

Buoyancy and Natural Convection in Photocurable Resins: Temperature, Density, Composition and Feature Distortion

Determining when liquid motion is negligible and when thermal or compositional buoyancy alters the optical-reactive field

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Abstract

Qualification of buoyancy-driven flow fails when temperature, composition and conversion are collapsed into one empirical setting. Polymerisation heat can destabilise an initially quiescent vat, while filler settling creates solutal density stratification that may reinforce or oppose thermal convection. The review therefore couples Rayleigh-type regime analysis with particle or tracer velocimetry, synchronised temperature mapping, density and viscosity measurements, and vertical composition sampling. Reversing vat or specimen orientation provides a discriminating test because it changes the buoyant direction without changing the optical exposure. These measurements define when natural convection can be neglected and when it must be treated as part of the process state used for profile transfer.

Keywords: natural convection; buoyancy; photocurable resin; Rayleigh number; thermal gradient; feature distortion

1. Qualification problem: natural convection

For natural convection, acceptance depends on separating a negligible perturbation from a mechanism that changes process transferability. The decision set comprises whether natural convection can be neglected for a given vat/feature scale, acceptable dwell before density stratification becomes process relevant, and whether orientation-specific profiles are required, evaluated against Rayleigh number, Prandtl number, and Lewis number. [1]

1.1 Scope boundary.

ER-353 owns buoyancy-driven flow. ER-351 owns heat generation, ER-352 reaction-diffusion fronts, ER-354 shrinkage-driven feeding and defect formation, ER-359 gravity-driven sedimentation and drainage, and ER-360 model verification; this review uses those topics only to define convective forcing, competing transport or validation evidence.

2. Governing balances for natural convection

Buoyancy becomes testable only after density-driven motion is compared with diffusive transport; the following relations provide that comparison.

$\rho = \rho(T, c, \alpha)$ makes temperature, composition and conversion potential buoyancy drivers

$Ra = g \beta \Delta T L^3 / (\nu \alpha_{th})$ estimates thermal-convection propensity

solutal Rayleigh numbers provide the analogous criterion for composition-driven density gradients

The resulting state map distinguishes onset of circulation from the rate at which an established flow redistributes heat or species.

3. Regime boundaries for natural convection

For natural convection, the table marks when neglecting flow, extending dwell, or reusing an orientation profile needs new evidence.

Table 1. Regime indicators for buoyancy-driven flow.

Indicator	Engineering meaning	Use
Rayleigh number	criterion for onset and intensity of free convection	Place Rayleigh number on the qualification map for 'whether natural convection can be neglected for a given vat/feature scale'. A change in this coordinate means criterion for onset and intensity of free convection has changed.
Prandtl number	momentum diffusivity relative to thermal diffusivity	Place Prandtl number on the qualification map for 'acceptable dwell before density stratification becomes process relevant'. A change in this coordinate means momentum diffusivity relative to thermal diffusivity has changed.
Lewis number	thermal diffusivity relative to species diffusivity	Place Lewis number on the qualification map for 'whether orientation-specific profiles are required'. A change in this coordinate means thermal diffusivity relative to species diffusivity has changed.

Convection may be declared negligible only inside the tested map; moving beyond it reopens the flow contribution.

4. Couplings that move the natural convection

Polymerisation heat can destabilise an initially quiescent vat.

Filler settling creates solutal density stratification that can stabilise or destabilise thermal convection. [1]

Viscosity rises strongly with conversion and can extinguish convection locally.

5. Failure signatures and false diagnoses

The fault tree distinguishes advective distortion of temperature and composition fields from migration of bubbles or low-density inclusions and nonuniform replenishment around tall or heated features. Evidence comes from particle-image velocimetry or tracer velocimetry in transparent model resins, temperature mapping with synchronised flow visualisation and density and viscosity versus temperature and conversion; assigning causality therefore requires the signature associated with the suspected branch, not merely a changed endpoint. The Table 2 interventions are deliberately non-equivalent. A mechanism is retained only when the row-specific response is consistent with the observed failure signature.

Table 2. Failure-mode discrimination for buoyancy-driven flow.

Failure mode	Observable signature	Discriminating evidence
advective distortion of temperature and composition fields	particle-image velocimetry or tracer velocimetry in transparent model resins	invert the vat or specimen orientation to change buoyant direction without changing optics
migration of bubbles or low-density inclusions	temperature mapping with synchronised flow visualisation	vary thermal length at matched dose
nonuniform replenishment around tall or heated features	density and viscosity versus temperature and conversion	impose controlled vertical temperature gradients
orientation-dependent cure asymmetry that is wrongly attributed to optics	vertical composition sampling before and after controlled dwell	compare low- and high-viscosity analogues with matched optical properties

6. Measuring natural convection with traceable uncertainty

Their uncertainties are propagated independently and only reconciled when the qualification boundary is evaluated. For natural convection, the evidence chain starts with independent resolution of density-temperature coupling and thermal Rayleigh scaling; during metrology of natural convection, solutal buoyancy is resolved against circulation onset. It then adds an uncertainty-controlled perturbation of solutal buoyancy, while separate monitoring of circulation onset is retained as a separate control so the three sources of information cannot compensate silently; the uncertainty record for natural convection keeps circulation onset separate from density-temperature coupling.

7. Experiments that discriminate competing mechanisms

The four interventions listed in Table 2 are executed as separate experiments. Their response ordering, rather than a single endpoint, determines attribution. The working sequence for natural convection has three parts: a causal contrast between density-temperature coupling and solutal buoyancy; a boundary challenge involving thermal Rayleigh scaling; and a replicate test of circulation onset; during the causal challenge for natural convection, circulation onset is tested against density-temperature coupling. Each part answers a different engineering question, so uncertainty or failure in one part is not repaired by a favourable result in another; the experiment for natural convection separates density-temperature coupling from thermal Rayleigh scaling.

8. Model identification and validation for natural convection

[3,5] [2,4] Each Table 3 boundary receives its own propagated uncertainty, preserving the distinction between calibration error and transfer error. Three independent checks structure the natural convection assessment; within model identification for natural convection, density-temperature coupling is not fitted through thermal Rayleigh scaling. Parameter estimation for density-temperature coupling and thermal Rayleigh scaling establishes the primary state, an uncertainty-bounded check on circulation onset tests whether that state survives transfer, and prediction against solutal buoyancy is the perturbation used when the two disagree; prediction for natural convection keeps thermal Rayleigh scaling independent of solutal buoyancy.

9. Qualification envelope and technology decisions

Table 3. Technology-decision matrix for buoyancy-driven flow.

Decision	Minimum evidence	Acceptance logic
whether natural convection can be neglected for a given vat/feature scale	For whether natural convection can be neglected for a given vat/feature scale, acquire particle-image velocimetry or tracer velocimetry in transparent model resins at several states bracketing the proposed limit rather than at one nominal condition.	Retain the decision only where 'invert the vat or specimen orientation to change buoyant direction without changing optics' produces the expected bounded change in particle-image velocimetry or tracer velocimetry in transparent model resins; evidence of advective distortion of temperature and composition fields rejects the transfer.
acceptable dwell before density stratification becomes process relevant	Support acceptable dwell before density stratification becomes process relevant with a traceable temperature mapping with synchronised flow visualisation series spanning the claimed range and an independent repeat at the boundary state.	The decision is supported if 'vary thermal length at matched dose' changes temperature mapping with synchronised flow visualisation in the validated direction without activating migration of bubbles or low-density inclusions; otherwise requalification is required.
whether orientation-specific profiles are required	The minimum record for whether orientation-specific profiles are required is density and viscosity versus temperature and conversion measured across the relevant state interval with calibration, repeatability and decision uncertainty reported.	Acceptance is conditional on a stable density and viscosity versus temperature and conversion response under 'impose controlled vertical temperature gradients' and on the absence of nonuniform replenishment around tall or heated features at the proposed limit.

For the natural convection problem, an explicit transfer limit on circulation onset defines the independent cross-check rather than a tuning variable; inside the natural convection envelope, thermal Rayleigh scaling and solutal buoyancy define different transfer limits. The main inference uses tested ranges in density-temperature coupling and thermal Rayleigh scaling, whereas a separate boundary for solutal buoyancy is reserved for the boundary test that can overturn the proposed interpretation; qualification of natural convection bounds solutal buoyancy separately from circulation onset.

10. Design consequences for natural convection

To keep mechanism and compensation separate, the study applies a design change governed by density-temperature coupling while whether orientation-specific profiles are required is controlled independently; loss of a requalification trigger tied to circulation onset opens a new qualification case; during design implementation for natural convection, solutal buoyancy is constrained by circulation onset. The engineering decision is released only for the tested natural convection envelope, not for an unmeasured extrapolation; the natural convection design record separates circulation onset from density-temperature coupling.

11. Evidence gaps for natural convection

An acceptable record for natural convection must show independent replication of circulation onset without inferring it from scale transfer of density-temperature coupling; for unresolved natural convection transfer, circulation onset is studied separately from density-temperature coupling. In parallel, uncertainty in thermal Rayleigh scaling versus solutal buoyancy probes the boundary condition most likely to change the interpretation, and the resulting uncertainty is carried forward explicitly; the evidence gap in natural convection distinguishes density-temperature coupling from thermal Rayleigh scaling.

12. Qualification outcome for natural convection

Acceptance applies to the intersection of the three Table 3 limits, with no presumption of transfer beyond the tested states. Evidence for natural convection is not accepted from a single nominal condition; at final qualification of natural convection, density-temperature coupling is reconciled with thermal Rayleigh scaling. The analysis requires agreement between measurement and prediction for density-temperature coupling, follows it with a renewed-evidence trigger when circulation onset changes, and uses causal evidence that separates thermal Rayleigh scaling from solutal buoyancy as a targeted challenge wherever the two indicate different mechanism or margin; the closing natural convection claim keeps thermal Rayleigh scaling distinct from solutal buoyancy.

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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.