Due to large scale development of shale gas and the current boom of new LNG construction, the total amount of LNG produced by 2030 will be approximately 550 million tpy, double the amount produced in 2012. A significant drop in the price of crude oil is a major reason for the increased demand for LNG as the best alternative renewable energy source in the existing market.

Simultaneously, construction costs of onshore LNG projects have risen significantly, due to increases in labour costs, complexities obtaining a permit due to environmental regulations, new infrastructure improvement requirements at construction sites, and increased construction time.

Choosing the Right Compressor

Isao ‘Zac’ Zukeran, J. Simpson and J. Baranowski, Kobelco Compressors America Inc., USA, consider the advantages of oil-injected screw gas compressors for floating LNG applications.
With rising expenses and complications, industry expectations indicate increased numbers of floating LNG (FLNG) units for small to mid-size LNG projects. Currently, more than 40 ships for FLNG are under development around the world for completion by 2025. The main benefits of FLNG include the following:

- No construction work is performed at the operating site (construction and assembly occurs in the shipyard and the FLNG barge is then moved to the LNG production site).
- No lack of skilled labour.
- Removal of the pipeline from the offshore site to the onshore facility is not required with FLNG technology (when the production of LNG is completed, the offshore gas well is simply closed).
- Less environmental impact onsite.
- FLNG vessels are better suited to developing smaller gas fields.

### Gas compressors required in LNG processing

There are several gas compressors required in typical LNG processing, such as feed gas, flash gas, regeneration gas, lean gas, fuel gas boosting, and boil-off gas (BOG) compressors, etc. In previous large scale LNG projects, centrifugal or reciprocating compressors have typically been applied due to design conditions requiring larger sizes. However, conditions for FLNG projects (i.e. low pressure, sub-zero temperatures, suction pressure and capacity control with internal built-in slide valve) indicate that API619 rated oil-injected rotary screw gas compressors are the best fit for process gas compressors on FLNG vessels.

Figure 1 shows the applicable range of Kobelco process gas compressors for API617 centrifugal, API618 reciprocating, and API619 screw varieties. Centrifugal compressors are well suited for larger capacities with stable operating conditions, while reciprocating compressors are effective for projects requiring a higher discharge pressure application. The optimised combination of each type of compressor increases the reliability and efficiency of the entire process and facility. Due to a number of advantages, an oil-injected screw compressor is now the best fit in various applications, where previously centrifugal and reciprocating compressors were utilised.

### Screw compressor benefits for FLNG projects

This article will now address the advantages of using API619 oil-injected rotary screw gas compressors for FLNG process gas compressors.

#### Compact skid

The available space for FLNG facilities is very limited. Screw type compressors are designed for compact packages and have the flexibility to accommodate the necessary arrangements for FLNG limited plot plans. All components, including the bare compressor, main electric motor, lube oil system, oil coolers, and oil separation system, are installed on a common base plate. The compression principle for a screw is a smooth rotating set of rotors without pulsation/vibration, so no special/heavy foundation is required, allowing for easy installation. This packaged arrangement minimises the transportation and construction costs at the conversion shipyard.

#### Ease of maintenance

The wearing part for an oil-injected screw compressor comprises one mechanical seal, with no critical or insurance spare parts required. A reciprocating compressor requires many wearing parts, including valves, piston rings, rider rings, cylinder liners, etc., while a centrifugal compressor requires insurance spare parts, such as a spare rotor, spare geared and dry gas seal. A major overhaul for a screw compressor is required every 4 – 6 years, while a reciprocating compressor requires maintenance once a year and a centrifugal compressor requires service once every two years. Compared to a typical onshore LNG plant, an FLNG facility does not have the flexibility or availability to maintain a rotating machine, since it will be operating offshore. Consequently, a lower maintenance requirement and longer intervals between overhauls of oil-injected screw compressors are benefits and key factors for an FLNG project. Another significant maintenance advantage for screw compressors (compared to centrifugal and reciprocating units) is that the main compressor (bare shaft compressor) can be pulled out from the skid easily and replaced with a spare compressor within a day, without requiring any welding work.

#### Flexibility to meet offshore project requirements

There are several special requirements needed to meet an offshore project’s unique operating conditions and environment. First, three-coat painting systems for all components on the skid are required, in order to avoid corrosion and erosion in harsh salt-laden atmospheres. Secondly, a strain on the ship deck is caused by six directional wave motions from the sea (i.e. surging, swaying, heaving, rolling, pitching, yawing), causing deformation and strains in the base plate of the compressor skid and the axis of rotation between each component. In order to prevent transmission of the strain of the ship deck to the compressor plate, an anti-vibration component. In order to prevent transmission of the strain of the ship deck to the compressor plate, an anti-vibration
mount (AVM) system, such as a stainless cushion, is normally applied to absorb loads from the directional motions and support the compressor system. Sufficient know-how and experience have been accumulated for the API619 rotary screw compressor industry for vapour recovery units on offshore floating production, storage and offloading (FPSO) projects, so these special requirements can easily be applied and translated to suit FLNG projects.

**Simple and robust structure**

Figure 2 shows a cutaway of the typical oil-injected screw gas compressor (single stage). There are two rotors inside the casing – a male rotor and a female rotor – in contact with each other along the lobe surface, which is coated by an oil film. Oil is injected directly into the rotor chamber to serve as the oil film lubricant, as well as for lubrication to the rotor bearings. The oil also acts as a cooling media for process gas, so typically screw gas compressors do not require an after gas cooler. The male rotor is directly driven by a 2-pole or 4-pole electric motor driver without any external speed up gear. The rotating speed is fixed at either 3600 rpm or 1770 rpm. Because oil is injected into the rotor chamber where it serves as a bearing lubricant, no shaft seal between the rotor and bearing is required. The oil-injected screw compressor has only one mechanical seal at the drive shaft end of the male rotor. A sleeve type journal bearing is applied on the end of each rotor, while thrust bearings are typically tilting pad type mechanical design.

Figure 3 shows a typical flow diagram of the oil-injected screw system. The process gas and lubrication oil mixture is discharged from the compressor discharge nozzle directly into an on-skid, high efficiency oil separation system with bulk oil separator and coalescing.

Table 1. A comparison summary between centrifugal, reciprocating and screw compressors

<table>
<thead>
<tr>
<th></th>
<th>Screw</th>
<th>Reciprocating</th>
<th>Centrifugal</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Reliability</strong></td>
<td>High (simple system)</td>
<td>Low (multiple stage)</td>
<td>High</td>
</tr>
<tr>
<td><strong>Power savings</strong></td>
<td>Yes – turndown cases and suction pressure increases</td>
<td>Limited – steps and no gains from increasing suction pressure</td>
<td>Limited – inlet guide vane and no gains from increasing suction pressure</td>
</tr>
<tr>
<td><strong>Footprint and installation</strong></td>
<td>Small and light</td>
<td>Large and heavy</td>
<td>Large and heavy</td>
</tr>
<tr>
<td><strong>Continuous operation</strong></td>
<td>4 – 6 years</td>
<td>1 year</td>
<td>2 years</td>
</tr>
<tr>
<td><strong>Turndown range</strong></td>
<td>100 – 15% (stepless control)</td>
<td>100-75-50-25% (stepped)</td>
<td>100 – 80% (limited range by inlet guide vanes)</td>
</tr>
<tr>
<td><strong>Wearing parts</strong></td>
<td>Only one mechanical seal</td>
<td>Many consumable parts</td>
<td>Insurance spare parts</td>
</tr>
<tr>
<td><strong>Cooling requirements</strong></td>
<td>N/A</td>
<td>Lube oil cooler and bypass cooler</td>
<td>Lube oil, inter and bypass coolers</td>
</tr>
<tr>
<td><strong>Inherent problems</strong></td>
<td>N/A</td>
<td>Pulsation and vibration issues</td>
<td>Surging and passing critical speed</td>
</tr>
</tbody>
</table>
filter, where the oil is removed from the process gas. Oil is separated from the process gas via the downstream oil separation system and then re-injected into the lubrication circuit.

Since the oil acts as both coolant and sealant, the allowable compression ratio by single stage is very high, while discharge temperature can be adjusted by the oil flow rate. Oil injected into the rotor chamber can absorb the compression heat generated in the compressor. When a higher compression ratio is required, a tandem arrangement of two stage compressors combined in one casing can be employed to achieve better efficiency (Figure 4). Typically, this tandem arrangement is used when the pressure ratio exceeds 8:1, and can be applied to a ratio of more than 50:1. As an example, for BOG compressor service for an FLNG project, inlet pressure to the compressor is atmospheric and requires a discharge pressure of 35 – 40 bar to feed the gas to the gas turbine. The compression ratio is therefore around 35:1 to 40:1, and in this case a tandem arrangement would be the best fit. It is important to note that there is no external intermediate cooler required, since the oil acts as the coolant. A reciprocating or centrifugal type requires multiple stages with additional equipment, such as an additional intermediate cooler or pulsation bottle, to achieve this high compression ratio.

**Principle of compression**

The principle of compression for a screw compressor is positive displacement type. This is the same for a reciprocating compressor, however the screw type does not have any pulsation vibration issues, since it is simply a set of rotors rotating smoothly. A screw compressor easily adapts to handle variable and changeable gas compositions using positive displacement compression, while a centrifugal compressor that utilises dynamic and kinetic energy is easily affected by any change in the gas molecular weight. This can incur considerable impacts on the performance of the impeller, and surge points can also be affected.

**Unique method for capacity control and inlet pressure fluctuation**

Depending on the operating conditions, turndown capacity control is required for the process gas compressor on an LNG project. A feature unique to oil-injected screw compressors is a built-in slide valve mechanism. With the built-in slide valve, oil-injected screw compressors have a wide, smooth, stepless turndown range between 100% and 15% with power savings. Additional turndown via recycle or spillback is only required from 15% down to 0%. The slide valve is an unloader device used to adjust the inlet volume of the compressor. During turndown operation, actual power consumption of the main motor will decrease significantly. The slide valve is located just underneath the rotors and moves parallel to the rotors in an axial direction, typically actuated by a hydraulic cylinder, which uses pressurised oil from the compressor lube oil line. When the slide valve is automatically moved towards the suction side of the compressor, the compressor operates fully loaded. The compressor starts to unload when the slide valve is moved towards the discharge power. During the full load operation, the entire length of the rotor is utilised and the inlet volume of the compressor is maximised. During turndown operation, the slide valve is moved towards the discharge side, linearly unloading the compressor. The effective length of the rotor is thus shortened and inlet volume of the compressor is reduced. Because compression is being performed with a lower inlet volume, the theoretical brake horsepower is reduced. Figure 5 shows the mechanism of a slide valve and power saving. As a comparison, a reciprocating compressor has a step capacity control (i.e. 100-75-50-25%), and a centrifugal compressor has a limited range between 100% and 70% using an inlet guide vane.

**Conclusion**

In addition to the BOG, fuel gas boosting, regeneration gas, and purge gas compressors used for FLNG projects, main refrigeration compressor studies are underway for future FLNG projects, in order to replace the traditional in-line single shaft or integral geared centrifugal compressor with API619 oil-injected screw technology. Advantages include a lower initial cost (equipment and installation), higher efficiency, high reliability, smaller installation area, and flexibility to meet unique operating requirements. The presence of API619 oil-injected screw compressors in FLNG projects can be expected to increase rapidly in the future. LNG