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Effective Stimulation of Horizontal Wells - A New Completion Method

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Abstract

Over the last several years there have been many developments in horizontal completions. These advancements have been designed to better stimulate the entire horizontal interval. The most notable advancement has been used in cased and cemented liner applications, where composite plugs have provided the mechanical diversion that has successfully stimulated the entire horizontal wellbore. However, the process of setting a plug on coiled tubing (CT), perforating, stimulating and then repeating the process for the required number of stages to optimize production and then running back in with CT to remove the plugs is costly and time prohibitive in many cases. In open hole applications, horizontal stimulations have relied almost solely on limited entry or bullheading in attempts to induce multiple fractures. This method has proven very inefficient and unsuccessful.

A new completion system has been developed that addresses all of the prior issues in stimulating horizontal wells. This system uses a series of mechanical open hole packers deployed on the production liner with fracturing or stimulation ports located between the packers that allow for stimulation in each desired interval. Without the requirement of cementing the liner in place, all the problems associated with cementing are eliminated. By placing a liner in the open hole section rather than leaving it barefoot, accessability and production issues are more easily addressed. Additionally, the mechanical packers provide mechanical diversion at high differential pressures. The system has also been designed, so all of the fracturing or stimulation treatments along the horizontal wellbore can be pumped in one continuous operation, thus minimizing all the associated risks and optimizing the efficiencies for both the personnel and equipment. With hundreds of jobs completed, this paper will detail the operational efficiencies and reliability of this completion system, as well as analyze the cost benefits and production increases that have been noted.

Introduction

Horizontal drilling has been steadily growing for well over a decade and in many cases has become the exploitation method of choice for infill drilling and reservoir depletion. As successful as horizontal drilling has been, there have been significant technology gaps hampering growth in certain applications. These are applications where fracturing or stimulating the reservoir is necessary to proliferate production to desired levels. For cased and cemented liner applications this issue was addressed some years back by the use of bridge plugs set on coiled tubing (CT) to establish mechanical diversion, followed by perforating and then stimulating the well as designed. The process is then repeated for the number of stimulations desired for the horizontal wellbore. After all the stages have been completed, CT is utilized to drill out the composite plugs to establish accessability along the horizontal.[1] This process has been effective for some applications, however, the inherent cost and time of multiple interventions with CT, perforating guns and stimulation equipment needed for each stage, coupled with the mechanical risks of setting and removing the composite plugs has been prohibitive in many cases. This problem is only exacerbated at higher temperatures and pressures, with additional exposure created to personnel and equipment. Further to these developments for cased and cemented applications has been the use of external perforating in recent years. This development has allowed multiple fractures to be placed into the wellbore without the costly intervention, however, the geometric considerations of the equipment are sometimes limiting.[2]

The other method for completing horizontal wells is open hole, either using a barefoot completion or running slotted or perforated liner. Both completion designs provide limited flexibility in stimulation and well control. Stimulations for both completions can either be done by limited entry or by CT washing.[1] However, CT access is limited in many barefoot completions due to the friction buildup in the open hole. This prevents the CT from reaching the toe of the horizontal wellbore in many cases and also any possibility of stimulation beyond where the CT can reach. In perforated or slotted liner completions the CT has the ability to reach further into the horizontal section for stimulation, but water or gas shut-off in these completion designs becomes a major obstacle, often leading to premature abandonment. Evaluating the economic loss is hard to quantify, but there are many things to consider. First, there is the cost of drilling the section of the horizontal wellbore that may contributed little or no production. Then there is the lost production from that section of the reservoir that was drilled, but did not produce. During the life of the well there are often attempts to stimulate or remediate based on particular problems encountered. All these have a cumulative cost affect.

There have been attempts to develop better techniques for accessing and stimulating horizontal wells. In open hole applications chemical diversion has been developed.[3] Chemical diversion has been effective in certain instances, but the need for mechanical diversion in open hole horizontal wells was evident. Further evidence of the need for mechanical diversion has been provided by the micro-seismic data obtained during horizontal limited entry treatments.[4] It was for this reason that in 2000 the development of open hole mechanical diversion was placed at the forefront of research and development. Over the next two years various product components and systems were tested and deployed in the field. These tests led to what is now the standard system for both carbonate and sandstone completions, with more than 200 successful runs to date.

By developing a system that would set in open hole, provide mechanical diversion and allow multiple stimulations or fractures to be performed along the entire horizontal wellbore, it would address the problems associated with open hole completions to date. What was developed was a mechanical open hole packer system capable of withstanding high differential pressures, with specially designed fracturing or stimulation ports that would be located between the packers. A series of these could be run simultaneously in the well on a liner and the fractures or stimulations could be pumped in succession. This system eliminates the problems often encountered when cementing horizontal liners in place, while also eliminating the need for repeated CT intervention into the well for setting bridge plugs and running perforating guns, and the repeated rigging up and down of the fracturing or stimulation equipment. The system provides the equipment be rigged up and down only one time, thus saving time, money and reducing the health, safety and environment (HSE) hazards associated with those activities. This system has significantly increased the applications where horizontal drilling is viable by lowered the completion and operation costs and increasing production.

System Developments

In 2001, it became apparent that there were significant deficiencies for diversion in open hole horizontal wells. It was also apparent, that if a system could be developed, the applications for horizontal drilling would expand exponentially. A product development initiative was undertaken to develop a system for open hole mechanical diversion that could withstand the high pressure environments of fracturing and stimulating.

Through extensive testing and past history, the use of inflatable packers was determined to not be a plausible product for the application for several reasons. First, inflatable packers could not withstand the high differential fracturing and stimulating pressures noted in the vast majority of horizontal drilling applications or potential applications. Second, was the issue of cooling the inflation fluid down during the pumping of the job, which decreased the inflate pressure, thus further reducing the differential capabilities of the tool. Armed with these results and experiences, development began on a more robust system that would be capable of holding 10,000 psi differential treating pressures for long durations. The results of those developments are as follows.

It was obvious if an inflatable packer would not suffice, a mechanical tool would be required. Various mechanical designs were evaluated that would adhere to the operational requirements set forth. These requirements were established after a thorough review of horizontal applications and corresponding performance criteria therein. The packer would be required to sustain differential pressure ratings of 10,000 psi at temperatures up to 400^{O}F and set in holes enlarged up to 30%. Further operational considerations while evaluating liner running procedures, determined that mechanically setting the packers would not be viable due to the required manipulation of the liner string. Through this initial evaluation it was concluded that hydraulic setting for the mechanical packers with mechanical retention would be the optimal solution. Based on input from various customers a dual element system was employed. This provides a redundant seal over a specified length in the event the fracture or stimulation were to propagate horizontally, the packer could retain mechanical diversion within the section length.

Although the design of the open hole packer was crucial, development of the fluid placement method between the packers was equally critical. Two systems resulted from these developments, one designed for carbonate stimulation and the second for sandstone fracturing. Each of these presented unique challenges. The fracturing system had to be designed to selectively open at specific times and once open withstand the abrasive fracturing fluids for extended periods of time. Initial designs for the fracturing port provided for the optimum flow area in conjunction with the system, while maintaining the desired tensile and compressive strengths. For example, in a 6" hole, the standard completion is 4-1/2", so the mechanical properties of the fracturing port were designed to exceed 4-1/2" 11.60 ppf P-110 liner. This provided a greater inflow area than the cross section of that same liner, thus not inducing a pressure drop through the completion. Initiation of the fracturing port was designed to be accomplished with balls that could be dropped from surface during the pumping operation. After dropping the ball, it could be pumped down in the flushing fluid of the previous fracturing interval and land in a specific seat to activate that fracturing port for the next interval and provide a seal on the seat to prevent treating the intervals below. Development of the ball seats was also challenging. The seats for the last stages of the system would be exposed to the majority of the proppant pumped inducing abrasion and erosional effects. Extensive engineering design and testing went into establishing, not only the geometry of the seat, but the proprietary material specifications for the seat. At the conclusion of the laboratory and field tests, the seats exhibited superior wear resistance to the fracturing fluid erosional and abrasion effects. The balls and seats were then sized to allow for the process to be repeated a number of times. Through the above mentioned laboratory and field testing, the balls and seats have evolved to their present configuration allowing eight different size balls to be dropped in the 4-1/2" design. (Figure 1)

The carbonate system used the same principles for activation and initiation, however, to effectively stimulate the horizontal carbonate section, multiple ports at spaced intervals would be required. Through numerous design iterations, a proprietary jetting sub was designed built that would allow various size nozzles to be placed within a single jetting sub and also allow multiple subs to be placed between the open hole packers. The engineering challenge was then to isolate all the nozzles for pressure integrity until the stimulation for each specific section was to be pumped. This challenge was accomplished by plugging the nozzles and establishing communication by using a ball and sub to active the nozzles. In conjunction with this system design was the development of a computer analysis program to optimize the nozzle configuration within a specified horizontal length for best stimulation and production results.

Case Histories

Over the last three years there have been more than two hundred open hole systems installed with more than 800 stages pumped in producing formations of sandstone, shale, limestone, dolomite and coal. To date the maximum number of stages pumped at one time has been nine. The maximum continuous pump time has been 26 hours and the maximum pumping rate has been 130 BPM. In one horizontal well, with eight stages, 3.5 million pounds of proppant was pumped. These systems have been routinely deployed in horizontal wells of +4,000 ft in length, with the maximum horizontal well run in to date being 6,700 ft.

Through this experience, there have been certain aspects of the system that vary compared to conventional operations in comparable areas or formations. The fracture initiation pressure is nearly always less than compared to cemented and perforated applications, but higher than compared to open hole bullheading applications. Evaluating this aspect of the system makes logical sense. When cementing and perforating, the fracture initiation pressure will in most likelihood be higher due to the cement and skin damage created by the operation. When bullheading in open hole, the fracture initiation pressure will be where the rock strength is weakest along the entire horizontal wellbore. Using the open hole packers to segment the horizontal wellbore, the fracture initiation pressure will be where the rock is weakest in that particular segment of the well and there will only be one segment where that pressure is as low as the bullheading scenario. The pressure variation of the system within each segment of the well has proven invaluable when determining the effectiveness of the mechanical diversion. What has been witnessed in the field is when the horizontal wellbore is partitioned, each compartment has a unique pressure signature for fracturing and or stimulating. (Figure 2) This unique pressure signature for each stage provides real time evidence that the packers are providing the mechanical diversion for which they are designed. If the fracture or stimulation was going past the packer, then the pressures would be the same for the adjacent interval.

The extensive field experience of these systems has also provided great insight into the efficiencies, cost savings and enhanced production of utilizing the continuous multi-stage open hole fracturing/stimulating system. In nearly every case, all the fractures and/or stimulations have been pumped in a single operation, taking less than a day to complete. In direct comparison to horizontal wells that previously had been completed by cementing in the liner and using composite plugs for mechanical diversion, the cost and time savings have been astounding. Comparing four wells drilled offset to one another with the same horizontal length yielded the following results. The average well completed by cementing, perforating and setting plugs took 14 days to complete five stages. The two wells using the open hole fracturing system averaged 13 hours to pump six stages. This resulted in more than 13 days saved in completing the well. Although the time and cost savings were significant, the true reward was the greater than five fold average production increase that was realized by using the system. This trend is indicative of other results that have been realized where the system has been utilized.

Conclusions

Although horizontal drilling has grown rapidly over the last decade there are still areas where improvements can have vast impacts on successful reservoir production and depletion. In 2001 a technology gap was identified for horizontal wells with open hole completions, where mechanical diversion was needed to effectively fracture and/or stimulate sections of the lateral that were not being treated effectively or in some instances treated at all. It is from these initial system developments that the horizontal open hole fracturing/stimulation system that exists today was spawned. A mechanical open hole packer was developed specifically to withstand the harsh environments encountered in the high pressure fracturing market. The packer was designed to hold 10,000 psi differential pressure at temperatures up to 400^{O}F and have expansion capabilities of more than 40% the original packer OD. System developments also included fluid deployment systems to be placed between the open hole packers to deliver the desired stimulation fluids. Two systems were designed, the fracturing port, primarily for pumping proppant and fracturing and the jetting sub, primarily for pumping acid into carbonate formations.

This field proven system is now over three years old, with more than 200 successful systems deployed in horizontal wellbores. The versatility of the system is evident in the application span which the system has been run. These applications include wells from 1,000 ft TVD to 15,000 ft TVD, in horizontal wellbores ranging in length from 500 ft to 6,700 ft and in formations from coal to shale to sandstone and various carbonates. Further evidence of the versatility in design of the system is the ability to design the stages at the rig site and put components from the two systems together. In some carbonate environments today, the optimum system being run is a combination of the fracturing ports with the jetting subs, all which are separated by the high performance open hole packers which give the mechanical diversion for the pumped fluid.

It has been through these several hundred case histories that the many efficiencies and benefits have been witnessed. Many horizontal wells that previously were completed using the cemented mechanical diversion system of setting composite plugs and perforating have reverted to the open hole system with mechanical diversion due to the operational efficiencies it affords. By pumping all the designed fractures or stimulations required in the horizontal wellbore in a single day, the well can be placed on production, weeks if not months ahead of previous systems being utilized. With pumping equipment in high demand, a single mobilization and pumping operation becomes very beneficial.

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Nomenclature

ft.	= feet
ID	= internal diameter
MD	= Measured Depth
OD	= outside diameter
ppf	= pounds per foot
psi	= pounds per square inch
TD	= Total Depth
TVD	= True Vertical Depth

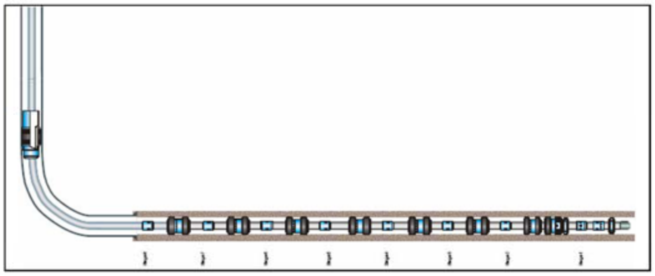

Figure 1 – 8 Stage Open Hole Mechanical Diversion System

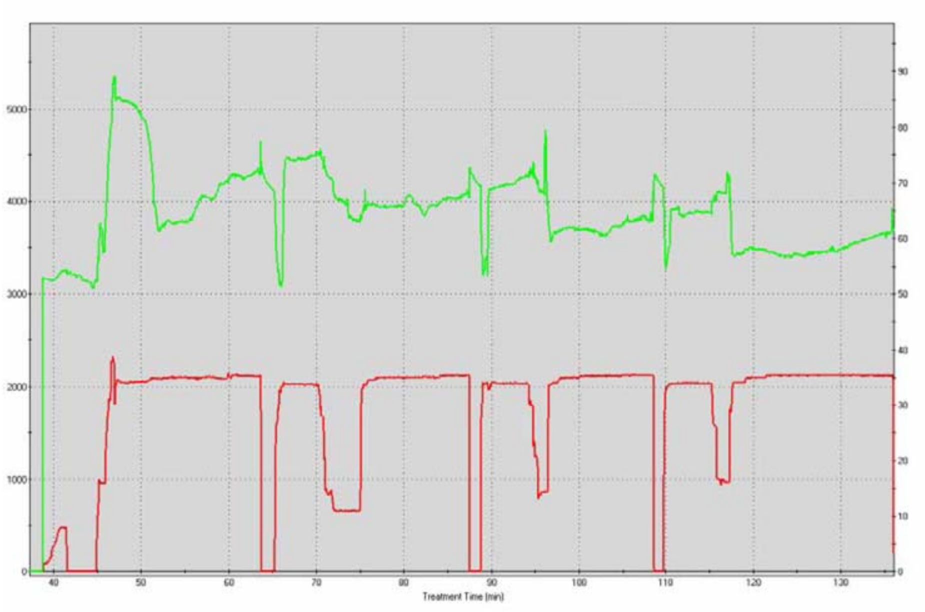

Figure 2 – Chart showing pressure signature for different stages pumped in horizontal well