WGCPARIS2015
WORLD GAS CONFERENCE
"GROWING TOGETHER TOWARDS A FRIENDLY PLANET"

26th World Gas Conference | 1-5 June 2015 | Paris, France

The Evolution of Completion Practices and Reservoir Stimulation Techniques in the Gas Fields of the Southern North Sea

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Contents

Background

Although North Sea gas production has been in decline for the last fifteen years as it can be seen in Figure 1, technologies exist that can improve production and can help access tighter gas reservoirs previously believed un-economic. Horizontal drilling and hydraulic fracturing are two technologies that, when combined, can slow down, stop or even reverse this declining trend.

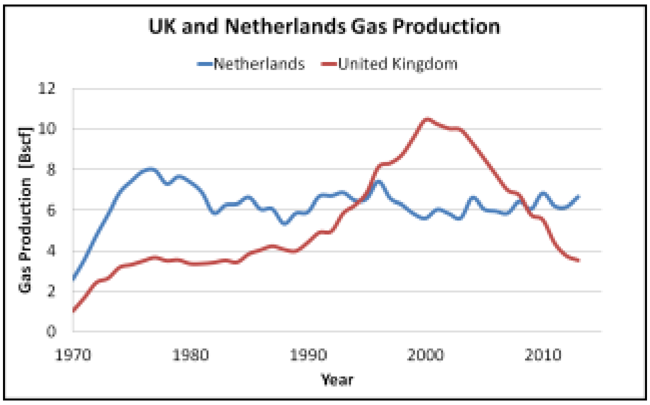

Figure 1: UK and Netherlands historic gas production

Hydraulic fracturing has been used in the North Sea for over 40 years to by-pass wellbore damage and/or access hydrocarbons from tighter reservoirs and increase production in underperforming assets. Its major effect was to extend the economic limit of offshore assets to include reservoirs thought un-economic if completed through conventional methods.

However, fracturing offshore has its specific challenges starting from the equipment required, which typically takes the form of a purpose built stimulation vessel, to the dedicated completion systems that allow for short cycle times in between fracturing stages of a horizontal well. Last but not least, a stringent environmental regulatory framework creates the need for environmentally improved chemicals specific to the North Sea oil industry.

Aim

The North Sea has been and remains at the forefront of safety, environmental awareness and technology within the oil and gas industry. This synthesis of the evolution of well completion practices and hydraulic fracturing in the North Sea aims to create a clearer vision of the future by looking into the past and the way technologies have evolved throughout the years.

The objective of this paper is to collate and share with the industry this evolution and the knowledge accumulated from both operator and service company perspectives. We will follow the evolution of completion practices, particularly in the gas fields of the southern North Sea, from the mid 60's, when hydraulic fracturing offshore was in its infancy, to present day practises where the combination of horizontal drilling and hydraulic fracturing has made possible the development of small stranded fields otherwise considered uncommercial.

Hydraulic fracturing came into spotlight in the past few years due to its extensive application in shale reservoirs however the technology was applied to conventional reservoirs long before the shale gas boom started. Hydraulic fracturing began as an experiment in 1947, and the first commercially successful application followed in 1950. As of 2012, 2.5 million "frac jobs" had been performed worldwide on oil and gas wells with over one million of those within the U.S. land.

In the North Sea the first fracturing treatments were introduced in the mid 60's and since the technology has evolved from a skin by-pass technique to a reservoir development tool [1].

Methods

Throughout the years there have been several milestones in the evolution of gas well completions with the most significant being the transition from single stage fracturing of vertical wells to multi-stage fracturing of horizontal wells in the drive for even greater reservoir contact.

Other major innovations were: the progression from rig/platform based skid equipment to dedicated stimulation vessels, the introduction of resin coated proppant, the evolution of fracturing fluids to meet the stringent environmental regulations and the introduction of dedicated multistage fracturing completions.

In the next paragraphs we will follow the evolution of these innovations.

The early day's pre 1980

The first stimulation treatments took place in the North Sea during mid 60's, and the first survey of stimulation treatments is done by LaFleur [2] in 1973.

During those times there were no stimulation vessels available and one of the biggest challenges was rigging up enough horse power on the deck of the offshore installation in order to achieve the pressure and rates required for hydraulic fracturing.

Up to 1973 there were twenty-seven wells hydraulically fractured in the Rotligendes formation that encountered fracture gradients between 0.7psi/ft and 0.9psi/ft.

Seawater was typical used for preparing the guar-gum based linear fracturing fluids at the time. Continuous mixing was employed and preferred over batch mixing mainly due to the fact that it allowed a reduction in equipment footprint.

Typical propping agents at the time were; 10/20 sand, 8-12 and 6/8 walnut shells, glass beads and a combination of these. The representative job size at the time was between 20,000 to 30,000 pounds of sand with a tail-in of 1,000 to 48,000 pound of walnut shells. In terms of fluid volumes the treatments ranged from 25,000 up to 80,000 gallon of fluid.

These early pioneering days that have seen the introduction of hydraulic fracturing in the North Sea have set the scene for operators to gain confidence in using the technique as well as for service companies to invest in equipment dedicated for hydraulic fracturing and this lead to the construction of the first dedicated stimulation vessels in the area. Figure 2 presents one of the first dedicated stimulation vessels built for the North Sea, the Normand Providence.

Figure 2: The Normand Providence, one of the first stimulation vessels ever built

North Sea Well stimulation in the 80's

North Sea oil and gas field development requires the use of platform facilities for wellhead and processing equipment, the construction and maintenance of the facilities is very costly and damage to the facilities represent a major safety hazard. As many of the southern North Sea reservoirs require stimulation to maximize production rates and economic returns, the damage to surface facilities due to fracturing proppant flowing back was seen as a major problem in the 80's and made some operators completely ignore the technique.

The proppant flowback problem was especially critical in the tight gas sands in the northwest flank of the Leman field which required massive hydraulic fracture (MHF) stimulation, where over a million pounds of proppant were pumped in one treatment.

The vast majority of fracture stimulations conducted in the North Sea during the 80's have been hydraulically propped fractures of tight sandstone gas reservoirs or carbonate oil reservoirs. Tight here refers to reservoirs permeability's in the range of single digit mD's. The 80's saw the development of many aspects of hydraulic fracturing and the North Sea has led the industry in the technology.

The evolution of stimulation equipment

Application of well stimulation, more specifically propped hydraulic fracturing, in the North Sea was limited. The space limitations on drilling rigs and platforms made application of hydraulic fracturing jobs virtually impossible.

In the late 70's and early 80's the first generation of dedicated well stimulation vessels (Normand Providence, Star Pegasus) demonstrated their value, however they could only carry limited volumes of materials and had insufficient flexibility to evolve at the same pace with the operators requirements for MHF.

A second generation of bigger and improved vessels (Big Orange XVIII, Scandifjord and Vestfonn) allowed the application of massive hydraulic fracture treatment offshore North Sea. Figure 3 shows the evolution in size of the stimulation vessels from the early to the mid 80's. These vessels were built during the golden age of the North Sea and their design was superior, especially the flexibility and adaptability of the stimulation equipment, such that some of the vessels are still operating today and are often more versatile than the new generation of stimulation vessels that were built after the year 2000 in an era of "cost savings".

Figure 3: The evolution of stimulation vessels. The first generation type vessel Normand Providence (right) next to the second generation BigOrangeXVIII (left).

Fracturing fluids

One of the technology advances that promoted the widespread use of fracturing was the development of cleaner, more efficient and cost effective fracturing fluids. In the early 80's the fluid of choice became crosslinked organic polymers often with an oil phase added to improve fluid loss. Borate crosslinkers were limited to 180 – 200 degF so for reservoirs above this temperature it was common to employ organo-metallic crosslinkers (eg. Zirconate) and more refined HPG polymers. However shear sensitivity, higher cost and post frac flowback performance in an era before the advent of encapsulated breakers where the main challenges. Most fracturing operations in the 1980s used filtered seawater as the base fluid. By the early 1990s high temperature borate crosslinkers started to be used for all wells below 300 degF and so the entire North Sea market changed to a single fluid system. Commonly prepared with natural guar these proved very reliable and operational simple fluids and with the introduction of encapsulated breaker well flowback performance was greatly enhanced.

Proppants

Initially the most common type of proppant was high quality Jordan sand, mostly 20/40 mesh. At greater depths a stronger proppant was required. The industry developed a range of manmade proppant such as light weight and intermediate strength ceramics.

With the arrival of high viscosity crosslinked fluids the use of high proppant concentrations – up to as high as 16ppa (pounds proppant added per gallon of fluid) – became popular. This lead to large amounts of proppant being produced during the initial flowback period as well as throughout the life of the well. Sometimes this caused serious safety problems due to the erosion of the surface facilities. Interestingly it hardly ever affected the post frac production rates.

Nevertheless it limited the application of fracturing dramatically in the late 80's. Some companies stopped fracturing and opted for alternatives such as acid treatments and somewhat later underbalanced drilling. At the same time it triggered the development of resin coated proppants which opened the way to widespread application of fracturing the North Sea.

Understanding rock mechanics

The 80's also saw the development of sophisticated fracture modelling based on an improved understanding of the rock mechanics involved in fracturing. Several computer programs were created to help with the design of the hydraulic fracturing treatments. Some greatly improved versions of this software are still used today. They now combine rock mechanics, fluid behaviour, proppant transport and tubing flow hydraulics with excellent user interfaces.

North Sea Well stimulation in the 90's

Large fracturing campaigns

Prior to the late 1980s the vast majority of stimulation operations were single fracture treatments on an individual well basis. As offshore discoveries moved to lower permeability reservoirs, but still with significant GIIP and OIIP, large scale stimulation moved from a one off case by case application to being the main option for appraisal and full scale development.

A number of major operators in the southern North Sea and the Danish sector were largely responsible for the maturing of hydraulic fracturing application. It should be remembered that the North Sea was, and still is, by far the greatest worldwide proponent of large scale offshore well fracturing.

It is interesting to review the methods used in The Ravenspurn developments and see how thinking was already moving to address challenges that still face us today. The stimulation operations at South Ravenspurn started in 1988. These wells drilled into the Leman sandstone which was formed by aeolian dunes with a total vertical thickness of 300 – 400ft. The operator realised that in the higher permeability naturally encountered offshore fracture conductivity, as well as length, was important to deliver the high rate producers. This led them to be early adopters of Tip Screenout (TSO) techniques. Given that TSO naturally includes a greater risk of overall screenout then to offset this, and maximise near wellbore conductivity, they undertook an extensive fracture simulation study using scaled wellbores in large stressed blocks to determine the interaction of wellbore to fracture plane [3]. The results of this testing, which dramatically illustrated the visual effects of tortuosity, prompted them to specify a maximum deviation in the payzone of 10 – 15 deg and so resulted in those wells to be hydraulically fractured having an s-shaped profile.

Another operator developing the northern part of the same field, they took on board the learnings already in place and decided to reduce costs by batch drilling then batch completing/stimulating. Three wells at a time were drilled to prearrange target locations and then hydraulically fractured via a packerless frac string and flowed to cleanup through a test spread. Each well took approximately 1 month to frac, flow to cleanup and then hookup to production. The packerless frac string had a number of advantages a) realtime bottom hole pressures no longer relied on gauge link to surface, b) the frac string ID could be designed to minimise surface and bottom hole pressures in a case of a screenout and c) any excess proppant in the string could be reversed out so screenout recovery was quick and inexpensive.

The advent of horizontal well completions

In the early 90's horizontal wells were becoming popular and touted as the solution to poor reservoir drainage. The simple analytical formulas used at the time indicated a horizontal wellbore in a tight reservoir would produce at the same rate as a conductive hydraulic fracture of the same length tip to tip. It was clear that horizontal wellbores would spell the end of hydraulic fracturing offshore. However as we now know the complete opposite came to pass since the adverse effects of vertical permeability, local sand face damage and reservoir heterogeneity etc. were often grossly underestimated leading to disappointing matrix productivity in many cases.

Much of the early horizontal well fracturing with acid and proppant was conducted in the chalk fields operated by ConocoPhillips at Ekfisk in Norway and Maesrk Oil& Gas in Denmark. These were followed by Amoco in 1996 at Valhall whom switched from acid fracturing the soft Tor formation to proppant fracturing instead after trialling such treatments at one month staged intervals on the DP platform. Every well after this successful trial was a multi-stage proppant fractured horizontal completion. Later in 1999 Hess in Denmark developed the South Arne chalk field using only multi-stage stimulations from horizontal wells, both prop and acid, for producers and injectors.

Hydraulic fracturing from horizontal wellbores continues to be the preferred tight reservoir drainage completion in the North Sea. It is used in both carbonate and clastic reservoirs for both gas and oil. It is a process invented and refined in the North Sea and then exported/adapted to other reservoir types around the world. Today 95% of all hydraulic fracturing conducted in the North Sea are staged treatments from horizontal wells and as such the treatment count is many times greater than in the predominantly vertical wellbore days before the late 1980s.

Advancements in pressure analysis

By the early 1990s G-Function analysis has almost completely replaced type curve matching and this was now the preferred method moving forward. By the late 1990s many fracturing engineers also took advantage 3D and pseudo-3D simulators to history match the post injection pressure decline curve and so incorporate more elements of non-ideal fracture behaviour in determining the fluid efficiency etc. Also at this time Post Closure Analysis was in its infancy allowing formation transmissibility to be estimated for the first time without resorting to a well test.

The evolution of resin coated proppants and their importance to the North Sea stimulation history

Resin coated proppant was invented by an American company in 1975. It was originally invented to achieve consolidation of proppant packs by adhesion of plastically flowing resins at their contact points. The resins would polymerize when exerted to heat. The first hydraulic fracturing job was carried out in Texas in 1976.

The coating evolved in the early 80's, into two different categories; a curable resin coated proppant and a pre-cured resin coated proppant.

The curable proppant was the original version that provided all the benefits mentioned above. And most of all provide flow-back control to the proppant pack. The down side was however that the highly floatable resins used at the time, concentrated at the contact points, when exerted to heat down hole, and hence reduced free pore space.

The other direction was the pre-cured resin coated proppant - or also referred to as tempered proppants. Here the resin has been hardened during manufacture. The main benefit is the added crush resistance to the grain and the lesser impact on free pore space, as this resin has less floatability compared to a curable version.

In the mid 80's, the two directions were merged, with the invention of dual coating – a process where you have a pre-cured inner layer of resin that adds strength to the proppant grain and a curable outer coating.

The weight of a resin coating on any proppant is representing less than 5% of the proppant weight, with this technology, and the coating film is just 0,001 inch.

Resin coated sand and ceramics has been used in the North Sea since the 80's.

North Sea, and to some extent for offshore application in general, is highly focused on flow-back control. A typical high overall investment in both wells and surface facilities calls for high end materials that provide adequate pack conductivity, environmental compliance and above all proppant retention in the fracture.

The resin coating used in the North Sea today is a 2nd generation version of a triple coated proppant, developed to meet the more stringent demand for this area.

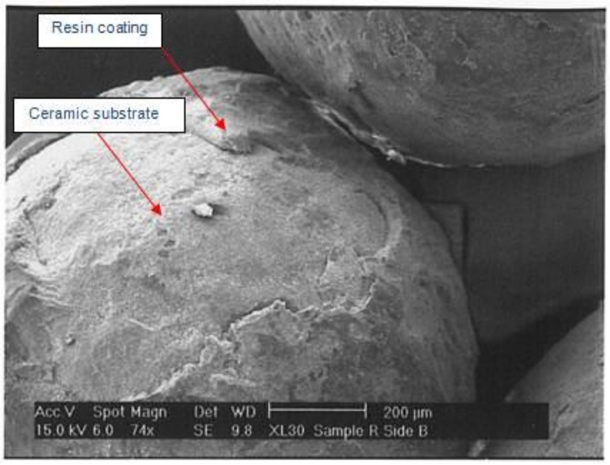

Figure 4:Triple coated proppant seen under SEM. The grains were bonded together and the pack tested up to the point of failure. Damage can be seen in the resin coat where proppant grains were bonded together

This involves, that beside the pre-cured inner layer, adding strength to the grain, and the curable outer coating which ensures the ability to bond grain to grain when exerted to heat in the formation, there is a third layer of a very thin pre-cured coating. The benefit from this coating is that under closure pressure the grain to grain contact points will break through the thin outer coating and get to the curable layer underneath. And here by the proppant will not have the risk for setting up in the well bore, where there is no closure stress. But it will bond and consolidate the proppant pack when formation closes. A second benefit is that the outer layer of today's resin coated proppant makes it very inert and does not affect the behaviour of cross-linked fracturing fluids.

To date there is no alternative way of getting the same security in flow back control of a proppant pack (short of a down hole screen), and achieving the other advantages present when using resin coated proppants.

The arrival of FlexSTIM vessels

By the mid-2000s the number of stimulation vessel in the North Sea was reduced by one to only two. No sooner had this event occurred when demands on the stimulation vessel supply increased to a steady 3 vessels. In order to address demand a new era of temporary platform supply vessel conversions (often term FlexSTIM) began. This involved working with the offshore and vessel certification authorities to fit temporary fracturing equipment spreads, every bit as powerful as the conventional stimulation vessels, onto the 800 – 1000m^2 aft deck of each selected PSV. Approximately 17 such vessels were mobilised and then demobilised between 2007 and the present day and covered both proppant and acid fracturing operations.

Figure 5: Two of the FlexSTIM vessels built in the North Sea during the last decade. Proppant fracturing set-up left and acid fracturing set-up on the right

Mobilisations were for as little as one treatment or for many months working for a series of operators in succession. To date such vessels have worked in every sector of the North Sea. By the late 2000s the number of stimulation vessels had again increased to 3 but now also with 2 long term FlexSTIMs servicing operations in Norway. Even today there is still FlexSTIM type fracturing operations undertaken when absolute vessel availability is a must.

Results

Case study 1: Development of a Stranded Tight Gas Field in the UK Southern North Sea Using Hydraulic Fracturing within a Subsea Horizontal Well [1]

There are more than 100 accumulations in the southern North Sea that are flagged as stranded fields. Tight reservoirs, distant infrastructure, small volumes, and anomalous gas qualities are amongst the main reasons why these resources have not yet been developed. One of these stranded tight gas fields have been successfully developed with the use of a subsea well, horizontal drilling, and hydraulic fracturing.

The Kew structure is a northwest/southeast trending horst straddling licenses 49/4c, 49/4a, 49/5a, and 49/5b of the UK sector approximately 2 km east of the Chiswick field[9][10]. The primary reservoir objectives are the Carboniferous sandstones of the Caister formation (Westphalian A). This gas field has now been developed with a single well that employs a combination of horizontal drilling and multistage hydraulic fracturing to achieve maximum reservoir contact in this low-permeability and interbedded structure.

The absence of data and analogue wells for the design and execution of the fracturing treatments necessitated extended injection tests prior to the execution of the stimulation treatments. To maximize the data acquired from this well, chemical tracers were injected during the stimulation treatments and returns evaluated to assess the flowback of each individual hydraulic fracture. As this was a subsea development well, all the hydraulic fracturing operations had to be performed with the rig in place. Hence, the utmost efficiency of the operations was paramount; otherwise, the economics of the project would be negatively impacted. Innovative techniques of isolation between each fracturing stage were developed to minimize the risk and decrease completion time.

The time of massive gas field discoveries has passed, and smaller developments are proving to be the future, through tying them to existing assets, to boost gas production in the North Sea and extend the life of the existing infrastructure. This challenge was successfully addressed for the Kew field by combining existing technologies and developing new techniques.

Case study 2: Offshore Horizontal Well Fracturing: Operational Optimization in the Southern North Sea [8]

Recently, there has been an increased interest in optimising the techniques used to complete low–permeability, offshore horizontal wells in the southern North Sea, using multistage hydraulic fracturing technology. The application of two complementary technologies enabled the placement of 1.4 million pounds of proppant in four treatments within 4 days. Prior to this, similar offshore completions have taken 12 to 20 days.

Historically, cemented liners and plug-and-perf completions have been used for horizontal fracturing in the area. Such operations involve extensive coiled tubing interventions in between fracturing treatments, including the associated operational and technical risks in long horizontal drains that are often used.

An openhole, ball-activated multistage system, only recently introduced into the North Sea, was applied. In tandem with the application of this completion technology, an environmentally compliant seawater fracturing fluid was also developed. The use of the new seawater-based system allowed sufficient fluid volume to be blended and pumped for the placement of four hydraulic fracturing treatments on consecutive days, without the need for the vessel to reload fresh water.

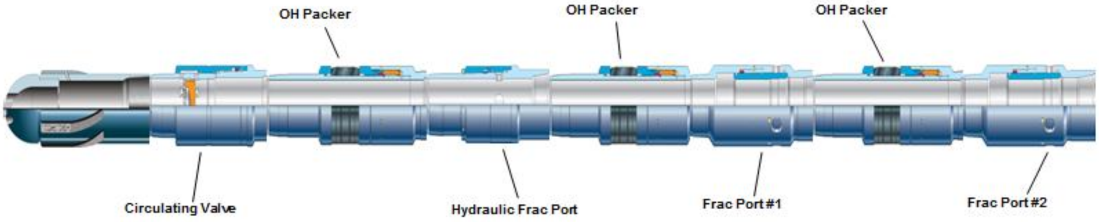

Figure 6: Schematic of a dedicated multistage lower completion system

As a result of the tandem development and correct application of the technologies, the completion eliminated coiled tubing interventions between stages, saving both vessel and rig time. Ultimately, such savings result in faster turnaround times for wells to be placed on production, thereby improving overall well economics.

This application has been so successful that the operator is not only using this as a template for future fracturing operations in the North Sea, but actively pursuing similar new complimentary technologies. Such operational improvements will not only enhance well economics, but possibly define future North Sea fracturing operations.

Conclusions

All of the technologies and techniques presented in this paper have contributed and improved the way we perform hydraulic fracturing in the North Sea today.

The evolution from single fracture vertical wells to horizontal wells with multiple fractures has allowed more reservoir contact for each well hence minimizing the number of wells required for field development, improving reservoir drainage, increasing production and allowing commercial access to tighter reservoirs.

Resin coated proppant (RCP) has removed the problem of produced proppant that existed in the early days of fracturing and gave operators the confidence to even hydraulically fracture subsea wells[1]; this stands as a proof of RCP's effectiveness.

Several challenges arose when multistage horizontal wells started being the norm in the North Sea, isolation between the subsequent stages and the time taken for a fracturing cycle being just two of them. Dedicated multistage completions and fibre enhanced sand plugs are just two of the methods that were used to make multistage fracturing treatments more efficient.

Modular FlexSTIM vessels have helped to tackle the problem of stimulation equipment availability by providing "on request" dedicated stimulation vessel for short or medium periods of time.

The latest advances such as flow-channel fracturing technique, dissolvable completion equipment and environmentally compliant seawater based fracturing fluids have just recently been introduced and promise further significant improvements to the overall completion cycle efficiency.

Even if in its infancy during the early 50's hydraulic fracturing started as a method to by-pass near wellbore damage, throughout the years it evolved into a field development tool that helped operators in the North Sea access very challenging low permeability reservoirs. Hydraulic fracturing helps you "do more with less" and this is crucial in today's challenging economic environment.

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