UK BATTERY INDUSTRIALISATION CENTRE

Optimising Electrode Quality: Controlling Air in Battery Slurries for Superior Coating Performance

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mtc where progress happens

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UKBIC

The UK’s battery manufacturing development facility

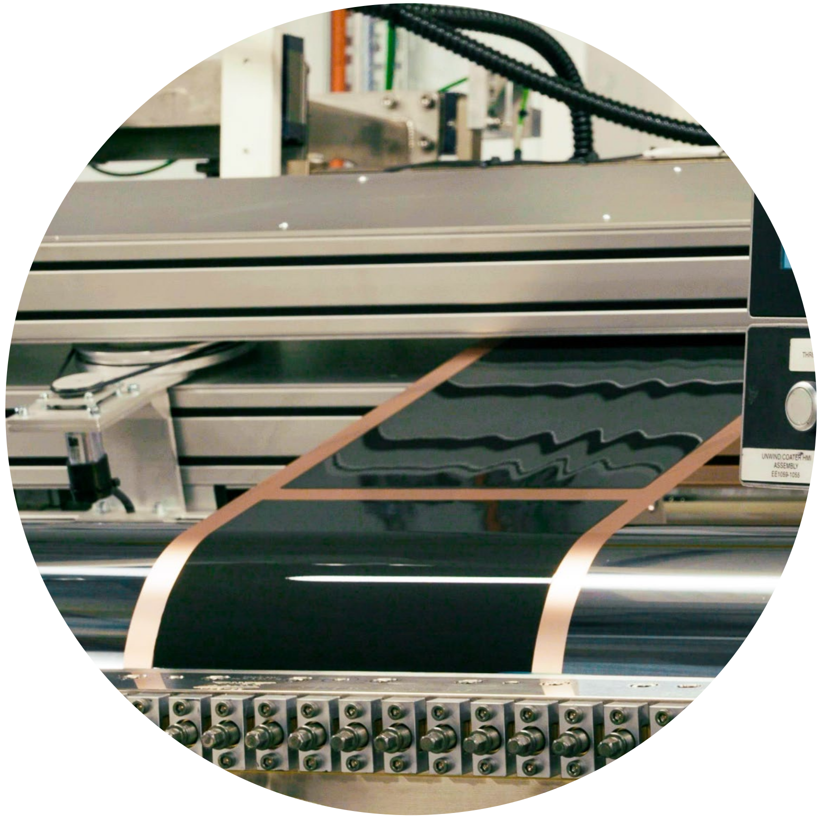
Providing scale-up, laboratory expertise, and helping develop skills to support the sector.

We link research and development to mass-manufacture.

UKBIC is a strategic delivery partner of the Battery Innovation Programme, funded by the Department for Business and Trade and delivered by Innovate UK.

Overview

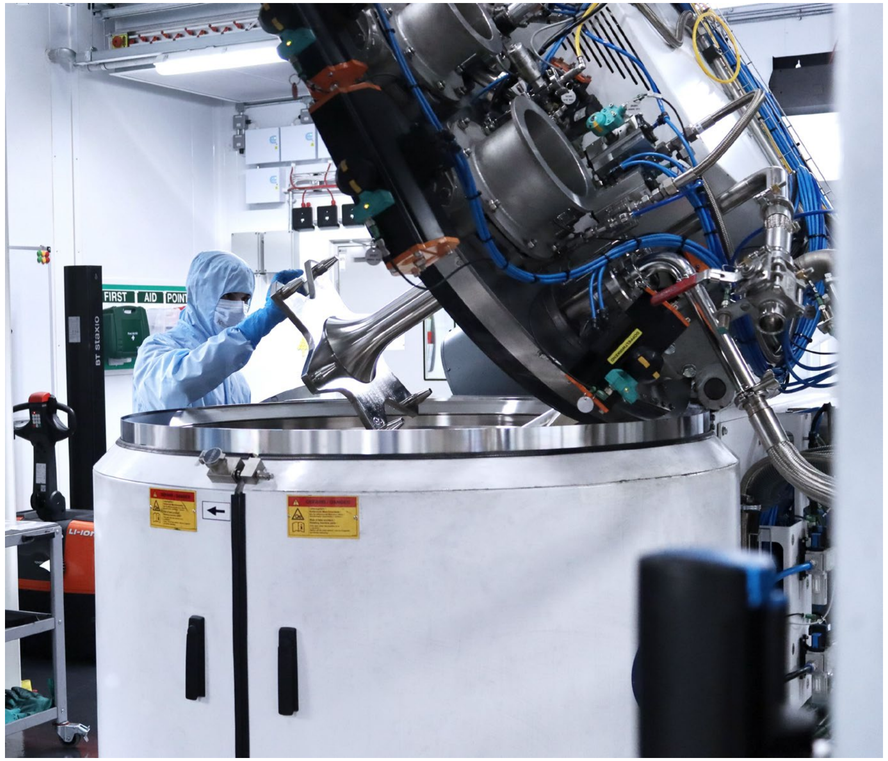
- Understanding degassing is essential
- Formulation and mixing strategies matter
- Equipment design is important
- Coating stability is a final safeguard
- Defect mitigation improves yield and reliability



Background and causes of air in battery slurries

Mixing

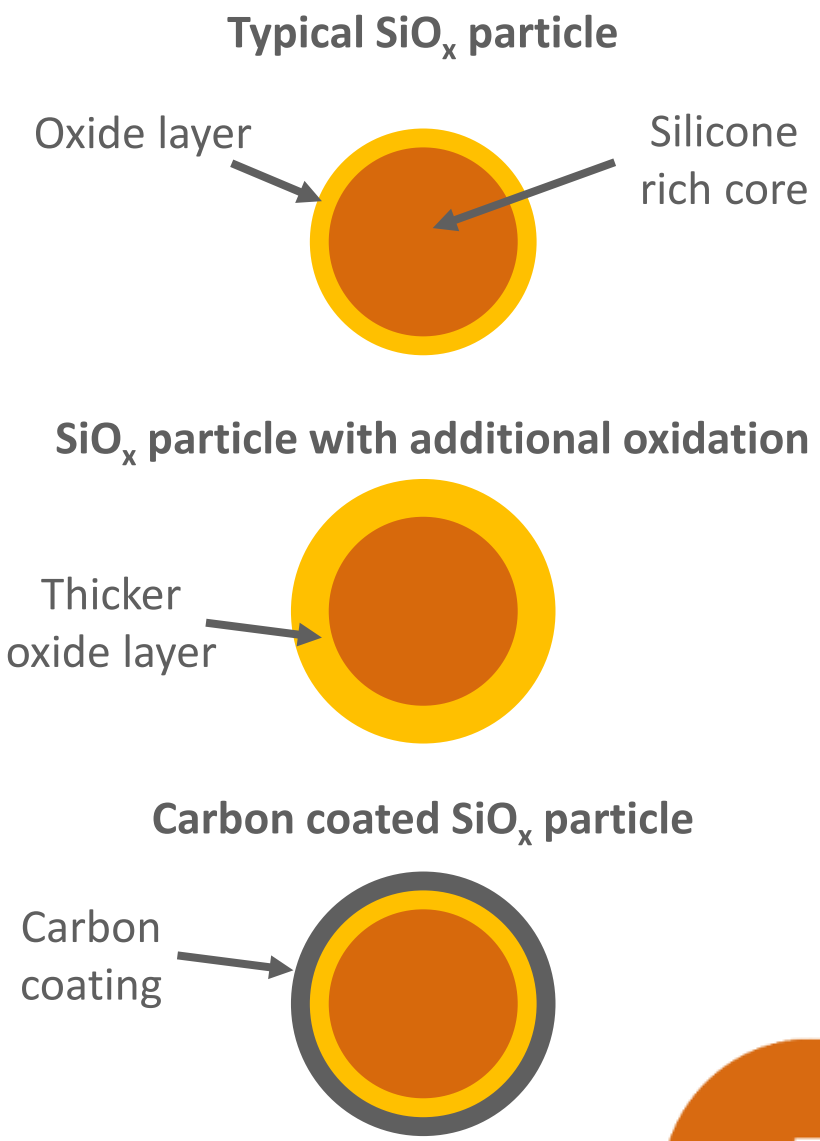
- The mixing process is highly turbulent, entraining air in the slurry
- Traditionally, batch mixing is used, but it often suffers from variability. Continuous mixing offers better scalability and reproducibility
- Regardless of the method, air entrainment remains a risk
- Mixing under vacuum can significantly reduce air bubbles, though vacuum mixers are more complex and costly than conventional systems
- Slurry viscosity must also be carefully managed at this stage



UKBIC's Eirich RLV12 intensive mixer

Causes of air in battery slurries - formulation

- Caution must be taken to ensure that other gases are not being generated within the slurry itself
- When silicon-based anode materials are processed in water-based slurries, chemical reactions with water can produce hydrogen gas
- Applying surface particles – carbon coatings are typically used – to silicon particles can significantly reduce unwanted gas evolution
- **Before large-scale mixing, monitor a trial batch for gas generation**
- **Additional care should be taken when processing pre-lithiated SiO_x as a reaction between lithium and water can also produce H_2 gas**



Background and causes of air in battery slurries

Degassing

- The slurry will be interspersed with tiny bubbles which will rise under buoyancy forces
- Their small size and the slurry's high viscosity make this process extremely slow. Vacuum degassing – typically at 50-200mBar – accelerates removal
- The reduced pressure causes bubbles to expand, decreasing their density enhances buoyancy and speeding their ascent
- As bubbles rise, they continue to grow and accelerate until they reach the surface

UKBIC's 250l transfer vessel used for degassing next to RLV12 intensive mixer

Background and causes of air in battery slurries

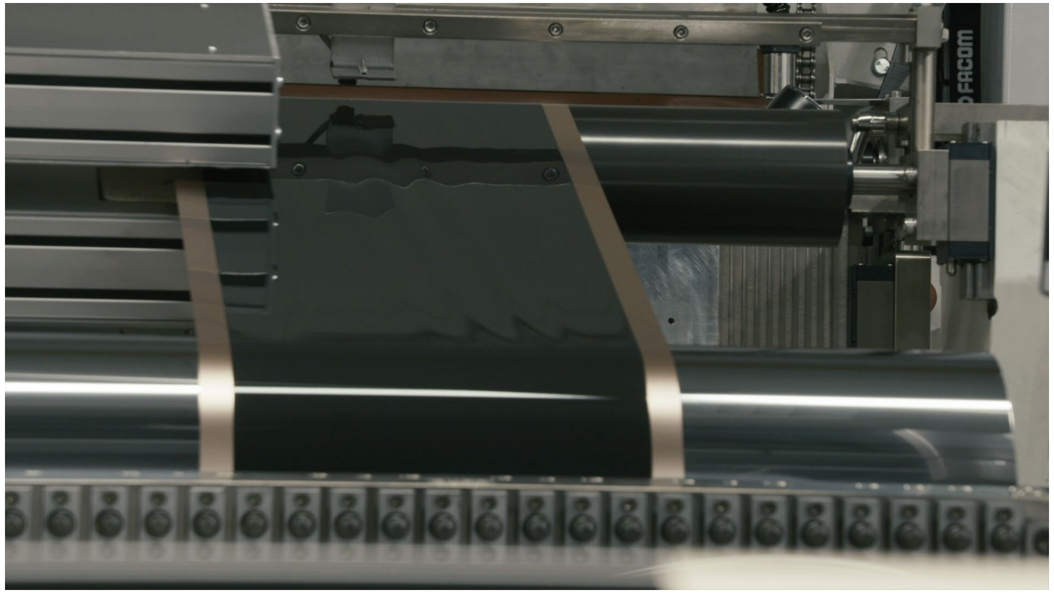
Slurry Delivery

- The slurry must be delivered to the coating head – typically a slot die, comma-bar, knife, or curtain coater
- This may involve moving the slurry through multiple vessels, pumps, pipes, filters, valves, and seals
- Each additional component introduces a risk of air re-entrainment

Original slurry delivery system used at UKBIC with rope seal pump and numerous sanitary clamps and T-junctions

Coating defects, detection and the impact on battery performance

- Air bubbles destabilise the coating bead, disrupt the meniscus, and create uneven coating thickness
- They also change flow behaviour, making coating performance unpredictable
- Intermittent coating is especially affected because it relies on precise pressure control during start/stop cycles
- Compressible air acts like a spring, causing pressure lag instead of an immediate response
- This leads to slow ramp-up, overshoot, uneven edges, or extra coating in the mass-free zones



Coating defects, detection and the impact on battery performance

- Air bubbles burst creating pinholes or fisheyes
- These disrupt the uniformity of the active material layer, disrupting the conductive network → **uneven current distribution**
- Resulting in local overpotential, thermal hotspots, accelerated side reactions, and under-utilised active material → **reduced energy density**
- Over repeated cycles, pinholes may enlarge and exacerbate impedance growth, **shortening cycle life and diminishing power output**
- Severe cases expose the current collector, increasing risk of **internal shorts** from lithium plating and dendrite growth

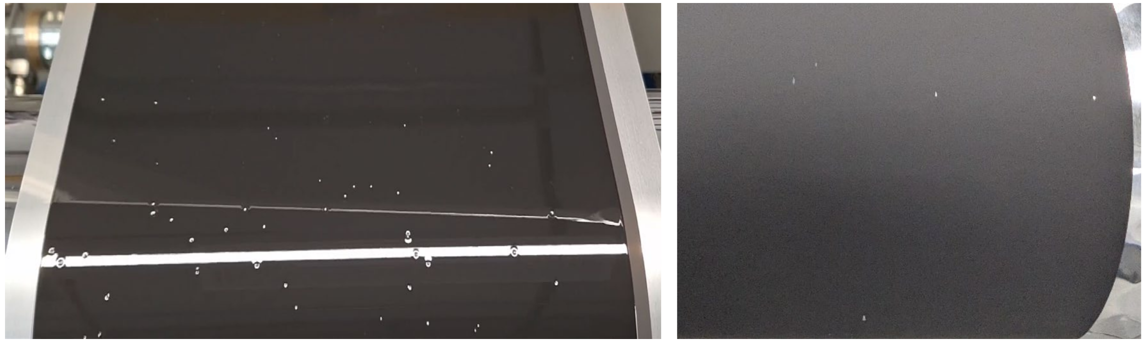


Figure 1: Pinholes or voids in wet (left) and dry (right) coating. These are defects which penetrate through the entire depth of the coating exposing bare foil

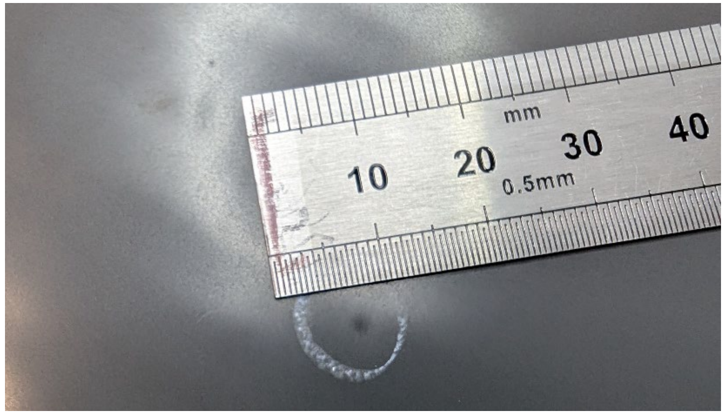
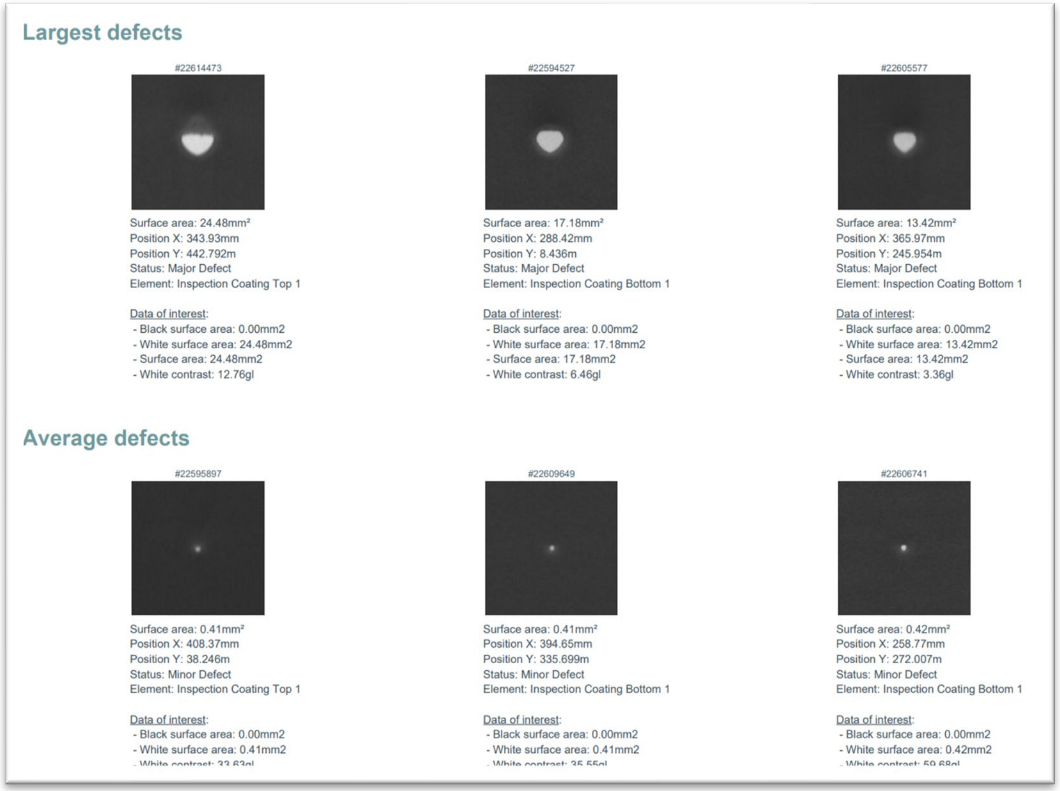


Figure 2: Fisheye defect. A localised spot of lower coat weight that does not penetrate the entire depth of the coating

Coating defects, detection and the impact on battery performance

- Vision systems detect surface defects by analysing contrast differences in real-time images
- High-contrast defects (e.g. pinholes) are easier to detect; low-contrast defects (e.g. fisheyes) need more advanced tuning
- Systems must be trained on the specific material and calibrated to focus only on defects that affect cell performance
- Proper calibration balances sensitivity with manufacturing tolerances, reducing false alarms while ensuring reliable quality control



Example output from UKBIC's Incore vision system

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Detection of air in slurry

UKBIC process

- Decant a small sample into a vacuum chamber and apply vacuum for a few minutes
- Avoid introducing air during decanting. Take multiple samples for reliability
- Bubbles on the surface indicates residual air, while rising fluid height signals significant trapped air

UKBIC degas check in laboratory vacuum oven. Speed x8

Detection of air in slurry

Take care not to pull the vacuum below the solvent's boiling point – it will give misleading results.

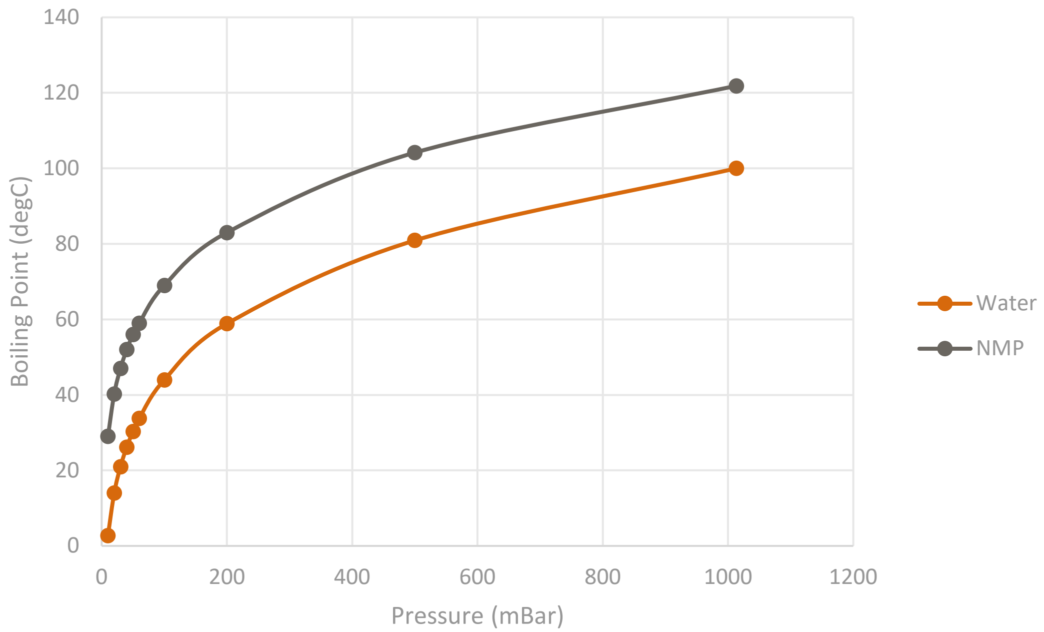
The Clausius–Clapeyron equation

$$\ln\left(\frac{P_1}{P_2}\right) = \frac{\Delta H_{vap}}{R}\left(\frac{1}{T_2} - \frac{1}{T_1}\right)$$

allows us to estimate the vapour pressure, P_2, at another temperature, T_2, if the vapour pressure, P_1, is known at some temperature, T_1

ΔH_{vap} being the enthalpy of vaporisation at P_1, T_1 and R the universal gas constant

Additional caution must be taken with water at very low pressures



Boiling point versus pressure for water and NMP from 10mbar to 1000mbar

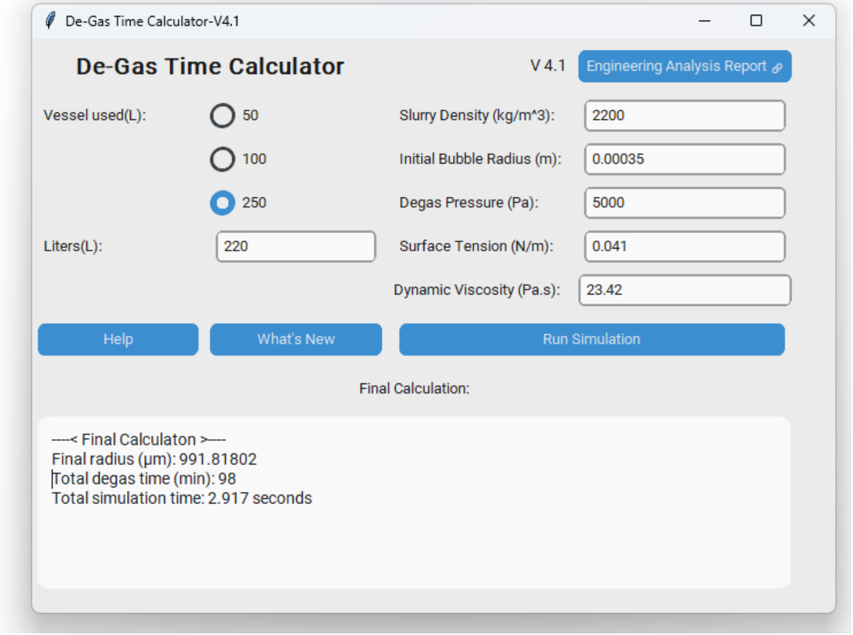
Degas modelling

Bubble expansion can be described by the Rayleigh-Plesset equation:

$$R(t)\ddot{R(t)} + \frac{3}{2}\dot{R(t)}^2 + \frac{4v}{R(t)}\dot{R(t)} + \frac{2\varphi}{\rho R(t)} + \frac{P_\infty - P(t)}{\rho} = 0$$

where $R(t)$ is the radius of the bubble, P_∞ is the far field pressure, $P(t)$ is the pressure inside the bubble, v is the kinematic viscosity and φ is the surface tension

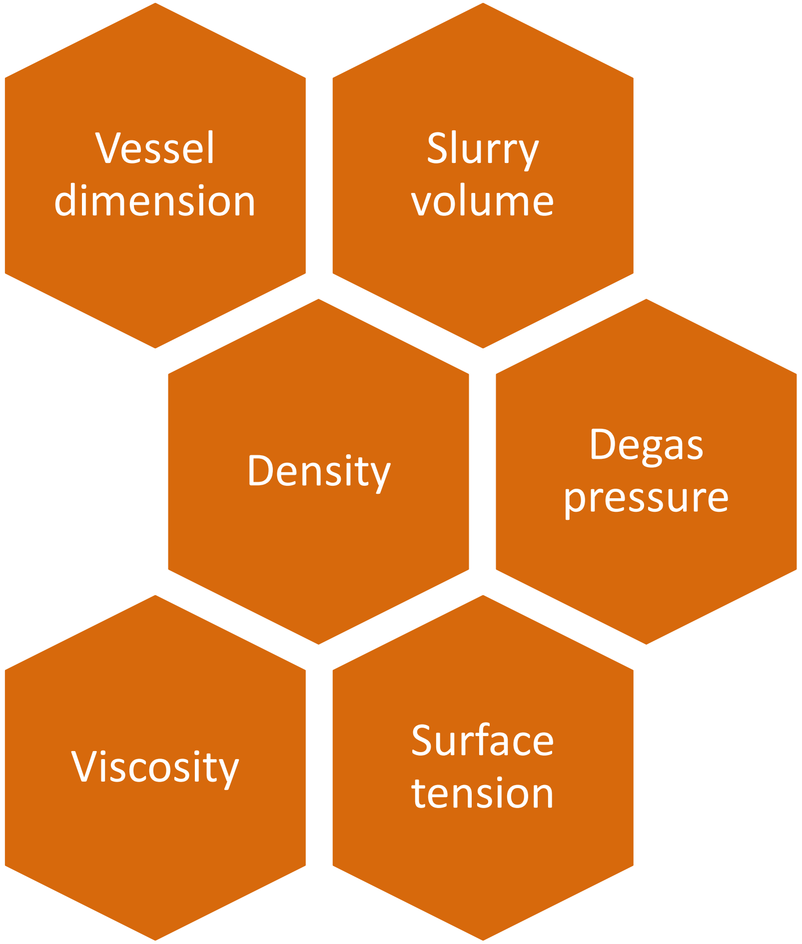
Combined with Stokes' Law – which predicts bubble rise velocity based on density differences – these models can predict both bubble growth and ascent through the slurry column



UKBIC degas tool packaged into an executable file for use by process engineers

Formulation modification

- The physics-based model also highlights how slurry properties influence degas time
- Lower viscosity (Stokes' Law) and higher density (Archimedes' principle) both accelerate degassing
- Slightly lowering solid content can significantly decrease viscosity while largely maintaining buoyancy forces
- Modify the mixing protocol – extended high-shear or kneading breaks agglomerates and lowers viscosity
- Dispersing agents or alternative binders can further reduce viscosity and shorten degas time



Agitator design

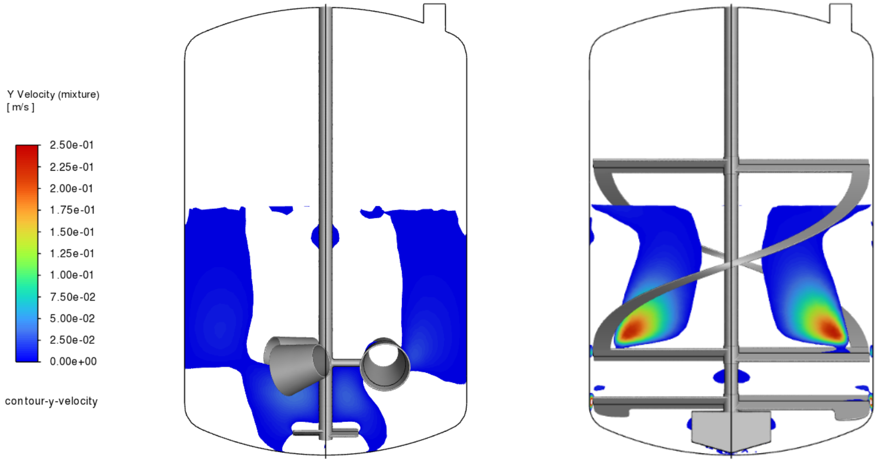
- Agitators generate strong circumferential flow but only some designs effectively induce vertical circulation
- Vertical currents help transport bubbles upward, allowing them to burst at the surface
- UKBIC has replaced its existing ‘cup’ style agitator with a helical design
- This delivers superior flow at the same rotation rate

Cups (left) vs helical (right) agitator design

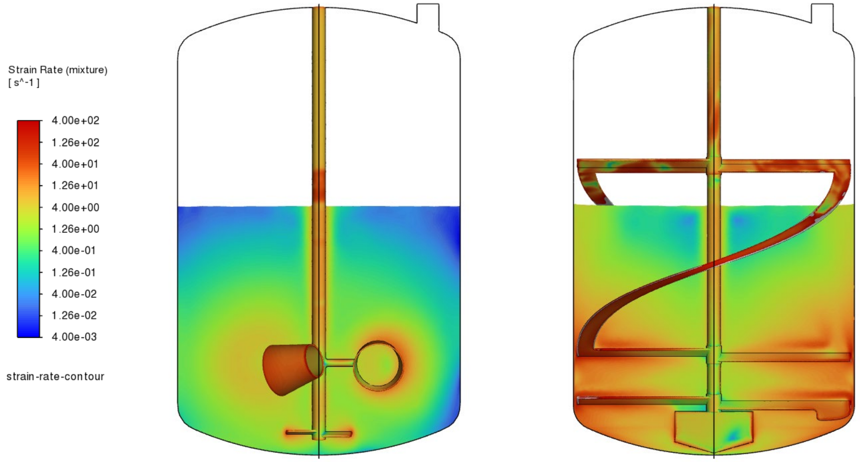
Agitator design

CFD modelling can be used to confirm why the change in rotor design leads to improved degassing:

1. The new agitator delivers superior vertical flow at the same rotation speed
2. The new agitator produced a higher average shear rate at the same rotation speed. For shear-thinning slurries, this reduces the effective viscosity



Positive vertical velocity for cups (left) vs. helical (right) agitator design at 30 RPM. Negative velocities have been clipped



Shear rate field for cups (left) vs. helical (right) agitator design at 30 RPM

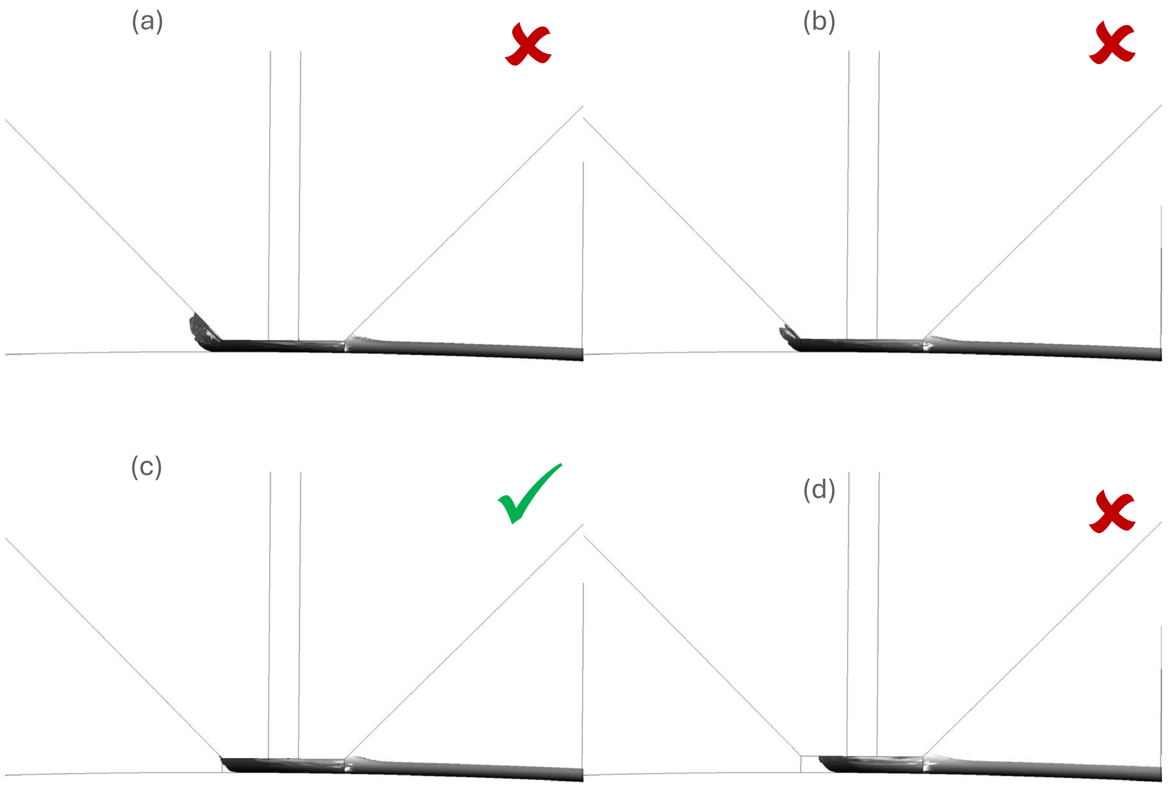
Slurry delivery system

*Original slurry delivery system used at UKBIC with **45 connections**, ball valves, and T-junctions, along with EPDM/PTFE seals that required frequent cleaning and reassembly. Self-lubricating rope seal pump*

*Streamlined slurry delivery system at UKBIC with **17 connections.** With inline gauges, reduced number of clamps and a purge value immediately prior to the pump. Mechanical seal pump*

Coating process optimisation

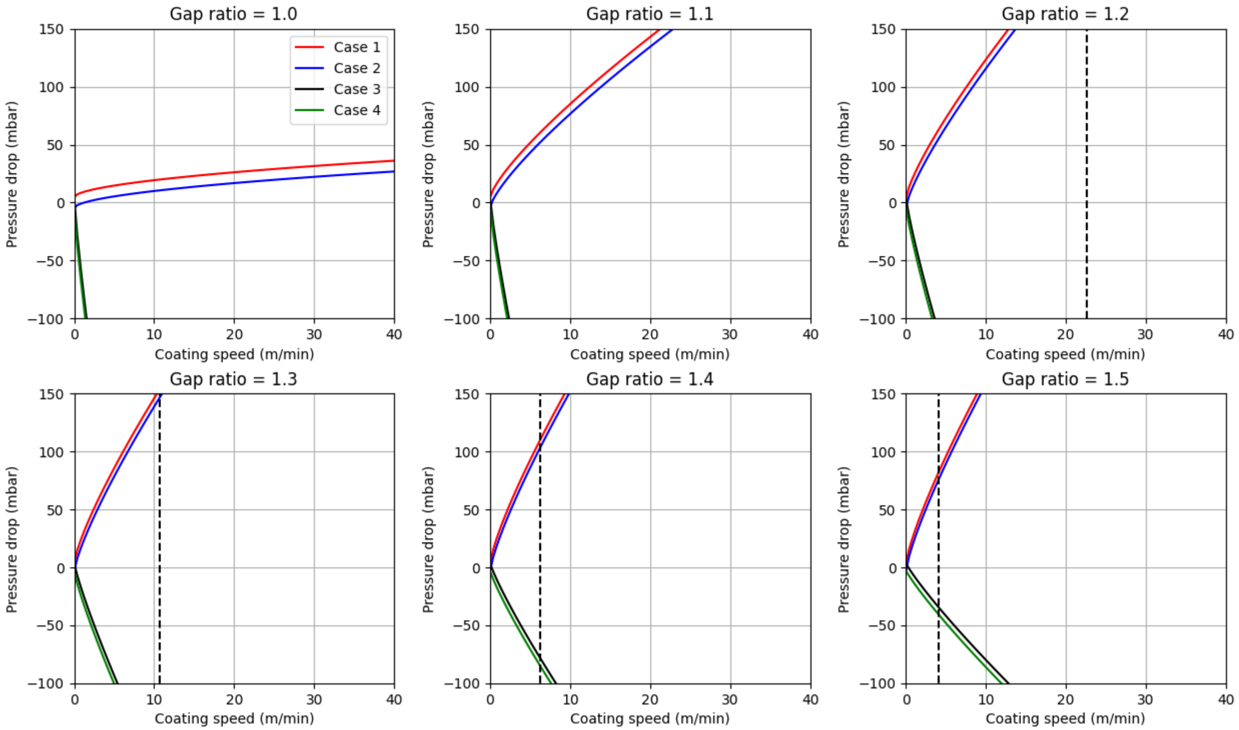
- Final risk of air entrainment occurs as slurry exits the slot die and forms the coating bead.
- Bead stability depends on balancing viscous, inertial, gravitational and surface tension forces.
- If this balance is disturbed, air can be pulled under the die lips resulting in voids or non-uniform coating thickness.
- Computational Fluid Dynamics (CFD) simulations (right) can be used to study this balance.



Computational Fluid Dynamics model of slot die coating. Coating bead meniscus for die on coat position (a) 195µm, (b) 215µm, (c) 235µm and (d) 275µm for a wet film thickness of 203µm. Roller motion is from left to right.

Coating process optimisation

- High-fidelity CFD models can predict cross-web uniformity and incorporate interfacial effects, i.e. contact angle
- These simulations are accurate but computationally expensive and slow
- Analytical models provide a faster way to estimate key process parameters
- They help define the coating stability window, such as the example shown for the UKBIC slurry in the figure to the right



Coating window stability model outlined by Schmitt (2016) and implemented for UKBIC cathode slurry. Bead swelling occurs above the red line, and air entrainment occurs below the green line and to the right of the dotted line

Conclusions

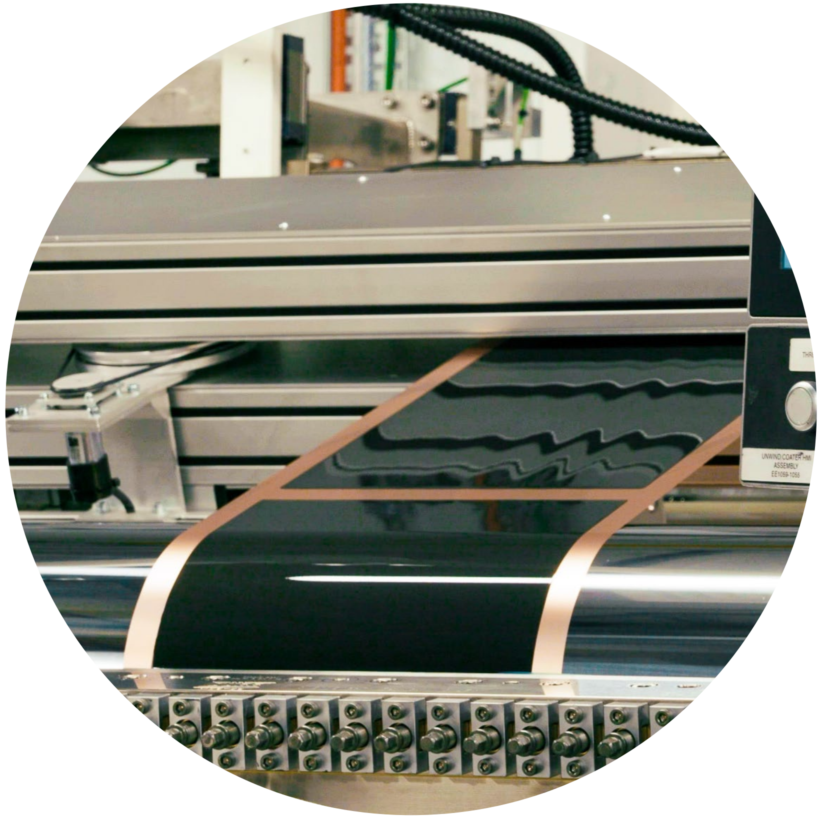
Understanding degassing is essential

Formulation and mixing strategies matter

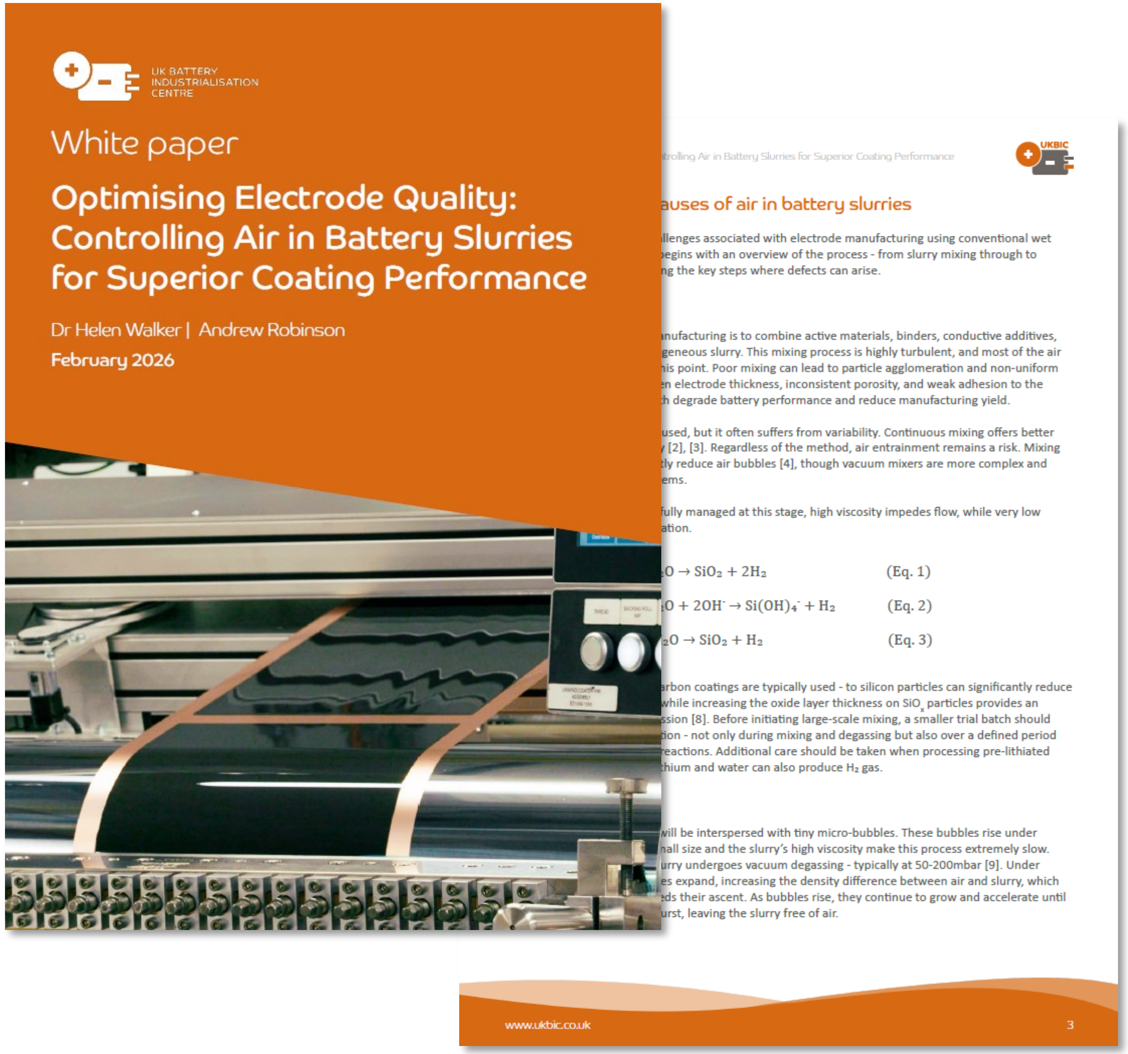
Equipment design is important

Coating stability is a final safeguard

Defect mitigation improves yield and reliability



The white paper



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Question and answer panel

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