

Resin-Level, Hydrostatic-Pressure and Free-Surface Control in Vat Photopolymerisation: Geometry, Refill and Drift

A measurement framework for global liquid-state stability

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Abstract

Vat photopolymerisation consumes and redistributes liquid resin while the optical and mechanical process assumes a stable reference level. Global liquid height sets hydrostatic pressure, immersion depth, refill head and free-surface geometry. Local menisci, waves and constrained gaps can depart from that global state. A level sensor can therefore be accurate yet insufficient, and a fixed refill volume can be repeatable yet wrong after density, temperature or geometry changes.

This review defines qualification of resin-level, hydrostatic-pressure and free-surface control. It separates inventory, bulk level, local interface, meniscus, pressure head and dynamic disturbance; establishes calibrated level-volume geometry; accounts for platform displacement and cured-volume removal; and couples make-up dosing to settling and bubble control. Sensors are challenged for wetting, fouling, optical interference and loss of signal. No universal level tolerance, refill increment, pressure head, dead band or settling delay is supported. The deliverable is a bounded level-control window that preserves geometry and refill capability throughout a declared build.

Keywords: vat photopolymerisation; resin level; hydrostatic pressure; free surface; refill control; meniscus; drift; process capability

1. Significance and scope

Global resin level changes as liquid is converted into the part, carried out on the platform, replenished from a reservoir, displaced by moving hardware or lost by leakage and evaporation. The consequence can be a geometry shift in top-down systems, a changed pressure head in feed paths, altered immersion or an apparently random refill delay.

ER-246 owns global resin inventory, liquid level, hydrostatic head and long-term free-surface drift in vat photopolymerisation.

1.1 Corpus boundary

ER-010 retains dimensional metrology; ER-030 retains oxygen inhibition and free-surface cure; ER-035 retains cure-depth interpretation; ER-071 retains general closed-loop control; ER-174 and ER-203 retain optical and radiometric state; ER-244 retains per-layer local refill, meniscus relaxation and bubble readiness; ER-245 retains temperature control; ER-247 retains continuous dead-zone transport; ER-248 retains complete top-down architecture; and ER-355 retains vibration fields. ER-203, ER-244, ER-245, ER-247, ER-248 and ER-355 are planned forward references, not published incumbents, and do not supply authority for this review. ER-246 owns the global liquid reference supplied to those processes.

2. Separate the controlled quantities

Define resin inventory V , bulk level h , local surface departure $z(x,y,t)$, density ρ and hydrostatic gauge pressure p . For a quiescent liquid of approximately uniform density,

$$p(z) = \rho g [h - z]$$

where g is gravitational acceleration and z is the elevation of the point of interest. This relation is a baseline. Acceleration, curvature, flow, confinement and gas pressure add terms that must be measured where relevant.

Do not use level, volume and pressure as synonyms. Each has a different sensor and uncertainty chain.

3. Calibrate vat geometry

Map liquid volume to level across the usable range with the actual vat, inserts, window, platform and plumbing state. Nonvertical walls, fillets, drains and submerged components make the area vary with height. A linear conversion is valid only where demonstrated.

Repeat after vat replacement or dimensional change. Record temperature because density and hardware dimensions can change.

4. Close the material balance

Over a bounded interval,

$$\Delta V_{\text{vat}} = V_{\text{in}} - V_{\text{out}} - V_{\text{cured}} - V_{\text{carry}} - V_{\text{loss}}$$

where V_{in} is replenishment, V_{out} deliberate withdrawal, V_{cured} resin incorporated into the build, V_{carry} liquid removed on parts or fixtures and V_{loss} leakage or evaporation. Estimate or measure each material term at the accuracy needed to diagnose drift.

The optical slice volume is not always equal to consumed liquid because shrinkage, overcure, supports and trapped resin alter the balance.

5. Distinguish displacement from consumption

Platform, part and recoater motion displace resin and can change the measured level without changing inventory. The sign and magnitude depend on immersed volume and timing. Synchronise level data with motion and interpret the signal at defined machine states.

Do not trigger refill on a transient caused by platform immersion unless the control design explicitly compensates it.

6. Measure global and local interface state

A point level sensor reports one location. The exposure region can have a different height because of tilt, meniscus, recirculation, refill jets or free-surface waves. Use multiple positions, scanning metrology or an independently validated model where the spatial state matters.

Bhanvadia and co-workers demonstrated a static liquid constrained interface for high-resolution stereolithography [1]. Their architecture is not a general level controller, but it illustrates that interface geometry can be deliberately constrained and must be defined.

7. Treat hydrostatic head as a process input

Pressure head influences gravity feed, leakage, membrane loading, refill and trapped-volume behaviour. Record the elevation difference between the controlled free surface and the relevant outlet, gap or seal. If a remote reservoir supplies the vat, qualify the coupled levels and line losses.

An unchanged sensor reading in the vat does not prove unchanged pressure at a downstream restriction when filters or lines foul.

8. Characterise refill dynamics

Measure dose volume, flow rate, valve delay, overshoot, mixing plume, bubbles and time to stable level. Pham and Ji showed that geometry and trapped volumes influence recoating and waiting behaviour [2]. ER-244 owns local layer readiness; ER-246 determines whether the global supply and head are restored.

Challenge minimum and maximum level, low and high credible consumption, interrupted dosing and restart.

9. Control free-surface transients

Refill jets, platform motion and recoating can excite waves. Moghadasi, Mollah, Marla, Saffari and Spangenberg modelled top-down interface stability under process motion [3]. Their times are geometry-specific. Define an acceptable local height or slope band and measure entry into that band.

Global level can be correct while the local surface remains unsuitable for exposure.

10. Manage meniscus and wetting

Wall wetting, contact-angle hysteresis, contamination and cured debris change the relationship between sensor reading and usable free surface. Map wall climb and pinning across fill range and after repeated cycles. A sensor near the wall may track the meniscus rather than the bulk level.

Specify cleaning and vat-conditioning procedures because they are part of the measurement state.

11. Select and qualify sensors

Possible methods include float, capacitive, ultrasonic, optical, pressure, mass and machine-vision sensing. Each can fail through foam, bubbles, optical absorption, coating, temperature drift, vibration, reflections or changing dielectric properties. The Smart Resin Vat work illustrates the value of in-vat monitoring for failure detection [4], but does not establish one universal sensing method.

Calibrate with traceable additions and removals. Include loss-of-signal, stuck reading and fouled-sensor tests.

12. Define the control law and dead band

State the controlled variable, sample time, filter, dead band, dose increment, maximum rate, interlocks and recovery logic. A narrow dead band can cause chattering and repeated bubble-generating doses; a wide band can permit geometric drift.

Tune on the actual vat and liquid dynamics. Do not hide oscillation with excessive signal filtering.

13. Couple level control to temperature

Density, viscosity, evaporation and sensor response can change with temperature. Cold make-up resin can alter both level reading and refill behaviour. ER-245 owns thermal control; ER-246 requires the level calibration and control law to remain valid across the qualified temperature band.

Record temperature with every level-capability test.

14. Detect leakage and unintended loss

Compare measured level or mass change with predicted consumption during idle, blank motion and build operation. Separate evaporation, line drain-back, seal leakage and resin carried by the part. Define stop thresholds and containment checks.

A controller that continually replenishes can mask a leak. Alarm on unexplained cumulative make-up, not only low level.

15. Validate geometry and optical consequences

In top-down systems, a level error can directly shift the exposure plane or liquid thickness. In constrained systems it can alter feed head, membrane load or bubble transport. Measure the relevant geometric or pressure endpoint, not only the sensor output.

Use independent dimensional coupons and interface measurements across the build. Exposure compensation shall not be used to conceal a level-control defect.

16. Drift and long-build testing

Run the longest credible build or an equivalent validated sequence, including pauses and refill events. Compare early, middle and late level error, cumulative dosing, interface stability and part geometry. Include minimum starting inventory and maximum carry-out challenge.

No short static test can establish long-term drift capability.

17. Transfer and change control

Requalify after changes to vat geometry, platform, sensor, location, reservoir, pump, valve, filter, tubing, firmware, temperature range, resin density, surface tension, build envelope or dosing policy. Transfer requires both sensor calibration and process-endpoint confirmation.

18. Non-compensatory qualification matrix

Gate	Required evidence	Unsupported shortcut prevented
Geometry	Calibrated volume-level map	Assuming a constant vat area
Inventory	Material-balance closure	Treating level as consumed volume
Pressure	Head and line-state measurement	Inferring downstream pressure from level alone
Interface	Spatial and temporal surface tolerance	Using one point sensor as surface proof
Refill	Dose, overshoot and settling challenge	Equating commanded volume with delivered volume
Drift	Long-build cumulative evidence	Qualifying only a short idle test

19. Minimum reporting set

Report resin identity and lot; density, temperature and surface condition; vat and reservoir geometry; fill range; submerged components; calibrated volume-level relation; sensor type, position, calibration and uncertainty; local-interface measurement; head reference elevations; pumps, valves, lines and filters; control law and firmware hash; dead band and dose increment; consumption model; refill rate and overshoot; bubble and wave response; drift and unexplained-loss limits; alarms and interlocks; challenge build; dimensional outcomes; raw-data hashes; transfer domain; and change triggers.

20. Knowledge boundary

Published work supports the importance of constrained-interface geometry, recoating volumes, surface stability and in-vat sensing [1-4]. These sources justify separating global level from local interface and measuring the coupled dynamics. They do not establish a universal level tolerance, reservoir height, refill increment, pressure head, sensor technology or settling delay.

21. Limitations

References [1] and [3] were examined at full-text depth; reference [2] at publisher-abstract depth; and reference [4] at bibliographic-record depth. The cited systems use different architectures and do not collectively validate one controller design. This review provides no proprietary vat geometry, sensor circuit, dosing recipe or commercial process setting.

22. Conclusions

Resin-level control is a global material and pressure problem, not a single sensor task. Qualification separates inventory, level, hydrostatic head and local free-surface state; closes the material balance; measures refill transients; and confirms geometry across a long build. A defensible controller preserves the declared liquid reference without masking leaks, bubbles or local interface disturbances. The deliverable is a bounded capability statement tied to a specific vat, feed path, resin and build regime.

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