LATEST ADVANCES IN LNG COMPRESSORS

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ABSTRACT

In the latest years, the attention of LNG producers has been concentrated on 3-5 MTPA production. All latest plants have been sized around this number. Some of them have been designed by optimizing existing layout, other brand new and few required the optimization of centrifugal compressors and so the introduction of some novelty to maximize production given a certain driver.

Improvements in the aerodynamic design have been necessary to maximize efficiency and increase operating range; advanced rotordynamic design to handle more capacity, new casings to increase design pressure and reduce the number are few examples of innovation continuously introduced in this segment.

Novelties have not been limited to main refrigerant compressor but also to auxiliaries such as BOG, CO2, End Flash.

Eventually also new drivers have been qualified for LNG plant (LM6000) and other are under study for its high efficiency and possible future application.

1 INTRODUCTION

LNG production has started in the sixties with the plants in Algeria and Libya, then restarted in the 80’s and boomed in the last 10 years. Since the 80’s we have seen a fast growing of LNG production starting from 3MTPA for QG 1 and WOODSIDE 1 to the 7.8 MTPY for large QG projects. After that time all the new plant has been designed around 4 MTPY. The paper will describe which are the recent novelties introduced in the latest LNG projects.

![Historical LNG Production](image1)

Figure 1 – LNG Production

2 PREVIOUS AND CURRENT TRAIN CONFIGURATION

Turbo machinery arrangement of latest main refrigerant compressor trains for 3-5 MTPA are recently built around aeroderivative gas turbines such as LM2500 or LM6000 while in the past FRAME 7 was most used. Typical Frame 7 train installed power is around 190MW just for main refrigerant compressor. This type of train is installed in Egypt, Nigeria, Malaysia, and Indonesia.
Same LNG production can be achieved with LM2500 even if, but more equipment and capital investment are required. So, for same LNG process drivers can be just two in case of Fr7, they need to be 4 in case of LM6000 and 6 in case of LM2500; in this latter case train will operate in parallel with the advantage to keep the production flowing even when one train is under maintenance. Aero derivatives GT as Mechanical Drive have been installed in Darwin for the first time and now are under commissioning in Papua New Guinea, Australia and USA.

The typical compressor used in the large LNG plant is the beam type centrifugal. For a specific service (LP MR), a process axial compressor has been also used. The main advantage of the axial compressor is the high efficiency and the large flexibility. Recently big steps forward have been done on the adjustable guide vanes reliability. Life has been improved with the target of same driver’s maintenance plan.
Table 1 – Axial vs Centrifugal compressor for LNG

<table>
<thead>
<tr>
<th>VOLUMETRIC FLOW [m³/h]</th>
<th>HEAD [m]</th>
<th>Normalized Polytropic Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>1500</td>
<td>0.85</td>
<td>1.0</td>
</tr>
<tr>
<td>2000</td>
<td>0.9</td>
<td>1.2</td>
</tr>
<tr>
<td>2500</td>
<td>0.95</td>
<td>1.3</td>
</tr>
<tr>
<td>3000</td>
<td>1.0</td>
<td>1.4</td>
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<tr>
<td>3500</td>
<td>1.05</td>
<td>1.5</td>
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<tr>
<td>4000</td>
<td>1.1</td>
<td>1.6</td>
</tr>
<tr>
<td>4500</td>
<td>1.15</td>
<td>1.7</td>
</tr>
<tr>
<td>5000</td>
<td>1.2</td>
<td>1.8</td>
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<td>5500</td>
<td>1.25</td>
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<td>6000</td>
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<td>7500</td>
<td>1.45</td>
<td>2.3</td>
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<tr>
<td>8000</td>
<td>1.5</td>
<td>2.4</td>
</tr>
<tr>
<td>8500</td>
<td>1.55</td>
<td>2.5</td>
</tr>
</tbody>
</table>

• 16 – 28 MW
• up to 5 Kg/m³ inlet density
• up to 300,000 m³/h inlet vol flow
• high efficiency 90%
• flexibility for operation and start up
• fixed speed, VSV, reliability

• 16 – 44 MW
• up to 60+ bar disch press
• IGV&speed variation
• good efficiency 88%
• up to 500,000 m³/h (double flow)
• High reliability

Looking to the future new LMS100 is a driver that can be used in the LNG for its high operating flexibility and efficiency. A possible layout of the train to reach 4MTPA could consist of 1 LMS100 and two compressor bodies.

![LMS100 train configuration with Process A](image)

Figure 4 – LMS100 train configuration with Process A

Worth to be mentioned is also the longest refrigeration train ever done that is installed in Angola and it’s done by Fr7 + 3CC + EM. This plant has also another train with Fr6 + 3CC + EM to complete the refrigeration loop. The entire liquefaction train is done by two trains with Frame 7 and two with Frame 6 for a final production of 5.2 MTPA.

![Longest LNG liquefaction train with Process B](image)

Figure 5 – Longest LNG liquefaction train with Process B

The configuration of Frame 7 with 3 compressors and the electric motor is very attractive because it can accommodate all the services (LPMR, HPMR and PR) on the same shaft for a single liquefaction train. This can then be copied and the liquefaction plant can have a parallel train configuration granting 365 days of production including maintenance of one driver.

Typical liquefaction plant also includes other auxiliary services. Here below also some configuration of auxiliary services for a 3-4 MTPA plant:
Compressor Design

2.1 Aerodynamics

2.1.1 Impellers

Aerodynamic is the building block of the compressors because it's directly connected to the efficiency and so to the LNG production: 1% increase in the compressor efficiency is equal to 1% increase in the LNG production for this kind of plant capacity. Enhanced aerodynamic solutions are under continuous development to increase the overall efficiency. State-of-art tools, tests, and operating experience contribute to the design success. For aerodynamics the best tool is the CFD (computational fluid dynamics). CFD is a relatively young science within the turbomachinery industrial world as it was only introduced at the beginning of the 1990s. Since then, much effort has been done to calibrate the tool and assess the level of accuracy of CFD, in order to reduce the need of testing activities and maximize the accuracy of the design even from the first attempt (FTY) of margin that needs to be applied within industrial applications. All OEMs need to dedicate a considerable amount of time to compare test results and CFD code results, benchmarking different types of software; it is commonly known that each type of software has multiple parameters that can be tuned (like turbulence parameters, flow distortions at the inlet, leakages modeling etc.) or that can better fit the test results. Once the design is optimized the newly developed aerodynamics need to be validated. Scale model testing is very useful for performance estimation and validation of any computational tool. The geometry of the stage is reproduced in geometrical scale and dynamic similarity is achieved as far as concerns flow coefficient, Mach and density ratio. According to the law of similarity OEMs have also developed good correlation to predict performance for the relative full scale impeller. A model test is a limited power demanding test and this limitation can raise concerns in terms of not being able to identify correctly the left limit (surge or stall of the stage). To avoid this limitation, the use of PCB probes is advisable. These probes demonstrated to be very useful to early detect any sign of flow instability either at surge or overflow allowing having a correct measurement of the real operability range of the stage. This instrumentation allows using a relatively low cost and time consuming tool like a model test to have a reliable and accurate anticipation of the performance that the stage will have in a real compressor. For this reason sometime on critical project these model test are requested by customer in side to have an advanced validation of critical component in order to take preliminary action before the machine is built and in order to avoid schedule impact to the project. Model test can be done in different configuration: intermediate stage, first stage with upstream suction volute, last stage with discharge volute, intermediate stage with side stream. For LNG the most critical stages are within the pre-cooling compressor where the combination of low temperature with high molecular weight and large volume flows leads to Mach number to the extreme. The continuous cost reduction in the O&G market has obliged the OEMs to optimize the rotating equipment for example by reducing the dimension. This leads to the reduction of the impeller exit diameter and the increase of the flow coefficient. Traditional pure centrifugal stages start suffering from poor efficiency and range when flow coefficient exceeds about 0.12 even though some has produced such stages up to flow coefficient 0.18.
improve efficiency and range for flow coefficient range [0.12:0.24] and relative Mach number range [0.8:1.05], an optimized family of stages has been developed. Grimaldi et al. (2007) clearly showed how satisfactory performance can be achieved for this level of Mach.

Figure 7 - Total Pressure profile for New and Old High Mach Impeller at flow coefficient 0.16 and Mu=1.05

Figure 8 - Relative Mach No profile for New and Old Impeller at flow coefficient 0.16 and Mu=1.05. Inlet view

Figure 9 - Relative Mach No profile for New and Old Impeller at flow coefficient 0.16 and Mu=1.05. Blade to blade

This incremental development has been done by following a three-step approach:

1- Review all internal test data and correlation of performance decay of pure centrifugal stages with "simple" geometrical parameters (specific impeller curvature, hub to shroud blade length ratio).

2- Identical activity was done comparing CFD RANS (Reynolds Average Navier Stokes) predictions with test data.

3- A base design respecting all criteria identified in step 1 was constructed and only local CFD optimization was performed

All the three pictures above are built in such a way that left picture is always relevant to the new impeller while the right one to the old impeller. Comparing total pressure and relative Mach number, as clearly shown by fig 5 total pressure distribution is much more uniform for the new solution. Also fig 6 and 7 show how relative Mach number is smoother in the new solution leading to a better efficiency
In the latter two the relative Mach number is shown. It’s visible in the two planes that the high Mach region (Ma>1) is very limited to the tip inlet for the new one granting a smoother flow and an higher efficiency even at such high flow coefficient.

A validation test plan was developed and the comparison between global performance parameters expected from CFD with the early test results showed excellent agreement. Noticeable improvements of range, efficiency, and head were visible. Fig.10 compares efficiency obtained by the five tested stages plus an additional test performed on a lower flow coefficient impeller: new design was proved to be aligned with existing stage at lower flow coefficient than 0.1 and more efficient at high flow coefficient when transition from radial exit to mixed shows its beneficial effect.

![Efficiency comparison between traditional pure centrifugal and Mixed Flow stages](image)

**Figure 10 - Efficiency comparison between traditional pure centrifugal and Mixed Flow stages**

### 2.1.2 Seals

Compressor efficiency can also be increased by acting on internal leakages, trying to reduce them at minimum. Standard labyrinth even if very reliable and proven don’t allow to minimize the leak due to the need of assuming no contact in all operating condition. As alternative and valuable solution abradable seals can be used.

![Abradable seals at impeller eye, interstage hub & balance piston](image)

**Figure 11 – Abradable seals**

They consist in an integral rotating labyrinth that works against a statoric insert arranged into the diaphragm. Abradable coating allows tighter clearance compared with traditional aluminum seals and prevents the possibility of rotor damage in case of abnormal vibrations. The needed clearance are directly generated by the rotor during the different operating condition. This solution is further interesting from a maintenance standpoint, because the inserts can be easily renewable by recoating of the abradable material.

Abradable seals are more effective for low flow coefficient (<0.1) where they can increase the impeller efficiency of about 1%. At higher flow coefficient this advantage is reduced to +0.5%.
2.1.3 Vaned Diffuser / Inlet guide vanes (IGV)

A further option to increase the efficiency is to use vaned parts. Vanes can be introduced upstream the impeller blades (so called IGV or inlet guide vanes) or downstream in the diffuser. Here there are multiple choices from wedge diffuser (typical for integrally geared compressor), vaned diffuser (or rib diffuser).

The IGV is a good solution if coupled with the constant section inlet plenum because of its capability to straighten the large distortions coming from the volute. This is leading to a more uniform flow to the impeller, i.e. it will increase efficiency and operability. Anyway the additional friction losses caused by the blades can minimize the efficiency increase.

The vaned diffuser can increase the efficiency close to the design. They usually reduce it for the alternate cases; for LNG service, operating points move along the curve during the 24h and so a good average efficiency is preferred. Vaned diffuser are more effective at low flow coefficient where the impeller blade exit angle is more tangential and the gas stays longer in a vaneless diffuser than in a vaned, increasing friction losses. In addition vaned diffuser also reduce margin to choke and stall.

Unfortunately vanes are a source for aerodynamic wakes that hit the impeller blades. In case of coincidence of frequency between vanes wakes and impeller natural frequencies the impeller can experience a severe failure. At the end, in case of vaned solution the design is more complicated, less reliable and equal or less effective that vaneless solution. This is the reason why preference is for the vaneless configuration.

![Vaned vs Vaneless](image)

**Figure 12 – Efficiency comparison**

2.1.4 Side streams

Refrigerator compressors are typically equipped with injections between one stage and another to keep all the service within one casing. Presence of side stream leads to increased challenges in performance predictability [12]. Same consideration on CFD design and model test validation can be applied to the statoric parts. OEMs have developed aerodynamic design practice to predict the impact of the shape of the injection stream onto the main stream. Side stream prediction rules have been validated with model test activity done both on test rigs or wind tunnel that have then been also confirmed by exhaustive full scale tests.
It worth to remember that real operating condition may widely differs from design condition for multiple reason such as:

- differences between expected and measured heat transfer on equipment
- differences between expected and measured pressure losses on pipes
- differences between expected and tested performances of pump, vessels, etc
- Favorable compressor performance relative to quoted polytropic efficiency
- API margin (extra head, delta efficiency)
- Allowances on available turbine power
- Any Licensor allowances

![Figure 13 - Tangential Side stream and Radial side stream](image1)

![Figure 14 – Typical Main Flow/ Side Stream ratio](image2)

![Figure 15 – Typical Operating condition for a variable speed compressor in just three months. Large performance variability](image3)

By combining all of the source of variability the result is that plat really operates in a fixed point but in a wide range of flow. If we compare the average efficiency of a machine equipped with vaned diffuser with the same machine but equipped with vaneless, the results is that vaneless solution shows 1.6% better efficiency.
2.2 Mechanical Design

2.2.1 Casing

LNG compressors are done either in, horizontally split and vertically split arrangement. The main reason of the utilization of the horizontally split configuration is the maintenance capability (compressor is arranged between two equipment) and larger volume flows. The inlet volume flow can reach 300,000m³/h and require a 70° flange.

![Graphs showing operating efficiency comparison](image)

**Figure 16 – Operating efficiency comparison**

The trend in increasing volume flow and design pressure (MAWP) dictated by the need of reducing the n. of casings leads to increase in bearing span and casing diameter. In order to minimize both span and internal diameter. A new design adopting bolted end cover solution similar to barrel type concept has been developed. References are available for LNG application with latest project in Australia, characterized by an internal diameter of 3000 mm and a design pressure greater than 40 bar, that has been successfully full loaded pressure tested. An interesting advantage provided by the new casing design is the reduction of rotor bearing span, with consequent benefits on the lateral behavior and stability of the compressor. Reduced bearing span and higher design pressure can lead to future developments to boost profitability by further reducing the number of casings and so CAPEX.

Compressor casing must be compliant to API and ASME requirements, avoiding sections with different design pressure and O-rings on the horizontal. O-rings are not allowed by API mainly because of the large possibility of by-pass at the end of the horizontal flange with possibility of leak.

Compressor wall and flanges must be thick enough to grant a safe operation during the years, compensating transient or out-of-design operation at site. The state-of-art for predicting casing is to use FE tools that should be validated by each OEM. The worst condition to be analyzed is the hydro test pressure which is 1,5 x MAWP. In order to further optimize the casing a thermal transient analysis can be performed to determine the effect of operating temperature on the casing assembly. Also piping load needs to be carefully evaluated.
2.2.2 Impellers

Impellers can take advantage of new tools such as finite element (FE) to improve its robustness, to keep peripheral speed limit at reasonable value (300 m/s), to reduce the weight and to increase the torque transmission. Every new stage design starts with the aerodynamic path, but once it's frozen, the optimum mechanical dressing can be achieved by the use of optimization tools and design of experiment analysis and with optimized cover shapes.
2.3 Rotordynamic

2.3.1 Lateral

One of the most important advance in rotordynamic is the possibility to measure the logarithmic decrement of the compressors by the use of a Magnetic Exciter installed at one end of the compressor. Anyway in the main compressors LNG trains, typically both ends of the compressor are connected with other rotating equipment (EM or other CC) and so the logarithmic decrement measurement with the exciter is not possible during the full load test. Stability tests must be accomplished during performance test or mechanical running test at reduced power with limitation on the effectiveness of the test with present exciter technology. This will not allow to measure log dec in the real site condition. Further step are needed to allow this technology being interesting for these machine.
2.3.2 Torsional

The most used technology for the helper/starter electric motor is the LCI. As known, this technology introduces torque ripple in the shaft line that can lead to severe alternate torque and to the coupling failures if not well evaluated, predicted and mitigated. In addition the larger is the size of the electric motor the stronger is the torque ripple.

Torque ripple needs to be managed in three ways:

- Accurate and validated torsional model to anticipate potential crossings and detune them during design phase
- Accurate and reliable measurement of alternate torques in the most stressed areas (couplings) to validate the model and to identify potential issues
- In case of issues during test have the possibility to install harmonic filters to reduce the amplitude of the dangerous ripples

OEM has gained large experience during last years in the use of this multi-step approach and in measuring and filtering harmonics (if needed) during string test or even during commissioning phase.

2.4 Internal Arrangement Patchwork

Some OEM is well referenced for LNG market and can also leverage on its wide installed fleet to provide fully proven compressors, as well as new reliable solutions.

Usual approach from End users is to maximize the use of proven components and even at the level of duplicating already tested machines (propane and/or mixed refrigerant compressors).
Unfortunately by going from one plant to another differences exist in the process that make very challenging the use of identical machines.

In order to minimize any novelty OEM looks to the possibility of reusing already tested components (casings, stages, seals etc.). During the development of a recent challenging project propane compressor aerodynamics has been built by arranging together impellers and diffusers already used in two different past jobs. These impellers represent the most challenging of the machine.

Final full load string confirmed the soundness of the approach aimed to minimize any risk of delay for the project.

Another positive side effect of this approach is the possibility to reduce performance margins and guarantee tolerances on power with a significant advantage for the End user in terms of project economics.

![Configuration approach](image1.png)

![Project#3 cross section](image2.png)

**Figure 25 – Robust and experienced design**

### 2.5 Operating experience for Rebundle

Some LNG plants are now approaching ten years or more of operations and some operational analysis could be advisable to evaluate re-bundle opportunities to optimize production. Latest technologies can bring significant improvements on efficiency. New High Mach High stages as described above have been designed to improve efficiency without impacting stage axial dimensions. In this way new stages can be installed in the same casing bringing immediate and limited impact benefits on efficiency.

The development of new high Mach stages now can offer more than 4 point of efficiency vs previous technologies. A possible rebundle for a PR compressor can easily increase the efficiency from 72% avg. to 80%avg, roughly 10% lower power.

![c3-3MCL1405 4th stage](image3.png)

**Figure 26 - Efficiency for current and re-bundle stage**
In another plant, a previous debottleneck of the plant has brought the compressor to work beyond choke limit, in a region that potentially can be detrimental for the compressor. New stages with larger operating range have been installed allowing to cover even high flow points with an efficiency close to the design one.

![Figure 27 – Compressor operation: outside the right before (left) the rebundle and inside with new wheels](image)

2.6 Auxiliary services

LNG plants are equipped with several auxiliary services made by different compression trains. These services are needed to increase plant efficiency (BOG, End Flash) or are necessary to keep the gas flowing (feed gas, domestic gas, stabilizer) or for fuel gas.

2.6.1 BOG compressor

Among all the auxiliaries services Boil-off gas compressor (BOG) is one of the most critical. The BOG service recovers gas from the tank avoiding flaring it. BOG typical train is done by fixed speed electric motor plus gearbox plus a two or three centrifugal compressors with the aim to pressurize gas from almost ambient pressure to a pressure needed in the plant that typical is the fuel gas pressure of a gas turbine. The critical aspect of BOG compressor is the temperature.

The minimum design metal temperature is typical -160° and that is also the suction temperature of the compressor; moreover the compressor must work in an alternate case at round -120° plus some other condition at ambient temperature (during recycle or at start-up). The presence of cases with wide range of inlet temperatures makes the compressor difficult to be designed under mechanical point of view: from IGV movement in cryogenic environment to transient operation to dry gas seals insulation.

![Figure 28 – Tank and Torque behavior during transient operation in model test arrangement](image)

In order to guarantee proper functioning of IGV mechanism in all the extreme operating temperatures and conditions OEM has built a dedicated cryogenic model test to verify the behaviour of IGV mechanism and relevant heat insulation system. A scale 1:1 model has been built and inserted in a tank with the possibility to
fill it with liquid nitrogen down to -190°. A detailed test sequence has then verified the proper functioning of the system at different temperatures with also aerodynamic load simulation on the IGV blades (fig 28).

The same tank has been also used to test a DGS insulation system done with synthetic oil (fig 29).

For other components, such as rotor and diaphragms, an intensive FEM campaign was performed to simulate all the transient behavior of rotor and stator and detailed check of relative movement and clearances has been performed to ensure no rubbing in all the conditions.

![Figure 29 – Inlet Flange insulation test arrangement and results with oil temperature of 70°C](image)

From a material standpoint, The only solution at such low temperature (-160°C) is the 9% nickel. A deep qualification test campaign was repeated to verify the behavior of the material at different temperatures and in order to avoid, any issue related to unexpected differential deformation of the casing and the diaphragm that could finally lead to severe failure of the machine.

The outcome of all of these activities was later applied to a BOG service for Qatar. In this case three compressors were built each one equipped with IGV to compress gas to feed Fr9. All the machines have smoothly passed all acceptance tests.

### 2.6.2 CO2 compressor

Recent Kyoto protocol and countries regulation will lead O&G companies to reduce CO2 emission. Many of them have decided to re-inject CO2 inside geological formation. In an LNG plant CO2 can be found in the well gas mixture and must be separated from the other components before liquefaction. For this reason the CO2 is not pure as in the petrochemicals plant, but it is mixed with water or H2S that makes it an acid gas service. Even if there is still a large debate on which technology should be applied on the CO2 service, in case of an high pressure acid gas the best choice till now is still a beam compressor versus an integrally gear for the better robustness required in such critical service.

![Figure 26 – Thermal transient results for rotor and diaphragm](image)
An example of CO2 reinjection service will be installed in the GORGON LNG plant where the service will be accomplished by two barrel compressor as described in details in “CO2 Compression at World’s Largest Carbon Dioxide Injection Plant” presented at Turbo symposium 2012 [15]

2.6.3 Other Compressors

All the other compressors are more standard compressors. There are services that deal clean natural gas such as Fuel gas, Feed Gas or Booster Gas compressors that are usually mid-size barrel compressor driven by Gas Turbine (25-30MW).

3 DYNAMIC SIMULATIONS

Dynamic simulation is relatively new for the O&G business; anyway it has increased its importance for multiple reasons such as:

- Start-up simulation
- Emergency shutdown (ESD) and Anti-surge valve verification
- Process Control software validation, debug and tuning (anti-surge, load sharing, performance controller)
The start-up simulation is extremely important to size the helper motor and to increase the start-up pressure of the compressor. An higher start-up pressure represents a significant saving in terms of refrigerating gas expenditure allowing to minimize flaring it. In addition it has a very positive outcome to the environment.

The ESD simulation can show how much time the compressor will stay on surge and will help to size the hot gas or the cold gas valve to avoid it.

Recently it was also introduced to help the operator to optimize and control the production.

New frontiers of the high fidelity dynamic simulation is the OTS (Operator training system) where it’s possible to train the operator in front of an HMI plus simulation that accurately represents the behavior of the real plant.

CONCLUSION

A complete overview of compressors duties for LNG has been presented. Many innovative considerations and solutions have been shown and ranging from new aerodynamics for impellers to new mechanical arrangement for impellers and casings; robust solutions for new projects and for rebundlings have been also presented in addition to new solution for auxiliary compressors. All these novelties can represent the immediate future of the next generation of centrifugal compressors for the LNG market

REFERENCES


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