Vacuum Technology for Chemical and Pharmaceutical Processes

Simon Janody ▪ **Meike Strasheim** ▪ Busch Group

A comprehensive understanding of the design and operating principles of each vacuum pump type is crucial for selecting the optimal solution for a given application.

Vacuum technology is an essential element of chemical and pharmaceutical manufacturing. It facilitates key operations — such as distillation, drying, conveying, and inerting — by providing process conditions that would be difficult to achieve under ambient pressure.

By lowering the boiling point of liquids, vacuum allows thermal separation at reduced temperatures, helping preserve thermally sensitive compounds. In inerting and drying processes, it minimizes oxidation and moisture ingress. Moreover, in regulated environments, vacuum reduces risk of contamination and supports solvent recovery, aligning with both sustainability and cost-reduction goals.

Traditional vacuum technologies, such as liquid ring vacuum pumps and steam ejectors, have been dependable workhorses of the chemical process industries (CPI). However, their reliance on operating fluids and substantial utility requirements often conflict with modern expectations for process consistency, optimization of resource utilization, and precise process control.

This article provides an in-depth comparison of conventional and dry vacuum pump technologies, with a focus on dry screw vacuum pumps. It aims to equip process engineers and plant designers with the insights necessary to specify and design vacuum systems that meet today's technical, regulatory, and economic demands.

Overview of vacuum technologies

Vacuum requirements vary significantly across chemical processes, depending on factors such as volatility, process temperature, gas composition, and contamination sensitivity. Different vacuum technologies offer distinct advantages and tradeoffs. Understanding the operating principles of each vacuum pump type is key to selecting the right solution for a given application.

Liquid ring vacuum pumps. Liquid ring vacuum pumps operate using an impeller mounted off-center that rotates within a partially filled chamber (Figure 1). The liquid, typically water or a compatible solvent, forms a ring along the chamber wall due to centrifugal force. As the impeller rotates, it traps gas between the liquid ring and the impeller blades, compressing it as the chamber volume decreases. The liquid absorbs heat from compression and acts as a sealant, keeping internal temperatures low and reducing the risk of ignition.

These vacuum pumps are valued for their simplicity, robustness, and ability to handle saturated vapors and small particles. However, they can only achieve relatively low vacuums — typically limited to approximately 33 hPa (mbar) absolute, depending on the liquid used and its corresponding vapor pressure. They are also less energy-efficient than dry technologies and require a continuous supply of operating fluid, which adds to utility and maintenance costs.

Liquid ring vacuum pumps include single- and two-stage designs. They are generally well-suited for handling vapor-saturated gas streams and are widely used in applications where reliability and tolerance to carryover are key.

Rotary vane vacuum pumps. Rotary vane vacuum pumps consist of a rotor mounted off-center in a cylindrical housing (Figure 2). As the rotor turns, vanes actuated by centrifugal force slide out to create sealed compression chambers. Gas is drawn into the expanding volume and expelled under compression as the chamber contracts. These vacuum pumps rely on oil for sealing, lubrication, and cooling, either through a closed-loop system or a once-through configuration to handle chemically active or condensable media.

Rotary vane vacuum pumps are compact, easy to install, and widely used in general applications. In chemical and pharmaceutical settings, single-stage vacuum pumps are most common due to their robustness and simplicity. Their typical vacuum range spans from 100 to 1 hPa (mbar) for single-stage versions. However, when lower ultimate vacuum levels are required, dual-stage rotary vane vacuum pumps — where two compression stages are arranged in series — can extend performance down to deeper vacuum levels. Dual-stage configurations can reach 10^{-3} hPa (mbar) when properly maintained and operated under optimal conditions.

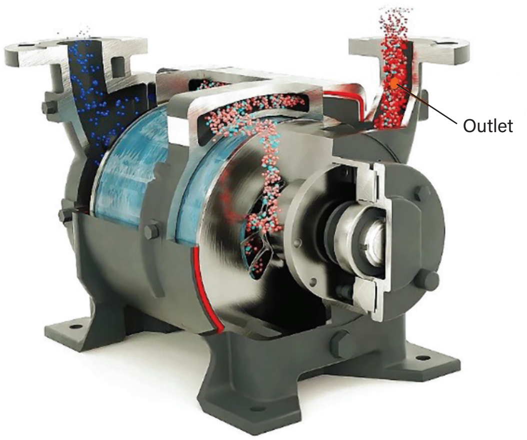
While versatile, these vacuum pumps are susceptible to oil contamination and degradation if oil is reused in a closed loop. In continuous operation, the oil condition must be monitored, replaced regularly, and filtered properly to avoid process interference.

Dry screw vacuum pumps. Dry screw vacuum pumps use two interlocking screw-shaped rotors that compress gas with no contact between the moving parts or operating fluid in the process chamber (Figure 3). As the rotors turn in opposite directions, gas is trapped between the twin screws and the housing, progressively compressed, and discharged. This oil-free design eliminates contamination risk, making the vacuum pumps ideal for processes involving solvents or reactive compounds, or for clean environments.

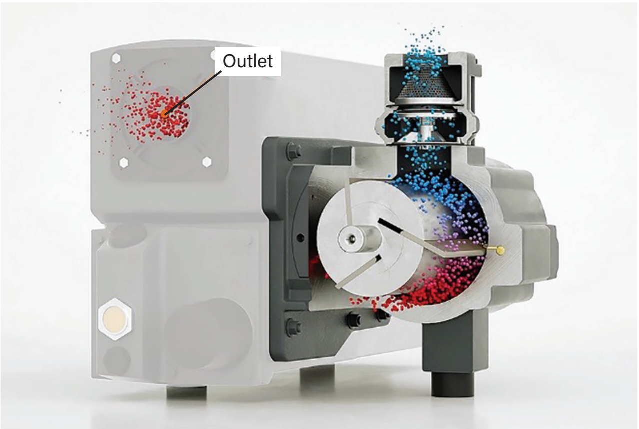
Dry screw vacuum pumps can achieve vacuum levels around 10^{-2} hPa (mbar) and are well-suited for reactive or solvent-rich environments. Their performance relies on precise thermal control to avoid condensation or polymerization, especially when operating with volatile process gases. Their higher initial investment is justified by long service intervals, low total cost of ownership, and high reliability under challenging conditions.

Dry screw vacuum technology often combines oil-free operation with high chemical resistance and efficient compression. These vacuum pumps are specifically designed for processes that demand deep vacuum, clean handling of aggressive media, and minimal maintenance.

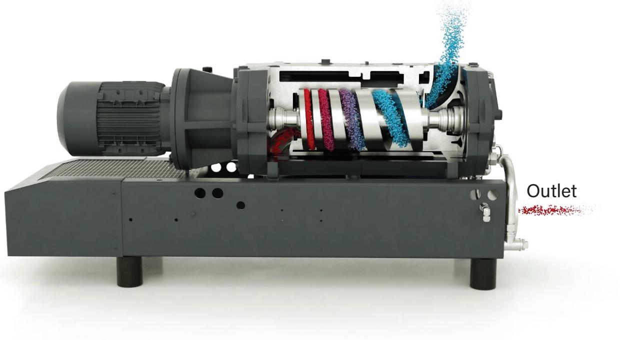
Steam ejectors. Steam ejectors operate based on the



▲ **Figure 1.** This cross-section of a liquid ring vacuum pump illustrates how process gas is trapped and compressed between the liquid ring and rotating impeller. Depicted is a model from the DOLPHIN series by Busch.



▲ **Figure 2.** Pictured is a cross-sectional view of an R5 single-stage rotary vane vacuum pump. The image illustrates how vanes slide within a rotating rotor to compress gas in a series of sealed chambers. R5 vacuum pumps are widely used in general applications due to their reliability and compact design.



▲ **Figure 3.** This cutaway view of a dry screw vacuum pump shows the internal rotor geometry. The intermeshing screw rotors rotate in opposite directions, compressing gas without internal lubrication or contact. This design is representative of Busch's COBRA series, used in applications requiring oil-free vacuum generation and chemical compatibility.

Venturi principle. High-velocity steam passes through a nozzle, creating a low-pressure zone that entrains process gases. The mixed flow is then recompressed in a diffuser. Ejectors have no moving parts, making them resistant to solids, corrosives, and thermal shock. Multi-stage systems can achieve deep vacuum levels.

However, they possess several drawbacks, including poor controllability, large utility demands for steam and cooling water, as well as environmental concerns from water use and condensate disposal. Maintenance is minimal, but energy costs are high. Ejectors are still used in large-scale or thermally extreme processes where mechanical alternatives may not be practical.

Some systems combine technologies to optimize performance and cost. For example, a dry screw vacuum pump paired with a vacuum booster extends the vacuum range while preserving gas purity. Similarly, ejector and liquid ring combinations are used to reach lower vacuum levels. These hybrids enable engineers to match technology capabilities with process demands more flexibly.

Design considerations for vacuum systems

Designing a reliable and efficient vacuum system extends far beyond choosing the suitable vacuum pump technology. It involves careful coordination of multiple factors, ranging from process conditions and material compatibility to layout constraints and automation strategies. Each of these elements influences not only the system's initial performance but also its long-term operational stability and cost-efficiency.

Process chemistry and material selection. The chemical composition of the process stream — especially the presence of condensables, corrosives, or reactive gases — dictates material selection and sealing technology. Stainless steel is a standard baseline for wetted components, but more aggressive environments may require specialized coatings, alloys like Hastelloy or titanium, or non-metallic materials such as polytetrafluoroethylene (PTFE). For dynamic sealing surfaces, especially around rotating shafts, double mechanical seals or magnetically coupled drives may be needed for leak-free operation.

Choosing suitable O-ring and gasket materials, such as perfluoroelastomer (FFKM) or ethylene propylene diene monomer (EPDM), is critical to prevent degradation when exposed to acids, solvents, or elevated temperatures.

System resistance and pressure drop. Every valve, filter, bend, and restriction between the process and the vacuum pump introduces pressure losses. In low-pressure systems, even minor pressure drops can significantly impact performance or cause the vacuum pump to be undersized. Therefore, a pressure drop analysis of the complete system from chamber or reactor to pumping unit should be part of the early engineering phase. Engineers often aim to maintain suction-side pressure losses below 10% of the total available differential pressure to preserve vacuum levels at the process inlet.

Selecting appropriate pipe diameters, minimizing bends, and choosing low-resistance filters are simple yet effective strategies.

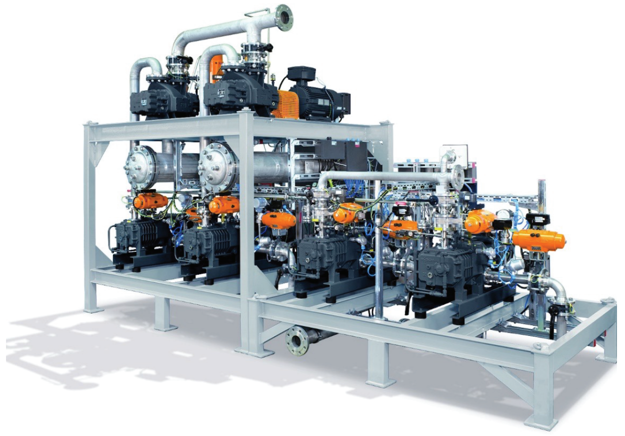
Thermal management. Thermal control is crucial in vacuum systems, especially for dry screw vacuum pumps that handle condensable or polymerizable vapors. The vacuum pump body must be maintained at a warm enough temperature to prevent internal condensation but below thermal material and safety limits. This is typically managed through heating jackets, cooling loops, and gas-ballast systems.

In processes involving solvent-rich streams, controlling the inlet piping temperature and pre-heating during startup helps prevent sticky deposits that may compromise rotor clearance or cause corrosion. A pre-condenser can also be a solution, allowing a reduction in the amount of chemicals reaching the pumping unit.

Layout and integration. Space constraints often dictate the form factor of the system, especially in retrofit projects. Skid-mounted, modular designs allow tighter footprints and easier maintenance access. Vertical stacking and wall-mounted control panels can help save floor space (Figure 4). Systems must also be accessible for cleaning, inspection, and potential part replacement without requiring full disassembly.

Compliance with local safety regulations, especially in ATEX zones, will influence enclosure design, ventilation strategy, and component certifications.

Automation and control. Vacuum systems increasingly integrate with distributed control systems (DCSs) or



▲ **Figure 4.** Vacuum systems can be configured in modular arrangements to meet space constraints. A gas cooler is integrated between stages to prevent overheating and reduce the temperature of the process gas before it enters the screw vacuum pumps. This tailored configuration ensures efficient multi-stage compression and reliable operation in demanding chemical environments. The image shows a custom-engineered vacuum system from Busch Vacuum Solutions with PANDA and PUMA vacuum boosters as the first stage and COBRA screw vacuum pumps as backing pumps.

programmable logic controllers (PLCs) to support advanced process control and diagnostics. Parameters such as inlet pressure, motor current, cooling flow, and seal integrity can be monitored in real time. In high-value processes, this supports predictive maintenance, early fault detection, and compliance tracking. Modern systems use control valves and frequency-controlled motors to dynamically adjust vacuum generation according to the process load, reducing energy consumption and mechanical stress.

Scalability and future-proofing. It is wise to design vacuum systems with expansion in mind. This may involve oversizing power supplies, reserving space on skids for additional vacuum pumps or vacuum boosters, or installing larger piping than needed to accommodate future flowrates.

A well-designed vacuum system reflects a balance between process performance, mechanical resilience, and operational flexibility. Taking the time to address these considerations early in the design phase yields long-term dividends in reliability, energy savings, and compliance.

To support engineers in designing optimized vacuum systems, many companies like Busch offer a wide range of accessories, system components, and engineering expertise tailored to specific process requirements. From modular skid assemblies to fully integrated, ATEX-compliant vacuum systems with intelligent control architecture, complete solutions can be delivered that align with both technical constraints and long-term operational goals.

Operational challenges of vacuum systems

Even the most carefully engineered vacuum system can fail to meet expectations if its operation does not account for real-world chemical and pharmaceutical process conditions. These environments are highly variable, involving a wide range of substances, batch dynamics, and regulatory constraints. To ensure consistent performance, several operational challenges must be understood and addressed proactively.

One of the most common and impactful issues is the condensation of vapors within the vacuum pump. When condensable gases fall below their dew point during compression, they can liquefy inside the vacuum pump, leading to corrosion, internal fouling, or in severe cases, hydraulic shock. The risk is highest in dry vacuum pumps, where there are no internal liquids to buffer phase transitions. Maintaining thermal stability inside the vacuum pump is therefore critical but can be difficult in systems with fluctuating solvent loads or ambient temperatures.

Related to this is the challenge of improper startup and shutdown sequences. If a vacuum pump is brought online while still cold, condensable vapors may condense immediately upon contact with internal surfaces. Similarly, stopping a process without removing residual vapors can result in unwanted deposition or corrosion during cooldown. The complexity increases when processes use monomers or reactive substances that can polymerize or crystallize when exposed to vacuum or heat. In batch processes, the buildup of residues between cycles is particularly problematic.

Another persistent challenge involves the ingress of solids and particulate matter. Dry screw vacuum pumps are especially sensitive due to their tight internal clearances. Even small amounts of powders, sticky residues, or abrasive crystals can accelerate wear or reduce compression efficiency. In processes where dust or condensable slugs are present, the vacuum pump's performance and longevity may be compromised if no pre-separation or filtration system is installed.

Beyond physical damage, vacuum systems must also cope with varying process loads. Switching between different vacuum levels, accommodating pressure ramps, or transitioning between standby and operation can introduce instability. Systems that are not designed to handle such variability may waste energy, overshoot pressure targets, or suffer from premature component fatigue.

Maintenance presents its own set of operational concerns. While dry vacuum pumps generally offer longer service intervals, the consequences of unexpected failure are often severe. Unmonitored shifts in power draw, temperature, or vibration can signal early-stage issues that, if ignored, lead to costly repairs and unplanned downtime.

Finally, safety and regulatory compliance add a critical layer of complexity. Systems that handle flammable, explosive, or toxic gases must demonstrate leak-tightness under all operating conditions. Compliance with ATEX, TA Luft, and other standards requires rigorous validation of seals, materials, and shutdown protocols. Process changes or minor deviations can easily introduce new risks if not carefully assessed.

Understanding these operational vulnerabilities is the first step in developing a vacuum system strategy that is both robust and compliant. The following section addresses how these challenges can be systematically mitigated through the application of proven protection strategies and system accessories.

Protection strategies and system accessories

To ensure vacuum systems remain reliable and efficient in chemically and thermally demanding environments, protection strategies must be thoughtfully designed and rigorously implemented. While vacuum pumps often draw the most attention, it is the surrounding system components — filters, seals, materials, and controls — that determine long-term performance.

Thermal stability is one of the key prerequisites for preventing internal condensation and phase-related damage. In processes involving solvents or reactive vapors, the vacuum pump body and associated piping must be maintained above the dew point of the gases involved. This is often achieved through external heating systems or thermal jackets. Gas-ballast valves are commonly used to dilute condensable vapors, reducing the likelihood of phase change within the compression chamber. These measures protect the vacuum pump from corrosion and from fouling by sticky or polymerizing residues.

Contaminant ingress is another major threat to vacuum equipment, particularly in systems handling solids or slurries, or in dusty environments. Effective filtration is essential to keep abrasive or reactive materials from entering sensitive components. Depending on the process, protection may involve fine-mesh inlet screens for large particulates, high-efficiency filters for fine powders, or knock-out pots and cyclonic separators to remove droplets and liquid slugs from vapor streams. In especially dusty applications, self-cleaning filters or inline flushing routines may be integrated to maintain consistent protection without excessive manual maintenance.

Corrosion resistance begins with material selection. Vacuum pumps and piping in contact with aggressive media must be constructed of chemically compatible materials. Stainless steel 316L is often used as a default in pharmaceutical settings, while more aggressive chemistries may require Hastelloy, titanium, or additional surface treatments such as PTFE or ceramic coatings. Elastomeric components such as seals and gaskets should be carefully matched to the media in question, with materials like FFKM, EPDM, or fluoroelastomers used depending on chemical resistance requirements. In uncertain or mixed-process environments, corrosion coupons or accelerated aging tests can help validate design assumptions before the final build.

Sealing performance plays a critical role in both environmental protection and regulatory compliance. Static seals must maintain integrity under pressure and temperature cycles, while dynamic seals — especially around rotating shafts — must ensure gas tightness without compromising mechanical efficiency. Double mechanical seals and magnetically coupled drives are frequently used in systems where leakage is unacceptable. For ultra-clean environments or processes involving toxic gases, bellows, seals, and encapsulated drives offer added layers of containment. These sealing strategies are often selected with compliance to frameworks such as ATEX, TA Luft, or regional emissions regulations.

Protective components can also support recovery and sustainability goals. Condensers positioned upstream of the vacuum pump can capture valuable solvents, reduce vapor load, and improve overall system economy. Cold traps are used to recover hazardous or condensable vapors. On the exhaust side, scrubbers (whether wet or dry) are deployed to neutralize or absorb residual emissions. The effectiveness of these systems depends on correct sizing and specification, including parameters such as condenser temperature, system pressure drop, and expected recovery volumes.

For operations where uptime is critical, redundancy and failover capabilities are key elements of protection. Duty or standby vacuum pump arrangements with automatic switching can help ensure continuity during maintenance or unexpected failure. Surge tanks and vacuum reservoirs buffer sudden process fluctuations, while uninterruptible power supplies support controlled shutdown in the event of a power loss. These features reduce the risk of downtime and, in regulated environments, help avoid the need for lengthy requalification.

Finally, system protection is greatly enhanced by intelligent monitoring and control. Sensor networks tracking pressure, temperature, vibration, and motor current can detect early signs of wear or instability. When integrated with plant automation systems, these inputs allow for automated shutdowns, maintenance alerts, and process adjustments in real time. Advanced data analytics tools further enable predictive diagnostics and long-term performance optimization. In good manufacturing practice (GMP) or quality-critical environments, this monitoring infrastructure also supports audit readiness, data traceability, and compliance documentation.

Taken together, these protective strategies create a vacuum environment that is not only technically robust but also operationally sustainable. By addressing mechanical, thermal, chemical, and digital dimensions of risk, engineers can design systems that protect equipment, enhance safety, and ensure compliance — ultimately delivering long-term value across the life of the process.

System commissioning and validation

Commissioning a vacuum system is more than a final procedural step; it is the critical transition from engineering design to operational reality. Especially in regulated or high-purity environments, a vacuum system must not only function correctly but do so predictably, reliably, and in full alignment with process as well as compliance expectations.

The process begins with confirming mechanical and containment integrity through rigorous leak testing. Depending on the application, this may involve a combination of pressure decay tests for gross leakage and helium mass spectrometry for fine leak detection. These tests validate that the system is sealed throughout the entire vacuum circuit (from the process connection to the exhaust outlet) and confirm that emission limits and exposure thresholds will be met under real-world conditions.

Once tightness is verified, the system undergoes functional testing. Pump-down performance is measured against design targets, and temperature behavior is monitored to ensure thermal stability under load. Critical control logic — including interlocks for purge gas supply, over-temperature alarms, and emergency shutdowns — is exercised and verified. In many facilities, commissioning also includes simulated failure scenarios such as blocked purge lines, power interruptions, or valve malfunctions to test system resilience and emergency response protocols.

In GMP-regulated industries such as pharmaceuticals or high-spec chemical processing, commissioning naturally extends into formal qualification. Factory acceptance testing (FAT) is often performed prior to delivery to ensure system compliance with specifications. Site acceptance testing (SAT) follows installation to verify integration into the operating environment. Installation qualification (IQ) and operational qualification (OQ) further confirm that components are installed as designed and perform as intended under defined operating parameters. These activities are supported by complete documentation, including calibration certificates, materials traceability, and process-specific standard operating procedures for routine use and maintenance.

Establishing baseline performance during the early operational phase is essential for future maintenance and diagnostics. Parameters such as base pressure, pump-down time, motor current, cooling performance, and sound pressure level (how loud the pump is in decibels at a certain pressure) should be recorded and trended. These benchmarks serve as a reference for identifying drift, fouling, or emerging mechanical issues over time.

Equally important is the operational handover. Operators must be trained not only on how to start, stop, and purge the system but also to recognize irregular behavior, interpret system feedback, and respond to alarms or warnings. Training sessions should include guided walkthroughs of the control interface, discussion of key safety interlocks, and routine maintenance procedures. Documentation should be readily accessible, clearly structured, and include quick-reference materials and visual aids where applicable.

For systems operating under GMP or other quality frameworks, integration with the site's quality management system is required. This includes tracking maintenance through computerized systems (like the CMMS), enforcing change control for any hardware or software modifications, and maintaining validated logs of performance, servicing, and alarms. In many modern installations, vacuum systems support these requirements natively with digital interfaces, audit trails, and remote diagnostics. Where applicable, data handling should comply with standards such as 21 CFR Part 11, ensuring traceability and access control.

Ultimately, a well-commissioned vacuum system is not simply operational — it is qualified, predictable, and audit-ready. Commissioning provides the foundation for stable, compliant, and cost-effective performance over the system's entire lifecycle, reducing risk while increasing confidence in both process and product outcomes.

Closing thoughts

Vacuum systems are more than peripheral utilities — they are critical enablers of process performance, product quality, and plant safety in the chemical and pharmaceutical industries. As regulatory standards tighten and expectations grow around sustainability, digitalization, and operational transparency, vacuum technology must evolve in both capability and complexity.

While established solutions like liquid ring vacuum pumps and steam ejectors continue to serve high-load or rugged applications, the industry's shift toward dry, oil-free technologies — particularly dry screw vacuum pumps — reflects a growing demand for clean operation, minimal maintenance, and seamless integration into automated process environments.

But selecting the right vacuum solution is more than achieving a target pressure. It requires a comprehensive understanding of the gases involved, thermal behavior, contamination risks, system layout, and utility infrastructure. Long-term success hinges on marrying the correct vacuum pump technology with effective safeguards, intelligent control systems, and well-structured operating procedures.

Crucially, a vacuum system's performance must be qualified, continuously monitored, and supported throughout its lifecycle. Commissioning is not the end of a project — it is the start of reliable, predictable, and efficient operation.

For modern production environments, the vacuum system is a strategic asset, one that protects process integrity, reduces risk, and delivers measurable value over time. Recognizing this early can redefine both the role and return of vacuum infrastructure across the plant floor. CEP

SIMON JANODY, PhD, is Head of Market Management for the chemical, pharmaceutical, and plastic industries at Busch Vacuum Solutions, part of the Busch Group, which includes both Busch Vacuum Solutions and Pfeiffer Vacuum+Fab Solutions. He holds a PhD in organic chemistry and has more than ten years of experience in chemical research and development (R&D), product management, and global market strategy. Before joining Busch, he conducted research at the French National Centre for Scientific Research (CNRS) and Bayer CropScience, focusing on homogeneous catalysis and reaction engineering. At Busch, he has led international initiatives to position vacuum technologies in areas such as solvent recovery, vacuum drying, and thermal separation. Based in Switzerland, Janody applies his scientific background to support technology development and market alignment in complex industrial environments.

MEIKE STRASHEIM is Head of Market Management Content Strategy at Pfeiffer Vacuum+Fab Solutions, part of the Busch Group, which also includes Busch Vacuum Solutions. She brings over ten years of experience in vacuum technology, with roles spanning technical support, process management, and market management. Her background includes in-depth work on vacuum applications for chemical processes such as drying, distillation, and containment. In her current role, she focuses on shaping how technical information is communicated across channels and markets. She holds a bachelor's degree in engineering and a master's degree in science and is based in Germany.