Abstract

Subsea pumping- and metering represent technologies which may contribute to simplifying and enabling developments of marginal, and remotely located oil & gas fields. The Asia Pacific region has already seen several subsea implementations of the multiphase technologies over the last years which include both subsea boosting- and metering. The multiphase technologies are particularly suitable for offshore- and subsea operations, and offer the operators a cost- effective solution.

The multiphase technology area has gained experience through successful operation since the mid 90s. The fact that natural gas has increased its value in many parts of the world, has driven the request for the next technology step – wet gas compression. However, there are two different system approaches to this challenge;

- **True Wet Gas Compression** – subsea rotating machinery working directly on the wellstream without or limited pre-processing, or
- **Subsea Gas Compression** – marinized dry gas compressors with upstream well-stream processing and associated control systems

This paper describes the development and full- scale test of a Multiphase Compressor, which is working directly on the well stream without pre- processing. A description of how this technology can simplify complex offshore field developments will be given, as well as an overview of the operating characteristics and main features of the compressor.
Introduction

As the world’s need for energy is ever increasing, several major gas field developments are taking place on a global scale. One example is the Snohvit project which went into production in 2006. The field is located some 140km offshore Hammerfest in Barents Sea, at a water depth of approximately 300m. A similar development is the Ormen Lange, which is located some 120km offshore Kristiansund off the west coast of Norway, at water depths in the range of 800- 1 100m. The two fields as mentioned here were developed entirely by the use of subsea technologies, producing back to onshore process terminals, hence eliminating the need for offshore production facilities. Another example may be the Gullfaks area, originally developed in the 1980s, where the Operator has selected the concept of subsea wet gas compression as a means of extending the life of producing assets.

A large part of remaining hydrocarbon resources is located offshore in significant water depths, in some locations as deep as 3000 m. The conventional strategy of implementing floating production facilities for offshore processing is in many cases a major challenge, or not viable, as the metoceanic conditions are simply too challenging. Examples of locations with challenging climatic and metoceanic conditions may be the larger part of offshore Norway, as well as the Northwest Shelf offshore Australia, and Gulf of Mexico.

To solve these challenges the strategy has been to execute complete subsea field developments, eliminating the need for floating production facilities producing back to onshore facilities. In general these projects will also face flow assurance challenges which in many cases are so severe that whole developments may have to be abandoned. The Multiphase Compressor represents a viable option to overcome flow assurance challenges, and at the same time extend the production plateau and increase the recovery of hydrocarbons.

The Multiphase Compressor facilitates a new approach for development and exploitation of typical “stranded gas” resources, and is built on many of the key components of the multiphase pump applications. This approach offers the opportunity to perform true wet gas compression, without relying on upstream separation.

The Concept of Seabed Boosting

Seabed boosting offers an alternative- or complementary system, to other artificial lift techniques and a range of advantages in production and field flexibility. In the multiphase flow domain, the helico-axial design is the core technology adopted, which best suits all process fluid operations as well as the typical operational challenges of slugging, emulsions and sand production. This technology has already been developed, tested, and installed in numerous subsea field applications since the mid 90s, and hence represents a well-proven core technique to meet the markets’ demands. A wide range of subsea pumping systems and technologies are available; single phase pumps (Cx), multiphase pumps (Hx), hybrid pumps (combining these core technologies, HxC) and Multiphase Compressor (WGC), optimising centrifugal technology in a counter rotating method providing a ‘true’ wet gas compressor with no separation required

Supplying subsea boosting systems is not just about having in-depth pump knowledge; but also about having knowledge about, and the responsibility of, the total system engineering and deliverables. Understanding the operational process regimes from start-up and continuous flow, through to managing operational upsets such as emergency shutdowns and the process dynamics, is essential. Accordingly, a pump system supplier should be having this kind of system knowledge in-house, combined with working closely with an Operator in performing dynamic process simulation modelling in the concept stage to maximize the potential of boosting.

Effects of Subsea MultiPhase Boosting

The effect of the subsea boosting on hydrocarbon recovery can be significant. Reference is given to Figure 1 where this is illustrated. The pressure from the well is used to drive the hydrocarbons (condensate and gas) to the first stage separator. The resistance is made up of a static- and dynamic flow resistance that together represent the system resistance curve.

The well production is found from the intersection of the two curves. Installation of a subsea compression system will increase the pressure in the well fluid, i.e., adding kinetic energy directly to the flow. The effect is as if the flowing wellhead pressure is increased. The flow from the wells will increase until a new balance between the fluid pressure and the system resistance is achieved, and consequently the effect is a net increase in oil production.
The Multiphase Compressor

The Multiphase Compressor is based on a counter-rotating principle with a hydraulic and mechanical design specifically designed for boosting of unprocessed well stream. The integrated and fully encapsulated design of the compressor unit is based on the well proven subsea design already applied for the booster pumps.

The machine consists of an upper- and lower drive section with the hydraulic section located in center. Figure 2 shows a general arrangement of the compressor. Two standard subsea process connections bring wet gas to- and from the compressor. An ROV panel provides the interface to signal and barrier fluid jumpers and provides access to the barrier fluid valves used during installation and retrieval of the unit.
Hydraulic Design

The impellers of the Multiphase Compressor are robust, designed to perform with high efficiency, but still managing operational conditions of 90 – 100 % GVF, without upstream gas scrubber or other forms of pre-processing/ separation of fluids. Every other stage is driven by the upper or lower motor respectively, which means that the process of providing energy to the well stream is combined with flow-stream alignment in the axial direction. The absence of the diffusers removes multiphase recovery losses that would otherwise result of this static part.

The compressor is a dynamic machine providing lifting height or head and the resulting pressure boosting is provided by this head. Speed is an important factor as the relation between head and speed is given by equation (1).

\[\Delta H = F (\omega^2), \text{where } \omega \text{ is rotational speed} \tag{1}\]

The pressure boost, which the production system benefits from, is given by the relationship in equation (2).

\[\Delta P = g \Delta H \left[ \rho_G + (\rho_L - \rho_G) \cdot (1-GVF) \right] \tag{2}\]

Where \(g\) is the acceleration of gravity, \(\rho_G\) is the density of the gas, \(\rho_L\) is the density of the liquid and GVF is the gas volume fraction.

This relationship shows that by obtaining a good mix of the phases, which will be the case with the counter-rotating principle, an enhanced density effect will result and increased differential pressure is achieved.

The counter rotating mixing effect provides an efficient cooling of the machine even when there are liquids present in the well-stream. This enables higher pressure ratio capability for the compressor.

One of the key features with the Multiphase Compressor design is elimination of surge. It is a very important part of the design strategy for this machine, that it will not require a complex and comprehensive subsea process and control system. It is even doubtful if an anti-surge system on a multiphase system would work, as the accuracy of measurement of the multiphase flow is not considered good enough. The impellers in the machine are designed with an angle of attack and have a blade loading that avoids phase separation and boundary layer separation, and consequently surge phenomena is avoided.

Mechanical Design

The compressor is designed in three main parts; upper electric motor, compressor section and lower electric motor, as illustrated in Figure 3. The shafts are supported by radial and axial hydrodynamic bearings. Tilt pad thrust bearings are provided in both the motors and the compressor section. Internally pressurized mechanical seals are used as primary seals for reasons of environmental control of the seal face area and to avoid possible erosion problems. A barrier fluid system is used to provide overpressure protection, lubrication and cooling of the compressor critical parts on a continuous basis, during all modes of operation. Suction and discharge flanges are designed to support nozzle forces as specified. All auxiliary connections are either integrally flanged or welded.

The electric motors are oil filled. The oil inside the unit is circulated through external filters and oil cooler by means of an impeller on the motor shaft. The impeller provides supply of oil to the seals, bearings and couplings. The circulation is internal to the compressor assembly; the HPU on shore (or topside) supplies only constant pressure top-up oil to the compressor.
Mechanical Seals
The primary function for the mechanical seals is to separate the process fluid from the barrier fluid in all situations. This is secured by a total of 4 single mechanical seals, two at each end of the compressor. Two of the seals are contra-rotating since they are installed between the outer and inner rotor assemblies. The barrier fluid is pressurized by the external control valve system.

The Multiphase compressor has only static seals against the environment. The internal dynamic seals are pressurized with a pressure higher than the process pressure at all times, any leakage will be from the clean hydraulic fluid into the process flow. Even in case of a total mechanical seal failure, the process fluid may only enter and contaminate the electric motor housing but will not leak out into the environment, as the motor housing is designed to withstand full line pressure.

Thrust Bearings
All pumps / compressors generate forces, both axially and radially, when in operation, and these forces can be carried by suitable bearings, either roller/ball type or dynamic bearings, or counter acted by means of design.

For the Multiphase Compressor the axial thrust is the most important. The generated compressor Δp result in an axial thrust force on both the rotors. The thrust force for the inner rotor is always higher than for the outer rotor due to the nature of the counter-rotating compressor design (part of the outer rotor area is inherently pressure balanced).

The compressor is designed with standard tilt pad bearings of the equalized design.

This version of the bearing has the following main features:

- Well suited for operation with low viscosity oil (the bearing is also designed for operation in water).
- Tolerate higher specific loads than standard white metal bearings.
- Can also operate at high temperatures (250 degrees C).
**Process**

Subject to the process parameters for the application, flowing temperatures and required differential pressure in the system, a process cooler may be required.

The nature of gas compression inherently results in a significant temperature increase across the compressors, and subject to the flow line design temperature a cooler may be installed to lower the temperature of the compressed fluids.

As the process cooler will be installed inline with the multiphase compressor(s) it is proposed retrievable to eliminate any flow assurance related issues. Figure 4 presents a model of the process cooler as is designed for a North Sea subsea compression application. The principle of cooling is free-convection, and is based on a mechanical frame work for process piping.

![Figure 4 Process Cooler](image-url)
Subsea System Design

There are several options for how to package and install the Multiphase compression system hardware. Further assessment and development of the design basis will identify the number of Multiphase Compressor stations to be applied in each case.

A generic concept has been developed, where the station has two compressors, operational valves, required process equipment, electrical power supply and variable speed drive equipment and required instrumentation/control systems. The Framo Dual Pump Station is based on the subsea pump stations as designed, manufactured and installed over the last 15 years, and thus has more than 1 300 000 running hours.

Figure 5 presents the subsea station concept, and is conceptually designed such that both step-wise, or ‘all in one’, installation of compressor capacity is possible.

In a field development scenario where gradually increasing compression capacity will be required over a long period of time, the capital expenditure can be phased over that period.

The modularization and subsea interfaces follows normal industry practices, applicable for control pods, jumpers, chokes etc. The largest retrievable module on the station is the Multiphase compressor module which weighs in the range of 60 tons.

In fields where environmental conditions require overtrawlable structures to be installed this is normally designed as a combined Protection – and Overtrawlable Structure. This is illustrated in Figure 6.
Figure 6 Subsea Dual Compressor Station – In protection structure
Summary

This paper presents the latest technology advance within subsea compression, a true Multiphase Compressor which is working directly on the well stream without pre-processing.

In line with the increase in global demand for energy, the number of gas field developments in remotely located offshore areas is ever increasing. The Multiphase Compressor System represents an attractive field development concept for recovery of hydrocarbon resources located in deep waters and remote fields.

The Multiphase Compressor represents a simplified systems approach to subsea compression, building on the experience of more than 140 years of accumulated run time of seabed rotating machinery. While alternative subsea gas compression systems are based on subsea separation systems utilizing marinized dry gas compressors with upstream well-stream processing and liquid pumps, the Multiphase Compressor will handle unprocessed wellstream comprising, condensate and water.

General data for the Multiphase Compressor range available is presented in Table 1. The WGC4000 and WGC2000 are based on test results from performance testing in Framo’s high pressure multiphase flow loop test facility in Bergen, Norway, presented in Figure 7.

Tests have also been performed in K-Lab, Norway. Typically the Multiphase Compressor has been tested on ideal fluids such as nitrogen and Exxol D80, however, extensive tests have also been carried out using live fluids.

<table>
<thead>
<tr>
<th>Compressor Size</th>
<th>Nominal flow rate [Am³/h]</th>
<th>Nominal head [m]</th>
<th>Max diff. pressure [psi/ bar]</th>
<th>Shaft power [MW]</th>
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</thead>
<tbody>
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<td>WGC2000</td>
<td>1100</td>
<td>5000</td>
<td>515 / 35</td>
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<td>4800</td>
<td>5800</td>
<td>515 / 35</td>
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<td>8000</td>
<td>7300</td>
<td>725 / 50</td>
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</table>

Subsea Multiphase Compressors are today available. The development has been based on the more than 20 subsea multiphase boosting systems that are in operation worldwide, and now offer a real alternative as a field development concept.