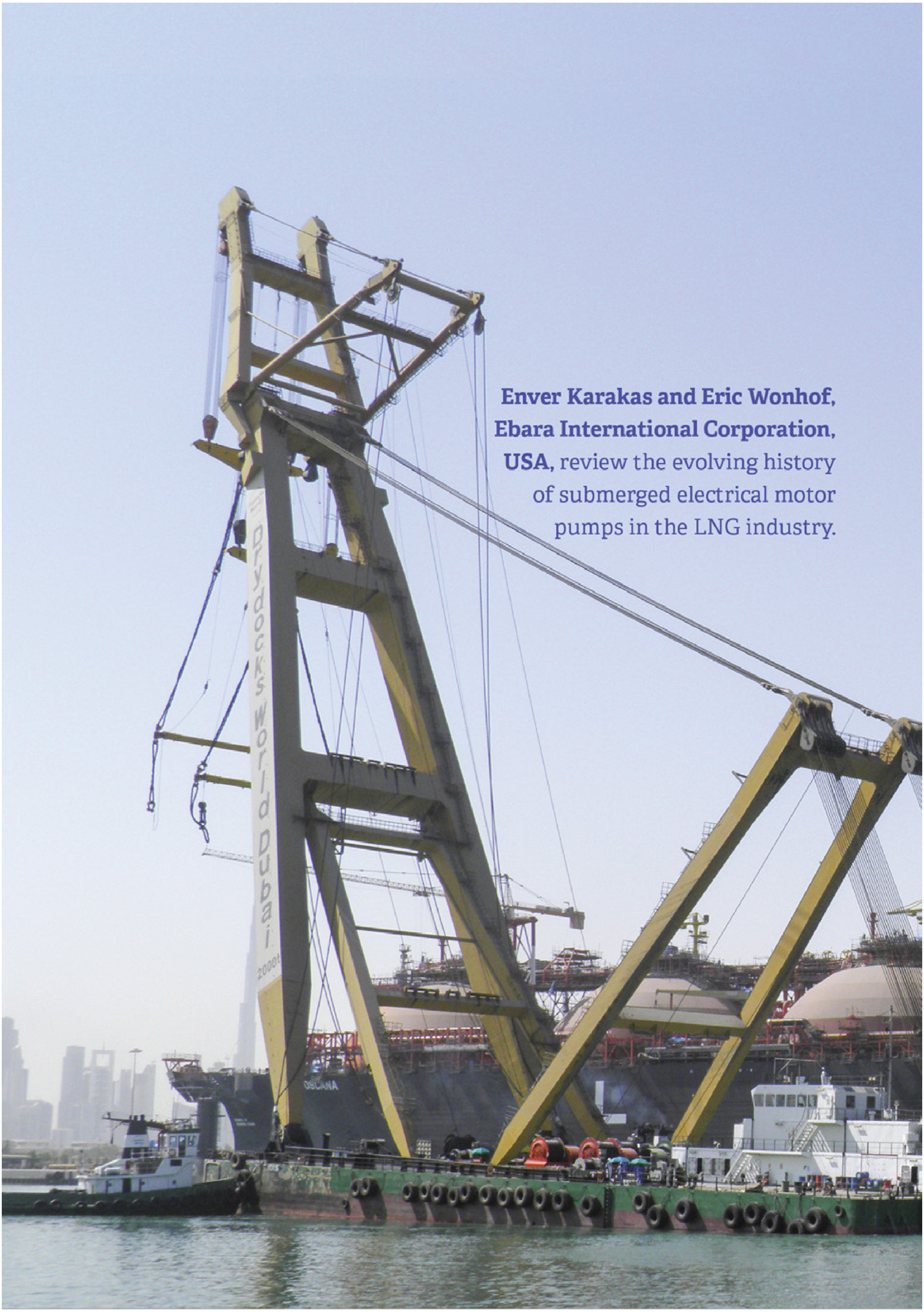

Enver Karakas and Eric Wonhof, Ebara International Corporation, USA, review the evolving history of submerged electrical motor pumps in the LNG industry.

A HISTORY OF PUMPS IN LNG

Introduction

Industry analysts predict that the global LNG market will double in the next 15 – 20 years, expanding worldwide access to natural gas. To handle the booming market, applications for cryogenic storage tanks and regasification units (SRUs) are on the rise, including floating storage and regasification units (FSRUs), and floating liquefaction (FLNG) vessels.

Lower initial costs, and a faster development timeline compared to onshore regasification units makes FSRUs an appealing choice. As of January 2017, there are 439 tankers in the global LNG fleet, of which 23 are currently chartered as FSRUs, and three as floating storage units (FSUs). In the 60 years since regular commercial exports of LNG began, cryogenic submerged electrical motor pumps (SEMPs) have played a critical role in LNG transfer and storage. This article highlights the major milestones in the development of SEMPs and their continuing evolution.

Figure 5. A regasification module, utilising high-pressure SEMPs, is added to an existing LNG carrier for conversion to FSRU service. This unit, the Toscana, was modified in a Dubai shipyard and now operates off the coast of Italy.

The start

The first marine vessel to transport liquefied gas, the *Methane Pioneer*, delivered its inaugural cargo in January of 1959. The ship employed a 225 m^3/hr deep-well cargo pump with an external motor in each storage tank. However, deep-well pumps proved to be a poor choice for use in LNG service because the temperature differential between the storage tank and external atmosphere caused the shaft to bind.

The development of the SEMP resolved this issue. The nature of LNG and its storage enabled the new technology. Oxygen is purged from storage tanks to reduce the risk of explosion. In addition, hydrocarbons such as LNG and other liquefied gases act as an electrical insulator, allowing for the electrical cables and the motor to operate safely submerged. J.C. Carter Company supplied the first SEMP to the French vessel *Beauvais* in 1961.

Figure 1. A submerged motor cargo pump inside an LNG carrier.

By the 1970s, SEMPs were commonly used on board LNG carriers (see Figure 1). Integration of the pump and motor into a single unit with a common shaft eliminated coupling and alignment issues. Because the shaft does not penetrate the tank, there is no need for mechanical seals, eliminating the potential for leakage. The development of a submersible pump that was retractable allowed the pump to be installed from the top of the LNG storage tanks, eliminating the need for connections below the liquid level. With these advantages, SEMPs quickly began to replace external motor pumps.

SEMP components

Motor

A three-phase, squirrel cage, induction motor is a SEMP's major component. The stator is fabricated from silicon iron laminations and copper windings. Epoxy insulation applied via vacuum impregnation protects the windings (see Figure 2). The rotor is also made from silicon iron laminations with aluminum bars between the two aluminum end caps. End caps can be cast in place or pre-fabricated, depending on the tensile stress induced in the aluminum bars as the rotor cools to cryogenic temperatures.

Safety is the most impactful advantage of a submerged motor versus an external motor. Because the motor is mounted on a common shaft with the pump hydraulics, there is no need for a mechanical seal. The motor 'air gap' is filled with cryogenic liquid gas, and the potential for leakage is eliminated. The submerged motor is isolated from the atmosphere in an oxygen-free environment that eliminates the risk of explosion. Together, these features negate the complex requirements of ATEX and other hazardous area certifications for the pump itself.

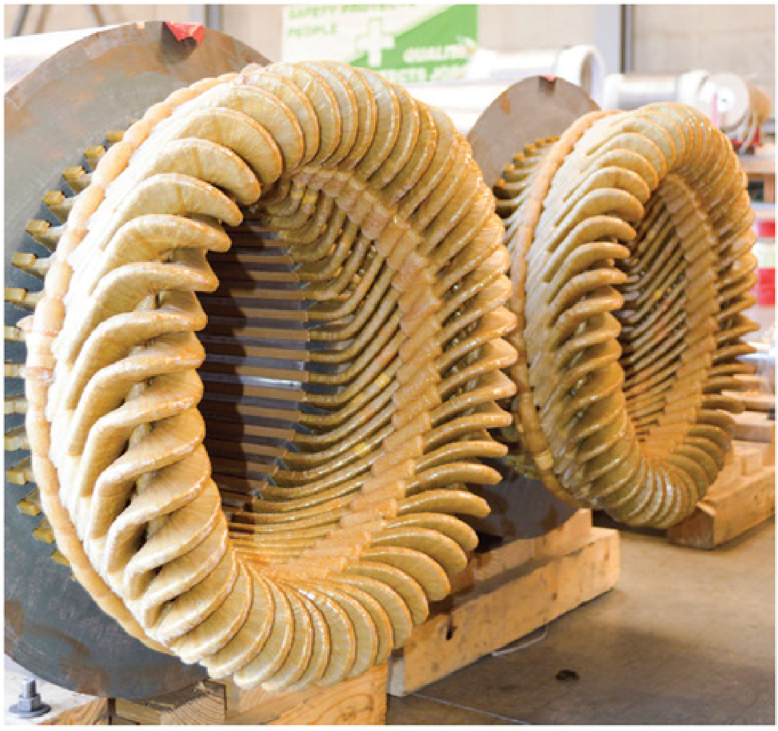

Figure 2. Epoxy insulated stator windings.

The compact design of cryogenic liquid-cooled SEMPs minimises their physical footprint, which is less than half that of an equivalent air-cooled motor (see Figure 3). Operating power (5 kW – 3MW), frequency (50 or 60 Hz), and speed (2 – 4 or 6 pole) are determined by the application and available power supply. Operation via variable frequency drive (VFD) is not uncommon.

Bearings

Bearings are a critical component in the SEMP design. The likelihood that cryogenic temperatures would freeze the grease precludes the use of standard sealed bearings. For this reason, open cage-style, product-lubricated bearings are the norm. The bearings are cooled and lubricated by the pumped cryogenic fluid.

Early testing showed that thrust bearings do not hold up well in cryogenic service because of the low viscosity of liquid hydrocarbons and the low boiling point of the fluid. Heat caused by friction from an axial load vapourised the cryogenic

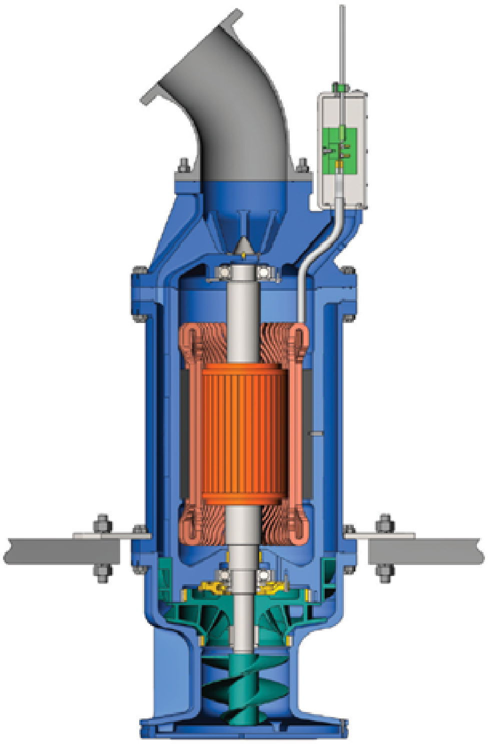

Figure 3. A SEMP's compact footprint is a major advantage in marine cargo applications.

Figure 4. A cryogenic liquid expander on test at the Cryodynamics facility in Sparks, Nevada, USA.

liquid. Under thrust loads, the pumped liquid could not provide a sufficient film layer between the balls and races, leading to premature spalling and reduced bearing life.

The solution was the development of deep-groove radial ball bearings made from either low alloy steel (such as 52100) or high carbon stainless steel (such as 440C). Deep-groove radial ball bearings are used today by most SEMP manufacturers. Cage design is usually proprietary, incorporating various graphite-impregnated thermoplastic materials.

In the late 1990s, a hybrid bearing featuring silicon nitride (Si3 N4) ceramic balls was developed and installed in a SEMP for methane wash service. The hard ceramic balls mated to the steel raceway to create a 'self-healing' effect, maintaining a high-level finish and limiting surface damage from debris. Because hybrid bearings exhibit less wear in low lubrication conditions and offer a longer life overall than standard steel bearings, their use has increased. Recent advancements include a specialty hybrid bearing developed by Ebara Cryodynamics that features a moulded resin separator between the steel races, insulating the bearing to prevent electrical arcing damage.

Ebara Cryodynamics has also developed a hydrostatic journal bearing system that can be used in SEMPs. Liquid feed ports supply pressurised fluid to form lubrication film within the bearing internal recess areas and the sliding surface. The supporting force of the lubrication film depends on the bearing shape, diameter and length, recess shape, and the feed port orifice diameters. Liquid properties, specific gravity, supply pressure, and rotating speed also have an influence. Because hydrostatic bearings do not rely on physical contact to support the shaft, and the clearance between moving parts is so large, fatigue and wear damage do not affect the bearing system. This greatly extends the time between pump overhauls. Hydrostatic bearing systems also provide a smoother running operation compared to mechanical bearing systems.

Thrust balancing

Product-lubricated thrust bearings perform poorly in cryogenic liquids. To counter this deficiency, most SEMP manufacturers adopted some type of hydraulic balance system that incorporated a balance disk or drum located at the top of the pump. The drawback was that early marine cargo pumps had difficulty eliminating the net thrust load over the entire operating range.

In 1973, Ebara Cryodynamics introduced a balancing system that eliminated the balance disk/drum at the top of the pump by transferring thrust balancing to the last-stage impeller and incorporating two orifices in series; a fixed radial orifice and a variable axial orifice. The fixed orifice has an offset wear ring at the upper shroud of the impeller, and the variable orifice has a stationary thrust plate in conjunction with an axial 'floating' rotating assembly. This arrangement proved both versatile and reliable, and the vast majority of SEMPs still use this balancing system today.

Hydraulics

SEMP hydraulic designs have evolved from the standard centrifugal AP-type vertical in-line pumps that were used in early SEMP units. Advances in diffusion technology, impeller design, hydraulic staging, and first-stage flow inducers have greatly expanded SEMP performance options and characteristics. Today's pumps can achieve capacities up to 3000 m^3/hr and over 3000 m of head. Hydraulic components are designed and accurately modeled using high-speed computers and computational fluid dynamics (CFD) software specifically written for turbomachinery applications. The hardware/software combination can simulate design cases in excess of supersonic speeds in two-phase flow conditions.

Testing and verification of hydraulic components is costly to perform in a full-scale LNG environment because of the cryogenic temperatures and the hazardous nature of LNG. Smaller hydraulics can be tested in a laboratory. To simulate larger hydraulics, scaled models of various turbine components are used to validate CFD results. In addition to typical measurements such as temperature, pressure, flow, power, and rotation speed, particle image velocimetry (PIV) is used to visually observe and understand the flow characteristics of each component. This laser-based technique combines high-accuracy point measurements with digital imaging to obtain instant velocity data over the entire flow region. FARO portable hand-held scanning arms and laser scanners capture complex geometries into modeling software, where a 3D representation, ready for design execution, is generated in a virtual workspace.

With the pump hydraulics and motor mounted on a common shaft, the rotating components are a single assembly that can be designed to fit any pump configuration. SEMPs can be mounted directly inside a tank (as in marine carriers), retractable in-tank (as in storage tanks), or in self-contained pressure vessels (as in product or transfer pumps). The configuration is independent of the hydraulic design, allowing for a wide range of adaptability.

Applied technology

SEMP technology has been applied to other machines in the LNG industry, including cryogenic liquid expanders, which can increase the train's LNG production by 3 – 5%, while also generating electrical power. Flowserve delivered the first cryogenic liquid expander in 1996 to the MLNG Dua plant in Malaysia. During the same time frame, Ebara Cryodynamics developed a submerged generator liquid expander, which was delivered to OLNG in Oman in 1999. Following their proven SEMP technology, Ebara Cryodynamic's expander featured an integral generator, fixed geometry axial nozzle vanes, and a variable speed constant frequency (VSCF) regenerative drive. The expander operates at various shaft speeds and generator frequencies, but maintains a constant frequency power input to the local power grid. Today, over 80% of all cryogenic liquid expanders in operation are a submerged generator design (Figure 4).

The future

Rising global demand for clean burning natural gas has sparked new technologies for developing natural gas resources in offshore fields that previously proved too costly and challenging to reach. FLNG, the newest SEMP application in the LNG industry, enables production, liquefaction, and storage of natural gas at sea. Floating production, storage, and off-loading (FPSO) vessels are moored near small at-sea gas wells. The LNG is processed and liquefied on board and then off-loaded to another vessel for transport. FSRUs receive LNG from the transport vessel. The LNG is stored and then pumped to an on-shore vapouriser via an undersea pipeline.

Due to their compact size, SEMPs are ideal for floating services. A SEMP operating on a floating barge must withstand buoyant forces during both operation and non-operation. Modeling these forces requires rotor dynamic simulations (RDS) to determine the axial and torsional forces that impact the pump from the heave, roll, and sway of the barge. Radial diffusers (referenced to shaft) provide a compact solution for the multi-stage pump. By using radial diffusers instead of elongated axial diffusers to diffuse the LNG from the impeller vane, the impeller can conveniently fit inside of the housing. Compact fluid passages then transfer the LNG from one stage to the next stage via the housings, resulting in an almost 20% reduction in pump height and weight. In many cases, hydraulic efficiency often increases because of the reduced disk friction caused by moving LNG over elongated axial diffusers. The end result is a more compact multi-stage high-pressure pump with higher hydraulic efficiency.

Golar Spirit, the first FSRU, began service off the coast of Brazil in 2009, and another FSRU, Toscana (Figure 5), off the coast of Italy in 2013. Both vessels feature SEMPs for their high-pressure send-out pumps.

Prelude FLNG, the world's second FLNG platform, as well as the largest offshore facility ever constructed (longer than four soccer fields), is expected to start up in late 2018 off the coast of Australia. India's first FSRU-based LNG import terminal is expected to be operational in the last quarter of 2019. Both projects will feature SEMP and submerged generator liquid expander technologies.

Conclusion

The application of SEMP technology has expanded from its initial use in LNG marine cargo pumps. Their compact footprint and proven safety features have made them the pump of choice for many liquefied gas applications. SEMPs are now standard equipment for such varying services as loading, circulation, marine gas fuel and send-out for LNG, LPG, ethylene, propylene, and many other liquefied gases. SEMPs can be found in liquefaction trains, marine carriers, re-gasification plants, peak shaving plants, fertilizer plants, and nitrogen rejection plants, with liquid temperatures ranging from -195°C – 45°C. The growth of the LNG industry, advanced pumping technologies, and the current growing interest in FSRUs and FLNGs will spur continued advancement in SEMP applications and performance. LNG

References

1. FOOKS, R., 'Natural Gas by Sea,' Witherby & Co., 1993.
2. RUSH, S., 'Submerged Motor LNG Pumps in Send-Out System Service,' Pumps and Systems, pp. 32-37, May 2004.
3. GABELLI, A. and KAHLMAN, L., 'Bearings that Heal Themselves,' SKF Evolution Magazine, pp. 26-29, September 1999.
4. MADISON, J., 'LNG Expanders – 10th Anniversary,' Keynote Address AIChE Spring Annual Meeting, April 2006.
5. International Gas Union (IGU) 2017 World LNG Report.

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