



HYDROGEN COMPRESSION *for tomorrow*

Svitlana Snelder, Yann Ardouin, and Rens Hulstijn, Howden, A Chart Industries Company, explain how diaphragm compressors are being advanced to deliver reliable performance at high pressures and scaled hydrogen flows.

Hydrogen is emerging as a key enabler of the energy transition, offering a sustainable alternative to fossil fuels. To meet 2030 climate targets, hydrogen production must scale up significantly – and the same applies to transportation and mobility infrastructure. Hydrogen transportation and mobility applications require compression systems capable of handling pressures up to 1000 bar, and scaling these systems presents significant technical and economic challenges.

Hydrogen compression for hydrogen tube trailer filling and fuelling applications

Tube trailer filling and fuelling applications demand technologies that combine oil-free operation,

high-pressure capability, reliability, and cost-effectiveness. While hydrogen compression is well established in refinery and petrochemical processes, scaling for renewable hydrogen applications introduces new challenges such as intermittent operation, gas contamination prevention, and stringent safety requirements.

Traditional technologies struggle when adapted for hydrogen filling and mobility applications due to a number of reasons:

- Extreme pressure requirements: tube trailer filling requires up to 550 bar; fuelling stations operate at 350 - 700 bar, with designs reaching 1000 bar.
- Intermittent operation: frequent start-stop cycles increase wear on critical components, require cost-effective hot standby solutions, and potentially raise maintenance costs.

- Footprint and modularity: compact, cost-effective compressors are essential for stations; large filling hubs need modular redundancy.
- Safety and compliance: leak prevention, embrittlement resistance, and reliable designs are critical at high pressures.
- Cost pressure: total cost of ownership matters more than upfront cost, emphasising reliability and low operating expenses.
- Unmanned operation: automated systems must ensure safety, high availability, and reliability without on-site supervision.

For hydrogen transportation and fuelling, the challenge is balancing high-pressure performance, dynamic operation, safety, and cost – areas where traditional compressors struggle. Moreover, hydrogen mobility is shifting toward heavy-duty applications, requiring very large flows and further scaling of existing technologies.

Comparison of gaseous hydrogen compression technologies in transportation and heavy-duty fuelling

Various oil-free compression technologies can handle large hydrogen flows and high pressures – 500 bar and above – under the constraints in Table 1.

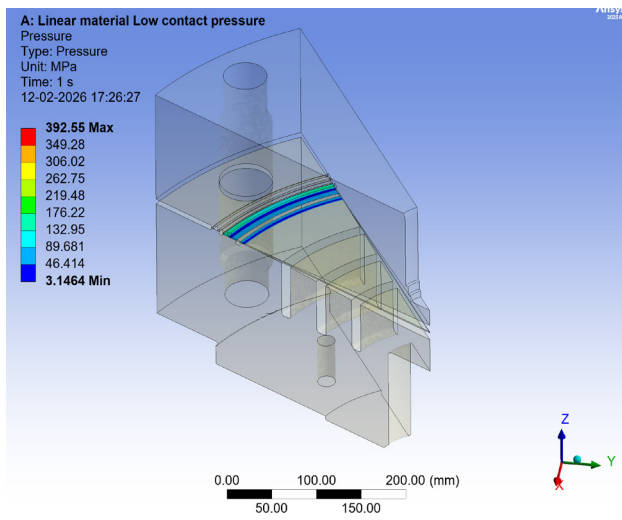


Figure 1. Dynamic distribution of contact pressure in the compressor seal area during diaphragm movement.

Diaphragm compressors provide an effective solution for hydrogen compression in transportation and fuelling applications. They deliver 100% oil-free operation, ensuring gas purity, and are a mature and reliable technology capable of handling pressures up to 1000 bar and beyond. Their design supports high pressure ratios, while integrated safety features – such as positive sealing and a fully enclosed compression area with no vent or gas losses – make them ideal for meeting stringent hydrogen requirements.

Recent advancements in Howden’s diaphragm compressor portfolio have enabled flow rates of up to 2450 Nm³/h (220 kg/h), keeping diaphragm technology the most established solution compared with high-pressure reciprocating compressors now entering this application space. While these reciprocating solutions show promise, they face uncertainties: limited field experience affecting reliability and operating costs, dependence on ongoing improvements in piston ring and packing case design, and critical sealing challenges that risk process gas losses.

Over the past five years, Howden gathered field experience and leveraged it to improve diaphragm compressor designs, enhancing performance and reliability in scaled-up applications. These efforts led to compressors optimised for availability and mean time between maintenance (MTBM) under intermittent conditions.

Optimising diaphragm compressors for high-pressure intermittent applications

Material compatibility at high pressure

One of the key challenges is ensuring material compatibility under high hydrogen pressures. To address this, the Howden team conducted an extensive material study and implemented a dedicated qualification programme, including high-pressure hydrogen cycle tests in elevated temperature environments. This programme validated the suitability of selected materials for various discharge pressures for all compression stages, ensuring optimal performance and safety. Combined with field experience from an installed base of more than 1500 compressors, these efforts formed the foundation for a robust design.

Sealing integrity at extreme pressures

Maintaining a leak-tight system at very high pressures is critical for hydrogen applications. Howden has implemented continuous design

Compression technology	High efficiency / pressure ratio	Intermittent operation	Process contamination risk	Reliability and MTBM	Footprint	Proven for 1000 bar compression
Smaller reciprocating	Moderate performance	Limited field experience	Moderate performance	Limited field experience	Moderate performance	Weaker performance
Large flow diaphragm	Stronger performance	Stronger performance	Stronger performance	Stronger performance	Moderate performance	Stronger performance
Large flow hydraulic piston	Moderate performance	Stronger performance	Moderate performance	Moderate performance	Stronger performance	Moderate performance



improvements in two complementary areas: seal materials and sealing system mechanical design.

Diaphragm compressor stages are positively sealed, typically using O-rings that must withstand maximum operating pressure and rapid decompression cycles. While common polymers have proven suitable for low-pressure applications, high-pressure conditions required a dedicated development programme to evaluate alternative materials. The selected O-ring compounds successfully passed rigorous testing, including thousands of hydrogen pressure cycles in elevated temperature environments.

The second area of improvement involves advanced static and dynamic modelling. At high-pressure compression cycles, sealing performance is highly sensitive to micro-movements and component deformation – far more than in low-pressure applications. Dynamic mechanical analysis of the whole compression stage enabled the definition of specific design rules to address these challenges and ensure long-term sealing integrity (Figure 1).

Intermittent operation and stress management

Frequent start-stop cycles and fluctuating flow and pressure conditions create transient stresses, with the most critical typically occurring during start-up. To mitigate these stresses, Howden's engineers developed solutions that include dynamic modelling of oil pressure within the compressor and pressure control valves. The integration of an improved oil pressure limiting valve has enabled better oil flow and pressure control, reducing conditions that could lead to high stress (Figures 2 and 3). Additionally, components such as membranes and oil plates were redesigned based on detailed stress analysis to improve durability and reliability.

A correctly designed filling circuit is essential to ensure proper oil filling in the head during intermittent operation. In addition to correct circuit design, early detection of anomalies is critical. To detect any oil distribution anomalies, Howden implemented real-time monitoring of the oil pressure cycle through a digital twin. If an anomaly is detected, the system triggers an immediate alarm – significantly improving operational safety and reliability.

Scaling diaphragm compressors for large hydrogen flows

Upscaling without compromise

Increasing volume flow for high-pressure applications naturally requires a compressor frame with higher rod load capability. Drawing on numerous references and proven designs from reciprocating compressors – also part of Howden's product portfolio – the complete motion work in diaphragm compressors has been upscaled using established design principles, while maintaining a compact

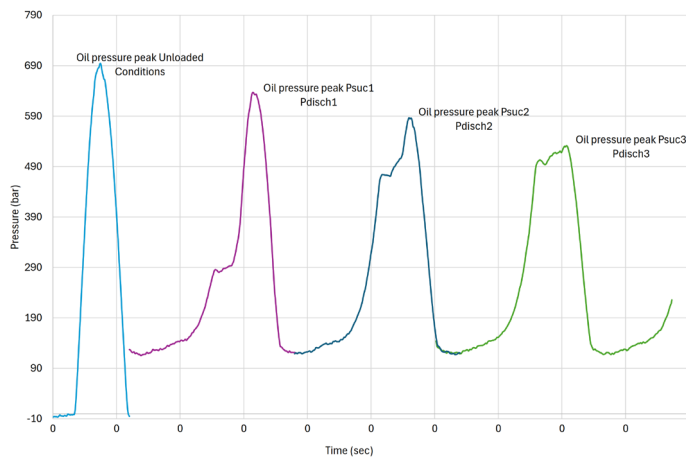


Figure 2. Compressor oil pressure peaks under different operating conditions with the standard pressure limiting valve. When the valve opening pressure is set based on the loaded operation, a high and uncontrolled pressure peak can occur when the compressor runs unloaded – typically during start-up – resulting in increased stress on the diaphragm.

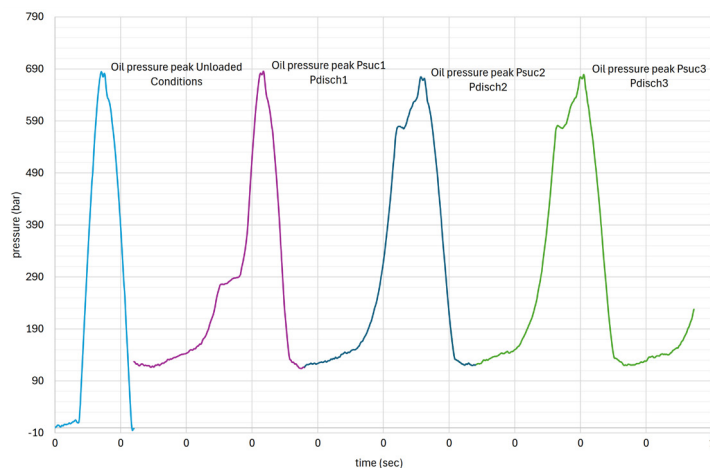


Figure 3. Compressor oil pressure peaks when using the improved pressure limiting valve. The much lower peak variability allows better control of the oil-gas pressure differential, keeping diaphragm stresses within safe limits, even during transient operation.

footprint and reasonable cost. This approach ensures high availability and extended MTBM for diaphragm compressors handling large flow rates.

Managing start-up torque

Diaphragm compressors usually start with full main driver torque; this is rarely an issue on smaller machines but becomes a challenge for the power supply and motors of several hundred kW. Howden implemented specific modifications to oil pressure regulation in the compressor, motors and power systems to reduce transient loads, achieving smooth start-up without exceeding diaphragm stress limits.

Complex fluid dynamics and system optimisation

With larger designs, unforeseen challenges emerged due to the interaction of two fluids separated by flexible



metallic diaphragms. Increasing the volume flow in diaphragm compressors requires handling a larger volume of oil per cycle, which affects mass distribution, pressure drops, oil compressibility, and heat transfer. In addition, increasing the compressor stroke for a given piston and head diameter changed the dynamics of opening and closing the oil pressure limiting valve.

These issues were resolved through advanced modelling, computing, and system optimisation, ensuring stable operation under all conditions.

Design for reliability and maintainability

Based on the gathered field experience, static and dynamic limitations were redefined for the upscaled design and the entire compressor system was re-modelled to maintain performance and reliability. In addition, manufacturing, assembly, and maintenance requirements were integrated into the design to efficiently handle larger, heavier components and ensure ease of serviceability.

Economic viability

Beyond safety and reliability, the hydrogen industry demands cost-effective compression solutions. To reduce total cost of ownership, Howden offers standardised compressor packages specifically engineered for large-flow, high-pressure hydrogen applications. These skid-mounted units integrate all process equipment, piping, and auxiliary systems into a single package – delivering a reliable, scalable solution that enables rapid on-site deployment and minimises installation complexity (Figure 4).

These packages can significantly reduce installation time and lifecycle costs compared to custom-built systems, while their modular design ensures easy scalability to meet future hydrogen demand.

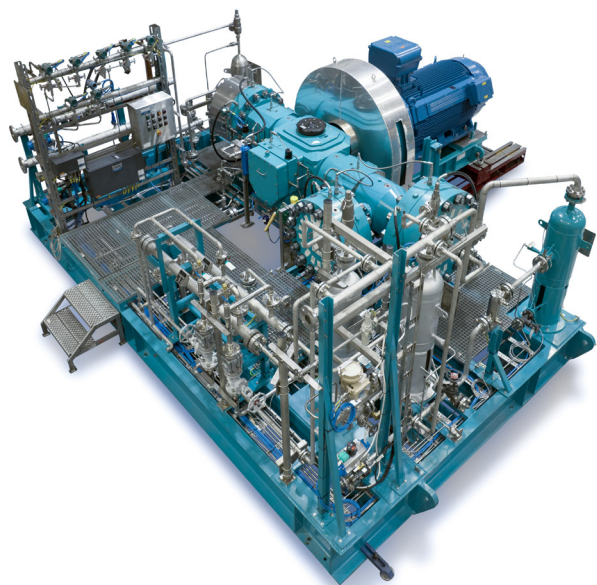


Figure 4. Howden's standardised skid-mounted diaphragm compressor for large hydrogen flows.

To further optimise performance, they include online condition monitoring and preventive maintenance, reducing the risk of unplanned downtime. The Howden Uptime digital suite provides comprehensive performance tracking and early-stage fault detection, while granting operators access to updated asset documentation and remote support from Howden OEM specialists. This combination ensures reliability, predictable costs, and peace of mind – while supporting sustainability through improved efficiency and reduced energy consumption.

Conclusions

Hydrogen mobility and transportation require compression systems capable of delivering high pressure, large flow capacities, and consistent reliability under intermittent, dynamic, and fully automated operating conditions. Diaphragm compressors have proven their ability to meet these requirements when specifically designed for this purpose and continue to evolve as global hydrogen infrastructure expands.

Selecting the right compression technology – and the right technology partner – is critical for ensuring safety, efficiency, and long-term performance. As a mature, oil-free technology, diaphragm compressors ensure gas purity and leak-tight operation while achieving discharge pressures up to 1000 bar. Recent engineering advancements have extended applicability of Howden's diaphragm compressors to large-flow, high-pressure hydrogen. Key developments include:

- Material qualification for high-pressure hydrogen: comprehensive study and testing under cyclic pressure and elevated temperature for long-term integrity.
- Sealing system optimisation: advanced static and dynamic modelling to define design rules to mitigate micro-movement effects at extreme pressures, complemented by high-performance elastomer selection.
- Stress management for intermittent operation: integration of improved oil pressure regulation, dynamic modelling of transient loads, and redesigned diaphragms and oil plates to reduce fatigue risk.
- Upscaling for large flows: adaptation of proven reciprocating design principles for diaphragm frames with higher rod load capability, maintaining a compact footprint and cost efficiency.
- System-level enhancements: digital twin monitoring, modular skid-mounted packages, and predictive maintenance tools to ensure high availability and minimise lifecycle costs.

These innovations position diaphragm technology as a robust and scalable platform for hydrogen compression in transportation and heavy-duty fuelling applications. Ongoing development in design optimisation and digital integration will further enhance reliability and performance, enabling hydrogen infrastructure to scale safely and economically in support of global decarbonisation objectives. ○

