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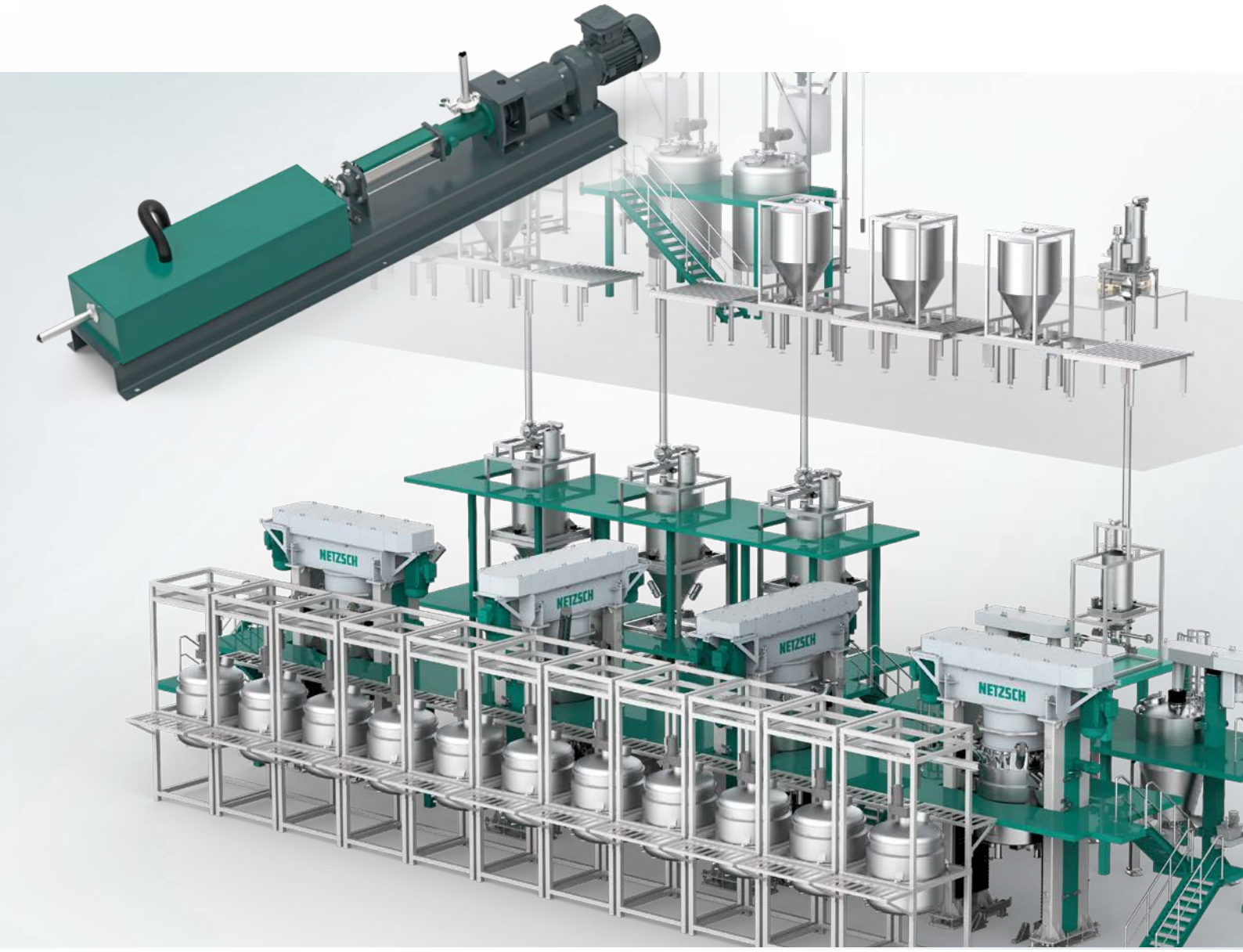


Innovative Real-Time Viscosity Measurement for Monitoring of Battery Electrode Slurries

A Complete NETZSCH Solution from Pump, Mill, Mixer to Rheometer – Enabling Precision Coating and Improved Quality Control in Battery Electrode Manufacturing

Quality Is a Success Factor in Battery Production

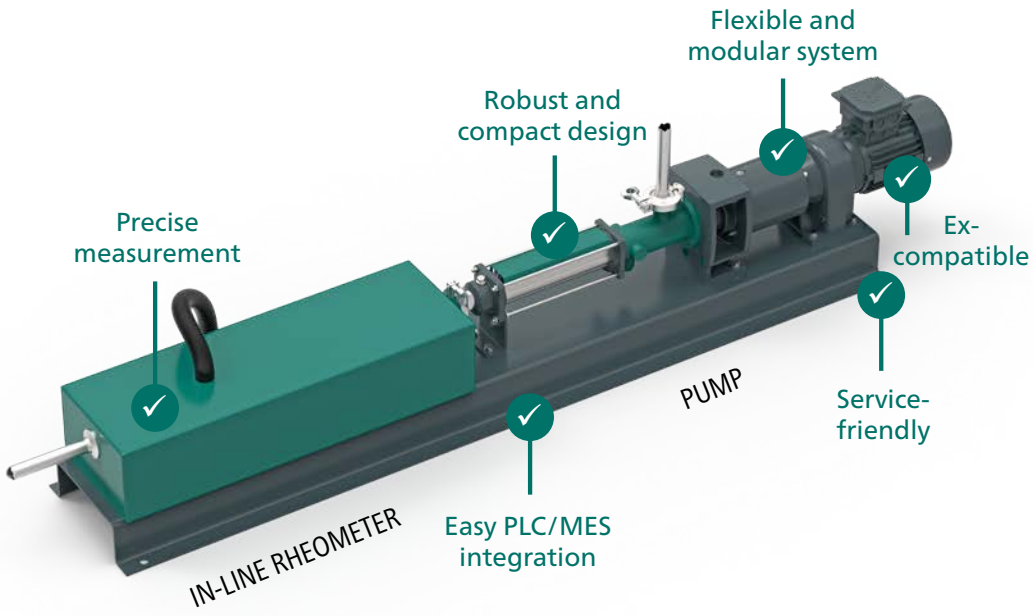
Lithium-ion batteries are central to the transition toward clean energy, powering everything from consumer electronics to electric vehicles and large-scale energy storage. As global demand soars, manufacturers face mounting pressure to increase production efficiency, reduce costs, and maintain the highest standards of quality and safety.

Yet battery production remains highly complex. Gigafactories producing millions of cells per month often struggle with real-time quality control, leading to scrap rates of over 10% even years after the start of production. Minor process variations can result in major performance issues – or even critical failures like thermal runaway.

Robust quality assurance is essential. Inline monitoring, especially of key parameters like slurry viscosity, enables early defect detection, reduces waste, and ensures that only safe, high-performance cells reach the market. In a competitive, quality-driven industry, such process control is no longer optional – it's a necessity.

In-Line Viscosity Measurement for Slurry Control

The NETZSCH In-Line Rheometer Novanti is a state-of-the-art solution for real-time, in-process viscosity measurement, designed to meet the stringent requirements of modern battery production. It delivers precise, continuous monitoring during both slurry mixing and coating applications – ensuring process stability, product consistency, and minimized waste across the entire manufacturing line.



Improving Battery Production by

Scrap Reduction: Early detection of deviations minimizes scrap and reduces material waste, enabling more sustainable and cost-effective production.

Operational Efficiency: Automated, in-line viscosity measurement eliminates manual sampling, lowering operational overhead, and maximizing uptime of critical equipment.

Enhanced Product Quality: Maintaining consistent slurry quality ensures high quality electrode coatings, enhancing battery performance, reliability, and cycle life.

Real-Time Process Control: Real-time viscosity monitoring shortens response times to deviations, ensuring process stability and reproducibility across batches.

Unique Challenges in Battery Quality Assurance

Battery manufacturing faces distinct quality assurance challenges, including a mix of batch and continuous processes, strict tolerances, non-repairable defects, and tightly interlinked production steps. These complexities make traditional, reactive quality control – based on sampling, parameter checks, and offline lab analysis – inefficient, slow, and difficult to scale.

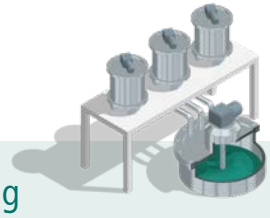
In-Line Inspection Systems

In contrast, in-line inspection systems offer real-time, non-destructive monitoring and greater process transparency. They enable early detection of deviations and support proactive process control – going beyond basic statistical methods to stabilize production more effectively. This is particularly critical in electrode manufacturing, where parameters like slurry viscosity and coating uniformity directly impact cell performance and safety.

Advantages of In-Line Inspection – Real-Time Process Control

In-line viscosimetry enables faster feedback and proactive process control, enhancing stability in battery electrode production. Monitoring key parameters like slurry viscosity supports higher coating uniformity and overall product quality, driving broader adoption of data-driven inspection systems.

Electrode Manufacturing: Product Quality Requirements



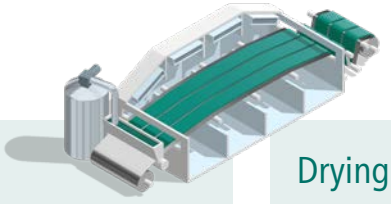
Mixing

Quality requirements

- Precise dosing
- Homogeneous slurry
- Agglomerate-free & contaminant-free

Product properties

- Viscosity [mPa·s]
- Slurry temperature [°C]
- Shear rate [1/s]
- Particle size distribution



Coating

Quality requirements

- Constant wet film thickness
- No coating defects (agglomerates, streaks, etc.)

Product properties

- Visual inspection [images]
- Wet film thickness [µm]
- Coating weight [g/m^2]

Drying

Quality requirements

- Minimal residual moisture
- Adhesion to the substrate
- Surface quality (no cracking, corrugations, etc.)

Product properties

- Dry film thickness [µm]
- Coating weight [g/m^2]
- Visual surface [images]
- Adhesion [N]

Complexity of Electrode Manufacturing – Monitoring Slurry Viscosity

Electrode production is a critical step in battery cell manufacturing, directly impacting performance and quality. It begins with preparing a stable, homogeneous slurry of active materials, binders, additives, and solvents. Poor mixing can lead to issues like particle agglomeration, sedimentation, and material degradation, affecting downstream processes. Monitoring slurry viscosity is essential to ensuring uniformity and stability. Additionally, precise thermal management is crucial to preventing heat-sensitive components from degrading.

Precision in Slurry Application and Drying

After mixing, precise slurry delivery to the coating tool is vital for forming uniform electrode layers. Since the slurry experiences high shear during coating, its rheology directly affects film quality and edge definition. In the drying phase, controlled solvent evaporation is crucial for the avoidance of defects like cracking or binder migration. These early production steps demand high precision and emphasize the need for integrated quality control. Monitoring properties such as viscosity is essential for optimizing processability and ensuring consistent electrode performance.

Importance of Viscosity Measurement

The viscosity and flow behavior of the slurry – different for anodes and cathodes – play a key role in ensuring proper application during coating. Even a single poorly coated electrode can compromise the performance of an entire battery pack.

Maintaining Viscosity

Viscosity is a key indicator of slurry quality, shaped by factors like particle size, solids content, and mixing conditions. Deviations often signal raw material variability or process issues, making viscosity monitoring essential for early detection and timely correction. Maintaining viscosity within the optimal "coating window" ensures uniform layer formation – viscosity that is too high leads to streaks and uneven films, while too low can cause run-off and coating defects.

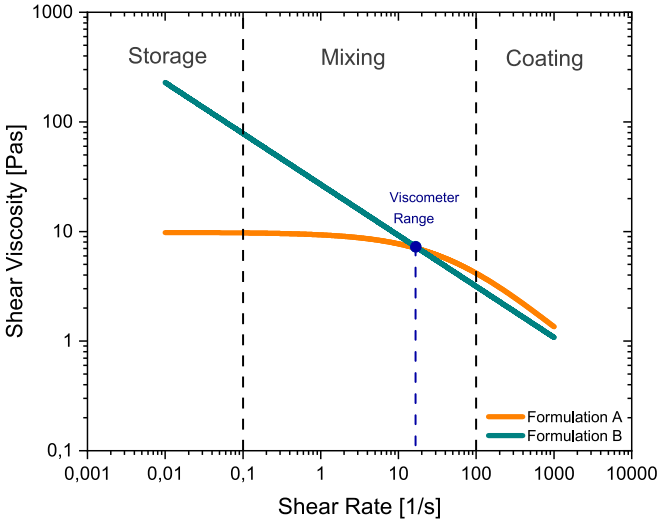
Since slurries may behave differently at high (processing) and low (storage) shear rates, a comprehensive viscosity profile is crucial. Effective viscosity control stabilizes production, improves coating consistency, and helps ensure overall battery performance and quality.

Applying the Slurry – Uniformity of Coating

A key step in battery production is precisely coating active anode or cathode materials onto thin metal foils, typically aluminum or copper. This forms the electrodes – the core of every battery.

Although these materials start as fine powders, applying them directly and uniformly in layers just fractions of a millimeter thick is not practical. To achieve the necessary consistency and spreadability, the powders are mixed with liquids and stabilizers to form a slurry – similar in concept to paint.

These slurries are then applied to metal foils using precision slot-die coaters. The uniformity of the coating is absolutely critical, as it directly impacts the cycle life, performance, and safety of the final battery cell.

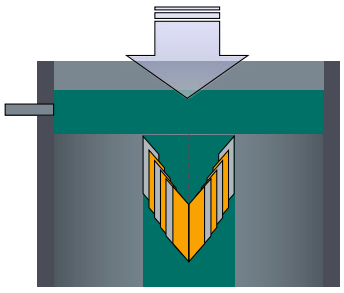


Viscosity profiles: Slurries exhibiting similar flow behavior at high shear rates (processing conditions) can still differ significantly in their low-shear (storage) properties.

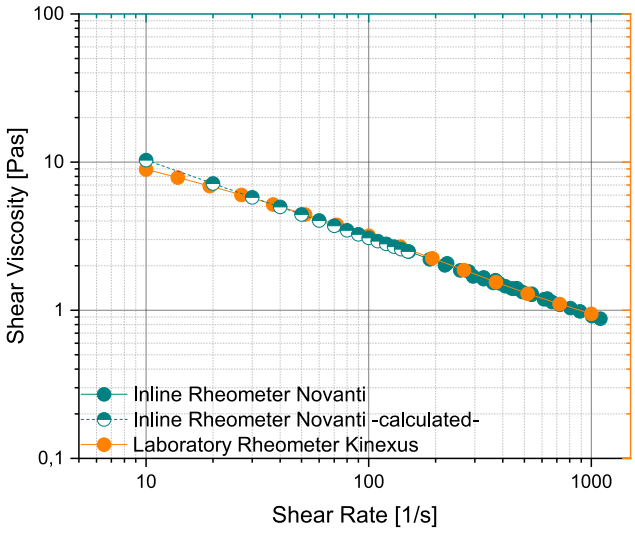
In-Line Viscosity Monitoring with Off-Line Rheology for Complete Shear Rate Insight

The in-line system Novanti is based on the capillary principle and measures the pressure drop across a defined geometry. The absolute shear viscosity is then calculated using automatic software corrections. The measurable range can be adjusted by varying geometry, sensor configurations and volume flow. The shear viscosity of a fluid is contingent upon the rate of shear, the shear stress, the temperature, and the time. These parameters are recorded during the measurement process.

This measurement plot shows the good correlation of the data obtained by the in-line rheometer Novanti during the manufacturing process and the off-line monitored shear viscosity obtained by means of the rotational rheometer Kinexus.



Scheme of the slit die including slurry flowing through the die (yellow)



Data comparison between in-line and lab measurements

Deeper Insight: Rotational Rheometer Kinexus

For comprehensive rheological characterization of battery slurries across the full shear rate range, our Kinexus rotational rheometer is an ideal solution. In addition to evaluating flow properties under mixing and coating conditions, it also enables analysis at low shear rates – for example, to assess leveling behavior after coating and sedimentation for storage stability.

Rotational Rheometer Kinexus Prime pro+

Laboratory Rotational Rheometers

The NETZSCH Kinexus Prime rheometer has the highest sensitivity air bearing and widest torque range, coupled with the unprecedented vertical (axial) control capabilities of the Kinexus platform, for advanced rheological testing. Unique sequence-driven rSpace software enables fully customizable test design to allow researchers to set up and investigate tailored rheological test protocols.

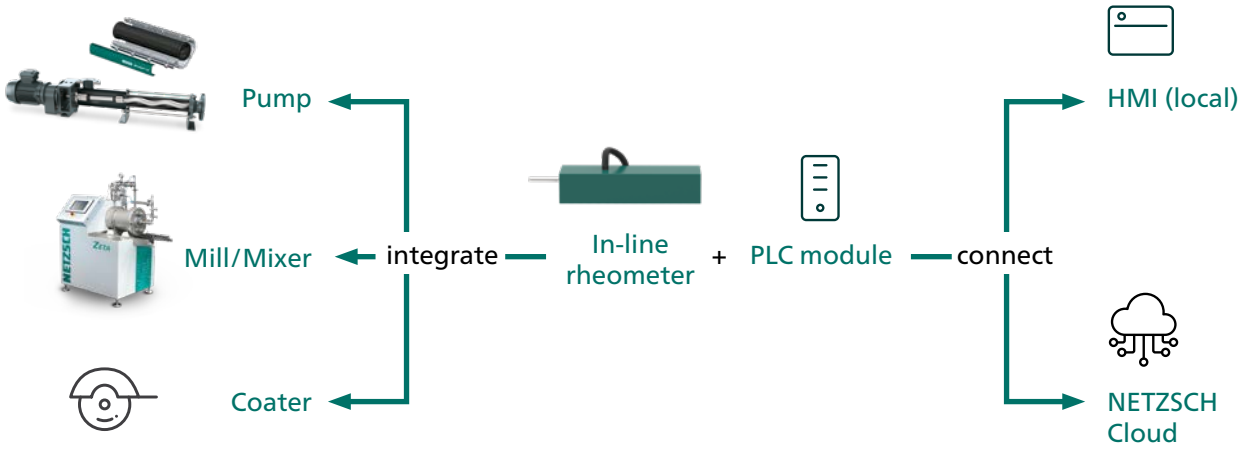
In-Line Viscosity Tool Novanti	
Output	At multiple quality control set-points: ▪ Shear viscosity ▪ Shear stress/shear rate ▪ Temperature
Measurement rate	1 s per measurement, depending on the equilibrium time needed
Viscosity range*	0.1 ... 100 Pa·s, range adjustable on request
Volume flow range	38 - 200 l/h; different flow rates adjustable upon request
Reynolds number	0.1 - 2,000; laminar flow required
Precision to laboratory equipment**	±10% or better
Operation pressure	0 ... 6 bar, higher pressures available on request
Pipe connectors	Tri-clamp or other connectors available upon request
Operation temperature	0 ... 80°C
Temperature control	Optional, from 0 ... 80°C
Size***	760mm x 90mm x 250mm (L x W x H)
Slit material	Stainless steel V4A
Weight	Up to 30 kg
Power supply	24V DC 1A
Process integration	Ethernet IP, Profinet, Modbus
Analog input pressure	4 ... 20 mA (differential pressure)
Analog input temperature	PT100

* Viscosity range is dependent upon differential pressure sensor used and measured fluid
** Accuracy of viscosity is dependent on process conditions, the measured fluid and the reference method used. References used in this case are air-bearing rotational and capillary rheometers
*** Includes measurement slits, the sensors and cabling

Key Technical Data

In-Line Rheometer – The NETZSCH Solution Connectivity and Process Integration

NETZSCH's in-line rheometer system Novanti is based on the capillary (or slit-die) principle, where fluid is forced through a channel with a known geometry and the resulting pressure drop is used to calculate viscosity under controlled flow directly in-line.



Key Components for Accurate, Real-Time In-Line Viscosity Measurement

The NETZSCH system combines advanced components in a modular, scalable design for easy integration and maintenance.

- **Low-Pulsation Pump:** A progressive cavity pump ensures steady, laminar flow with minimal pulsation – essential for accurate and reproducible viscosity readings during continuous operation.
- **Modular Slit Dies:** Interchangeable slit dies with varied geometries replicate the shear rates found in real coating processes. Each is equipped with two high-precision pressure sensors positioned at fixed distances.
- **Pressure-Based Viscosity Calculation:** The system calculates apparent viscosity in real time using the pressure drop across the slit die, based on the Hagen-Poiseuille equation adapted for slit flow.

Together, these components enable precise, real-time viscosity monitoring directly in-line – supporting data-driven process control and consistent slurry quality.

Optional Feedback Control

With an optional feedback control loop, the system can automatically adjust pump output based on real-time viscosity data – stabilizing the process toward a set target. This transforms the in-line rheometer from a passive sensor into an active control device.

System Integration

To maximize the benefits of in-line viscosity monitoring, NETZSCH offers flexible integration options tailored to your production environment. Choose either an existing NETZSCH solution such as Notify for processing and visualizing your data, or opt for seamless integration via common interfaces into an existing manufacturing execution system (MES) from leading manufacturers. This ensures enhanced process stability, reduced variability, and greater manufacturing efficiency.

Advantages of In-Line Viscosity Measurement

Precise In-Line Viscosity Measurement

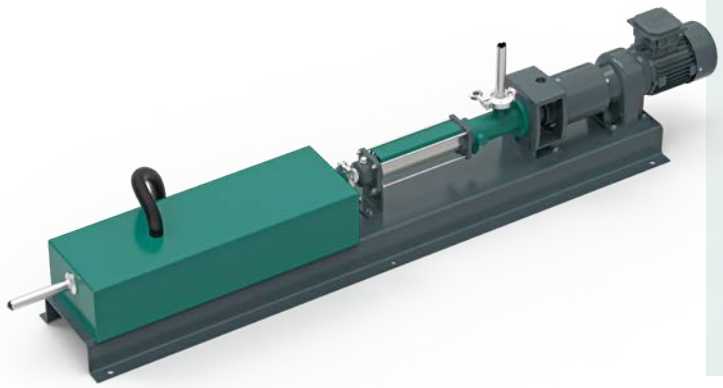
Viscosity measurement technologies differ in accuracy and adaptability. NETZSCH's in-line rheometer Novanti, based on the capillary principle, delivers reliable, shear-rate-dependent results across a wide viscosity range and varying production conditions.

Unlike other methods, the capillary system directly measures pressure-flow behavior under real flow conditions – ideal for non-Newtonian fluids. Its slit-die design ensures laminar flow and precise shear control, enhancing process relevance and performance.

Resonance principle	Coriolis principle	Capillary principle	Rotational principle
▪ Single point, relative viscosity ▪ Mainly for Newtonian fluids ▪ Limited to monitoring relative change of viscosity over time	▪ Single point, relative viscosity ▪ Mainly for Newtonian fluids ▪ Limited to monitoring relative change of viscosity over time	▪ Multi-point, absolute viscosity ▪ For Newtonian and non-Newtonian fluids ▪ Limited by pressure transducer range and diaphragm size	▪ Multi-point, absolute viscosity ▪ For Newtonian and non-Newtonian fluids ▪ Limited to viscous fluids with medium shear rates
Results not comparable with lab rheometer	Results not comparable with lab rheometer	Results comparable with lab rheometer	Results comparable with lab rheometer

Your Benefits for Battery Manufacturing

- Early detection of deviations in process to minimize material waste
- Improved understanding of slurries for achieving high process consistency
- Optimized coating quality via precise viscosity management
- Reduction of machine downtime during mixing due to faster and improved process control
- Direct comparability to laboratory rheometer measurements



Why the NETZSCH Solution?

- **Modular Slit-Die Design** – Adaptable to process conditions and slurry viscosities
- **Easy cleaning and exchangeable to different slot dimensions**
- **True Shear Viscosity** – Accurately measures Newtonian and non-Newtonian fluids, aligned with lab rheometers
- **Real-Time Monitoring** – Captures process fluctuations instantly with continuous in-line measurement
- **High Data Throughput** – Automated readings match lab-level precision with superior acquisition rates
- **Minimized Human Error** – Replaces time-consuming, error-prone offline testing
- **Early Issue Detection** – Flags raw material and formulation changes for proactive intervention

In-Line Viscosity Measurement in Battery Production

In-line viscosity measurement can be integrated at key stages of electrode manufacturing – slurry production, storage, or transport – offering flexible application. Integration ranges from basic monitoring to advanced process control. Two typical use cases, concept A and B, mixing and coating, show how continuous, real-time data enables early detection of process deviations and timely corrections.

Integration into the Mixing Process:

Integrating the viscosity measurement system Novanti into the mixing stage enables continuous monitoring of slurry properties from the start of electrode production. Real-time feedback supports immediate adjustments to parameters such as mixing time, energy input, or component ratios to consistently achieve target viscosity. This proactive control prevents downstream defects caused by inconsistent slurry behavior, improving process stability and reproducibility. Once specifications are met, the slurry proceeds to the next step or storage; if they are not, it is diverted for further analysis or disposal.

Integration into the Coating Process:

Installing the viscosity measurement system Novanti upstream of the coating process enables a final quality check of the slurry just before application. This real-time monitoring ensures that off-spec material is identified and diverted before reaching the coater, helping to reduce material waste and avoid equipment downtime caused by cleaning and contamination. To further enhance efficiency, an optional supplementary mixing unit can be integrated into the system. This unit allows for reprocessing and adjustment of the slurry, making it suitable for reuse in the coating process rather than being discarded.

Integration at Mixing Stage

Description

- Slurry is continuously circulated through a bypass during the mixing process, where viscosity is measured in real-time
- After mixing is complete, a second viscosity measurement is performed before the slurry enters downstream processing.

Key advantages

- Real-time monitoring of slurry viscosity after mixing
- Closed-loop control of the mixing process (e.g., based on viscosity parameters)
- Early detection of formulation errors or raw material deviations
- Improved batch homogeneity and consistency

Integration at Coating Stage

Description

- Slurry is continuously fed towards the coating unit while viscosity is measured in real-time
- Depending on the process state, the slurry can be either coated directly to the electrode foil, stored temporarily, or reprocessed and reintroduced into the process.

Key advantages

- Real-time monitoring of slurry viscosity during the coating process
- Detection of slurry aging or sedimentation effects caused by storage or transport
- Material cost savings (electrode foil) by preventing coating with defective slurry
- Increased coating quality and layer uniformity

Core Benefits of the Two Integration Possibilities

Both possibilities have the potential of in-line viscosity measurement to enhance quality assurance in electrode production. The system can be tailored to specific production requirements, e.g., by integrating visualization software that delivers real-time data, enabling early detection of deviations and more efficient troubleshooting on the shop floor.

Additionally, the system can be configured to automatically adjust process parameters and trigger alerts in response to critical viscosity deviations. These capabilities support precise process control, minimize defects, and ensure consistent product quality.

These possibilities can be integrated in a unique and compact system, *Cellvos®*, which combines two essential steps in battery production, mixing and beat milling.

Intensive Mixing and Bead Milling – *Cellvos®*

What is *Cellvos®*? – The Combination of Two Technologies During Battery Production

Cellvos® is a compact, turn key mixing system that integrates two advanced dispersion technologies – intensive mixing and bead milling – alongside a high-speed powder feeding unit and real-time analytic feedback loops by the Novanti system. Designed as a mini mixing plant, *Cellvos®* offers key advantages such as increased production capacity, a small footprint, short process times, and higher yields.

Intensive Mixer

Agitator Bead Mill

The intensive mixer utilizes a specially designed container with two mixing tools that generate a vortex for intensive mixing and dispersing.

+ Fast Powder Dosing 1,000 kg per minute
+ Fast Mixing and Dispersing < 90 mins
+ Controlling Viscosity

The agitator bead mill consists of a horizontal chamber filled with grinding media. The agitator activates the grinding media and provides intensive movement. The slurry is continuously pumped through the chamber.

+ Smaller Footprint
+ Less Equipment
+ Controlling Particle Size – Polishing
+ Reducing Mixing Time

Design of the NETZSCH Pump System NEMO® MY

Pulsation-Free Pump System with Corrosion Resistance

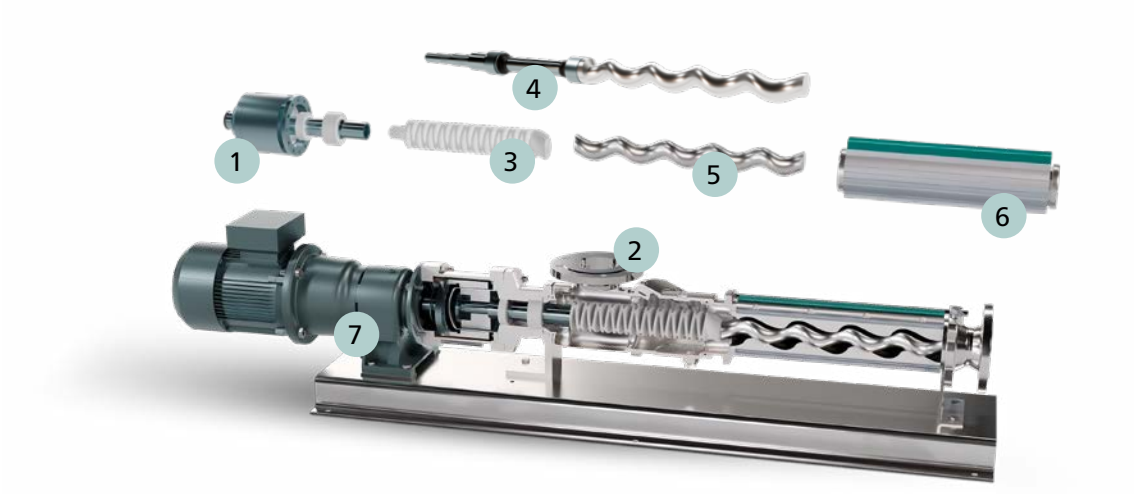
The pump's design, operation, and compatibility with the slurry characteristics directly affect the quality, consistency, and performance of battery electrodes. Choosing the right pump is essential to ensure reliable electrode manufacturing and optimal electro-chemical performance. Our pumps and systems offer pulsation-free delivery, high-precision dosing and maximum corrosion resistance in all process steps. The pumps and systems from the global specialist in complex fluid management are extremely powerful and reliable. Since they can be operated over a long period without problems, they represent a cost-effective solution.

The Magnetic Coupling

The NEMO® MY combines the pulsation-free operation progressing cavity pump technology with a hermetically sealed magnetic coupling, eliminating external seals. It enhances plant safety, reduces costs, and minimizes product waste through optimized design features like a PA12 coupling rod and tangential inlet.

Stator

The unique iFD® stator housing offers maximum flexibility and durability. Various rotor materials, including ceramic, ensure a long service life and prevent metal wear.



1. Magnetic Coupling: Hermetically sealed, optional flushing & temperature probe
2. Pump Housing: Tangential inlet for improved cleanability
3. Coupling Rod (PA12): Flexible, metal-free, CIP-optimized
4. B/K Joint Option: Alternative to PA12 rod
5. Rotor: Ceramic or alloy, long life, no metal abrasion
6. Stator: PA12/elastomer with iFD® housing
7. Block Design: Direct drive flanged to pump lantern

The Role of the Pump in Slurry Application for Battery Electrodes

- **Consistent Flow:** A stable, pulsation-free flow ensures uniform coating thickness and reliable electrode performance.
- **Gentle Handling:** The NEMO® MY pump minimizes shear stress, preserving slurry integrity and maintaining proper particle dispersion.
- **Precision Dosing:** Accurate flow control enables reproducible results – essential from lab to production scale.
- **Pump Selection Matters:** Whether using peristaltic, gear, diaphragm, or progressive cavity pumps, matching the pump to your slurry properties is key.
- **Performance Impact:** Poor slurry delivery can lead to coating defects, reduced capacity, and lower cell reliability.

The NEMO® MY pump offers smooth, efficient, and high-quality slurry application – because every layer counts.

Key Technical Data Performance Range

NEMO® MY	
Type	Magnetically coupled progressing cavity pump
Hermetic tightness	▪ No mechanical seal ▪ No leakage toxic / aggressive media
Sealing system	▪ Magnetic coupling ▪ Maintenance-free system
Flow rates	30 m^3/h
Pressure range	Up to 30 bar
Slurry viscosity range	▪ Media up to 50,000 mPa·s and more ▪ High solid content
Area of application	▪ TA-Luft compliance ▪ Abrasive, aggressive and toxic media ▪ Battery slurries
Suction capabilities	Very low NPSHr values
Easy cleaning	▪ External flush connections for the magnetic coupling ▪ CIP designed pump
Standards	Certified in accordance with ATEX and FDA

In-Line Viscosity Measurement in Electrode Coating of Anode and Cathode

Application Overview: In-Line Viscosity Measurement in Slurry Coating Trials

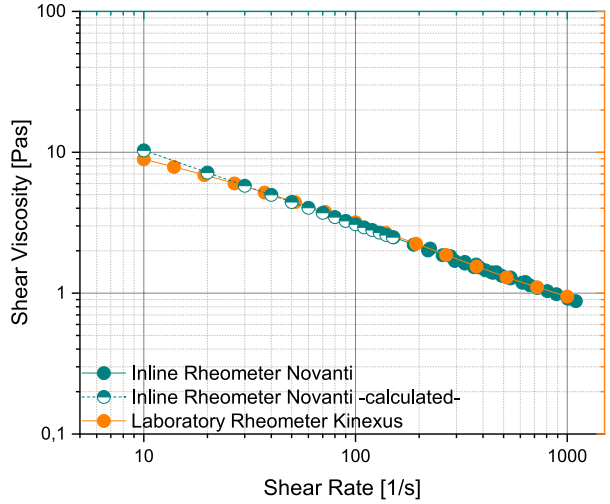
This application highlights the performance of a measurement module installed directly downstream of a slurry pump. The study involved multiple coating trials using both anode and cathode slurries. Key aspects of the experiment include:

- Installation Setup: Measurement module placed in-line, immediately after the slurry pump.
- Trial Conditions: Coating trials conducted with both anode and cathode slurries.
- Process parameters such as:
  - Slurry feed rates
  - Presence or absence of the measurement module
- Product parameters such as:
  - Solid content variations
- Measurement Validation: In-line viscosity readings were compared to calibrated off-line laboratory measurements to assess accuracy.

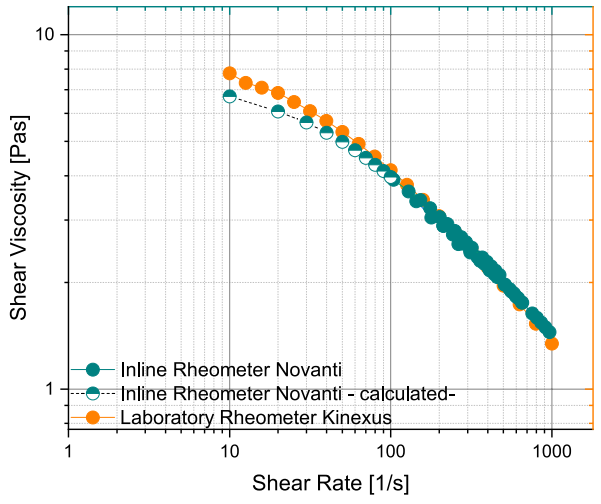
Performance Evaluation of In-Line Viscosity Measurement

The evaluation focused on the precision and reproducibility of in-line viscosity measurements. Both anode and cathode slurries were tested across multiple coating trials, with viscosity measured in-line and verified off-line using laboratory equipment.

- The resulting viscosity profiles showed excellent agreement, with deviations limited to ±10% across a shear rate range of 100 to 1,000 s^{-1} (optionally available adjustable range).
- Repeated measurements confirmed the robustness and reliability of the system.
- These results demonstrate the module's suitability for real-time monitoring and control of slurry processing operations.



Comparison of viscosity measurements in-line (green) and off-line (orange) of slurries during the production of anodes



Comparison of viscosity measurements in-line (green) and off-line (orange) of slurries during the production of LFP cathodes

From One Source to Full Control

Your One Partner for Smarter Battery Production

All-in-One Solution

- Reduction of material waste
- Minimizing machine downtimes
- Minimizing time-consuming off-line testing
- Easy integration into existing production environment or as system solution with *Cellvos®*

Operational Efficiency

- Elimination of manual sampling
- Lower operational overhead
- Maximizing uptime of critical equipment

Enhanced Product Quality

- Maintaining consistent slurry quality for high-quality electrode coatings
- Enhanced battery performance
- High reliability and cycle life

Pulsation-Free Pump System

- Stable and pulsation-free flow enabling minimized shear stresses
- Corrosion-resistant
- High-precision dosing
- Elimination of external seals
- Enhanced plant safety
- Maintaining proper particle dispersion

Real-Time Process Control

- Shorter response times to deviations
- Ensuring process stability
- Increased reproducibility across batches

Two-in-One – Mixing and Bead Milling

- High-speed powder feeding for increased production capacity
- Real-time feedback loops
- Continuous slurry pumping and monitoring viscosity in real time
- Increased battery performance
- Reduction of mixing times
- Shorter process times

Scrap Reduction

- Early detection of deviations minimizes scrap and reduces material waste
- Sustainable and cost-effective production

Increased Safety

- Closed loop mixing and milling
- Hermetically sealed pumping system for enhanced plant safety
- Reducing cost and minimizing material waste

The owner-managed NETZSCH Group is a leading global technology company specializing in mechanical, plant and instrument engineering.

Under the management of Erich NETZSCH B.V. & Co. Holding KG, the company consists of the three business units Analyzing & Testing, Grinding & Dispersing and Pumps & Systems, which are geared towards specific industries and products. A worldwide sales and service network has guaranteed customer proximity and competent service since 1873.

Proven Excellence.

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In-Line Viscosity Measurement 02 · EN · 1025 · Technical specifications are subject to change.