

Wettability and Capillary Flow in Vat-Printed Microfluidic Channels

Contact Angle, Hysteresis, Surface State, Roughness, Ageing, Surface Modification and Flow Qualification

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ER-097 · Engineering Review · Version 0.3 · 28 August 2026

Statement of Significance

A water contact angle is not a complete capillary-flow specification. In vat-printed microchannels, apparent wetting is coupled to surface chemistry, layer-generated topography, post-processing, ageing, liquid composition, contact-angle hysteresis and channel geometry. ER-97 defines how to separate these variables so that a surface-treatment or self-filling claim is tied to a measured final channel state rather than inferred from one sessile-drop number.

Keywords: wettability; contact angle; contact angle hysteresis; capillary flow; microfluidics; DLP; SLA; surface energy; roughness; surface modification; vat photopolymerisation

Abstract

Vat photopolymerisation enables monolithic microchannels but also creates process-dependent surfaces whose wetting behaviour can influence filling, droplet motion and two-phase flow. Direct DLP evidence shows that layer thickness and lamination direction can change surface roughness, contact angle, contact-angle hysteresis and capillary movement [1]. A separate SLA study found time-dependent contact-angle change in a printed polymer and linked that evolution to the practical window for self-driven capillary microfluidics [2]. Surface modification can deliberately change channel wetting, as demonstrated in DLP-printed devices for two-phase flow [3], while printed microtexture can alter apparent contact angle even when bulk chemistry is unchanged [4]. ER-97 therefore distinguishes static contact angle, advancing/receding behaviour, surface free energy, roughness, capillary pressure and actual flow. It also separates final-part wall wettability from resin-vat/release-film wetting during printing, an important boundary in microchannel overcure studies [5]. The qualification architecture requires final-state conditioning, defined probe liquids, multiple locations/orientations, roughness or topography where relevant, ageing checks after surface treatment, and direct channel-flow validation under the intended fluid and geometry.

1. Scope and controlling boundaries

ER-97 owns the **liquid-wall interaction and capillary-flow layer** of vat-printed microchannels. It asks how the delivered internal surface wets a specified liquid, how that behaviour changes with printing and post-processing, and when a contact-angle measurement predicts or fails to predict device-level flow.

The scope is separated from ER-12 organ-on-chip material qualification, ER-53 substrate/build-platform adhesion, ER-54 molecular gas permeability, ER-88 surface topography and finishing as a general metrology subject, and ER-89 leak/seal qualification. ER-97 can use roughness or leak-free geometry as inputs, but its endpoint is wetting/capillary function rather than adhesion, permeability, finish quality or sealing.

The paper also distinguishes **resin-process wetting** from **final-part fluid wetting**. Contact between uncured resin and a vat film can affect printing dynamics, but it does not directly establish how water, oil, culture medium or another service liquid will wet the washed and post-cured channel wall.

2. Static angle, advancing/receding angle and capillary motion are different quantities

A sessile-drop contact angle is an apparent interfacial measurement on a specific solid state with a specific liquid. It is influenced by chemistry and by surface morphology. Contact-angle hysteresis, commonly expressed as the difference between advancing and receding angles, adds information about pinning and heterogeneity and can be directly relevant to moving menisci and droplets.

Kang et al. measured both contact angle and contact-angle hysteresis on DLP-printed surfaces and connected printing conditions, roughness and capillary movement in microchannels [1]. Their work is especially useful because it prevents the common shortcut of treating one static angle as a complete flow descriptor.

Capillary filling adds further variables: channel dimensions, liquid surface tension and viscosity, dynamic contact-line behaviour, pressure losses, entrapped gas and evaporation. ER-97 therefore requires direct flow measurement whenever a device-level self-filling or flow-rate claim is made.

Quantity	Evidence provided	What it does not establish
Static/apparent contact angle	Local equilibrium-like droplet geometry on a defined surface/liquid state.	Dynamic meniscus mobility or capillary flow rate by itself.
Advancing angle	Angle as a wetting front advances under the chosen method.	Receding behaviour or pinning.
Receding angle	Angle as the contact line retreats.	Advancing behaviour or one universal hysteresis value.
Contact-angle hysteresis	Difference/path dependence associated with pinning and heterogeneity.	Surface chemistry alone.
Surface free energy estimate	Model-derived solid-surface descriptor from defined liquids/contact angles.	Direct channel flow or universal adhesion.
Capillary flow	Integrated liquid/geometry/surface response in a channel.	Intrinsic surface property independent of fluid and geometry.

Table 1. Wetting quantities and claim boundaries.

3. Printing conditions can create surface-state differences

DLP does not create one universal surface. Kang et al. varied lamination thickness and direction and observed changes in roughness and wetting metrics; the same study then assessed capillary-driven flow in printed channels [1]. The source supports a process-surface-function chain within that material, not a universal rule that thicker layers always increase or decrease wettability.

Davoudinejad et al. fabricated microstructured surfaces by additive manufacturing and showed that printed microgeometry shifts the apparent contact angle, with dynamic behaviour predicted by volume-of-fluid simulation validated against those measurements [4]. This is important for VPP because layer steps, cure bleed and intentional texture can change the apparent wetting state without changing the nominal resin chemistry.

Accordingly, ER-97 treats surface topography as a co-variable. ER-88 remains the controlling general topography paper; ER-97 records only the roughness/texture information needed to interpret wetting and flow.

4. Post-processing and ageing can move the wetting state

The final channel wall is created by printing plus washing, drying, post-cure and subsequent ageing or treatment. Stark et al. characterised a commercial SLA polymer with contact-angle measurements and observed time-dependent material-property changes relevant to self-driven capillary microfluidics [2]. The engineering implication is not that all SLA surfaces age in the same direction, but that the time between post-processing and use is part of the specimen state.

Surface modification can also deliberately change wetting. Warr et al. modified DLP-printed microfluidic channels to make them more hydrophobic for controlled two-phase flow [3]. Their method is a demonstrated route for that resin/process combination; it is not a universal post-treatment recipe for all VPP materials.

Any surface-treatment claim should therefore include initial state, treatment chemistry/process, ageing time, storage conditions and repeat wetting measurements. A surface that meets a target immediately after plasma, coating or grafting but drifts before service has not been fully qualified.

5. Process wetting versus final-part wetting

Wang et al. studied the relationship between resin properties and over-curing in VPP microchannels [5]. That is a manufacturing-interface question involving the uncured resin and the evolving printed structure, not evidence about the wettability of the final channel surface. Xu et al. showed that residual uncured resin and over-curing inside enclosed channels are fabrication problems in their own right [6]; the internal surface eventually contacted by a liquid is therefore partly determined by how completely the channel was cleared during and after printing. This is fabrication evidence, not leak-rate evidence.

ER-97 concerns the **delivered microchannel wall** after the specified wash/post-cure/conditioning sequence. A low resin contact angle on a release film does not establish a low water contact angle inside the final channel, and the reverse is also true. Mixing these evidence levels can lead to incorrect process or device conclusions.

For a microfluidic qualification report, the process-surface data may be retained as causal context while the service-liquid wetting and channel-flow results remain separate acceptance evidence.

6. Standards provide adjacent measurement architecture, not a VPP microfluidic acceptance standard

ASTM D7334-08(2022) is an active practice for advancing contact-angle measurement on coatings, substrates and pigments [S1]. It explicitly deals only with advancing contact angles and therefore cannot substitute for receding-angle or hysteresis measurements when those are relevant.

ISO 19403-2:2024 specifies contact-angle measurement for determining surface free energy of solid surfaces, with stated applicability to substrates and coatings and explicit recognition that morphological and chemical homogeneity affect results [S2]. This is useful adjacent architecture for printed polymer surfaces, but it is not a VPP-specific microfluidic performance standard.

No single contact-angle standard converts a coupon result into a self-filling, droplet-formation or two-phase-flow acceptance criterion. Device-level qualification remains application-specific.

7. Minimum qualification architecture

Define the final surface state. Resin/version, print orientation, layer thickness, wash, dry, post-cure, treatment, storage and age.

Define the liquid. Composition, temperature and surface tension where material to interpretation; do not generalise water results to surfactant, oil or biological fluids.

Measure more than one local point when heterogeneity matters. Record face/orientation and internal versus external surfaces where feasible.

Add advancing/receding or hysteresis data when motion/pinning is the endpoint. A single static angle may be insufficient.

Link to actual channel flow. Record geometry, pressure/head condition, time-dependent front position or flow rate, failures to prime, trapped gas and repeatability.

Layer	Minimum record	Acceptance question
Surface identity	Print/post-process/treatment/age plus roughness or texture when relevant.	What surface was actually tested?
Contact-angle method	Liquid, drop protocol, temperature, location, advancing/receding/static designation.	What wetting quantity was measured?
Hysteresis / pinning	Advancing and receding angles or another justified dynamic metric.	Will a moving contact line behave as assumed?
Surface-energy estimate	Model, probe liquids and assumptions, if used.	Is the derived value traceable to the chosen model?
Channel test	Geometry, fluid, pressure/head, front position/flow versus time, repeats.	Does the delivered channel perform the required capillary function?
Ageing durability	Recheck after realistic storage/service interval for modified surfaces.	Does the wetting state persist long enough for use?

Table 2. Suggested ER-97 evidence chain.

8. Reporting rules and prohibited shortcuts

Do not use “hydrophilic” or “hydrophobic” as a complete specification without the liquid, method and surface state. Do not infer capillary flow rate from static contact angle alone. Do not infer chemical surface energy from roughness alone. Do not transfer external coupon contact angles to inaccessible internal channels without justification. Do not infer organ-on-chip biocompatibility or fluidic sealing from wettability data.

Where a treatment is proprietary or formulation-specific, publish the measurement architecture and final-state evidence without disclosing confidential composition or process windows.

9. Conclusions

Wettability in vat-printed microfluidics is a coupled surface-state and fluid problem. Printing orientation/layering, topography, post-processing, ageing and deliberate surface treatment can all change the apparent and dynamic wetting response.

Static contact angle, hysteresis, surface free energy and capillary flow must remain separate evidence layers. Direct DLP/SLA studies demonstrate why: printing conditions can alter roughness and hysteresis [1], a printed surface can evolve with time [2], and deliberate modification can change two-phase-flow behaviour [3].

ER-97 therefore qualifies the delivered channel by linking controlled surface-state measurements to direct fluidic performance rather than treating one contact-angle value as a universal descriptor.

Scientific literature

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Standards

- [S1] ASTM D7334-08(2022). Standard Practice for Surface Wettability of Coatings, Substrates and Pigments by Advancing Contact Angle Measurement. DOI: 10.1520/D7334-08R22. <https://doi.org/10.1520/D7334-08R22>
- [S2] ISO 19403-2:2024. Paints and varnishes - Wettability - Part 2: Determination of the surface free energy of solid surfaces by measuring the contact angle. Edition 2. <https://www.iso.org/standard/87262.html>

It does not establish a universal hydrophilic/hydrophobic threshold, a universal surface-treatment recipe, organ-on-chip suitability or a medical-device claim.