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(54) METHOD OF INTENSIFICATION OF NATURAL GAS PRODUCTION FROM COAL BEDS

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(57) ABSTRACT

A method of intensification of natural gas production from the coal beds, comprising exposure of the coal bed to pressure pulsing is disclosed. An embodiment comprises exposure of the coal bed to pressure pulsing in combination with hydraulic fracturing of the coal bed. Another embodiment comprises exposure of the coal bed to pressure pulsing in combination with creation of a cavity in the coal bed by cyclically increasing pressure of the fluid in the well and depressurizing rapidly the fluid.

METHOD OF INTENSIFICATION OF NATURAL GAS PRODUCTION FROM COAL BEDS

[0001] The present invention relates to methods for intensification of natural gas production from the coal beds.

[0002] The reserves of natural gas associated with coal deposits worldwide are estimated at 8,000 trillion cubic feet. This gas is adsorbed onto the coal surface and desorbs upon reducing pressure. The desorbed natural gas can flow towards production wells through the butt and cleat network of the coal bed. Because of the low effective permeability of coal beds, stimulation methods are applied to increase the rate of production. Another complicating factor is that some coal beds are wet, and require dewatering in order to reduce the pore pressure and allow the desorption process to begin. Water is more difficult to remove than gas because its viscosity is two orders of magnitude higher, this causing greater flow resistance in the low permeability butt-cleat porosity network. In addition, water must be pumped out of the well using some mechanical lift assistance. Moreover, water reduces the effective permeability of the butt-cleat network by creating interfaces that resist entry into small constrictions in the flow path and by occupying a large fraction of the pore space.

[0003] The most common existing methods of methane extraction include the creation of a cavity in the coal seam (cavitation), hydrological fracturing of the coal bed, or directional drilling parallel to the bedding of the seam.

[0004] The method of creation of a cavity in the coal seam reduces the amount of damage to the surrounding structure that may have resulted during drilling, and gives an area from which the methane can be extracted. Typically cavitation is performed on open-hole completed wells (no casing across the production interval) in a cyclic manner. Thus the treatment is usually referred to as cavitation cycling.

[0005] Conventional hydraulic fracturing technique is performed on cased-hole perforated completion wells typically when the coal permeability is less than 20 mD. As an option of this method, the hydraulic fracture drilling technique might be used; it involves drilling an initial cased borehole and a second borehole some distance away from the original one which acts to collect loose coal material and as a dewatering location of the formation.

[0006] Directional drilling involves angling the drill stem so that drilling is not vertical, but will parallel the coal seam.

[0007] Once the appropriate borehole is completed by using whatever method, dewatering must also occur to reduce the pressure in the formation. Pressure drop promotes methane release from within the coal into the cleats directed along the beds. If the cleats contain a high enough permeability, that is, inter-connectivity, then the methane will flow from the coal into the well bore and can be extracted.

[0008] Cavitation cycling, the most characteristic method for methane extraction, uses several mechanisms to link the wellbore to the coal fracture system: creates a physical cavity in the coals of the open-hole section (up to 10 feet in diameter); propagates a self-propping, vertical fracture that extends up to 200 feet away from the wellbore (parallel to the direction of least stress), and creates a zone of shear stress failure that enhances permeability in a direction perpendicular to the direction of least stress, as disclosed e.g. in book by Palmer, I. D., Lambert, S. W., and Spitter, J. L. "Coalbed methane well completions and stimulations", Chapter 14 in AAPG Studies in Geology 38, pp. 303-341, and publication by Khodaverian, M. and McLennan, "Cavity completions: a study of mechanisms and applicability", Proceedings of the 1993 International Coalbed Methane Symposium (Univ. of Alabama/Tuscaloosa), 1993, pp. 89-97.

[0009] Cavitation is accomplished by applying pressure to the well using compressed air or foam, and then abruptly releasing the pressure. The over-pressured coal zones provide a pressure surge into the wellbore, and the resulting stress causes dislodgement of coal chips, while abrupt fluid flowback carries the chips up the well. These cycles of pressure and blowdown are repeated many times over a period of hours or days, and the repeated alternating stress-shear failure in the coal formation creates effects that extend laterally from the wellbore, as disclosed e.g. in publication by Kahil, A. and Masszi, D. "Cavity stress-relief method to stimulate demethanation boreholes", SPE Paper No. 12843. Proceedings 1984 SPE Unconventional Gas Recovery Symposium, 1984.

[0010] Conventional hydraulic fracturing technique is described in many literature sources, as well as when applied to coal rocks, e.g. in publication by Holditch, S. A. 1990. "Completion methods in coal seam reservoirs", SPE 20670. Proceedings 65th SPE Annual Technical Conference (New Orleans), p. 533.

[0011] Directional drilling cannot be considered as a pure stimulation technique for natural gas production. It is worth to note that both fracturing (either conventional hydraulic fracturing or cavitation) and directionally drilling simply increase the amount of the coal seam which is associated with the well bore, but fail to increase the original porosity of the formation.

[0012] The prior art contains a tool which utilizes mechanical cutting action by means of jets to create cavity in the bed and clean its volume, as disclosed in U.S. Pat. No. 6,609,688 (Aug. 26, 2003). The tool is provided with a plurality of ports for jetting a combination of air, water and/or drilling foam pumped through each of the ports while the tool rotates. The tool is designed to clean and flush out coal wells not in production.

[0013] The benefit of this tool is that it opens the hole, enlarging the hole size, and cleans out the well in one run. But this tool does not use pulsing.

[0014] The following references disclose methods that involve pressure pulsing in oil and gas industry for oil recovery enhancement. However none of these applications were aimed at enhancement of coal-bed methane production.

[0015] The principle of pumping and vibrations simultaneously is described in U.S. Pat. No. 4,164,978 (1978); RU patent 16074 (1962); book "Research Activities", M, MGI, 1975, p. 61: "Use of vibration in oil production", M., Nedra, 1977; EP patent No. 0512331 (1992); U.S. Pat. No. 4,164,498 (1978); RU patents Nos. 1165801 (1985); 2084705 (1993); 2085721 (1997); 2100571 (1992); 2085721 (1994); 2175718 (1997); 2193649 (2002).

[0016] Pumping and vibrations simultaneously, and vibrations with special frequencies (calculated resonance frequencies) are described in U.S. Pat. Nos. 4,702,315 (1987); 3,863,717 (1975); 3,744,017 (1973); RU patents Nos. 1143150 (1994), 2231631 (2002). Pumping and vibrations simultaneously, pulse regime of pumping are described in U.S. Pat. No. 4,456,068 (1984); RU patents Nos. 2221141 (2004); 2176728 (2000); 2200832 (2001).

[0017] Pumping and vibrations simultaneously, vibrations with special frequencies, burning of solid/liquid fuel-oxidizer mixtures are described in U.S. Pat. Nos. 3,520,362 (1970); 3,768,520 (1973); RU patents Nos. 2128770 (1994); 2191896 (2002); 2003111855 (2004); 1434831 (1999); 1639127 (1987); 2087756 (1994).

[0018] Pumping and vibrations in period of pressure decline, cycle regime of pumping, vibrations with special frequencies are described in U.S. Pat. No. 3,520,362 (1970), RU patents Nos. 2128770 (1994); 219896 (2002); 2003111855 (2004); 1434831 (1999); 1639127 (1987); 2087756 (1994); 2066746 (1996); 94023110 (1994).

[0019] Pumping and vibrations simultaneously, pulse regime of pumping, vibrations with special frequencies, injection of chemical agents, proppants, are described in U.S. Pat. Nos. 5,197,543 (1993); 5,662,165 (1997); RU patents Nos. 2193649 (2002); 2186953 (2000); 2243364 (2002); 2003111855 (2004); 2066746 (1996); 94023110 (1994).

[0020] Pumping and vibrations simultaneously, vibrations with special frequencies, injection of chemical agents are described in U.S. Pat. No. 5,718,289 (1998); RU patents Nos. 2175058 (1999); 2186953 (2000), 2111348 (1994), 2078200 (1994).

[0021] Pumping, vibrations, injection of foam agents, simultaneously vibrations with special frequencies, injection of foam agents are described in U.S. Pat. Nos. 6,467,542 (2000); 6,015,010 (2000); 6,405,797 (2000); 6,241,019 (2000).

[0022] The object of the present invention is to provide methods of intensification of natural gas production from the coal beds, comprising exposure of the coal bed to pressure pulsing.

[0023] The object of the invention is attained in a method of intensification of natural gas production from the coal beds, comprising exposure of the coal bed to pressure pulsing and hydraulic fracturing of the coal bed.

[0024] The pressure pulses can be low frequency high-amplitude pressure pulses.

[0025] The hydraulic fracture can be created by the steps of injecting into the coal bed a fracture fluid at high flow rates and pressures to create the fracture; further injecting a proppant in the fracture fluid to prevent closing the fracture created, and finally injecting the fracture fluid without proppant for washing the well. The pressure pulsing can be applied either before creating the fracture, or during injecting the fracture fluid to create the fracture, or during injecting a proppant in the fracture fluid, or during finally injecting the fracture fluid without proppant, or during some or all said steps.

[0026] An embodiment of the method can comprise, before starting hydraulic fracture of the coal bed, the following steps:

[0027] running a pressure pulse generator into the wellbore at the level of treated interval;

[0028] loading the wellbore with an incompressible fluid in order to couple the coal bed to the pressure pulse generator;

[0029] adjusting the generator to create pressure pulses of specific frequency and amplitude;

[0030] transmitting the pressure pulses created by the generator to the coal bed through the incompressible fluid;

[0031] injecting the fracture fluid to the coal bed.

[0032] The aforementioned object of the invention is further attained in a method of intensification of natural gas production from the coal beds, comprising exposure of the coal bed to pressure pulsing and hydraulic fracturing of the coal bed by injecting into the coal bed a fracture fluid without proppant at high flow rates and pressures.

[0033] The object of the invention is also attained in a method of intensification of natural gas production from the coal beds, comprising exposure of the coal bed to pressure pulsing and creation of a cavity in the coal bed by cyclically increasing pressure of the fluid in the well and depressurizing the fluid.

[0034] The pressure pulses can be low frequency high-amplitude pressure pulses. The low frequency high-amplitude pressure pulses can impact the coal bed during increasing the pressure of the fluid in the well.

[0035] The method can further comprise the step of cleaning the well, wherein the fluid used for transferring pressure pulses is replaced by the efficient foamy cleaning medium.

[0036] A fluid driven generator can be used for creation of the pressure pulses and the foamy cleaning medium is pumped through said generator.

[0037] In another embodiment, a generator for creation of the pressure pulses can be placed in nearby well, and pressure pulsing of the coal bed can be simultaneously accompanied with injecting the foamy cleaning medium in the treated well.

[0038] The object of the present invention is further attained in a method of intensification of natural gas production from the coal beds, comprising exposure of the coal bed to pressure pulsing, creation of a cavity in the coal bed by cyclically increasing pressure of the fluid in the well and depressurizing rapidly the fluid, and well cleaning, comprising the steps of: running a pressure pulse generator into the wellbore at the level of treated interval; loading the wellbore with an incompressible fluid in order to efficiently couple the coal bed to the pressure pulse generator; adjusting the generator to create pressure pulses of specific frequency and amplitude and transmitting the pressure pulses created through said fluid to the coal bed; creating a pressure gradient in the near wellbore zone by injecting fluid above the pressure of the coal bed; depressurizing rapidly the fluid in the wellbore to cause breakdown of the coal bed and produce rubblized coal; running well cleaning by circulating efficient foamy cleaning medium across the treated interval to aid fluidization and transport of the rubblized coal to the surface.

[0039] In this method, a fluid discharge pressure pulse generator without a resonator can be employed, so that a pulsing jet produces cutting/reaming action on the coal bed.

[0040] The aforementioned method steps can be repeated after refilling the wellbore with the incompressible fluid.

[0041] Application of pressure pulses to coal seams promotes opening the butt-cleat network and enhancing its permeability. The pressure pulses can be applied alone, or they can be combined with hydraulic fracturing and cavitation operations.

[0042] Application of stand alone high amplitude, low frequency pressure pulses to the coal bed will cause tensile and shear failure of the formation fabric. These tensile and shear cracks may form preferentially along the butt and cleat network, as in the case of a coal seam, or they may form along new failure planes. The cracks will tend to become somewhat misaligned due to the relaxation of anisotropic stress that pre-exists in some coal formations. What's more, spalling, rubblization, or shear displacement of the reservoir material may occur which prevents the tensile and shear cracks from healing completely. In all cases, the apparent permeability of the formation will increase, enabling higher gas production rates, and higher dewatering rates (if water is present).

[0043] Application of pressure pulses can be used to enhance the cavitation process which is limited by the strength of the coal formation and the ability to create tensile and shear failure deep around the wellbore during each over-pressure/depressurization cycle. Applying high amplitude, low frequency pressure pulses during the over-pressure/depressurization process will expand the failure zone during each cavitation cycle. Thus, either fewer cycles are required to cause the desired growth of the effective wellbore diameter, or the ultimate diameter of the effective wellbore can be significantly larger than in the standard cavitation process.

[0044] Application of pressure pulses can be used to enhance the hole cleaning process. After a cavitation cycle the use of water or other efficient medium for propagating pressure pulses is replaced by an efficient foamed cleaning fluid. This cleaning cycle would then fluidize and transport the small coal fragments out of the wellbore and enable unrestricted evolution of gas from the coal formation. The use of pressure pulses is superior to a conventional steady-pressure process because the pulsing will cause the foam gas cells to periodically compress and expand. During compression, the foam will invade the porosity of the formation debris. During expansion the foam will dilate the bed of formation debris, facilitating its entrainment in the flowing stream. This fluidization process is required for efficient borehole cleaning and is enhanced by pressure pulses.

[0045] Application of pressure pulses can be used to enhance hydraulic fracturing. Hydraulic fracturing is accomplished by injecting a fracture fluid into the wellbore at high flow rates and pressures to create the fracture, and further injecting a proppant, such as sand, in the fracture fluid. The fracture that is created becomes filled with the proppant, which prevents the fracture from closing. This high conductivity channel enables both water and gas to flow at a high rate from the coal formation into the wellbore. Important parameters of the hydraulic fracture include the fracture conductivity and the fracture geometry. The artificial fractures have a capacity to conduct the produced fluids. Fractures with the regular geometrical characteristics will connect to a vast number of natural cracks, penetrating the reservoir and coupling with the well. Applying pressure pulses to the formation, either before the fracture treatment, during the pad stage of the fracture treatment, during injecting a proppant in the fracture fluid, or during the entire fracturing treatment, may have the following effects.

[0046] The cracks (cleats) in the coal bed arranged longitudinally that are intersected by the fracture become dilated and misaligned, thereby increasing their permeability and ability to feed the fracture.

[0047] The coal formation fabric along the fracture face undergoes tensile and shear failure. Coal becomes rubblized and the resulting fracture is wider than a fracture created by normal processes. The wider fracture has higher hydraulic conductivity than a more narrow fracture. Possibly, the fracture will not require proppant to maintain the fracture faces separate. Eliminating proppant from a channel will increase the channel porosity (if the channel does not close due to effective stress), thereby increasing hydraulic conductivity of the fracture. The fracture may propagate more easily because the pressure pulses have the effect of fatigue breakdown of the rock.

[0048] To create pressure pulses in these methods for intensification of natural gas production from coal beds the following several pressure pulse generator variants can be employed. A downhole hydrodynamic generator can be employed that creates pressure oscillations when fluid is pumped through the generator. Some mechanism to temporarily block and release the fluid flow creates oscillations. The mechanism can include mechanical valves, swirl type inertial valves, rotating ports that discharge fluid upon alignment and block flow upon misalignment. In a fully mechanical pressure generator, shock waves are created by two objects striking each other. An electrodynamic pulse generator utilizes electric discharge to create strong shock wave. Use could be also made of water hammering generators, and combustion pulse generators.

[0049] Pressure pulse generators that can be used in methods according to the present invention are disclosed in the following patents: U.S. Pat. Nos. 4,164,978 (1978); 4,164,4978 (1978); 4,702,315 (1987); 3,863,717 (1975); 4,456,068 (1984); 3,520,362 (1970); 3,768,520 (1973); 5,197,543 (1993); 5,662,165 (1997); 5,718,289 (1998); 6,467,542 (2000); 6,015,010 (2000); 6,405,797 (2000); 6,241,019 (2000); RU patent documents Nos. 16074 (1962); 1165801 (1985); 2084705 (1993); 2085721 (1997); 2100571 (1992); 2085721 (1994); 2175718 (1997); 2193649 (2002); 1143150 (1994); 2231631 (2002); 2221141 (2004); 2176728 (2000); 2200832 (2001); 2128770 (1994); 2191896 (2002); 2003111855 (2004); 1434831 (1999); 1639127 (1987); 2087756 (1994); 2066746 (1996); 94023110 (1994); 2193649 (2002); 2186953 (2000); 2243364 (2002); 2003111855 (2004); 2175058 (1999); 2186953 (2000); 2111348 (1994); 2078200 (1994); 2175058 (1999); 2186953 (2000); 2111348 (1994); 2078200 (1994) and the aforementioned publication "Research Activities", 1975, p. 61.

[0050] The preferred, but non-limiting embodiment for the claimed methods includes the use of downhole pressure pulses to generate pulses in production well. The downhole generators which can be used in methods according to the present invention include e.g. a generator described in U.S. Pat. No. 6,015,010 for producing a shock wave in a borehole including a pumping unit arranged at the wellhead, a tubing string extending downwardly into the production casing of the well, a hollow cylinder assembly connected with the bottom of the tubing string, and a pair of plungers arranged within the cylinder assembly and connected with the pumping unit with sucker rods and a polish rod for compressing liquid contained within the cylinder assembly and discharging the compressed liquid into the production casing, thereby generating a shock wave. The cylinder assembly includes a hollow upper cylinder, a hollow lower cylinder arranged below the upper cylinder, a crossover cylinder arranged between the upper and lower cylinders, and a compression cylinder containing a compression chamber arranged between the crossover cylinder and the upper cylinder. The lower cylinder has a larger inner diameter than the upper cylinder inner diameter, and the lower plunger has a larger diameter than the upper plunger. In addition, the lower cylinder is adapted to receive the lower plunger and the upper cylinder is adapted to receive the upper plunger. When the plungers are displaced upwardly in the cylinder assembly, the lower plunger travels into the compression chamber and the upper plunger travels out of the compression chamber. Due to the lower plunger having a greater diameter than the upper plunger, the volume of the compression chamber is reduced and the liquid contained therein becomes compressed. When the pumping unit reaches the top of its stroke, the lower plunger allows the compressed liquid contained in the compression chamber to be discharged into the well. At this moment the stored pressure is suddenly released and a very amplitude shock is created in the wellbore, with amplitude on the order of 200 to 250 bars.

[0051] A method of intensification of natural gas production from the coal beds, comprising exposure of the coal bed to pressure pulsing can be accomplished by applying low frequency high-amplitude pressure pulses to the coal bed to cause fracturing in the bed structure. The method is performed in the following manner.

[0052] To prepare the wellbore for the operation, the pressure pulse generator is run into the wellbore to approximately the treatment zone and the wellbore is loaded with an incompressible fluid, if needed, in order to efficiently couple the formation to the pressure pulse generator and transmit pressure pulses to the formation. Then the pressure pulse generator is adjusted to create pressure pulses of desired frequency and amplitude. The low frequency waves, preferably close to resonant frequency of formation, should be used in the treatment for down to a few meters penetration depth. References on selection of proper frequency and amplitude of pressure pulses for a particular type of formations might be found in many patents, e.g. EP patent No. 0512331 (1992); U.S. Pat. No. 4,164,4978 (1978); RU patents Nos. 1165801 (1985); 2084705 (1993); 2085721 (1997); 2100571 (1992); 2085721 (1994); 2175718 (1997); 2193649 (2002).

[0053] Time of treatment is defined empirically depending on rock properties and regime of treatment. Recommendations on the operation duration might be also found in the aforementioned patents.

[0054] After termination of the pressure pulsing, dewatering is run, if needed, using a pump to remove excessive water from well, or to dewater the well completely. Then, the well may be cleaned, if needed, from spalled material by any known method, e.g. by injecting expanding agents (nitrogen, foam, or energized liquid).

[0055] The aforementioned steps may be repeated for the desired number of cycles. If required, the generator is removed and production equipment is installed to start gas production.

[0056] A method of intensification of natural gas production from the coal beds can comprise exposure of the coal bed to pressure pulsing to enhance cavitation in the coal bed.

[0057] To perform this method, the wellbore is prepared for the operation by running the pressure pulse generator, such as a fluid-driven generator, into the wellbore to approximately the treatment zone, and the wellbore is loaded with an incompressible fluid, if needed, in order to efficiently couple the formation to the pressure pulse generator and transmit pressure pulses to the formation. The pressure pulse generator is adjusted to create pressure pulses of desired frequency and amplitude. Regime and time of treatment are chosen as mentioned above. One may operate fluid discharge pressure pulse generators without resonator, so that a pulsing jet produces cutting action on the formation. Then pressure is increased in the well above the pore pressure by injecting fluids such as nitrogen, foam, or energized liquid, which may be performed through said generator. The wellbore is rapidly depressurized, this resulting in production of rubblized coal pieces. A surface valve is opened to a “blooie pit”. The well is then cleaned if needed by circulating energized fluid or foam across the treated interval to aid fluidization and transport the rubblized formation to the surface.

[0058] In case of another cavitation cycle, the wellbore is refilled with an incompressible fluid and the aforementioned steps are repeated until no additional formation material is produced during the depressurization process. If required, the generator is removed and production equipment is installed and production is started.

[0059] Application of pressure pulses can be used to enhance the process of cleaning the borehole from coal pieces. To this end, after a cavitation cycle fluids are switched from water or other efficient medium for propagating pressure pulses to an efficient foamed cleaning fluid. During compression, the foam will invade the porosity of the coal bed debris and fluidize the debris, facilitating thereby its entrainment in the flowing stream. This fluidization process is required for efficient borehole cleaning and is enhanced by pressure pulses.

[0060] The method combines application of pressure pulses and injection of cleaning fluid. For fluid driven generators the cleaning fluid is pumped through the generator. For generators placed in nearby wells, pulsing is continued while injecting cleaning fluid in the treated well. Circulation of cleaning fluids is finished if no more spalled material is produced on to surface.

[0061] The pulse pressure treatment can be used to enhance hydraulic fracturing.

[0062] The method involves preparing the wellbore for the operation by running the pressure pulse generator into the wellbore to approximately the treatment zone, and loading the wellbore with an incompressible fluid, if needed, in order to efficiently couple the coal formation to the pressure pulse generator.

[0063] Preparation is carried out for injecting a fracture fluid into the formation and the pressure pulse generator is adjusted to create pressure pulses of desired frequency and amplitude. Regime and time of treatment are chosen as mentioned above.

[0064] Hydraulic fracturing of the coal bed is accomplished by the steps of injecting into the wellbore a fracture fluid at high flow rates and pressures to create the fracture, further injecting a proppant in the fracture fluid to prevent closing the fracture created, and finally injecting the fracture fluid without proppant for washing the well. Pressure pulsing is applied to the coal bed either before creating the fracture, or during injecting the fracture fluid to create the fracture, or during injecting a proppant in the fracture fluid, or during finally injecting the fracture fluid for washing the well or during some or all said steps. The selected regime of pressure pulsing at different steps of hydraulic fracturing affects the resulting fracture geometry.

[0065] An embodiment of the method comprises hydraulic fracturing steps without a proppant. The possibility of this embodiment has been explained above.

[0066] Upon completion of the fracturing job, if required, the generator is removed and production equipment is installed and production is started.

[0067] Some particular examples of implementing the methods in accordance with the invention will be described below.

[0068] To determine the appropriate pressure pulse generator frequency for the various applications in the above methods, the following algorithms are employed that will be referred to as "Algorithm" in the following examples.

[0069] Algorithm 1 comprises using experimental data that indicates that the effective tensile and shear crack formation occurs within a range of pulse frequency (number of pulses per second) of between 0.1 to 500 Hz.

[0070] Algorithm 2 comprises installing, before the treatment, a measuring device in an observation well to measure characteristics of formation vibrations. The measuring device should be coupled to the productive interval of interest. Then a pressure pulse generator is installed in a nearby well and activated so that it produces pressure pulses; the frequency of the pressure pulse generator is incremented; the formation movement in the observation well is recorded, and the most effective frequency is selected through evaluation of the measured formation vibrations in the observation well corresponding to specific frequencies in the nearby well.

[0071] Algorithm 3 comprises writing a system of equations for a linearly elastic porous medium representing the formation surrounding the wellbore; solving the equations for the condition that the formation is exposed to a periodic pressure pulse or a pressure shock; estimating the zone of tensile and shear failure in the formation surrounding the wellbore, and selecting the pressure pulsing frequency and amplitude that maximize the extent of the failure zone.

[0072] Algorithm 4 comprises writing a system of equations for a linearly elastic porous medium representing the formation surrounding the wellbore; solving the equations for the condition that the formation is exposed to a periodic pressure pulse or a pressure shock; estimating the zone of tensile and shear failure in the formation surrounding the hydraulic fracture, and selecting the frequency and amplitude that maximize the extent of the failure zone.

[0073] A pressure pulse generator employed in the Examples presented below is disclosed in U.S. Pat. No. 6,015,010; the generator is mechanical and creates pressure pulses by up and down strokes of pump rods of the pumping jack operating on surface, and is capable to produce a hydraulic impact in the wellbore with amplitude of 200-250 bars.

EXAMPLE 1

Application of Pressure Pulsing to Coal Formation to Enhance Efficiency of Cavitation

[0074] (a) A well penetrates a coal formation containing adsorbed methane gas at a depth of approximately 800 meters. The production interval is 10 meters thick, has a porosity of 2%, effective permeability of 25 mD, temperature is 25° C., reservoir pressure is 50 bars, Young's modulus is 0.5 million psi, and Poisson's ratio is 0.34.

[0075] The Algorithm is used to determine that it will be suitable to treat this well using a generator that generates 50 bar pressure pulses at a 60 Hz frequency.

[0076] The well is filled with a 4 wt % KCI brine to control pressure. A workover unit is used to remove the sucker rod pump, pump rods, and production tubing and tubing packer. The pressure pulse generator is attached to the production tubing and the production tubing is run back into the wellbore. Injection of treatment fluid for the near wellbore region begins when the generator reaches the depth corresponding to the top of the production interval. Filtered solution (of the same 4 wt % KCI concentration) is injected through the generator. Injected liquid flowing through the generator periodically pressurizes an accumulator. During pressurization, the accumulator receives some of the injected fluid, and the net injection rate into the formation is less than the average and the bottom hole injection pressure falls. Once the accumulator is filled, it builds an overpressure which initiates a rapid discharge of the stored liquid. This discharge causes the net injection rate into the formation to exceed the average rate, and the bottom hole injection pressure increases. By this periodic oscillation mechanism, the required pressure pulse amplitude and frequency is generated. The injection is continued until the "break-down" pressure or fracture pressure of the formation is reached. This hydraulic fracture pressure is the pressure at which a hydrostatic column of fluid will initiate a fracture at the wellbore. The pressure pulses generated by the generator periodically exceed the fracture pressure. As the injected fluid flows into the formation, a pressure gradient is developed in the near wellbore region. This pressure gradient, coupled with the periodic pressure pulses leads to tensile failure of the rock in the near wellbore region. These pressure pulses disaggregate the matrix blocks of the coal formation, effectively shattering the coal seam along the network of face and butt cleats. This pressure pulse treatment continues for 15 minutes to several hours.

[0077] At the end of pressure pulsing, the brine is displaced into the formation with foamed nitrogen (a mixture of 70% by volume nitrogen and 30% by volume water containing viscosifier and surfactant to stabilize the foam structure; volume percentage is measured at the bottom hole conditions). The foamed nitrogen injection continues in an effort to pressurize the near wellbore formation to a pressure much greater than the reservoir pressure. The foam is able to easily penetrate the weakened, disaggregated coal formation. After the complete foam volume is injected (the volume should be sufficient to fill the entire production interval to a radial depth of 3 meters), the wellbore is rapidly depressurized. Depressurization mobilizes the weakened, rubblized coal, and those coal fragments are conveyed out of the formation through the well into a "blooie pit." This depressurization continues until no more coal and nitrogen gas are produced. The process enlarges the wellbore radius and cleans pores in the rock immediately around the wellbore. A total of 2 to 10 or more treatment cycles including pressure pulsing, foam pressure charging, and vigorous well depressurization steps may be carried out over a period of a few hours to one or more days. The act of applying pressure pulses significantly enhances the efficiency of the coal rubblization process and the subsequent cavity creation process.

[0078] A well cleaning operation is performed by injection and circulation of the foamed fluid through the wellbore in order to dilate and carry out the slurry away from the wellbore. The circulation occurs by injecting fluid down a coiled tubing lowered to the top of the production interval, and then in rather small measured increments, the coiled tubing is lowered progressively to the lowest extreme of the well. Periodically the coiled tubing depth is held constant to insure that debris is thoroughly removed from one segment of the wellbore. Coiled tubing cleaning continues until the lowest extreme of the well is tagged. Then the coiled tubing is removed from the wellbore, continuing circulation. After removal of the coiled tubing, the pump rods and pump reinstalled. The well is put back onto production.

[0079] (b) An embodiment of Example 1 is carried out similarly to embodiment (a) except that the well cleaning operation is modified.

[0080] Similarly to the described embodiment (a), the well cleaning operation is performed at the end of the pressurizing and depressurization cycles. Circulation occurs by injecting fluid down a coiled tubing lowered to the top of the production interval, and then in rather small measured increments, the coiled tubing is lowered progressively through any fill that has accumulated. Periodically the coiled tubing depth is held constant to insure that debris is thoroughly removed from one segment of the wellbore before proceeding deeper into the wellbore. Coiled tubing cleaning continues until the lowest extreme of the well is tagged. In this embodiment, the foam cleaning is enhanced during this treatment by operating a pressure pulse generator during foam circulation. The action of the pressure pulse generator is to cause foam bubbles to pulsate, alternatively becoming larger and smaller. During compression, the foam invades the porosity of the coal debris that resides in the wellbore. During expansion, the foam dilates the bed of coal debris, facilitating its entrainment into the flowing stream. The pressure pulse generator is installed at the end of the coiled tubing. It has the same pressure pulse generation mechanism and the same pulse amplitude and frequency as the generator used during the cavity completion treatment. The major difference is that the wellbore pressure is reduced during the cleaning operation to a level less than the formation hydraulic breakdown pressure and a level low enough to allow the fluids to be produced up the well. At the end of the cleaning operation the coiled tubing is removed from the wellbore, continuing circulation. After removal of the coiled tubing, the production tubing is restored, pump rods and pump reinstalled, and the well is put back onto production.

EXAMPLE 2

Application of Pressure Pulsing to Coal Formation to Amplify Hydraulic Fracturing without Proppant

[0081] (a) A well penetrates a coal formation containing adsorbed methane gas at a depth of approximately 800 meters. The production interval is 10 meters thick, has a porosity of 2%, effective permeability of 25 mD, temperature is 25° C., reservoir pressure is 50 bars, Young's modulus is 0.5 million psi, and Poisson's ratio is 0.34.

[0082] The Algorithm is used to determine that it will be suitable to treat this well using a generator that generates 75 bar pressure pulses at a 20 Hz frequency.

[0083] The well is filled with a 4 wt % KCI brine to control pressure; the pressure pulse generator is installed, and treatment fluid injection begins when the generator reaches the depth corresponding to the top of the production interval.

[0084] During the hydraulic fracturing operation, a fracture fluid is injected down both the tubing and the tubing-casing annulus. Additives are incorporated into the fracture fluid so that it has increased viscosity. The composition in this treatment is 0.4 wt % polymer viscosifier, such as guar, 0.014 wt % boric acid, enough sodium hydroxide to raise the fluid pH to 9.6, 0.003 wt % biocide, 0.2% surfactant to cause the coal surface to be hydrophobic (ethoxylated butoxylated alcohols) plus 0.25 wt % encapsulated oxidizer for fluid degradation. This fluid will be called crosslinked gel.

[0085] Crosslinked gel injection begins down the annulus and the tubing simultaneously. The total injection rate increases slowly until the formation break-down pressure is reached. The injection rate is then increased from approximately 0.5 m^3/min to a steady rate of 3 to 4 m^3/min to extend the fracture a great distance away from the well. The flow rate of the crosslinked gel down the annulus is steady, whereas that discharged from the end of the tubing oscillates under the action of the downhole pressure pulse generator. The crosslinked gel flowing through the generator periodically pressurizes an accumulator. During pressurization, the accumulator receives some of the injected fluid, and the net injection rate into the formation is less than the average, and the bottom hole injection pressure falls. Once the accumulator is filled, it builds an overpressure, which initiates a rapid discharge of the stored liquid. This discharge causes the net injection rate into the formation to exceed the average rate, and the bottom hole injection pressure increases. By this periodic oscillation mechanism, the required pressure pulse amplitude and frequency is generated. During this treatment, crosslinked gel only is being injected: a total of 200 m^3 of crosslinked gel is injected. The pressure pulse generator operates the entire time of injection. As the fracture fluid injection creates and extends a fracture away from the wellbore to a length of 300 to 400 feet, the pressure pulses act to cause tensile failure of the formation at the fracture face combined with shear failure in planes parallel to the fracture face. The pressure pulse induced cracks are orientated along the face and butt cleat network in the coal matrix, longitudinally and perpendicular to coal shims. These pressure pulses disaggregate the matrix blocks of the coal formation, effectively shattering the coal seam along the network of face and butt cleats. This combined hydraulic fracturing and pressure pulse treatment continues for approximately 1 hour as the entire fluid volume is injected into the formation.

[0086] At the end of the crosslinked gel injection, the crosslinked gel is flushed to the bottom of the casing with 4% KCl water containing only 0.2 wt % guar. Displacement is then transitioned to foamed 0.2% guar and KCl solution being injected to lighten the hydrostatic column in the wellbore (bottom hole foam characteristics are 70% by volume nitrogen and 30% viscous water containing 0.2 wt % guar, and 0.1 to 1.0 volume % surfactant). Injection is stopped in the annulus once the crosslinked gel is entirely displaced into the formation (and the foamed uncrosslinked guar solution fills the entire annulus and tubing). Foam injection continues down the tubing. An annulus valve is opened allowing the wellbore fluids to flow from the wellbore through a valve to a waste collection pit. During this flowback procedure, the bottomhole pressure in the wellbore is reduced to a level of approximately 5 to 10 bars and the injected fracturing fluid is recovered out of the well. During the flowback process, the disaggregated coal blocks reorientate in a manner that prevents the fracture and dilated cleats from closing entirely. The resulting fracture has high hydraulic conductivity.

[0087] A well cleaning operation is performed at the end of the flowback process in a manner similar to that in Example 1.

[0088] (b) A well penetrates a coal formation containing adsorbed methane gas at a depth of approximately 800 meters. The production interval is 10 meters thick, has a porosity of 2%, effective permeability of 25 mD, temperature is 25° C., reservoir pressure is 800 psi, Young's modulus is 0.5 million psi, and Poisson's ratio is 0.34.

[0089] The Algorithm is used to determine whether it will be suitable to treat this well using a tool that generates a 200 bar pressure shocks at a 0.1 Hz frequency.

[0090] In this embodiment, the method is accomplished similarly to the embodiment (a), except that the pressure pulse generator is lowered into the well to a position 5 meters above the top of the production interval, and the fluid used as a fracturing fluid comprises 4 wt % KCl plus 0.5 to 3 volume % viscoelastic surfactant, plus 0.2 to 0.4 volume % of an organic surfactant of the type ethoxylated-butoxylated glycols having 1 to 5 ethylene oxide groups and 5 to 10 butylene oxide groups. This composition is a non-damaging viscoelastic surfactant solution. A well cleaning operation is performed without a pulse generator.

[0091] (c) A well penetrates a coal formation that contains adsorbed methane gas at a depth of approximately 800 meters. The production interval is 10 meters thick, has a porosity of 2%, effective permeability of 25 mD, temperature is 25° C., reservoir pressure is 50 bars, Young's modulus is 0.5 million psi, and Poisson's ratio is 0.34.

[0092] The Algorithm is used to determine whether it will be suitable to treat this well using a generator that generates a 70 bar pressure shocks at a 300 Hz frequency.

[0093] The method is carried out similarly to embodiment (a) except that the pressure pulse generator comprises a venturi that is built into the tool. The crosslinked gel flowing through the venturi produces cavitation. The collapse of gas bubbles in the expanding part of the venturi is the source of the pressure shocks. By this periodic oscillation mechanism, the required pressure pulse amplitude and frequency is generated. During this treatment, crosslinked gel only is being injected. A total of 200 m^3 of crosslinked gel is injected. The pressure pulse generator operates the entire time. The pressure shocks generated by the tool are focused down the fracture and cause high stress concentrations as the bubbles collapse near the fracture walls. As the crosslinked gel creates and extends a fracture away from the wellbore to a length of 300 to 400 feet, the pressure shocks act to cause tensile failure of the formation at the fracture face combined with shear failure in planes parallel to the fracture face. As mentioned earlier, these pressure shocks disaggregate the matrix blocks of the coal formation, effectively shattering the coal seam along the network of face and butt cleats. This combined hydraulic fracturing and pressure pulse treatment continues for approximately 1 hour as the entire fluid volume is injected into the formation.

EXAMPLE 3

Application of Pressure Pulsing to Coal Formation Only During Injection of Fracture Fluid with Proppant to Amplify Hydraulic Fracturing

[0094] A well penetrates a producing coal formation containing adsorbed methane gas at a depth of approximately 800 meters. The production interval is 10 meters thick, has a porosity of 2%, effective permeability of 25 mD, temperature is 25° C., reservoir pressure is 50 bars, Young's modulus is 0.5 million psi, and Poisson's ratio is 0.34.

[0095] The Algorithm is used to determine that it will be suitable to treat this well using a tool that generates 75 bar pressure pulses at a 20 Hz frequency.

[0096] The well is filled with a 4 wt % KCI brine to control pressure; the pressure pulse generator is installed in the wellbore and a treatment fluid injection begins when the generator reaches the depth corresponding to the top of the production interval.

[0097] During the hydraulic fracturing operation, fluid is injected down both the tubing and the tubing-casing annulus. The fracture fluid in this treatment is the aforementioned crosslinked gel or a solution of viscoelastic surfactant. The hydraulic fracturing process is accomplished as in other examples, wherein the injected fluid flowing through the generator periodically pressurizes an accumulator. During pressurization, the accumulator receives some of the injected fluid, and the net injection rate into the formation is less than the average, and the bottom hole injection pressure falls. Once the accumulator is filled, it builds an overpressure, which initiates a rapid discharge of the stored liquid. This discharge causes the net injection rate into the formation to exceed the average rate, and the bottom hole injection pressure increases. By this periodic oscillation mechanism, the required pressure pulse amplitude and frequency is generated. During this treatment, 70 m^3 of crosslinked gel is injected without proppant; this step is called the pad stage. The pressure pulse generator operates only during the pad stage. As the crosslinked gel creates and extends a fracture away from the wellbore to a length of 300 to 400 feet, the pressure pulses act to cause tensile failure of the formation at the fracture face combined with shear failure in planes parallel to the fracture face. This combined hydraulic fracturing and pressure pulse treatment continues for approximately 1 hour as the entire fluid volume is injected into the formation.

[0098] After the pad, proppant is added to the remainder of the injected crosslinked gel. The proppant concentration begins at a low concentration and is progressively ramped up to a high concentration. In this treatment, the proppant concentration begins at 1% by weight of fracture fluid and ends at 50% by weight of fracture fluid. The fracture fluid/proppant slurry is only injected down the annulus. A total of 140 m^3 of slurry is injected. The pressure pulse generator is not operated during slurry injection. The subsequent steps are carried out as in Example 2.

EXAMPLE 4

[0099] Application of Pressure Pulsing To Coal Formation Continuously During Both Pad and Proppant Injection Stages of Hydraulic Fracturing

[0100] (a) A well penetrates a producing coal formation that contains adsorbed methane gas at a depth of approximately 800 meters. The production interval is 10 meters thick, has a porosity of 2%, effective permeability of 25 mD, temperature is 25° C., reservoir pressure is 50 bars, Young's modulus is 0.5 million psi, and Poisson's ratio is 0.34.

[0101] The Algorithm is used to determine whether it will be suitable to treat this well using a tool that generates 75 bar pressure pulses at a 20 Hz frequency.

[0102] The well is filled with a 4 wt % KCl brine to control pressure; the pressure pulse generator is lowered into the wellbore. Treatment fluid injection begins when the tool reaches the depth corresponding to the top of the production interval.

[0103] Fluid is injected down both the tubing and the tubing-casing annulus. The composition in this treatment is the aforementioned crosslinked gel or a viscoelastic surfactant solution.

[0104] Injection of fracture fluid without proppant under pressure generator pulses is carried out as in Example 3.

[0105] This combined hydraulic fracturing and pressure pulse treatment continues for approximately 1 hour as the entire fluid volume is injected into the formation.

[0106] After the first injection stage, proppant is added to the remainder of the fracture fluid. The proppant concentration begins at a 1% by weight of crosslinked gel and ends at 50% by weight of crosslinked gel. The fracture fluid/proppant slurry is only injected down the annulus. A total of 140 m^3 of slurry is injected. The pressure pulse generator operates during the step of injecting the fracture fluid with a proppant also. The remainder of the process is accomplished as in the previous Examples.

1. A method of intensification of natural gas production from the coal beds, comprising exposure of the coal bed to pressure pulsing and hydraulic fracturing of the coal bed.

2. The method of claim 1, wherein the pressure pulses are low frequency high-amplitude pressure pulses.

3. The method of claim 1, wherein the hydraulic fracture is created in the coal bed by the steps of injecting into the coal bed a fracture fluid at high flow rates and pressures to create the fracture, further injecting a proppant in the fracture fluid to prevent closing the fracture created, and finally injecting the fracture fluid without proppant for washing the well.

4. The method of claim 3, wherein the pressure pulsing is applied to the coal bed either before creating the fracture, or during injecting the fracture fluid to create the fracture, or during injecting a proppant in the fracture fluid, or during finally injecting the fracture fluid without proppant, or during some or all said steps.

5. The method according to claim 4, comprising, before starting the hydraulic fracturing of the coal bed, the following steps:

running a pressure pulse generator into the wellbore approximately at the level of treated interval;

loading the wellbore with an incompressible fluid in order to couple the coal bed to the pressure pulse generator;

adjusting the generator to create pressure pulses of required frequency and amplitude;

transmitting the pressure pulses created by the pressure pulse generator to the coal bed through the incompressible fluid;

injecting the fracture fluid to the coal bed.

6. A method of intensification of natural gas production from the coal beds, comprising exposure of the coal bed to pressure pulsing and hydraulic fracturing of the coal bed by injecting into the wellbore a fracture fluid without proppant at high flow rates and pressures.

7. A method of intensification of natural gas production from the coal beds, comprising exposure of the coal bed to pressure pulsing and creation of a cavity in the coal bed by cyclically increasing pressure of the fluid in the well and depressurizing rapidly the fluid.

8. The method of claim 7, wherein the pressure pulses are low frequency high-amplitude pressure pulses.

9. The method of claim 8, wherein the low frequency high-amplitude pressure pulses impact the coal bed during increasing the pressure of the fluid in the well.

10. The method of claim 8, further comprising the step of cleaning the well, wherein the fluid used for transferring pressure pulses is replaced by an efficient foamy cleaning medium.

11. The method of claim 10, wherein a fluid driven generator is used for creation of the pressure pulses and the foamy cleaning medium is pumped through said generator.

12. The method of claim 10, wherein a generator for creation of the pressure pulses is placed in a nearby well, and the pressure pulsing of the coal bed is simultaneously accompanied with injecting the foamy cleaning medium in the treated well.

13. A method of intensification of natural gas production from the coal beds, comprising exposure of the coal bed to pressure pulsing, creation of a cavity in the coal bed by cyclically increasing pressure of the fluid in the well and depressurizing rapidly the fluid, and well cleaning, comprising the steps of:

running a pressure pulse generator into the wellbore at the level of treated interval in the wellbore;

loading the wellbore with an incompressible fluid in order to couple the coal bed to the pressure pulse generator;

adjusting the generator to create pressure pulses of required frequency and amplitude and transmitting the pressure pulses created through said incompressible fluid to the coal bed;

creating a pressure gradient in the near wellbore zone by injecting fluid above the pressure of the coal bed;

depressurizing rapidly the fluid in the wellbore to cause breakdown of the coal bed and produce rubblized coal;

cleaning the well by circulating efficient foamy cleaning medium across the treated interval to aid fluidization and transport of the rubblized coal to the surface.

14. The method of claim 13, comprising using a fluid discharge pressure pulse generator without a resonator, so that a pulsing jet produces cutting action on the coal bed.

15. The method of claim 13, wherein said steps are repeated after refilling the wellbore with the incompressible fluid.

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