

# Ultrasonic Spray Deposition as a Scale-Up Path for Layered Hybrid Perovskite Thermal-Insulation Films

MicroSpray Brands — Technical White Paper September 2026

*Scope note: the studies cited here were carried out by independent research groups on their own equipment. They are cited as evidence for what solution processing and ultrasonic atomization can do, not as demonstrations of MicroSpray hardware. The process designs in Sections 3–7 are engineering proposals grounded in that literature, not reported results.*

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## Summary

A September 2026 report in *Science Advances* describes spin-cast layered hybrid perovskite thin films — azobenzene ethyl ammonium lead iodides — with a record-low thermal conductivity of  $\sim 0.04 \text{ W/m}\cdot\text{K}$  at room temperature combined with an elastic modulus of 7.7 GPa: an extreme thermal insulator that is also mechanically rigid [1]. The films are deposited from solution by spin coating, a technique that does not scale to large areas or continuous manufacture. This paper examines ultrasonic spray deposition as the scale-up path: ink compatibility, the drying physics that governs film quality, the role of gas quenching and how it interacts with an ultrasonically produced droplet field, a roll-to-roll (R2R) station layout including heated-roller design, and the use of a swirl-gas (vortex) nozzle as an in-flight quench control. Conservative starting process windows are given.

## 1. Background: a rigid extreme insulator, currently spin-cast

Wang et al. report that layered hybrid organic–inorganic perovskite films combine ultralow thermal conductivity ( $\sim 0.04 \text{ W/m}\cdot\text{K}$ ) with stiffness exceeding most plastics, foams and aerogels [1]. The low conductivity is tied to the oriented layered structure of the film; orientation is established during solution drying. Public discussion of the work emphasizes potential for large-area printed films — but the reported deposition method, spin coating, wastes most of its ink and is restricted to discrete small substrates. Ultrasonic spray coating is an established route for transferring spin-cast perovskite processes to large and continuous areas: ultrasonically spray-coated hybrid perovskite solar-cell absorbers were demonstrated as early as 2014 [2], and fully spray-coated perovskite devices have since been reported [3].

## 2. Ink compatibility with ultrasonic atomization

Hybrid perovskite precursor inks are true solutions: the organic ammonium halide and  $\text{PbI}_2$  dissolved in polar aprotic solvents (DMF, DMSO, or blends). Such solutions run on the order of 1–10 cP at working concentrations — far below the  $\sim 50 \text{ cP}$  practical ceiling for ultrasonic atomization — and contain no particles, eliminating the clogging failure mode of hydraulic nozzles. A 120 kHz nozzle, producing the finest droplet population in the MicroSpray range, is the natural starting point for thin, smooth layers; 60 kHz suits thicker builds and higher flows.

### 3. The governing physics: a wetness and evaporation balance

Across the ultrasonic spray literature, film quality reduces to one balance: droplets must arrive wet enough to spread and merge into a continuous film, but not so wet that flooding or coffee-ring flows dominate [4]. Frequency sets the initial droplet population, but in-flight evaporation shrinks droplets between nozzle and substrate, so the arrival state depends on diameter, solvent fraction, temperature and flight time together. Three process levers act on this balance largely independently:

1. **The nozzle and its gas environment** set how wet the film starts.
2. **Substrate (bottom-side) temperature** sets the baseline drying rate.
3. **A gas quench** sets when — and how sharply — drying finishes.

### 4. Gas quenching and its interaction with an ultrasonic droplet field

Perovskite film quality depends on crossing into supersaturation quickly and uniformly: slow solvent loss nucleates few crystals that grow coarse and disconnected; a sudden, film-wide crossing nucleates densely and yields compact, well-oriented films. Spin-coating labs trigger this with an antisolvent drip; scalable processing replaces it with a **gas quench** — a dry nitrogen or air knife that strips the solvent-vapor boundary layer from the wet film so evaporation rate jumps everywhere at once.

Three couplings arise when the wet film is produced ultrasonically:

- **The spray is already a partial quench.** In-flight evaporation concentrates each droplet, so with stand-off, gas flow and substrate temperature tuned, droplets arrive already near supersaturation. Partial quenching to near-supersaturation has been achieved with ultrasonically produced droplets; the film-level gas quench then has less work to finish than after blade or slot-die coating, where the liquid film starts dilute.
- **The quench overrides droplet-scale drying.** A sprayed film is thousands of merged droplets, each edge prone to its own coffee-ring flow. The knife's job is to impose one fast film-level drying event before individual droplet edges pin — the window is seconds after droplet merge.
- **The knife must not touch the plume.** Ultrasonic plumes are low-momentum by design; a high-velocity knife near the deposition zone deflects droplets and destroys uniformity. Deposition gas-shaping (a gentle co-flow or shroud) and the quench knife are separate flows with separate jobs, spaced apart in position or time.

Practical arrangements: a trailing knife on the spray carriage (fixed delay set by traverse speed); a separate knife-only pass (simple, but quench delay varies across the part); or a chamber quench under laminar dry N<sub>2</sub> for batch coupons. Starting points: dry N<sub>2</sub>, a few m/s at the film, 20–40 mm working distance, 1–5 s after deposition. DMSO is hygroscopic; quench-gas humidity is a first-order reproducibility variable.

### 5. Roll-to-roll architecture

R2R converts the quench-timing problem into geometry: fixed stations along a moving web give every point an identical deposition-to-quench delay equal to station spacing divided by web speed.

**Station order:** nozzle array (cross-web, stationary, overlapping plumes) → short merge gap → cross-web gas-quench knife → in-line anneal zone, all under a dry-N<sub>2</sub> tent.

**Coverage:** wet thickness = total flow ÷ (web width × web speed).

### Heated roller (bottom heating) — design notes:

- Deposit **on the roller wrap**, never in a free span: the wrap is a machined mechanical reference that removes web flutter, stabilizing stand-off — a first-order variable for droplet arrival wetness.
- Thin webs equilibrate to roller temperature in tens of milliseconds; the design variable is **dwelt**: heated arc = radius × wrap angle; dwelt = arc ÷ web speed. Example: 150 mm roller, 180° wrap → ~0.47 m of controlled-temperature path; ~28 s at 1 m/min.
- The heater's real load is **evaporative cooling** (DMF latent heat ~0.6 kJ/g → ~10 W per g/min evaporated), concentrated in a narrow band: use a thick-walled, internally heated roller with the control sensor near the shell in the coating zone; hold cross-web uniformity to ±2–3 °C.
- **Web limits:** PET distorts by ~120–140 °C; PEN reaches ~160–180 °C; polyimide and metal foils remove the limit. A practical split for PET: deposit and partially dry at 70–90 °C on the roller, finish the anneal in a longer downstream oven.
- Watch items: back-side contact quality (tension/wrap; nip or vacuum roller if needed), solvent recondensation on cold surfaces upstream/downstream (extend heating and extraction), and thermal isolation of the nozzle transducer from roller heat.

## 6. Swirl-gas (vortex) nozzle as an in-flight quench control

Wrapping the plume in a controlled swirling co-flow turns the partial quench of Section 4 into an adjustable process knob: dry N<sub>2</sub> through the swirl at higher flow strips solvent vapor from around the droplets and moves their arrival state along the wet-to-supersaturated axis independently of stand-off and substrate temperature; mildly heating the swirl gas adds a finer second knob. The bounding failure mode is nucleation in flight — droplets crossing supersaturation before arrival land as powder that never merges; the specular-to-matte-to-dusty progression of the film maps the usable window directly. On a web, swirl confinement additionally defines a stripe width, allowing self-patterned parallel stripes — the geometry perovskite modules use — without masking or absorber scribing.

## 7. Conservative starting window (bench, 120 kHz)

| Parameter             | Starting range                                           |
|-----------------------|----------------------------------------------------------|
| Ink                   | Precursor solution in DMF/DMSO, 1–10 cP, 0.2 µm-filtered |
| Flow rate             | 0.05–0.3 mL/min                                          |
| Stand-off             | 30–60 mm                                                 |
| Substrate temperature | 70–110 °C (web-material limited)                         |
| Traverse / overlap    | 25–75 mm/s, 50–70 % overlap, alternating passes          |

| Parameter  | Starting range                                                 |
|------------|----------------------------------------------------------------|
| Quench     | Dry N2 knife, few m/s at film, 20–40 mm, 1–5 s post-deposition |
| Atmosphere | Dry N2 over all wet stations; monitor RH                       |

Anneal per the source material's published procedure. Film orientation and thermal conductivity must be re-verified against the spin-cast benchmark; matching them is the central development task, not the atomization.

## 8. Safety

Lead-containing inks require enclosure or fume-hood operation, spray capture, and lead-waste handling; DMF and DMSO carry their own exposure limits, and DMSO enhances skin transport of dissolved species — full solvent-rated PPE.

## References

1. Wang, Z. et al. Extremely Low Thermal Conductivity in Rigid Layered Hybrid Perovskites. *Science Advances* 12, eaee5269 (2026). <https://doi.org/10.1126/sciadv.aee5269>
2. Barrows, A. T. et al. Efficient planar heterojunction mixed-halide perovskite solar cells deposited via spray-deposition. *Energy & Environmental Science* 7, 2944–2950 (2014). <https://doi.org/10.1039/C4EE01546K>
3. Bishop, J. E. et al. Fully spray-coated triple-cation perovskite solar cells. *Scientific Reports* 10, 6610 (2020). <https://doi.org/10.1038/s41598-020-63674-5>
4. Stryckers, J. et al. Layer formation and morphology of ultrasonic spray coated polystyrene nanoparticle layers. *Physica Status Solidi A* 213, 1441–1446 (2016). <https://doi.org/10.1002/pssa.201533026>