Compressors Q&A

LNG Industry asked several companies to discuss some issues regarding LNG compressors.

Mike Sicker – SVP of Business Development

Mitsubishi Heavy Industries Oil & Gas Division

As the Global Account Manager, Michael is responsible for developing new markets and strategies for the continued growth of Mitsubishi's presence in the Americas, specifically in the LNG arena. Michael started his career with Mitsubishi International Corporation in 1992, in the Akron, Ohio (US) office, and has worked in various management positions in the oil and gas sector since 2005.

Thomas Hess – Manager Business Development LNGM

Burckhardt Compression

Thomas Hess is a German citizen and graduated in Mechanical Engineering in 2002. He joined Burckhardt Compression directly after graduating, working in R&D and the engineering division. Thomas gained further experience in project management before taking up a new position as Head of Contracting in China, where he lived for six years. On returning to the head office in 2012 he took over responsibility for project execution in the marine business, leading to his current position in business development. He has 18 years' experience with compression machinery and their auxiliary systems for land and marine-based hydrocarbon transport and storage installations.

Gianluigi De Mitri – Market Analyst & Business Development

SIAD Macchine Impianti

Gianluigi De Mitri graduated with an MSc in Management Engineering from the University of Bergamo, Italy. He then studied Lean Start-up and Business Model Innovation at the Berlin School of Economics and Law, Germany. Gianluigi joined SIAD Macchine Impianti in 2015, where he leads and manages strategic market intelligence and business development initiatives on a global scale, specifically within the LNG and hydrogen economy industry.

Todd Omatick – New Product Introduction Manager

Klaus Brun – Director of Research & Development

Elliott Group

Todd Omatick, P.E. is the New Product Introduction Manager in Elliott's Product and Technology Development Department. He has been with Elliott for 24 years, holding multiple positions focused on LNG. He holds BS and MS degrees in Electrical Engineering from the University of Pittsburgh, US.

Klaus Brun, PhD, leads a group of over 60 professionals in the development of turbomachinery and related systems for the energy industry. His past experience includes positions in product development, engineering, project management, and executive management at Southwest Research Institute, Solar Turbines, General Electric, and Alstom. He holds nine patents, is the author of over 350 papers, and the editor of three textbooks on energy systems and turbomachinery. Dr. Brun is a Fellow of the ASME.

Compressors Q&A

Q Why are compressors so crucial to LNG operations?

A **Mike Sicker** - Mitsubishi Heavy Industries Oil & Gas Division

Due to the nature of the LNG liquefaction process itself, main refrigeration and auxiliary compressors can have the largest impact on overall efficiency (power consumption) and operational reliability, therefore, they are considered the most critical equipment in an LNG facility. Compression equipment requires a high level of advanced design expertise and manufacturing accuracy in order to achieve long-term reliable performance under operation under varying operating conditions.

A **Gianluigi De Mitri** - SIAD Macchine Impianti

Compressors are amongst the most critical components of an LNG facility – whether onshore or offshore – along all the elements of the LNG value chain (liquefaction, loading, transport, offloading, storage, and regasification). They strongly influence overall plant performance and efficiency, including safety and environmental impact.

Due to its volume and density characteristics, LNG is transported and stored in tanks as a cryogenic liquid at temperatures below boiling point (-162˚C) and near atmospheric pressure. While heat is leaking continuously into the LNG storage tanks and during loading and unloading activities, a part of the LNG in the tank evaporates, creating what is known as boil-off gas (BOG). The increase of BOG increases the LNG operating tank pressure since the volume of the gas is much higher than the liquid form. Thus, for maintaining tank pressure, temperature, and Wobbe index effective control within process specifications, BOG shall be continuously removed.

Compressors allow BOG recovery and monetisation by compressing and reliquefying it, sending it to the pipeline, or feeding a gas turbine in a power generation plant – thus minimising energy loss and environmental impact, as well as improving plant efficiency.

A **Thomas Hess** - Burckhardt Compression

LNG is stored and transported as a fluid under cryogenic conditions in special, highly insulated tanks. Despite continuous improvements in storage technologies, heat ingress during storage and handling, however, is unavoidable, causing the liquid to evaporate. Accumulating BOG must be managed: it might be used as fuel, reliquefied, or burned under controlled conditions. In any case, the problem of boil-off is unavoidable and asks for a technical solution.

This is why compressor operation is crucial to LNG operations: gas consuming equipment such as dual fuel engines or reliquefaction plants require a certain operating pressure, which can range from low-pressure systems at 5 - 7 bar to high-pressure systems with operating pressures up to 300 bar.

Mitsubishi Heavy Industries: MHI's LNG Refrigeration Compressor performance testing before site installation.

A **Todd Omatick & Klaus Brun** - Elliott Group

LNG production is a very large refrigeration process that takes natural gas from the gaseous to the liquid phase, thereby reducing its volume by a factor of approximately 600 and making it easy for transportation by ship or tanker truck. To cool natural gas to its liquid state requires several complex cooling steps.

All refrigeration cycles require compression, so the cooling cycle compressors are the core equipment of the LNG production process. These refrigeration compressors consume significant power and can require up to several thousand horsepower in modern large LNG facilities. Their efficient and reliable operation is critical to make an LNG facility successful.

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Q: Describe the importance of co-ordination and communication between different compressors in a system.

A: Mike Sicker - Mitsubishi Heavy Industries Oil & Gas Division

First tier compressors (main refrigeration) and second tier auxiliary compressors (fuel gas, BOG, end flash gas, residue gas, or feed gas) must operate in unison and communicate with the plant distributed control system (DCS) to ensure smooth, continuous plant operation. Co-ordination among compressors is critical to sustained and reliable plant operation.

A: Todd Omatick & Klaus Brun - Elliott Group

Depending on the refrigeration process that is required, LNG facilities operate several refrigeration cycles that progressively cool natural gas from ambient temperature to -260°F. These refrigerant compressors have to operate in a very narrow pressure and temperature range within a finely tuned plant process. Any process deviation, machinery upset, or equipment shutdown can bring the entire plant to a halt, and would require significant cost and time for a restart of the entire plant. All compressors in an LNG plant have their own unit control system which interfaces with the overall plant process control system. These control systems continuously monitor all process variables and control the compressors such that the overall production process stays within its allowable limits.

A: Thomas Hess - Burckhardt Compression

If compressors are applied in series, co-ordination and communication is of high importance. This directly contributes to the complexity of a system, requiring multiple compressor installations linked to each other.

Ideally, such an arrangement is avoided and combined into one single compressor platform. As an example, modern Burckhardt Compression Laby®-GI technology combines sophisticated cryogenic, low-pressure labyrinth piston design and state-of-the-art ring-sealed, high-pressure technology on one compressor frame. This allows simultaneous fuel gas supply to low-pressure four-stroke auxiliary engines and high-pressure gas supply to the two-stroke main engines and a dedicated high-pressure reliquefaction system.

Q: How do compressors improve the efficiency of the LNG process?

A: Mike Sicker - Mitsubishi Heavy Industries Oil & Gas Division

LNG production and power consumption are directly proportional to a compressor's overall polytrophic efficiency. Main refrigeration compressors can represent up to 70% of an LNG plant's overall power consumption, so even a minor increase in compressor efficiency can represent a significant savings in power usage and subsequent carbon production.

Burckhardt Compression: Laby-GI compressor being transferred to a ship for onboard installation.

A: Todd Omatick & Klaus Brun - Elliott Group

Since the compressors are the main energy consumers within the LNG production process, their efficiency is critical to the commercial viability of an LNG production plant. Large LNG plants spend tens of millions of dollars each year in fuel or electricity to power these compressors, so any efficiency improvement resulting in a reduced power consumption has a direct impact on operating costs.

A: Thomas Hess - Burckhardt Compression

With reference to the usage of LNG BOG as fuel in modern two-stroke, dual-fuel propulsion systems on LNG carriers (thanks to the high thermal efficiency of two-stroke engines), compressors helps to boost the efficiency of the vessel propulsion system. Compared to earlier applied propulsion technologies using steam turbine (ST) and dual-fuel diesel electric (DFDE) technologies, the efficiency increased from approximately 30% (ST) respectively 40% (DFDE) to a value above 50%. This achievement in general increased the efficiency of LNG transportation by ships and therefore directly contributes to the efficiency in the global LNG supply chain.

A **Gianluigi De Mitri** - SIAD Macchine Impianti

Effective handling of the BOG not only guarantees the safety and stability of the system, but also improves the efficiency of an LNG facility. BOG could indeed represent a loss of the valuable LNG product, and its flaring is not an option.

The energy required to compress BOG for its valorisation is a major cost, and several solutions have proved effective in addressing this issue.

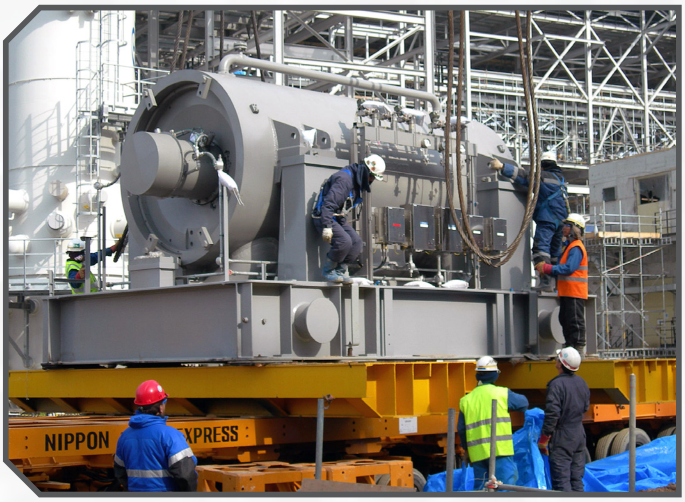
For reciprocating compressors, cooling down compressor cylinders and gas piping is not necessary. Due to ultra-low gas suction temperatures, the thermal expansion coefficient is low enough to avoid thermal stresses of mechanical parts and the reliability and durability of sealing elements, which ensure avoidance of gas leakage, i.e. product loss. Pre-heating, conversely, is normally necessary for screw compressors, where the suction temperature is limited due to thermal stress dilatation restraints. However, a pre-heater not only requires further energy, but also increases the shaft power of a screw compressor because it reduces the density of the inlet gas and, consequently, increases the volume to be compressed.

Finite Element Method (FEM) and Computational Fluid Dynamics (CFD) analysis are widely used to improve gas flow dynamics into cylinders and reduce mechanical friction and heat transfer inside the compression chamber and suction/discharge pockets. Far better than other compression technologies, reciprocating compressors offer a substantial variety of effective capacity control systems with tangible benefits on power consumption and mechanical efficiency. Continuous changes in suction gas temperature and the capacity of processed BOG emphasise the role of reciprocating compressors in maintaining the required delivery under variable process conditions and reducing power consumption at an operating condition of partial load.

Q With new LNG markets arriving and others expanding, how is compressor technology changing/adapting?

A **Mike Sicker** - Mitsubishi Heavy Industries Oil & Gas Division

New LNG markets have emerged over the past few years in terms of plant production size. Producers are now targeting production capacities based on the specific market they plan to serve, such as large (resource-based production), flexible (medium scale production), or small scale (peak shaving or bunkering) operations. MHI offers some of the highest compressor efficiencies on the market and works to continuously improve efficiency and production capacity through advanced aerodynamics and manufacturing production techniques. MHI's flexible frame design (FFD) allows the company to customise individual compressor designs to meet the specific application required by LNG customers.



Elliott Group: Mixed refrigerant compressor for Sakhalin LNG.

A **Thomas Hess** - Burckhardt Compression

Apart from the growing size of LNG producing and receiving installations – especially with the change in the shipping industry switching from high sulfur containing liquid fuels to gas as fuel – a large demand for maritimised LNG boil-off compressor systems evolved.

Ship-based compressor installations must be treated differently from onshore based installations, since special requirements arise when a compressor is installed on a moving, remote structure in combination with harsh environmental conditions. Apart from the operational challenges, the product must suit the given infrastructure onboard a ship. This is especially important when considering the long expected lifetime of more than 25 years and its related maintenance considerations.

Additionally, we can clearly see a growing demand in cryogenic and oil-free compressor technology. The

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operational flexibility of these compressor systems and the savings on utilities without the risk for oil carry-over to the precious clean energy are of high advantage to their operators.

A **Gianluigi De Mitri** - SIAD Macchine Impianti

Choosing the right compressor technology is always a balance between flowrate and pressure requirements, which vary according to process specifications and the installation site. However, LNG applications are more demanding than others.

The critical aspects of BOG compressors, which are better suited by reciprocating compression technology, are the cryogenic temperature and bone-dry gas seal operation, which require very accurate material selection and excellent wear resistance and lifetime of sealing components. Additionally, flexible operations through gas capacity control is a crucial challenge to handle changing process conditions (varying pressure, temperature, mass flow, and gas composition) in order to adjust suction flow and improve efficiency by reducing the power consumption. Modularisation is a further area of interest to help customers to get the job completed profitably in order to meet the need for increased responsiveness, agility, and customisation. Finally, new digital solutions and application of machine learning and artificial intelligence practices can support business execution, monitoring, and the recognition of the earliest onset of compressor issues.

SIAD Macchine Impianti: A SIAD MI BOG compressor HDS2-2 running efficiently at an LNG plant in China with the dry gas sealing system having operated continuously for more than 16 000 hours.

A **Todd Omatick & Klaus Brun** - Elliott Group

There have been several LNG plant design trends over the last few years, but the major indicator is that LNG plants continue to grow in size and, thus, larger compressors are required. Generally, the larger the LNG plant, the lower the LNG production costs. Whereas gas supply limited the size of LNG plants in the past, with the significant increase of gas production due to shale gas, this is not the case anymore. LNG operators have also become more concerned about process and equipment efficiency due to international price pressures on LNG over the last few years.

Q What are the current limitations of compressor technology?

A **Todd Omatick & Klaus Brun** - Elliott Group

The larger a compressor, the more challenging its design, manufacturing, testing, and installation. With the trend toward very large compressors, manufacturers face serious issues in the areas of rotordynamics, vibration, sealing, casting, machining, and factory testing. Significant manufacturing and testing infrastructures are required to build the large compressors currently required for LNG plants.

A **Mike Sicker** - Mitsubishi Heavy Industries Oil & Gas Division

MHI is continuously improving impeller flow coefficient and Mach number references through the use of single piece and 3D impeller technology. Advances in Computational Fluid Dynamics (CFD) and material science also allow the company to overcome traditional limitations of impeller design.

A **Gianluigi De Mitri** - SIAD Macchine Impianti

As far as reciprocating compressors are concerned, one limit could be represented by the maximum allowable gas discharge temperature, due to the limits of the ring material. These rings are typically made from PTFE and their maximum working temperature is 200˚C. Actually, this is not an issue for the cold stages of a BOG compressor, but it could be critical for warmer stages

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or for a recycle compressor. On the other hand, gas intercooling after the first compression stage completely resolves such a limitation and results in power saving by the compression of cooler gas.

The other main technology limitation is the mean time between maintenance – which is kept at a relatively low figure by the cylinder valves – which in BOG services need to be overhauled approximately every 8000 running hours.

A: **Thomas Hess** - Burckhardt Compression

In a general view, limitations stay not with compressor technology itself but within the individual compressor type, such as centrifugal, screw, or reciprocating piston type.

As a maker of reciprocating compressors, with more than 125 years of experience, Burckhardt Compression can clearly state that limits have been continuously newly defined over the past years. As a reference, we can review the development of modern oil-free, dry-running ring sealing technologies. As in the past, this technology was mainly limited to a pressure range below 200 bar and slow rotating reciprocating compressors, it can nowadays be successfully applied to high-pressure applications above 300 bar with rather high average piston speed. In parallel, meantime between overhaul (MTBO) for such ring sealing systems is continuously developing and can reach intervals of 12 000 hours and above.

Q: Detail a compressor solution that was more challenging than usual.

A: **Mike Sicker** - Mitsubishi Heavy Industries Oil & Gas Division

MHI is partnering with a major oil company to develop LNG trains with the best economy of scale and lowest cost per tonne of LNG produced. This required integration of the largest two-shaft industrial gas turbine driver on the market with the largest barrel-type compressor ever used in LNG production. MHI met the challenge of developing this first of a kind compressor in co-operation with the project developer by utilising the latest advanced design and state-of-the-art manufacturing technologies.

A: **Thomas Hess** - Burckhardt Compression

High-pressure fuel gas compressor systems for modern two-stroke propelled LNG carriers are characterised with a much higher demand on technology as comparable to onshore installations. The development and implementation of this technology required not only extensive internal research and development activities, but especially close co-operation with external parties, such as shipyards and marine classification societies.

A: **Gianluigi De Mitri** - SIAD Macchine Impianti

The compressor applications in LNG fields are well known and are not affected by the typical issues such as the presence of liquids in the gas stream, the appearance of dirt and solid particles which may clog valves and rings, plus a high content of corrosive gas such as H_2S. The LNG BOG application itself, from this point of view, is not as demanding as the ones in oil and gas. The challenges faced in an LNG application were related to capacity regulation where a client wanted to combine different capacity control systems, through a combination of suction valve unloaders for step regulation, a variable frequency device to continuously modulate the electric motor speed (and consequently the compressor speed), and adjustable compressor cylinder clearance pockets. Finding the best control philosophy to let the whole system be as stable as needed was rather demanding.

Another challenging situation the company faced was related to a methane BOG compressor where a cold performance test was scheduled in our facilities before shipment. Thanks to the fact that the compressor manufacturer, SIAD Macchine Impianti (SIAD MI), belongs to SIAD, an industrial gas company,

Elliott Group: End flash gas compressor package.

we were able to run the compressor using cold nitrogen directly gasified from liquid product at -160˚C to simulate LNG BOG and compressed exactly according to the project design temperatures and pressures. The creation of a test circuit and the execution of the test itself in a production plant to perfectly simulate field and process conditions was a challenge SIAD Macchine Impianti successfully completed, all that with the client's utmost appreciation.

A **Todd Omatick & Klaus Brun** - Elliott Group

Large refrigeration compressors are the critical operating machinery at the heart of every LNG process. Elliott is a pioneer of refrigeration and LNG compression systems, and has built some of the largest, most efficient and reliable compressors in operation in the LNG industry. The capacity of an LNG compression train, and by extension, the entire production facility, is determined by the size of the refrigeration compressors.

Different refrigeration processes require different compression solutions, and there are a limited number of manufacturers with the expertise and technology to provide those solutions. Adding one or more side streams to the main flow of a compressor increases the challenge of accurately predicting the machine's performance, and Elliott has particular expertise in sideload optimisation.

Q How are compressors helping to reduce emissions from the LNG process?

A **Gianluigi De Mitri** - SIAD Macchine Impianti

Natural gas and its liquid form LNG play a key role in the energy transition and decarbonisation process. Due to its chemical composition, natural gas is the cleanest burning hydrocarbon and offers a considerable opportunity to reduce CO_2 emissions. However, the LNG value chain produces large quantities of CO_2 which can be reduced by increasing the energetic efficiency of the processes.

Focusing on LNG transport and storage, the BOG can be compressed and sent to a condenser for reliquefaction, to a pipeline or power plant for heat and power generation or, again, fed into vessel propulsion and auxiliary engines or reliquefaction plant.

When it comes to compressor design, extreme attention has to be paid to sealing characteristics as well as wear resistance to avoid leakage and minimise frictional heat generation. Gas losses must be avoided to neutralise environmental impact and improve efficiency. In the unlikely event of leakage, compressors are equipped with special features to allow the recovery of methane, which is re-injected back to the compressor suction.

Compressors are therefore crucial to avoid flaring or venting BOG for most operating conditions and for reducing emissions.

A **Todd Omatick & Klaus Brun** - Elliott Group

Compressor efficiency directly impacts plant emissions or power consumption. Advanced aerodynamic design tools and testing are being utilised to make LNG compressors highly efficient and to reduce the overall emissions footprint of the plant. Also, many modern LNG plants use large electric motors instead of gas turbine drivers to reduce air emissions during the production process. Carbon capture and storage (carbon sequestration) is another method of reducing carbon emissions, and CO_2 compressors are inherent to this process.

A **Thomas Hess** - Burckhardt Compression

Unfortunately, despite its contribution to reduce global CO_2 emissions when using LNG as a fuel respectively for power generation, methane emissions contribute approximately 25 times more to global warming than CO_2 itself.

Sophisticated 'zero leakage' compressor solutions help to handle LNG boil-off as a fuel. At the same time, due to their gas tight design they minimise methane leakages to the atmosphere.

Compressors are indispensable in the LNG production, storage, and transportation processes to handle the BOG and prevent it from being vented to the atmosphere. Therefore, compressors are contributing in two ways: enabling LNG BOG usage as a fuel, and avoiding the need for methane release to atmosphere – respectively flaring of gas when the pressure inside the storage tank increases.

A **Mike Sicker** - Mitsubishi Heavy Industries Oil & Gas Division

Future LNG buyers are already demanding low carbon LNG. MHI currently has the highest efficiency compressors and class leading, two-shaft industrial gas turbine driver. MHI has also recently introduced a hybrid combined cycle solution to the LNG market which will achieve 55% overall thermal efficiency within the LNG liquefaction process. This represents a 30% decrease in CO_2 intensity of the LNG train compared to a traditional LNG plant operating simple cycle gas turbines.

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Q What are the main factors driving innovation?

A Todd Omatick & Klaus Brun - Elliott Group

Increasing demand for LNG in the world is driving plants to increase in size, requiring innovation in design and manufacturing of very large compressors. Similarly, price pressure on LNG is a market driver to improve the aerodynamic efficiency of compressors. A recent trend is modularisation, that is, designing and manufacturing complete compressor modules that can be tested and then moved to the site, saving installation time.

A Thomas Hess - Burckhardt Compression

The main drivers for innovation can be summarised as follows:

- Ease of installation and commissioning, asking for fully packaged, skid mounted solutions.
- Reduced delivery lead times for highly sophisticated, fully tested, skid mounted compressor units.
- Extension of MTBO for key components to reduce down-time due to maintenance.
- Flexible handling of maintenance based on actual condition of parts rather than following fixed intervals – the so-called condition-based maintenance approach.
- The growing LNG demand in the shipping industry and the development of related technologies, such as LNG as fuel, LNG bunkering, etc.
- The demand for oil-free gas compression.
- Performance improvements based on real-time operating data (not based on theoretical models).

A Mike Sicker - Mitsubishi Heavy Industries Oil & Gas Division

LNG producers are focusing a great deal of attention on efficiency improvements, carbon reduction, and overall plant cost – all three of which will be required to meet the changing dynamics of the LNG market. To meet the current needs of its customers, MHI offers the main rotating equipment with the smallest footprint and lowest cost of LNG production to both brownfield and greenfield LNG plant developers. In order to fulfil the future needs of its customers, MHI is focused on delivering hydrogen ready gas turbines to their LNG customers, a market that the company is actively leading.

A Gianluigi De Mitri - SIAD Macchine Impianti

Product cost optimisation, connected to its design and material selection, and new LNG markets are the main drivers of innovation, together with power efficiency, which is extremely important. First, let me elaborate on product cost optimisation through an example. The first BOG compressor was used to adopt plenty of exotic materials (mainly Nickel alloys) in order to have ductile materials even at cryogenic temperatures. Many years ago, at the beginning of this application, the temperature distribution within each compressor component was not yet clear. Over a number of years, with the experience accumulated and the studies we performed on the materials, it was possible to fine-tune the material selection by adopting special (and expensive) components only when and where really needed.

Last but not least, a mention of availability. For reciprocating compressors, the most delicate components, in terms of duration, are cylinder valves and piston rings. Thanks to the large improvements made during the last 20 years in their design and material selection, it has been possible to significantly increase their lifetime and, consequently, the mean time between maintenance. Proven both long-term reliability and availability established reciprocating compressors as the perfect solution in terms of the total cost of ownership even for BOG service, with demonstrated benefits on the constant availability and the operating margin of an LNG plant. **LNG**

Burckhardt Compression: Fully packaged Laby®-GI compressor system.