photopolymer nanochannels, including surface charge, wetting, fouling and transport. ER-333 owns active microfluidic valves and pumps, ER-281 microreactors, ER-282 analytical labware, and ER-208 surface-chemistry mapping methods. ER-340 uses those surface measurements only to interpret nanofluidic transport and does not take ownership of general surface metrology.

2. At nanoscale, the wall becomes part of the fluidic system

As channel dimensions approach interfacial length scales, surface charge, adsorption layers and roughness occupy a significant fraction of the cross-section. Nominal width and height are therefore insufficient descriptors of transport.

3. Fabrication and clearing define the accessible channel

Incomplete polymerisation control can close a channel, while retained resin or developer residue can reduce the hydraulic or ionic aperture. Cross-section, connectivity and post-process cleanliness should be verified before transport data are interpreted [1-3].

4. Wetting and charge are state variables

Contact angle measured on a flat coupon may not represent confined-channel behaviour, but surface chemistry, zeta potential or electroosmotic response can provide complementary evidence. Conditioning history, pH and ionic strength must accompany electrokinetic measurements.

5. Fouling changes both geometry and chemistry

Protein, particle or organic adsorption can simultaneously reduce cross-section and alter surface charge. Time-resolved pressure-flow or ionic-conductance tests should therefore be paired with cleaning/recovery studies.

6. Qualification architecture

Qualification should establish channel continuity and cross-section first, preferably with methods capable of detecting collapse or partial occlusion. Surface charge is then characterised through a suitable electrokinetic or conductance method under declared pH and ionic strength. Wetting and adsorption/fouling tests follow, and transport is measured only after the electrolyte and conditioning history are fixed. Dedicated nanofluidic literature demonstrates that surface-charge state can dominate ion transport and electroosmosis [3,4].

7. Minimum evidence for transfer

Transfer evidence includes channel dimensions and uncertainty, resin/material state, fabrication and development history, wall conditioning, electrolyte composition, pH, ionic strength and temperature. Conductance, electroosmotic velocity or pressure-driven flow should be reported with enough information to test whether geometry alone explains the result. Chemically modified polymer nanochannels show how wall chemistry changes electroosmotic behaviour without changing nominal channel size [4].

7.1 Evidence hierarchy and transfer

A reduction in throughput should not automatically be interpreted as narrowing. If imaging shows stable geometry but zeta-potential or electroosmotic response changes, wall chemistry or fouling is the stronger explanation. Conversely, conductance changes that scale with measured occlusion support a geometric cause. Paired structural and electrokinetic measurements are therefore more diagnostic than either alone.

7.2 Research priorities

Priority work includes non-destructive dimensional metrology of enclosed polymer nanochannels, reference protocols for surface-charge measurement on printed polymers, and ageing studies that separate chemical drift from physical fouling. Additive laser processing is promising for integrated micro/nanofluidics, but reproducibility of the final wall state remains a key evidence gap [5].

Table 1. Minimum qualification matrix for photopolymer nanofluidic channels.

Nanofluidic state	Minimum measurement	Qualification purpose
Geometry	channel dimensions and connectivity	defines confinement
Surface	wettability and charge/electroosmotic proxy	defines wall-fluid interaction
Transport	pressure-flow or conductance versus composition	tests coupled response
Cleanliness	residue and extractables check	separates fabrication residue from fluid physics
Fouling	drift and recovery after exposure	tests service stability

8. Interpretation matrix

Low conductance, electroosmotic reversal, poor wetting and progressive flow loss are different observations. The matrix assigns geometry, surface-charge, contact-angle/adsorption and cleaning controls so that transport anomalies can be attributed to a measured state variable.

Table 2. Diagnostic interpretation matrix for nanofluidic transport anomalies.

Transport observation	Competing mechanism	Discriminating control
Conductance changes with pH	surface charge regulation	pH/ionic-strength sweep
Pressure drop rises over time	fouling or swelling	imaging plus recovery/cleaning test
Nominally open channel has low flow	residual resin or reduced aperture	cross-section/connectivity measurement
Electroosmotic direction changes	surface chemistry modification or adsorbate	zeta/electroosmotic characterisation before/after exposure

9. Limitations and evidence gaps

Much of nanofluidic theory and metrology was developed on glass, silicon or thermoplastics rather than photocured networks, while printed nanochannels introduce additional conversion and development variability. Quantitative surface-charge or slip values should therefore not be transferred between materials without verification. This review does not assume that a microfluidic scaling law remains valid under nanoconfinement.

10. Conclusions

Photopolymer nanochannels are qualified when geometry and wall state jointly explain measured transport. Channel size alone cannot establish function once surface charge, wetting and fouling become comparable in importance to cross-section. ER-340 therefore requires structural and electrokinetic evidence in the same state description, providing a basis for distinguishing occlusion, surface-chemistry drift and true transport phenomena.

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Competing interests

The author is Founder, CEO and CTO of 3Dresyns by Resyner Technologies S.L. No comparative product recommendation is made.

Data availability

No new experimental dataset was generated for this review.