Carlo del Vescovo, GE Oil & Gas
Pasquale Manicone, GE Oil & Gas
Lorenzo Bergamini, GE Oil & Gas

DOWNSTREAM TECHNOLOGY SOLUTIONS | PRODUCTS & SERVICES

Centrifugal pumps for upstream oil and gas applications

Abstract

Upstream oil and gas applications present technical challenges to OEMs in terms of materials, pressure, flow rate, installation, integration and general constraints. This article describes, from a deep technical perspective, the main experiences of GE Oil & Gas with upstream applications such as CO_2 re-injection, BB3 pump-produced water re-injection, and BB5 pumping for treated sea water re-injection.

Introduction

For 50 years, GE Oil & Gas has manufactured a wide range of API 610/ISO13709-compliant centrifugal pumps for hydrocarbon processing, refineries, water injection and pipeline services, with almost 20,000 pump units installed worldwide. In the last 20 years, by leveraging our vast experience with R&P pumps and the research and design practices applied to high-pressure sour gas centrifugal compressors, GE Oil & Gas has executed centrifugal pump projects in upstream applications whose complexity was particularly related to the adoption of special materials like superduplex/nickel alloys, discharge pressure beyond 500 bar, and a composite balance of plant integration.

CO_2 Pump Re-Injection for Tupi Pilot

The BB5-type multistage barrel pump was selected for very high pressure CO_2 re-injection by floating, production, storage and offloading (FPSO) systems in the Tupi pilot field. The opposed impeller back-to-back rotor configuration provides good overall efficiency compared to the inline rotor configuration. This is because the central balancing bushing has a smaller diameter when compared to a balancing drum, thus reducing the internal leakages that become a significant source of power losses, especially when dealing with low-viscosity fluids. The configuration also provides improved rotordynamic damping, even in worn clearance conditions, for pumps with such high deltaP and flexible rotors.
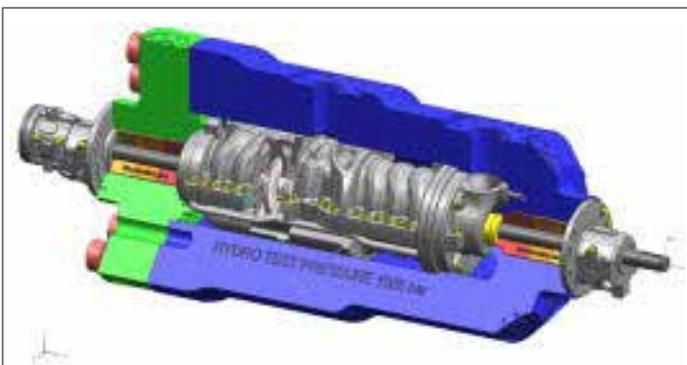
The scope of supply consisted of four pumps operating in series and installed on two separate skids. Each skid has one motor with double shaft-ends, driving two pumps. The selection of pumps in series directly coupled with the driver was due to the small mass flow rate required. Each skid has a dedicated seal system that serves 53B triple mechanical seals buffered with ISO VG5 oil. The suction pressure of the first pump is 30 MPa (4350 psi), whereas the last pump has a rated discharge pressure of 54 MPa (7830 psi). The design pressure of the barrel casing is 67 MPa (API 10000 rating class). The pumps increase the pressure of process fluid after the initial stream compression and liquefaction.

The main features that distinguish CO_2 pump design from conventional centrifugal pumps for incompressible flows are summarized in the following paragraphs, each related to a main design topic:

Impeller design

The impeller was designed to accommodate the variation of the volumetric flow rate through the pump caused by the dense phase compressibility so that the stream could be elaborated with only one identical impeller. (CFD results are shown in Figure 2.) The design of the new impeller family has a more streamlined pattern flow with subsequently higher stall tolerance.

Rotor dynamics

The low density of warm supercritical CO_2 implies low damping and stiffening effects of internal wear ring leakages. Therefore, rotordynamic assessment is a critical aspect of the design process. It's especially important to assess the residual imbalance derived from the balancing capability of a slender shaft that is experiencing the actual damping and stiffening effect of the low density, low-viscosity supercritical CO_2.

Performance predictions

The selection of the pump – like that of a centrifugal compressor – must always account for the high compressibility of supercritical CO_2. Therefore, the polytropic head is the correct parameter expressing the work per unit of mass provided by the pump. Moreover, the polytropic efficiency also is preferred for compressors.

Validating the equation of state, as it's tailored to stream components and related percentage, becomes vital to providing the most accurate performance prediction. While this is normal for compressors, machinery manufacturers have never had to handle a supercritical mixture in dense phase that contains a

FIGURE 1 Cross section of the CO_2 injection pump for the Tupi pilot project
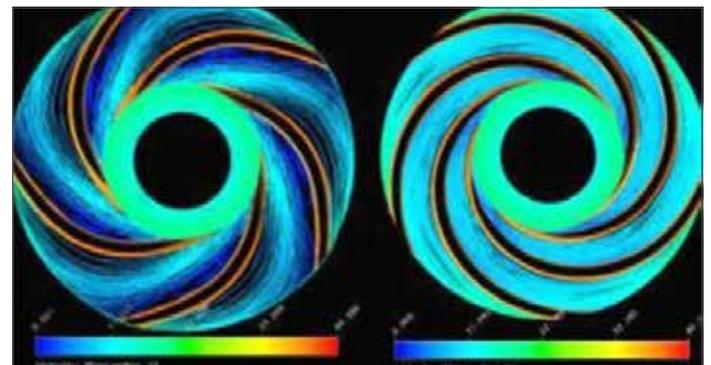
FIGURE 2 CFD of old and new impeller

high amount of.contaminants. The Tupi pilot re-injection stream had a very high percentage of contaminants at pressures and temperatures never experienced by compressor applications. Therefore, a research institute was commissioned to perform density and heat capacity tests that reproduced the same main conditions of the stream in terms of contaminants percentage, pressure and temperature. The identified discrepancies between the mathematical prediction based on mixed rules and the test results enabled the fine tuning of the polytropic head and performances. Figure 3 illustrates a rough operative envelope of the CO_2 pump. The pump adoption also depends on the density variation predicted.
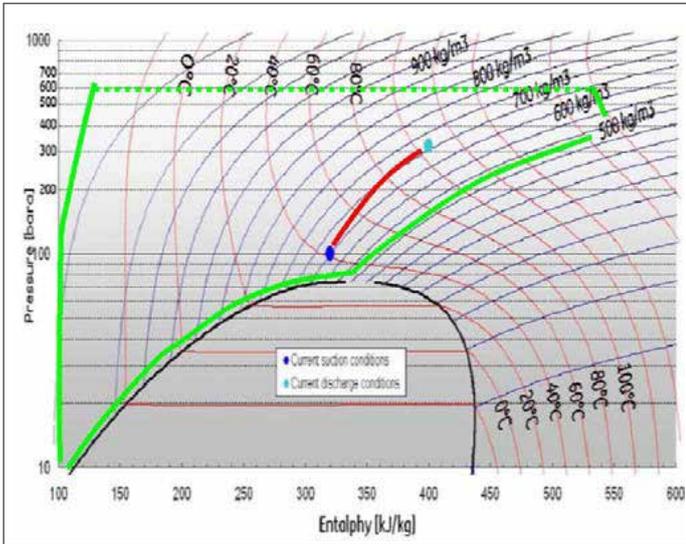
FIGURE 3 Operating envelope of CO_2 pumps

Pressure boundary and materials

The structural design and material selection criteria were derived from the proven experience of CO_2 compressors. For example, the mechanical seals assembly with pump case was made with special shear rings that GE designed to withstand almost 1,000 kN of axial thrust produced by a barrier fluid pressure equal to 550 bara. Given the negligible viscosity of supercritical CO_2, the wear rings were built with self-lubricating composite materials. All outer barrel flanged connections were designed to meet an API 6A standard 10000 rating.

Mechanical seals

The selected seals, which were specifically engineered, were triple seals coupled to the pump case with shear rings, in accordance with the 53B API 682 plan, and a barrier fluid pressurized at 550 bara. The barrier pressure is segmented with an additional seal toward the atmospheric side so that the barrier pressure could be halved in an additional level. In this way, the seal faces design was safer and more robust, with a deltaP on each seal of approximately 275 bar. The mechanical seals were qualified at the supplier's workshop and later tested with the pump on GE's CO_2 test bench.

CO_2 Pumping Testing

The CO_2 test campaign conducted at GE's Bari site had three main phases:

- A low speed (3,580 rpm) campaign with the same Tupi pilot mechanical seals and seal system, using a mixture containing 83 percent CO_2 and 17 percent N_2. Suction conditions were the same on all four installed pumps.
- A high speed (up to 7,600 rpm) campaign with dry gas seals, pure CO_2, and a suction pressure and temperature of 10 MPa and 15°C, respectively.
- A high speed (up to 7,600 rpm) campaign with dry gas seals, pure CO_2, and a suction pressure and temperature of 10 MPa and 40°C, respectively.

GE was able to validate the integration of the pump with the mechanical seals and seal system during the first phase of the testing campaign. The mechanical running was completed successfully with no signals out of the allowable range. Temperature/pressure rise and pump efficiency were validated in the four suction conditions, which were reproduced through subsequent venting, filling, heating and cooling. From the inlet pressure of 30 MPa, to the final outlet pressure of 54 MPa, the gas temperature rose from 40°C to 76°C.

The test was instrumental in adjusting the impeller trimming laws, based on the politropic head required.

The same pump, retrofitted with dry gas seals, also was tested with pure CO_2 at the full design speed of 7,600 rpm. With this configuration, the differential pressure reached 45 MPa (6,525 psi) and the flow rate was 35 kg/s. The stability of the rotor would have allowed the speed to be increased if there had been no limitations on the driver.

FIGURE 4 CO_2 pump testing at GE facility

Figure 5 shows graphs of the measured discharge pressure and total efficiency. The pump was operated at 7,600 rpm with 10 MPa (1,450 psi) suction pressure, whereas the suction temperature was varied between 15°C and 40°C – the typical seasonal range of water-cooled CO_2. It's clear that the same suction pressure yields different discharge pressures at different average inlet densities. The performance chart shows that the values and the shape of the Q-H and efficiency curves vary. Increasing the suction temperature progressively decreased the efficiency.

As expected, the two high-speed test phases confirmed that it was possible to regulate the discharge pressure acting on the water cooling flow rate of the cooler installed upstream from the pump. Even though speed regulation was confirmed as the most efficient and rapid way to regulate, suction temperature regulation is a competitive way to regulate discharge pressure if there are no requirements for system time response.

One of the most important results of the test is the data on the behavior of dry gas seals with liquid CO_2. The assessment referred to the need to heat the CO_2 bled by the pump discharge and used as buffer fluid so that the primary seal of the tandem arrangement wouldn't freeze. This assessment is shown in Figure 6, which reports the thermodynamic scheme of a tandem dry gas seal.

BB3 CO_2 pump

GE's BB3 pump (Figure 7) design has been upgraded to provide a competitive product fit for low-pressure CO_2 re-injection (<200 bara) applications. The main upgrade, involving the mechanical seal chamber, was done to avoid large protruding mechanical seals when there are double or engineered seals, and to guarantee a safe sealing of the gaskets at the outer diameter, which was accomplished by assembling a one-piece sleeve in the seal chamber together with a robust axial gasket at the end of the chamber. The arrangement, which was tested and validated, is shown in Figures 7 and 8.

BB3 pump for produced water re-injection

If the total injection flow rate is split into more than two or three injection lines, the required impeller diameter allows the selection of a BB3 pump instead of a BB5 pump – a choice that improves competitiveness and shortens maintenance lead time. Even though API 610 suggests that BB3 pumps only be used in applications with design pressure lower than 100 bara, GE's BB3 pump can operate with a 10-inch impeller diameter to withstand pressures that are typical of well re-injection applications (>200 bara). In remote areas with natural gas-rich oil fields but poor electrification, high-pressure re-injection pumps can be driven by reciprocating gas engines. In the North Rumaila field in Iraq, GE provided a full package of 10 trains comprised of a gas engine, air starting system, jet-pulse air intake filters, station fuel treatment systems, air coolers, high-pressure BB3 pumps and 10 produced water booster pumps.

FIGURE 5 Experimental test results
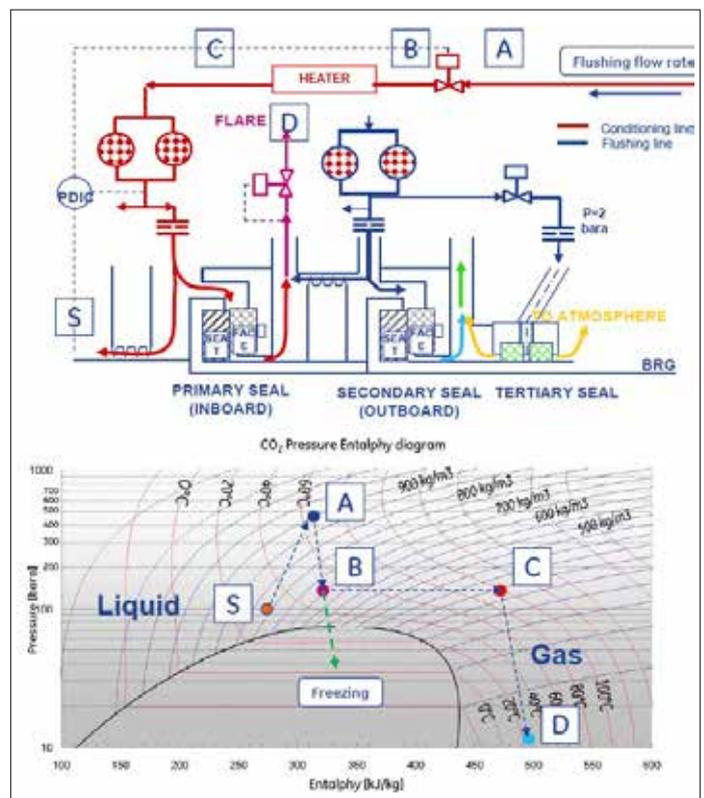
FIGURE 6 CO_2 dry gas seal thermodynamic scheme
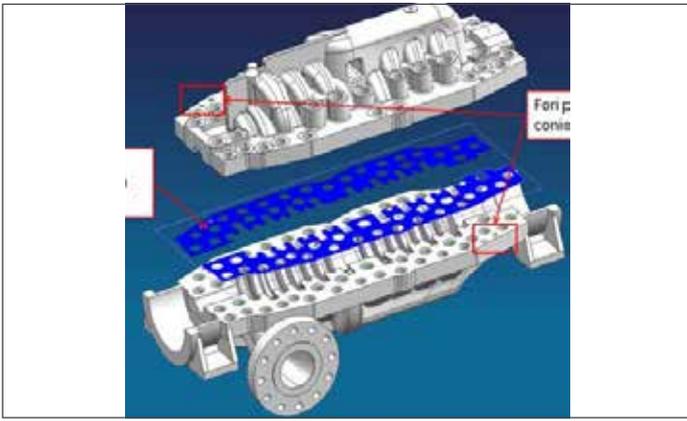
FIGURE 7 BB3 pump features
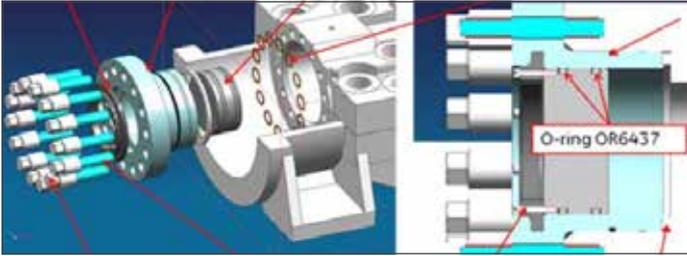
FIGURE 8 BB3 seal chamber re-styling
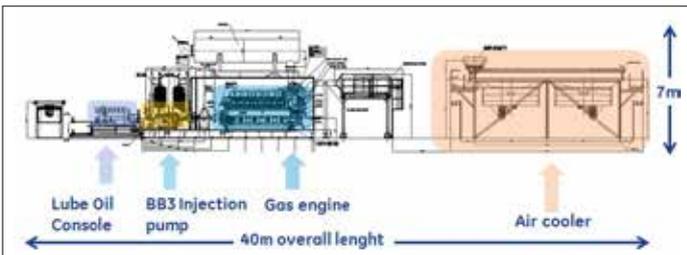
FIGURE 9 Produced water re-injection train with main components
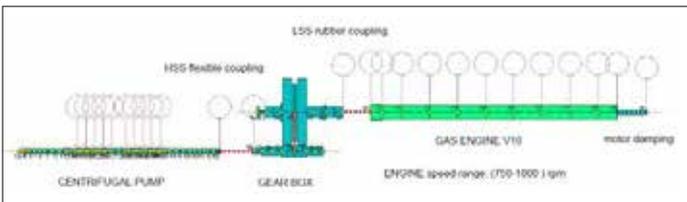
FIGURE 10 Complete rotor torsional model

The main challenge for such a train is ensuring robust and reliable torsional behavior under all operating conditions. Building and simulating such a complex rotor scheme requires significant effort and joint responsibility between pump and engine OEMs, all of whom were within GE for this project (see Figure 10).

Total fluctuating torque, generated by gas pressure and the inertia of engine cylinders, was modeled in stationary and transient conditions. Particular care was taken to address the possibility of misfire combustion in the 16-cylinder engine, a condition in which major harmonic orders could undermine rotor and visco-elastic coupling stability (see Figure 11).

The complete train was string tested successfully during four hours of mechanical running. GE's comprehensive expertise and products simplified the significant integration effort on the package. That said, the produced water re-injection pump itself (Figure 12) certainly presents the greatest technical challenges. The main pump features are summarized in the following table:

Pump model	3x9 MSN10stgs
Speed	5725 rpm
Rated power	2.2 MW
Design pressure	350 bar
Max flow rate	320m3/h
Hydro-test pressure	530 bar
Efficiency	74.2 percent
Process fluid	Water with H2S and very high percentage of chlorides
Materials	Super duplex/nickel alloys
Full NACE compliance	

FIGURE 12 Produced water re-injection BB3 pumps

Misfire combustion engine torque

Rotor stresses
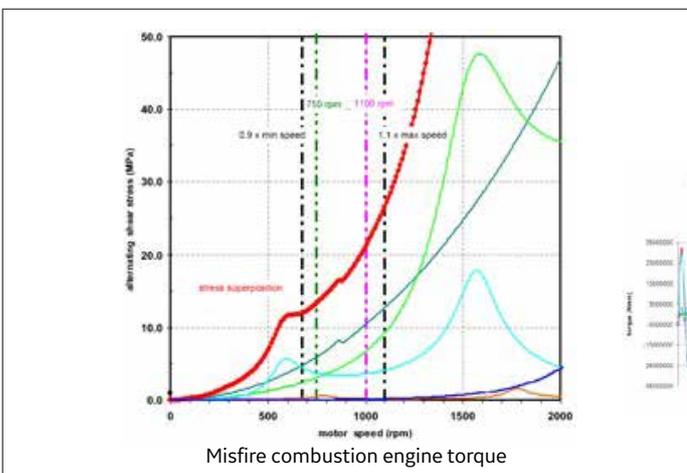
FIGURE 11
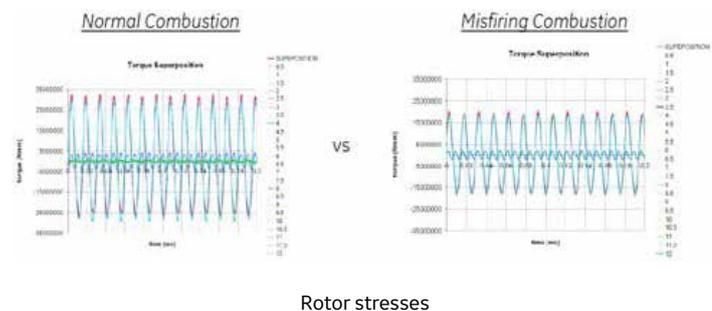
Because of the moderate H2S content of the produced water, the required pump material class was D2 in accordance with API 610 and compliant with NACE. In addition, because of the hardness limit, the NACE compliance excluded ASTM A276 S32760 in strain-hardened conditions for bolts and nuts (considered as wetted parts). On the other hand, ASTM A276 S32760 in annealed conditions doesn't have mechanical properties compatible with design pressure of 350 bara (hydro test pressure 530 bara). Therefore, these conditions induced the adoption of bolts in Inconel 718 instead of Annealed Super Duplex ASTM A276 S32760. Because of the big difference between yield strengths of casted super duplex and Inconel 718 ($\sigma_{Inconel} \approx 2\sigma_{super-duplex}$), and because of the predicted torque applied to the bolts based on ~90 percent of yield of Inconel 718 yield strength, a tightening test was performed to validate the design of threaded joining and the actual axial preload provided by the torque wrench to isolate the torque friction component.
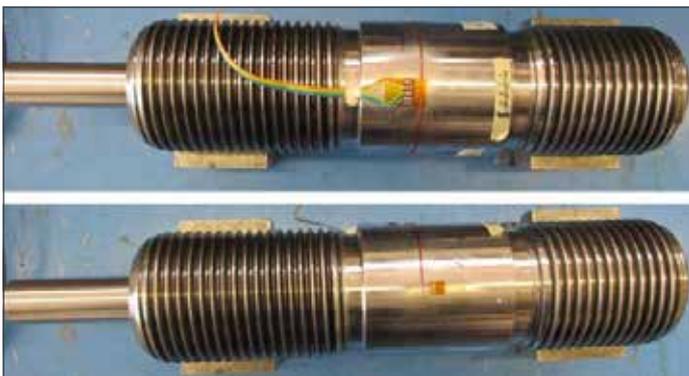
FIGURE 13 Sample - bolts with strain gauges

A M80 bolt sample in Inconel 718 was strain-gauged and assembled with a part in casted super-duplex that reproduced the threaded joining.

The test was made with three lubrication configurations – Molikote paste, Molikote spray, and no lubrication – with all possible combinations between nuts and bolts.
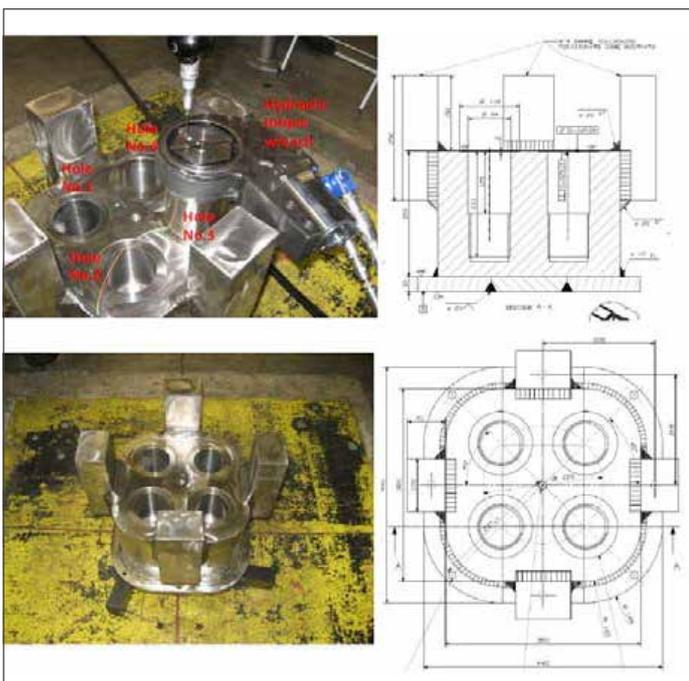
FIGURE 14 Bolting assembly test

This test helped define two important conditions: the function law that correlates preload and torque with a specific lubrication configuration on the threads of nut and bolt and the washer contact area, and the max torque that's possible without any potential damage to the threads of casted super-duplex. Figure 15 illustrates one example of function law of strain and preload versus tightening torque.

This pre-assessment also made it possible for the tightening procedure to successfully conduct a hydro test at 530 bara without any leakage between the mating surfaces of the two pump halves.
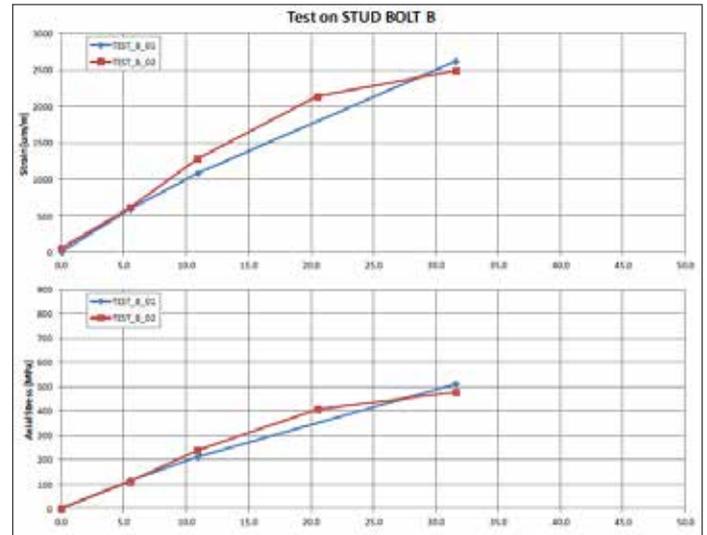
FIGURE 15 Strain and preload versus tightening torque

High-power BB5 pump for treated sea water injection

In 2009, GE Oil & Gas supported increased oil production from the M'Boundi field in Congo Brazzaville by supplying a complete package for sea water injection, including intake transfer, booster and main pumps. All the pumps were in the API 610 D2 material class. The M'Boundi field is 80 km from the coast, where the installed intake and export pumps feed the sea water pipeline up to the injection pumping system that mainly is comprised of a booster pump and main injection pump. Figure 16 summarizes the features of the main injection pump:

Pump model	6x15 DDHF/6stgs
Speed	4200 rpm
Rated power	6.3 MW
Design pressure	255 bara
Max flow rate re-injection	800m3/h
Hydro-test pressure	380 bar
Efficiency	78.5 percent
Process fluid	Treated sea water
Materials	API 610 D2 material class

The BB5 pump was tested successfully, with vibrations widely within API 610 limits (see the spectra in Figure 17).

FIGURE16 M'Boundi main treated sea water injection pump
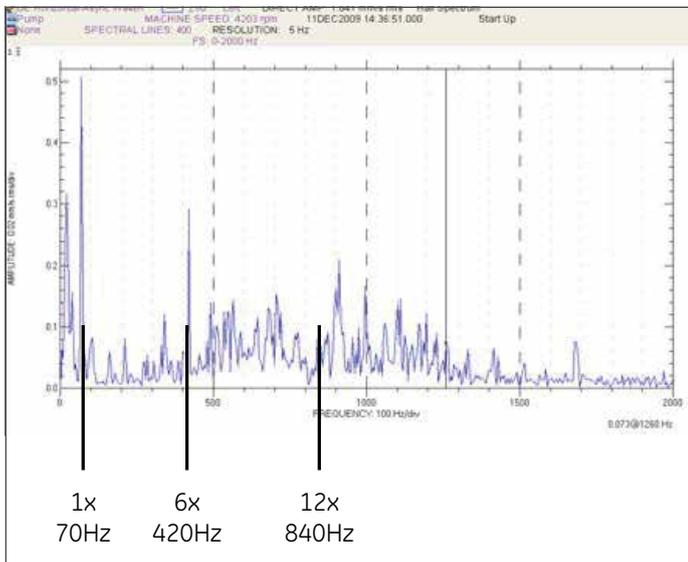
FIGURE 17 Horizontal DE probe vibrations spectra

The overall vibration measured by the Horizontal DE probe was 1.8mm/sec versus the API limit of 4.5mm/sec. The low synchronous (and multiple) vibration level indicates very good rotor balancing and assembly in general. A low vibration level at vane passing frequencies (and multiple vibrations) indicates that the hydraulic design of the impeller was effective, since it was compatible with the pump power/stage ratio.

Spectra measured by the remaining probes raise analogue rotor dynamic and hydraulic considerations. Prior to June 2013, the main re-injection pump accumulated almost 19,000 hours, with just one interruption for mechanical seals (API 682 plan 11) substitution due to unexpected sand content.

Even though the main pump represents the core of the project scope, the project's complexity and balance-of-plant integration make it unique. The project scope was the widest ever performed by GE as a pumping system manufacturer, since only civil works, piping connection, and cable routing weren't covered by it. The scope architecture is displayed in the following single-line scheme:
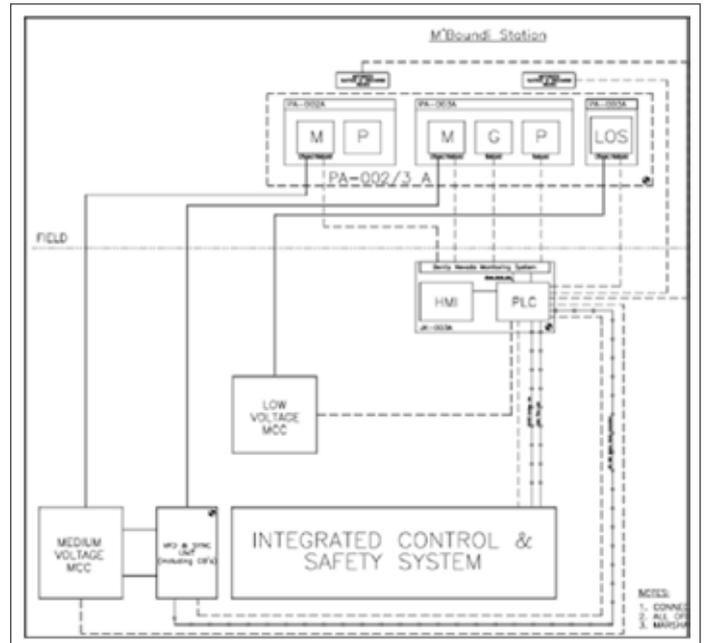
FIGURE 18 Architecture for the M'Boundi re-injection plant

Here is a list of the main items of balance-of-plant:

- VSDS unit
- Transformers
- Monitoring system and programmable logic
- Switch gears
- VSDS chilling units
- HV motor control centers
- LV motor control centers

Conclusions

In the coming decades, upstream oil and gas production certainly is one area where OEMs will have their technology and project management skills put to the test. The essential flexibility demanded by the diverse features of the plant, combined with the nature of the well, give OEMs an unprecedented chance to promote technology solutions that transcend their existing design comfort zone. (High power subsea installation is the best example of this challenge.) Since OEMs in the upstream market have a huge learning curve to travel, only the ones who invest in new, safer, and more reliable technology will form closer partnerships with oil field operators.

Imagination at work

GE Oil & Gas - Global Headquarters
The Ark - 201 Talgarth Road, Hammersmith - London, W6 8BJ, UK
T +44 207 302 6000
customer.service.center@ge.com

Nuovo Pignone S.p.A. - Nuovo Pignone S.r.l
Via Felice Matteucci, 2 - 50127 Florence, Italy
T +39 055 423 211
F +39 055 423 2800

Downstream Technology Solutions
4424 West Sam Houston Parkway North - Houston, TX 77041-8200, US