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Development of a Downhole Separator and Intensifier for Coiled Tubing Jetting

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Abstract

Wells often build scale deposits on the inside of their tubulars that can impede production or interfere with a workover operation. When this scale buildup is over long intervals, coiled tubing (CT) is often the conveyance system used to deliver either acid, drilling or jetting technologies to remove the scale. Acidizing through coil can be effective only if the scale is acid soluble and can be expensive. Drilling with motors can be very effective but motors are susceptible to performance issues especially if high nitrogen ratios are required. Jetting the scale is possible, but this technology also faces challenges. Delivering sufficient downhole hydraulic pressure to overcome the scale's threshold pressure is very difficult due to the limited pressure capacity of CT and frictional pressure losses in long CT strings. Further, if nitrogen is required to ensure returns, the gas phase quickly disperses the fluid jet as it exits the jetting tool and very little power is delivered to the scale face.

Recent technical advances in CT jetting technology include a rotary separator to separate the nitrogen from the fluid and a downhole pressure intensifier to take the separated water and increase the hydraulic pressure delivered to the jetting tool.

The paper first discusses measurements of the threshold pressure required for removal of oilfield scales. The development of a gas separator and downhole intensifier are discussed next, followed by the results of testing of these tools.

Introduction

Mineral scale deposits inside of production tubing can reduce production or interfere with workover operations. Coiled tubing is used to remove this scale using motors or jetting tools. Jet milling of scale is an attractive option because fluid jets will not damage tubulars or other downhole equipment.

Jet milling capabilities are limited by the threshold pressure required to initiate milling and by fluid jet dissipation. The jet pressure delivered to the scale surface determines the ability of the jet to cut a given scale. The jet power then determines the rate at which the scale can be removed. The pressure that can be delivered to a jetting tool through CT is limited by fatigue limits of the coil and the pressure capabilities of available pumps. The jet power, which determines milling rates, is further limited by friction pressure loss in the CT. These losses become more significant in deep wells. One approach to cutting scale at the pressure available through coil is to add abrasives[1], however this approach adds cost and complexity to the operation. Another approach is to boost the pressure of the jets with a downhole intensifier. In the 1990's the FlowDril Corporation manufactured a large scale downhole intensifier pump to drill 7-7/8" to 8-3/4" holes with jet assisted roller cone bits[2]. The unit was designed to work with a conventional rotary drill string and run on drilling mud. The intensifier ratio was 14:1 - delivering 84 lpm at 200 MPa from mud supplied at 1260 lpm and 23 MPa. A similar approach would allow CT pressure to be boosted to a level capable of milling hard scale.

The effectiveness of fluid jetting tools is further limited by dissipation of the jet in the high-pressure well environment. Submerged, non-cavitating fluid jets are subject to rapid dissipation due to turbulent mixing of the fluid. The maximum length of the high-pressure jet core produced by an ideal jet under these conditions is under seven nozzle diameters[3]. Intense turbulence persists to a range of around 20 nozzle diameters. By contrast, water jets in air can be effective at ranges of over 1000 nozzle diameters. Jet dissipation effects are critical in through-tubing well cleaning applications. When nitrogen is added to the jetting fluid to maintain well circulation, jet dissipation is severe.

Cyclonic gas separators have been developed for use with CT[4,5] , however the effectiveness of small-diameter cyclonic separators is limited and no attempt to use the gas to prevent jet dissipation has been published.

A new suite of tools has been developed to allow more effective jetting with coil. A rotary gas separator removes the nitrogen from the jetting fluid to allow jetting with a straight fluid jet. Dual passage rotary jetting tools port the nitrogen around the jets to enhance jet range. A downhole intensifier has been developed to boost the jetting pressure available downhole to enable hard scale milling with standard CT and pumps.

Scale Milling Threshold Pressure

Scale milling threshold pressure measurements were made in a pressurized test stand shown schematically in Figure 1. The scale sample is held inside of a pressure vessel. A rotating jet is passed across the face of the sample. This process is repeated at increasing pressures and the cut depth is observed each time. A photograph of a Barite sample before and after a sequence of cutting tests is shown in Figure 2. Typically, the jet has no effect until a threshold is reached at which point the cut depth begins to increase rapidly. A plot of cut depth versus pressure provides a measure of the threshold pressure as shown in Figure 3, The specific energy of scale removal is defined as the jet energy dissipated divided by the volume of scale removed.

For a given material there is an optimum pressure that minimizes the hydraulic energy required to remove a unit volume of material. Solid materials have a threshold pressure below which virtually no jet cutting occurs. Above this pressure the material removal rate is nearly linear with increasing pressure. A good first order approximation is that volumetric material removal rate is proportional to the square of nozzle diameter. Figure 4 shows the relative energy needed to jet cut material as a function of jet pressure normalized by threshold pressure. The specific energy is normalized to the minimum specific energy. The curve shows that the jet pressure should be at least 20% higher than the threshold pressure for effective scale removal. Table 1 lists the results of jet threshold pressure measurements made in a range of crystalline minerals representative of scale. Data was also obtained for samples of tubing blocked by heavy Aragonite scale and class G neat cement. The tubing scale, which is more porous than crystalline Aragonite. Porosity reduces the threshold pressure required for jet erosion and increases erosion rates.

The tests show that hard scale requires pressures on the order of 100 MPa for effective removal.

Coiled Tubing Pressure

Typical CT pumping pressures range from 28 MPa for low pressure coil to 70 MPa for heavy wall, high strength coil. In areas where hydrogen sulfide is present, the maximum coil pressure will be reduced. The pressure delivered to a jetting tool may be 10 to 30 MPa lower than the pump pressure depending on flow rate and coil size. Figure 5 shows the fluid horsepower delivered to the end of a coil tube as a function of flow rate for a typical deep CT unit. There is a maximum in the hydraulic power delivered of 38 kW at a flow rate of 120 lpm. The pressure available at the bottom of the coil is about 20 MPa. Higher pressures can be delivered by reducing nozzle size, which will reduce flow rate and power, but the maximum pressure available is still not sufficient to cut hard scale.

Gas Separator

Two-phase flow, commingled water and nitrogen, is commonly used in CT interventions to reduce bottomhole pressure and maintain circulation in depleted wells. The reduction on bottomhole pressure increases the differential pressure available on bottom for jetting, however two-phase jets dissipate very rapidly because of gas expansion in the jet

A CT gas separator was developed to take advantage of the increased differential pressure available from commingled flow, while allowing single-phase water jetting. The prototype tool specifications were:

- Diameter: 42.9-mm (1-11/16")
- Length: 375-mm (15")
- Upstream gas fraction: 50%
- Total equivalent flow rate: 190 lpm
- Jet differential pressure: 35 MPa
- Separator pressure loss: < 1MPa
- Gas cut in separated water: < 1 vol%

Engineering Prototype Tests

An analysis of gas separation based on Froude number scaling was carried out to evaluate rotary drum and cyclonic separation parameters. The analysis (summarized in the Appendix) shows that a rotary drum separator is capable of meeting the design specifications. A series of tests were carried out with an engineering prototype separator at a gas pressure of 1 MPa to evaluate rotary speed effects on separation at 95 lpm water flow rate and 50 vol% inlet gas fraction. The separator was constructed with a transparent housing and drum to allow visualization of the flow separation interface as a function of drum speed. As shown in Figure 6, the flow remains mixed until the Froude number approaches the critical value of 1, which corresponds to a rotary speed of 4500 rpm. A gas trap was used to measure gas cut in the water discharge as a function of rotary speed. The results are shown in Figure 7. The gas cut increases dramatically as the speed approaches the theoretical critical speed. Marginal separation occurs at 3300 rpm, which corresponds to a Froude number of 1.4.

Turbine Drive

The prototype separator was equipped with a turbine drive to provide the required rotary speed. The turbine is driven by the mixed flow entering the separator. At increased flow rates, the turbine speeds up ensure separation. In bench tests, this tool provided a gas cut of 0.25 vol% or less. These experiments verified the analysis approach, which was then used to design the high-pressure prototype.

Integrated Tool Development

A high-pressure separator was integrated with a rotary jet milling tool (GS-RJMT) as shown in Figure 8. The high pressure design used Froude number scaling to account for increased gas density downhole. Gas exhaust from the separator is ported through a siphon tube to gas ports on the rotary jetting head, shown in Figure 9. The gas ports discharge in parallel with the water jet nozzles. The water jets are surrounded by a shroud of gas, which reduces the turbulent dissipation of the jets and extends the jet range.

High-Pressure Jet Visualization Tests

High-pressure (35 MPa) testing of the separator and siphon tube was carried out by porting the gas and water discharge through separate, fixed jets and photographing the water jet discharge at atmospheric pressure. Nitrogen expands by a fact of 300 at this pressure, so a small fraction of gas in the water discharge will greatly increase the jet diameter. A gas cut of 1 vol% would double the jet diameter. The separator gas port was sized to operate at up to 50 vol% gas fraction. As shown in Figure 10, gas cut does not occur until the gas flow rate exceeds the capacity of the gas port.

Nitrogen Solubility Effects

It can be assumed that the water entering the separator is saturated with nitrogen, At the tool operating conditions the dissolved gas is equivalent to 1 to 2 vol% which is not separated. Exsolution of gas is a time-dependant diffusion process. If the dissolved gas were to come out of solution in the jets, dissipation would occur and would be visible as jet expansion. The high-pressure jet visualization tests demonstrated that the gas does not come out of solution during transit in the jet.

Gas Separated Milling Tests

Milling tests were carried out with the complete GS-RJMT in hard carbonate scale as shown in Figure 11. The scale was about 98% calcium carbonate with trace amounts of other carbonates, such as $CaMgCO3$ or $MgBaCO3$. It is 100% soluble in acid. The calcium carbonate is in the form of Aragonite. This type of carbonate is much harder than Calcite and more difficult to mill through. The tubing was cleaned to bare metal at feed rate of 1 m/min . The surface roughness seen inside the tubing is due to tubing corrosion.

Cement milling tests were carried out to compare the performance of the GS-RJMT with an unseparated tool operated on commingled water/nitrogen and water only. Cement milling resulted in removal of cement and scale adhering to the tubing without any damage to the underlying tubing. A graphic comparison of the milling rates in class G neat cement are provided in Figure 12. When operated on commingled flow, the gas-separated tool was capable of milling cement at 0.42 m/min without stalling. This rate is 2.5 times the rate of a standard tool operated on water alone. The standard jet milling tool was not able to mill without stalling when operated with commingled flow. Gas-separated jet milling of cement is three times more efficient than the standard jet milling based on the specific energy of milling. The enhanced efficiency demonstrates that the gas is effectively shrouding the jets. Increasing the pressure from 33 to 45 MPa quadruples the milling rate and is twice as efficient.

Job Planning

The GS-RJMT incorporates a gas orifice and water nozzles, which must be sized to provide sufficient jetting pressure and power for effective scale milling. At the same time sufficient nitrogen must be pumped to ensure circulation of jetting fluid and cuttings. Nozzle sizing requires a balance between these competing requirements. A two-phase flow circulation model was used to determine the gas and water nozzle sizes required to provide 35 MPa minimum differential pressure while limiting pumping pressure to 56 MPa. The model assumes full circulation with no fluid loss or well production.

The selection of gas port and water nozzle sizes will depend on the size of production tubing to be cleaned. In particular, circulating pressure losses in the annulus limit the water and gas flow rate that can be used in 2-7/8-inch production tubing. In 3-1/2-inch production tubing or 4-1/2-inch casing, the circulating pressure loss is less significant and larger water nozzles can be used to increase jet power and range. Higher gas flow rates are required to ensure cuttings transport in the larger tubing.

The gas flow capacity of the tool increases as the tool depth increases so the gas flow rate should be increased with depth to maintain differential pressure across the nozzles. The gas flow rates listed are about 1 scmm below the gas capacity of the tool. Operation at higher gas flow rates will cause a gas cut in the water jets and degrade jetting performance. Reducing the gas flow rate will reduce the differential pressure across the tool by about 1 MPa per scmm gas flow rate.

Scale Milling Case Histories

Four jobs were completed in August, 2006 using the GS-RJMT. These gas wells were all highly depleted so the treatment called for cleaning with commingled nitrogen and water. The objective in all cases was to remove heavy carbonate scale from surface to the end of the production tubing and to clean profiles in the tailpipe.

The bottomhole circulating pressure was predicted using a numerical model based on the Lockhardt-Martinelli correlation for liquid holdup, which provides a straightforward means of estimating pressure gradients in two-phase annular flow that can be used over a limited range of flow regimes[6]. This model is coupled to a jetting model that accounts for gas separation and sonic flow through the GS-RJMT and gas port. Predicted circulating pressures for operation in 2-7/8" and 3-1/2" tubing are shown in Figure 13. Flow rates on all jobs were fixed at 110 lpm water and 18 scmm N2. Under these conditions the model predicts that the bottomhole circulating pressure should be well below hydrostatic and the tool differential pressure should be about 43 MPa. This is substantially higher than the 35 MPa tool differential pressure available when operating on single-phase water.

A 5300-m 38.1 mm heavy wall coil was used to provide the service. A second pumper was available during the operation to provide a backup in the event of pump failure during long duration high pressure pumping.

In all cases a 50 micron filter skid was used on surface and a 150 micron screen sub was deployed above the tools. The maximum planned feed rate for scale removal was 6 m/min to ensure complete coverage of the tubing.

Well #1

Total measured depth of the well was 3300 m with 19 MPa estimated bottomhole pressure. Milled 3-1/2” production tubing with GS-RJMT from surface to an obstruction at 2867 m at high feed rate (15 to 20 m/min). Good returns of carbonate scale were obtained throughout the job. Pump pressure was 59 MPa until the CT connection leaked between 2400 and 2800 m causing the pressure to drop to 45 MPa. Total job time to mill this well was 10 hours.

The production tubing was open to casing at the obstruction depth and a wireline impression tool identified a taper and central circular metal obstruction.

Well #2

Bottomhole pressure of 15.9 MPa at 3400-m. Milled 2-7/8” production tubing to 1500-m with GS-RJMT, water only at 130 lpm. Milled hydrate and carbonate scale to 2165-m with GS-RJMT with water only at high feed rate. Milled to 2250-m with commingled water/nitrogen starting at 2 m/min and dropping to zero with hard carbonate scale returns. The pump pressure was 59 to 61 MPa. After pulling out-of-hole, the screens and tools were found to be packed with ferrous iron sulfide that disabled the gas separator. The contamination was traced to the water supply.

Well #3

Total depth was 3318 m with 20 MPa wellhead pressure. Milled 2-7/8” tubing with GS-RJMT using water only to 2575-m. POOH. Milled with GS-RJMT on commingled water/nitrogen to TD at 3318-m. The feed rate was 4 m/min from 2700-m to TD. Pump pressure was 56 to 59 MPa at TD. Iron sulfide scale returns. Pulled out of hole and the tool was still in good shape. Total job time was 12 hours.

Well #4

Milled 2-7/8” production tubing to 750-m with GS-RJMT and water only. POOH. Milled to 2753-m with GS-RJMT with commingled water/nitrogen. Pump pressure was 10 MPa low. POOH. GS-RJMT tool was still effective but CT connector O-rings had failed. The remaining 500-m of tubing was later milled to TD using a motor and mill over a period of 5 days.

Case History Discussion

Two of the four milling jobs demonstrated the ability of the GS-RJMT to remove heavy carbonate and iron sulfide scale at high feed rates with commingled water/nitrogen in 2-7/8” and 3-1/2” production tubing. Operation with commingled water and nitrogen provided good returns to surface in these highly depleted wells. The two-phase jetting and circulation numerical models provided reliable predictions of pump pressure and ability to circulate in these depleted wells.

Two of the jobs were unsuccessful due to job execution issues. On Well #2 heavy internal deposits from contaminated water stopped the separator. Good control of water quality is essential for any jet milling job. A CT connection failure on Well # 4 prevented high-pressure milling. Commingled operation of the GS-RJMT provided substantially higher differential pressure across the tool than operation on straight fluid because the gas reduces the bottomhole pressure. A premium CT connection should be used for this work to withstand the higher differential pressure and nitrogen in the fluid.

Accurate tubing profiles were not available for these wells leading to unnecessary trips and added costs. Pre-job well pressure data was also limited, preventing accurate planning of tool configuration.

The scale milling operation required the use of a high pressure coil and pumper operating for up to 8 hours at 60 MPa. The hourly cost of high-pressure pumping and coil is about twice the cost of a low-pressure coil with a conventional motor and mill. Jet milling must therefore be twice as fast as motor milling to be cost effective. Trouble costs associated with poor water quality and coil connection failures can be avoided with careful job planning and execution.

Downhole Intensifier Development

As discussed previously, hard scales such as crystalline Aragonite and barium sulfate have threshold pressures as high as 80 MPa. Efficient and reliable milling of these scales requires 100 MPa, which is 25% higher than the threshold pressure. The RJMT incorporates pressure-balanced seals and bearings that can be configured to operate at 100 MPa (14,500 psi) differential pressure but surface CT pumping pressure capacity is typically limited to 28 MPa with a smaller number of 50 MPa units. The RJMT differential pressure that can be delivered at reasonable single-phase flow rates is limited to 20 to 35 MPa. Two-phase flow with a gas separator increases the differential pressure across the GS-RJMT to 30 to 55 MPa.

A downhole intensifier has been developed to boost the pressure delivered to the end of a coil to levels high enough to efficiently remove the hardest scales encountered in the oilfield. The intensifier is integrated with a gas separator and high-pressure RJMT. This BHA is designed to operate on two-phase flow to take advantage of the increased BHA differential pressure and gas shrouding benefits. The design specifications were:

- Diameter: 54 mm (2.125”)
- Differential jet pressure: 50 MPa with 30 MPa BHA differential and 28 MPa surface pressure.
- Differential jet pressure: 100 MPa with 55 MPa BHA differential and 50 MPa surface pressure.
- Two-phase operation with gas separator.
- Gas shrouded jets.

A schematic of the double acting intensifier design is shown in Figure 14. Commingled nitrogen and water are separated into a gas-rich and water-only discharge. The gas-rich side pressurizes a large-area piston that drives a smaller piston to boost the pressure of the water. A shift mechanism is actuated when the piston reaches the end of its stroke to reverse the stroke direction. The piston reciprocates to provide continuous high-pressure water. The area ratio between the low-pressure and high-pressure piston determines the pressure intensification ratio. The low-pressure, gas-rich exhaust is ported to shroud the water jets.

The prototype BHA shown in Figure 15, consists of a 2.00” gas separator (GS), 2.125” intensifier (DHI) and a 2.125” high-pressure rotary jet milling tool (HP-RJMT). A screen sub (not shown) increases the total BHA length to 2.82 m (111 in).

For a given flow rate, a high-pressure nozzle is smaller than a low pressure nozzle. In order to ensure complete coverage of the cutting face, the high pressure tool incorporates a larger number of jet nozzles. Figure 16 shows a six jet high-pressure milling head with nozzles configured to cut the entire area ahead of the face. Gas is ported to each jet nozzle. Figure 17 shows the cutting pattern produced by this nozzle head in hard sandstone at atmospheric pressure. Each jet cuts to the radius of the next jet radially outwards to ensure penetration.

Performance Tests

The prototype tool was instrumented with transducers to allow observation of primary and secondary pressures as shown in Figure 18. The high-pressure rotary jetting tool discharges into a pressure vessel. Pressure in the vessel is maintained with a choke valve. An example pressure record is shown in Figure 19. The record shows the total high-pressure discharge, vessel pressure and intensification ratio. The outlet pressure drops dramatically at the end of each stroke.

The pressure output of the tool is sensitive to the size of the high-pressure discharge nozzles. The outlet differential pressure versus inlet pressure is shown for two fixed nozzles and the six-jet milling head in Figure 20. The observed intensification ratio is 2:1. The prototype DHI has an area ratio of 2.5:1. The difference is due to frictional pressure losses snf leakage in the tool.

Scale Milling Tests

Scale milling tests were carried out with the prototype BHA in the pressurized test stand shown in Figure 21. Operating conditions were 100 lpm water, 15 scmm N2, 5 MPa vessel pressure and 30 MPa differential pressure across the BHA. This tool milled through 40 cm of heavy scale in 2.875” production tubing under varying differential pressure and feed rate conditions. Two 10-cm sections were milled at an average speed of 0.6 m/min. The milling pattern in the scale is shown in Figure 22. Note that the tool removed the scale to bare metal.

Conclusion

Hard scale milling requires differential jet pressures of up to 100 MPa in the hardest scale and 50 MPa in heavy carbonate scale. Single-phase totary jet milling tools deployed on standard, corrosion resistant CT can deliver about 20 MPa differential pressure with a pump pressure of 28 MPa and 35 MPa at 60 MPa pump pressure. The higher pressure operation requires high cost pumping and coil units. In those cases where commingled water and nitrogen are required to maintain well circulation during scale milling, two-phase jets are ineffective.

A gas separator rotary jet milling tool (GS-RJMT) has been developed to allow jet milling with a commingled water and nitrogen. Pumping nitrogen increases the jet differential pressure to 45 MPa with less than 60 MPa pump pressure. Shrouding the jets with gas increases the range and effectiveness of the jets to allow cleaning of downhole profiles and equipment. Field trials have demonstrated high rate jet scale milling and cleanup of downhole profiles while maintaining circulation in depleted wells. The hourly cost of the operation is higher than with a motor and mill. If higher feed rates can be sustained the tools can provide a net cost benefit to the customer. High-pressure operation requires careful attention to water quality and CT connections to ensure trouble-free operation.

A downhole intensifier has been developed to address the costs and availability of high-pressure pumping. This tool boosts the pressure available downhole by a factor of two. These tools provide the ability to mill the full range of oilfield scales using conventional CT equipment. The jetting tools further offer the capability of cleaning profiles and mandrels without the risk of mechanical damage to tubing.

NOMENCLATURE

a	=	acceleration (m/s^2) \
F_r	=	Froude Number
l	=	liquid layer thickness (m)
r	=	separator drum radius (m)
Q	=	volumetric flow rate (m^3/s)
v	=	mixed flow velocity in separator (m/s)
v_a	=	axial flow velocity (m/s)
ϕ	=	gas fraction (%)
ρ_l	=	fluid density (kg/m^3)
ρ_g	=	gas density (kg/m^3)
ω	=	angular velocity (rad/s)
BHA	=	bottom hole assembly
CT	=	coiled tubing
DHI	=	downhole intensifier
GS	=	gas separator
HP	=	high pressure
POOH	=	pull out of hole
RJMT	=	rotary jet milling tool
TD	=	total depth

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Appendix

Separation Analysis

Both rotary and cyclonic separation were considered for this application. Effective gas separation requires that the buoyancy of the gas phase overcomes the turbulent shear forces that cause mixing. The ratio of shear mixing to buoyancy forces can be described by the densimetric Froude number[7],

$$F_r = \sqrt{\frac{\rho_l v^2}{al(\rho_l - \rho_g)}} \quad \text{.....(1)}$$

where a is the radial acceleration, l is the thickness of the liquid layer, ρ_l is the liquid density, ρ_g is the gas density and v is the mixed flow velocity relative to the surface. If F_r is less than one, the phases will separate and the fluid flow will be uniform with no further mixing. The flow layer thickness is the difference between the radius of the gas core and the separator radius and is determined by the gas fraction, ϕ, in the separator,

$$l = r\left(1-\sqrt{\phi}\right) \quad (2)$$

The centrifugal acceleration in a rotating system is given by

$$a = \omega^2 r \quad (3)$$

where ω is the angular velocity in rad/s and r is the radius in m.

Rotary Gas Separator

The velocity relative to the drum of a rotary gas separator is

$$v = v_a = \frac{Q}{\pi r^2}, \quad (4)$$

where Q is the mixed flow rate at the pressure and temperature conditions in the separator. These equations can be combined to give the critical drum angular velocity required for separation,

$$\omega > \frac{Q}{\pi r^3}\sqrt{\frac{\rho_l}{(1-\sqrt{\phi})(\rho_l-\rho_g)}} \quad (5)$$

The separator drum radius inside the 43-mm (1-11/16") diameter prototype GS-RJMT tool is 15-mm (.015-m). The flow specification is 190 lpm (.0032 m^3/s) with 50% nitrogen. At 37 MPa and 60 °C the nitrogen density is ρ_g=335 kg/m^3. the critical drum speed is 6400 rpm, which can be readily achieved with a turbine drive and pressure drop under 0.5 MPa. The engineering prototype testing discussed in the paper confirmed that separation initiates at $F_r \approx 1.4$ and very low gas cut is achieved when $F_r \leq 1$.

Cyclonic Separation

The separation force in a cyclonic separator is generated by high velocity circumferential flow, which also results in high shear flow. The flow velocity used in the Froude number calculation is the vector sum of the axial flow velocity, v_a and the circumferential velocity, ωr. The Froude number is

$$F_r = \sqrt{\frac{\rho_l(v_a^2+\omega^2 r^2)}{\omega^2 r^2(1-\sqrt{\phi})(\rho_l-\rho_g)}}, \quad (6)$$

which implies that

$$F_r > \sqrt{\frac{\rho_l}{(1-\sqrt{\phi})(\rho_l-\rho_g)}}. \quad (7)$$

The Froude number for a cyclonic separator is greater than one for any gas fraction or density greater than zero. From the specifications for the GM-RJMT, $F_r > 2.3$, which is too high for effective separation.

Table 1. Jet erosion threshold pressure.

Material	Threshold Pressure (MPa)	Specific Energy @ 100 MPa (J/mm^3)
Barite (barium sulfate)	85	5.0
Hematite (iron oxide)	55	4.0
Aragonite (carbonate)	65	33
Bone coral (carbonate)	80	20
Heavy Aragonite scale	23	0.9
Pyrrhotite (iron sulfide)	70	1.0
Portland cement (Class G neat)	60	0.6

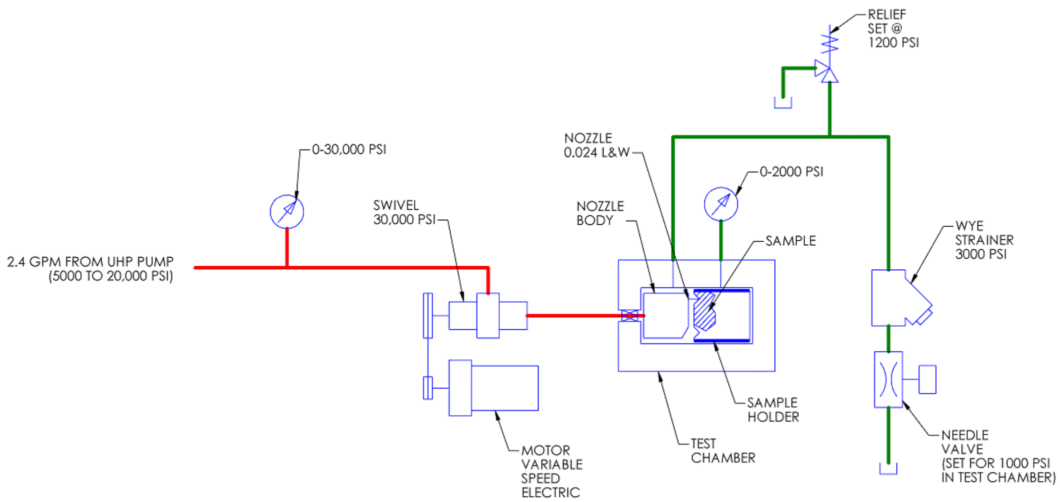


Figure 1. Threshold pressure test stand schematic.

Figure 2. Barite sample before and after jetting at 90 MPa (13,000 psi). Dark material is epoxy.

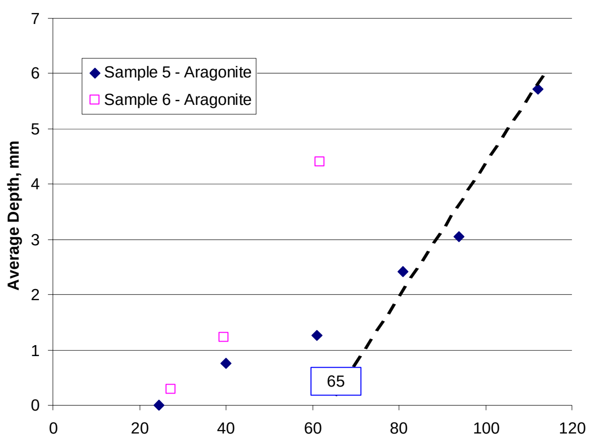


Figure 3. Example of threshold pressure data for crystalline Aragonite.

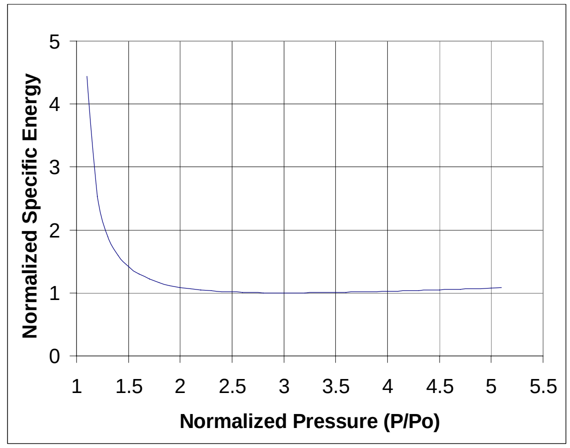


Figure 4. Specific energy for versus normalized pressure, (Po is threshold pressure).

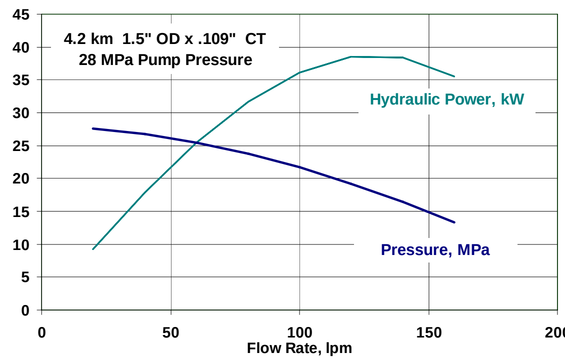
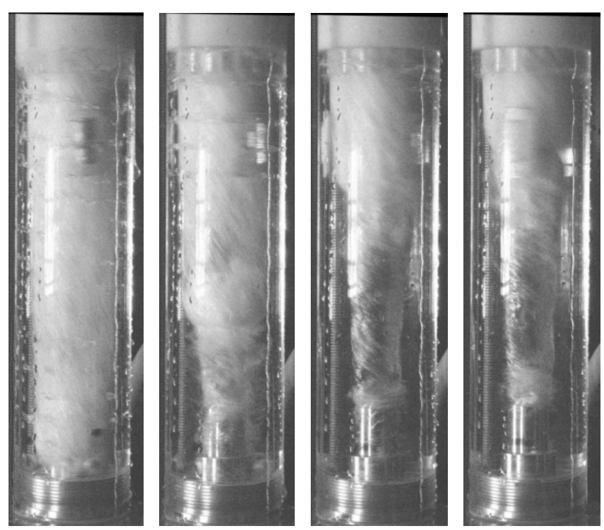


Figure 5. Fluid power and pressure available at the end of a low-pressure coil on straight fluid.



F_r = 2.1 1.6 1.2 .96

Figure 6. Visualization of water/gas interface in transparent separator drum as a function of decreasing Froude number (increasing drum speed).

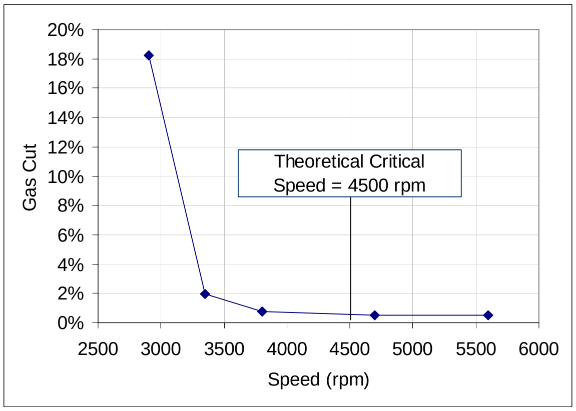


Figure 7. Gas cut versus drum speed.

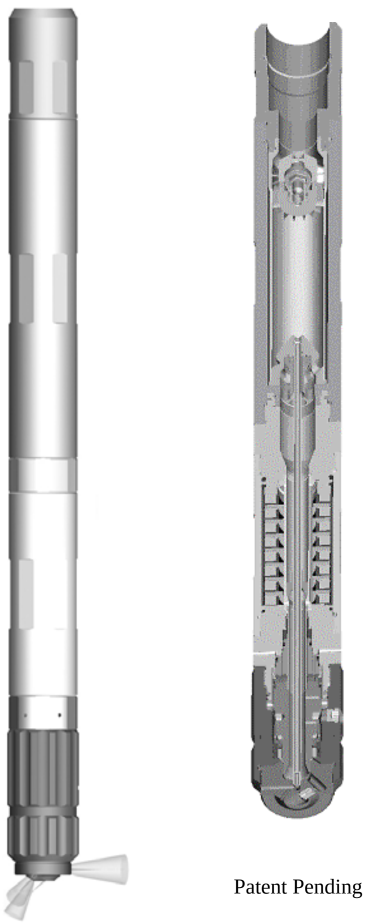


Figure 8. Gas separated rotary jet milling tool (GS-RJMT). Tool diameter is 51 mm (2”), length is 643-mm (25.3”)

Figure 9. Jetting head showing forward facing water jet nozzles and gas ports after service.

0% gas upstream

48% gas upstream

52% gas – gas cut in fluid jet

Figure 10. 35 MPa water jet discharge from gas separator at increasing inlet gas fraction. Fluid discharge port on fixed head.

Figure 11. Heavy carbonate scale milled at 1 m/min with GS-RJMT at 34 MPa differential pressure, 90 lpm water, 15 scmm nitrogen.

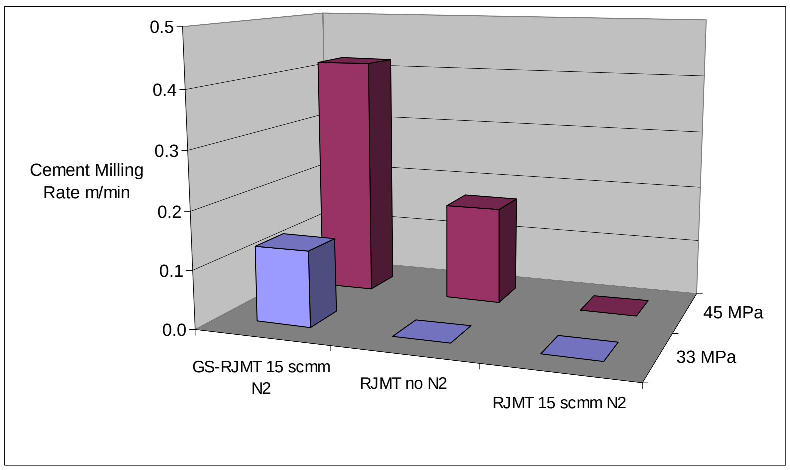
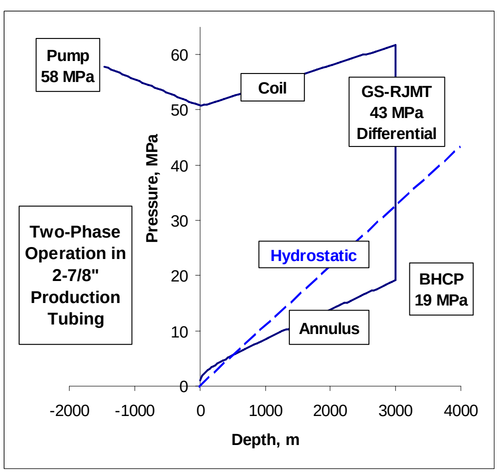


Figure 12. Comparison of class G cement milling rates with GS-RJMT and unseparated RJMT.



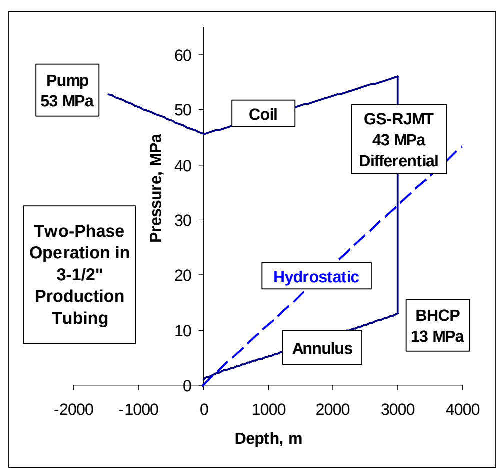


Figure 13. Commingled (110 lpm water/18 scmm N2) circulation in 2-7/8" and 3-1/2" production tubing at 3000-m vertical depth with 4456-m of 38.1-mm high-pressure coil. Hydrostatic gradient is also shown.

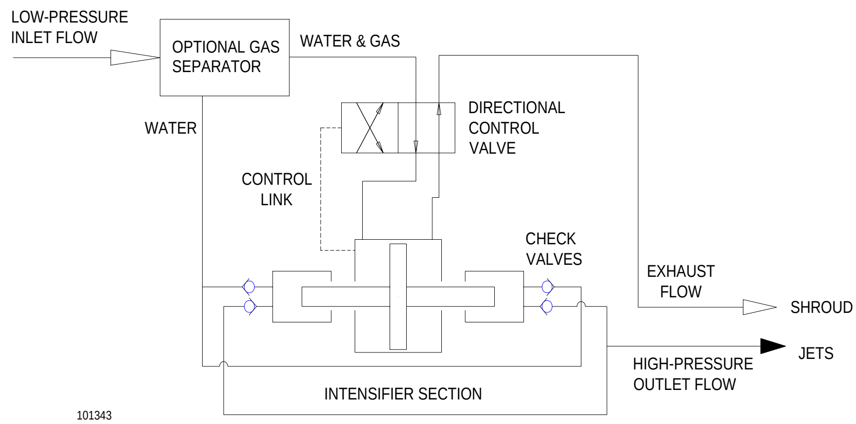


Figure 14. Intensifier schematic.

Figure 15. Downhole intensifier BHA including gas separator, downhole intensifier and high-pressure rotary jet mill.

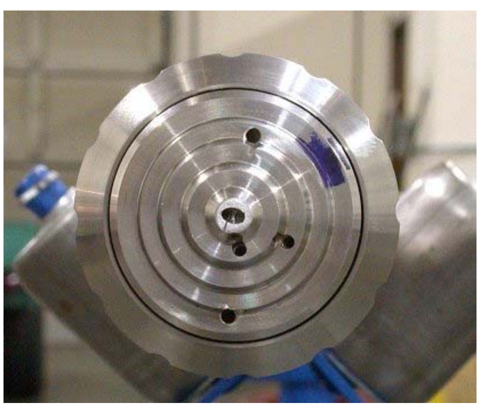


Figure 16. Six jet high-pressure rotary jet milling head.

Figure 17. Cutting pattern in sandstone produced by six-jet high-pressure milling head.

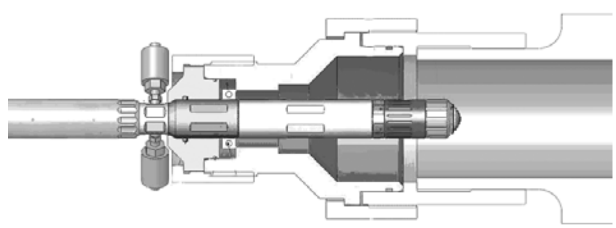


Figure 18. Instrumentation setup for pressure recording.

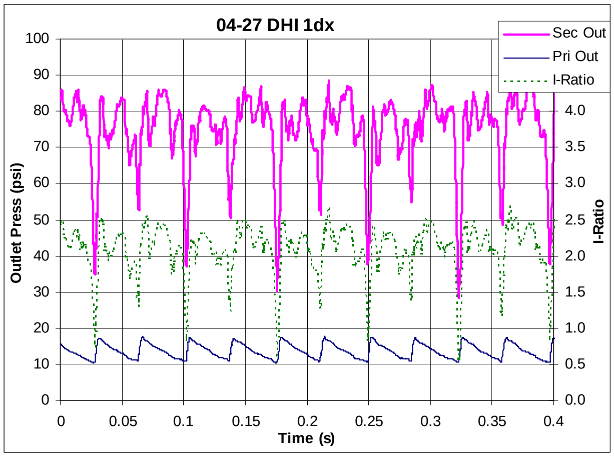


Figure 19. Intensifier output, 92 lpm water 15 scmm N2, 10-18 MPa vessel pressure, 30 MPa BHA differential.

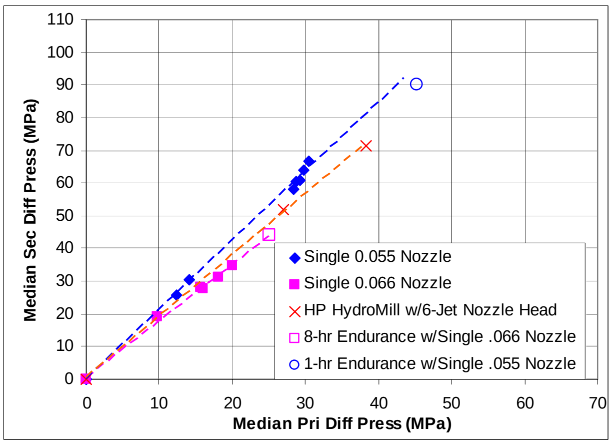


Figure 20. Outlet versus inlet differential pressure for different nozzles. Median intensification ratio is 2:1.

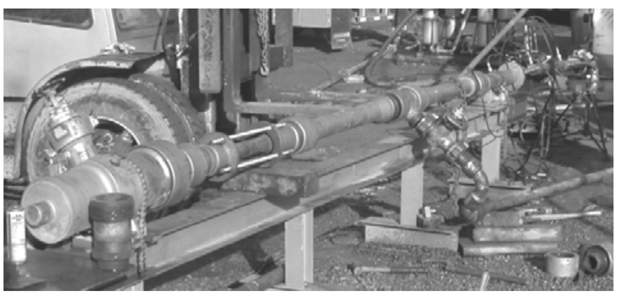


Figure 21. Pressurized milling test setup.

Figure 22. Six-jet milling head cutting patterns in heavy carbonate scale.