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(19) **United States**(12) **Patent Application Publication**
Schultz et al.(10) **Pub. No.: US 2006/0118303 A1**(43) **Pub. Date: Jun. 8, 2006**(54) **WELL PERFORATING FOR INCREASED PRODUCTION****Publication Classification**(51) **Int. Cl.****E21B 29/10** (2006.01)**E21B 43/11** (2006.01)(52) **U.S. Cl.** **166/297; 166/55**(75) Inventors: **Roger L. Schultz**, Aubrey, TX (US);
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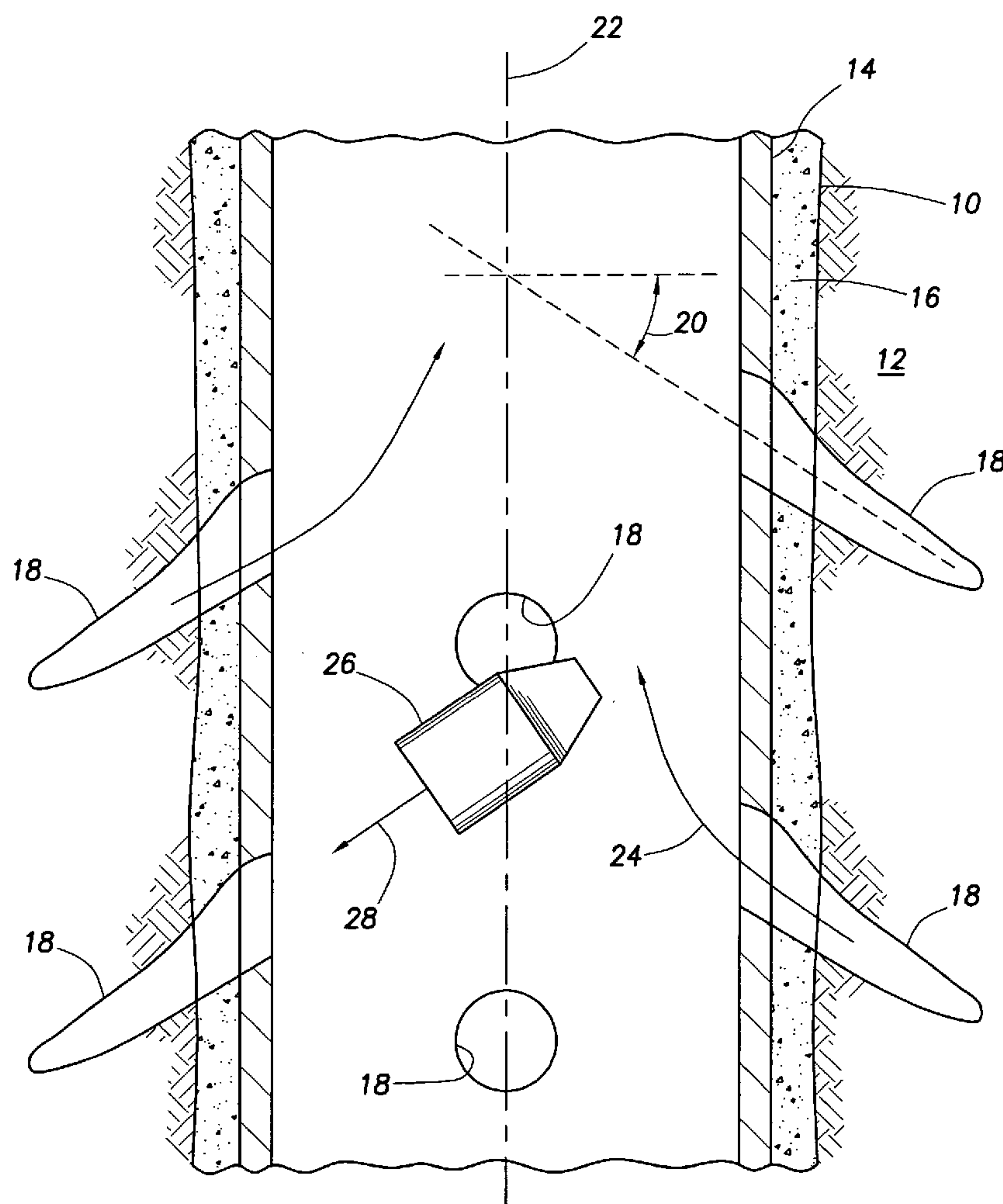
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(57)

ABSTRACT

Perforation structures which allow increased production of fluids from a well. The perforation structures direct the flow of fluids into the well in a direction having a component parallel to the axis of the well and/or having a component which does not pass through the central axis of the well. Perforations in a productive zone may be slanted downward relative to the central axis of the well. Perforations may be tangentially deviated away from the central axis of the well so that fluid flowing from the perforation has a direction somewhat tangential to the well casing and circular motion is generated in fluids in the well. Fluids flowing through such perforations experience less pressure drop at the perforations, increasing pressure in the well and providing more energy to flow fluids up the well.



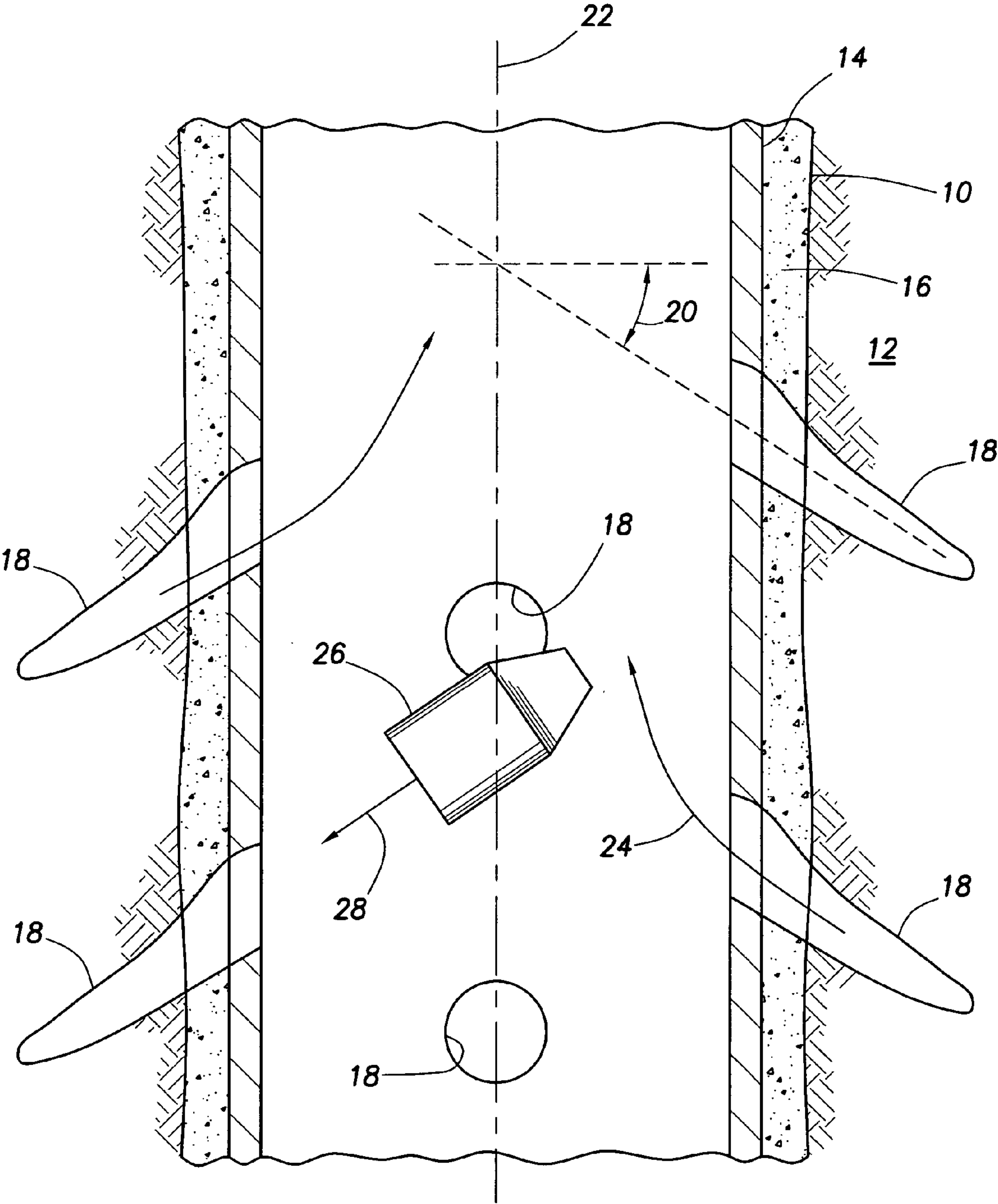


FIG. 1

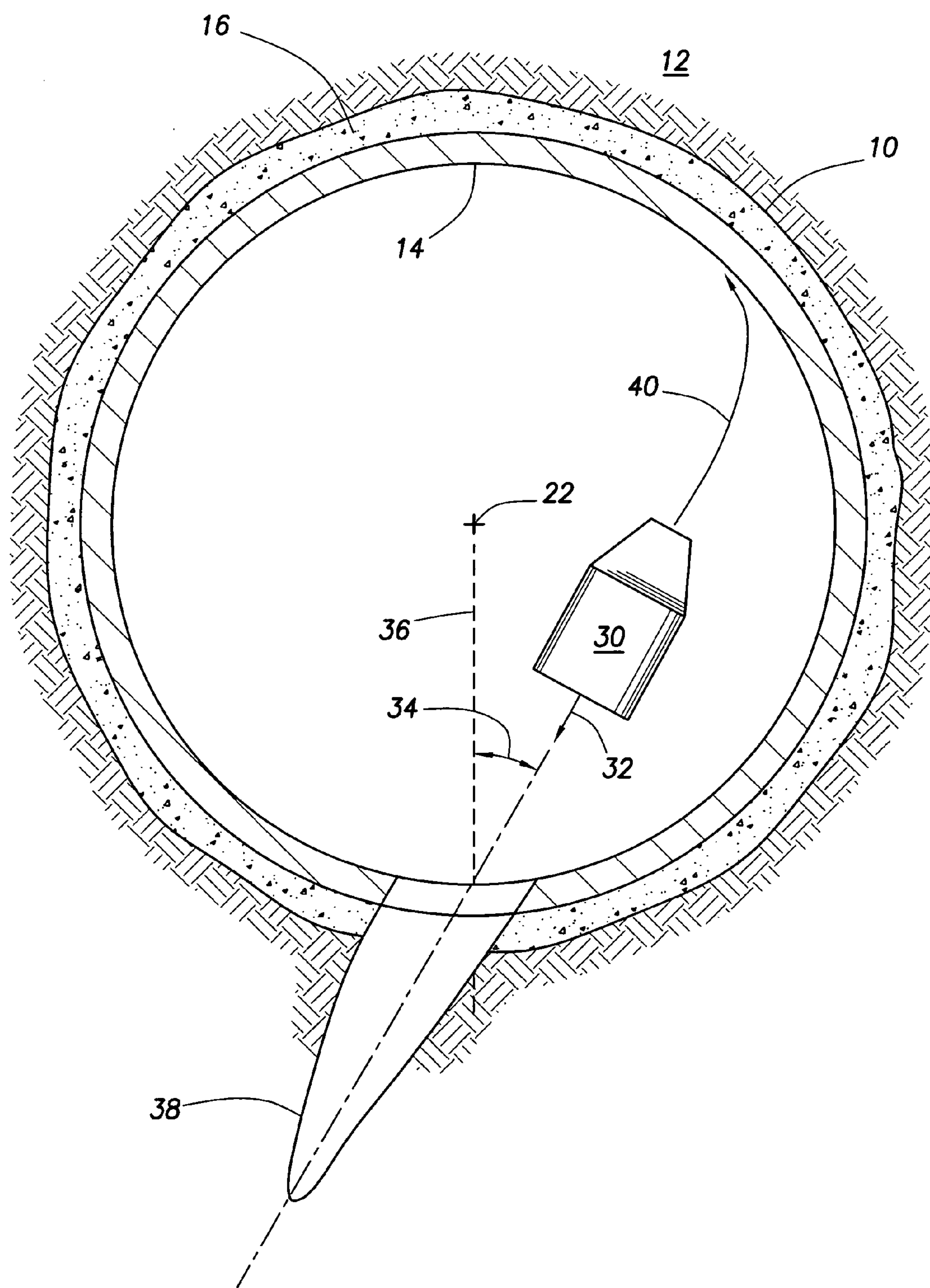


FIG. 2

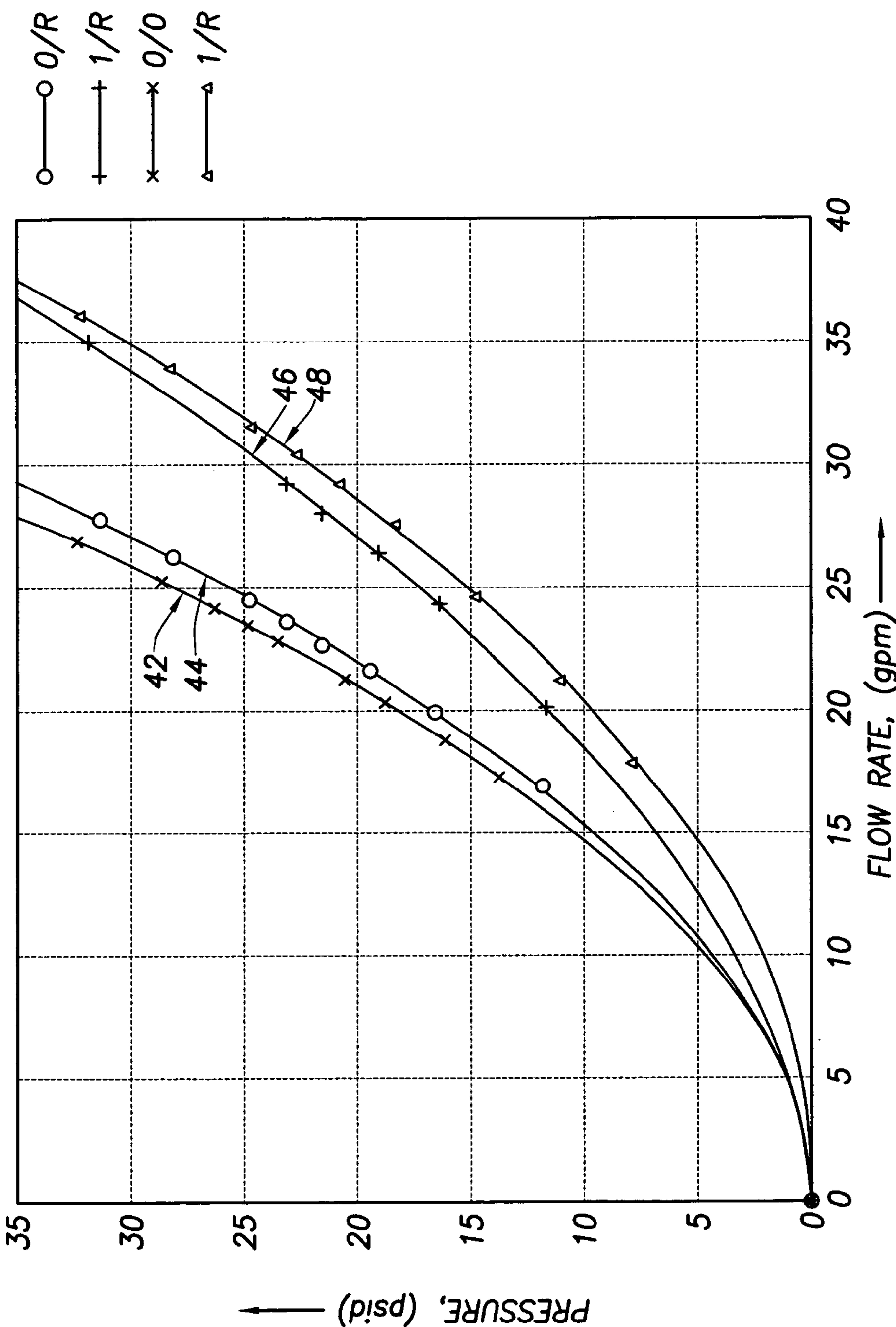


FIG.3

TOTAL PRESSURE DROP (psi)	FLOW RATE (bbl/day) (STANDARD PERFORMANCE)	FLOW RATE (bbl/day) (ANGLED PERFORMANCE)	PRODUCTION INCREASE (%)
10,000' OF TUBING			
5.83	1000	1070	7
48.99	3000	3162	5.4
132.06	5000	5257	5.14
5,000' OF TUBING			
3.46	1000	1120	12
29.33	3000	3294	9.8
79.37	5000	5452	9
1,000' OF TUBING			
1.58	1000	1320	32
13.61	3000	3717	23.9
37.22	5000	6109	22.18
100' OF TUBING			
1.162	1000	1509	50.9
10.07	3000	4090	36.3
27.73	5000	6653	33.1

FIG. 4

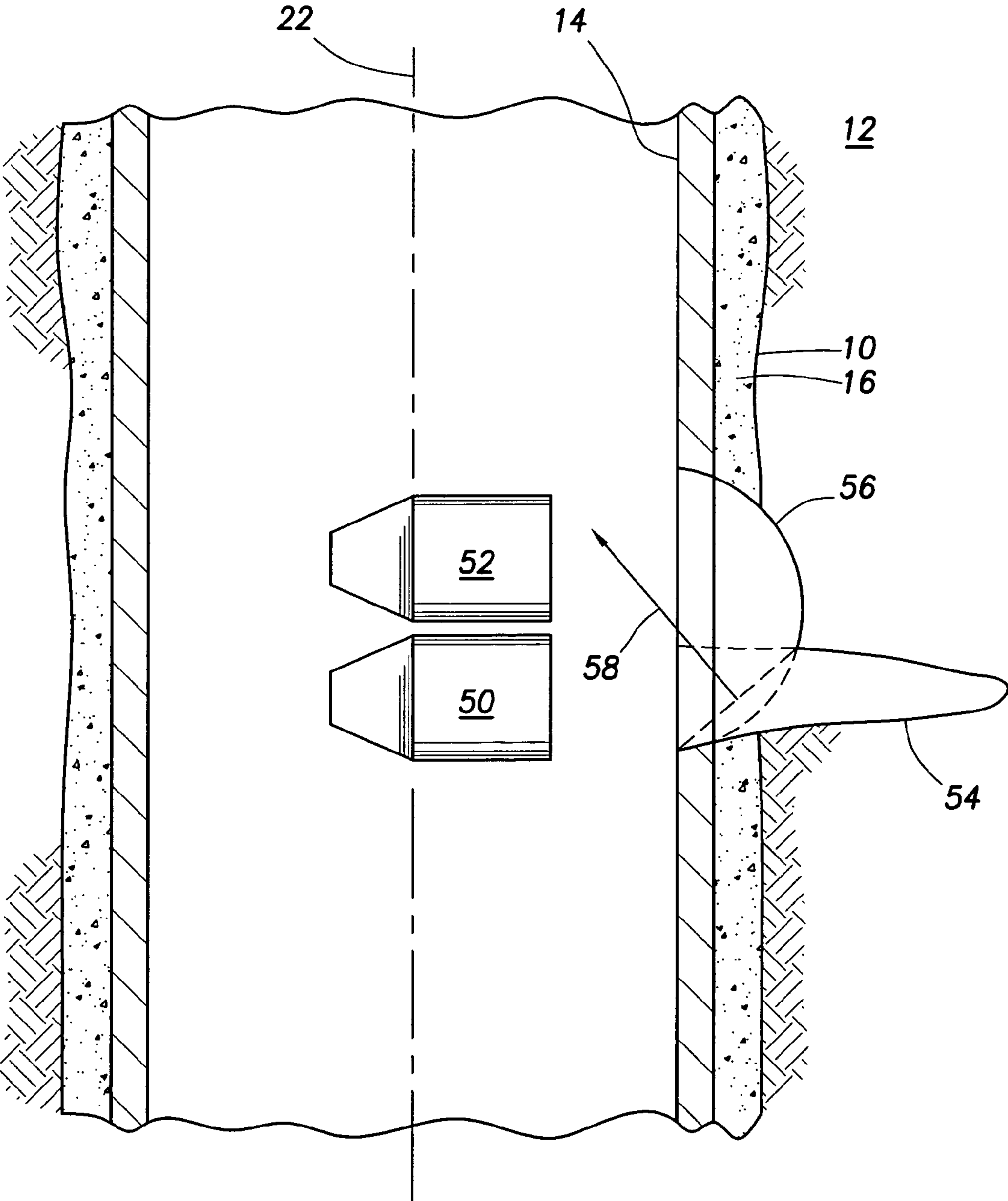


FIG. 5

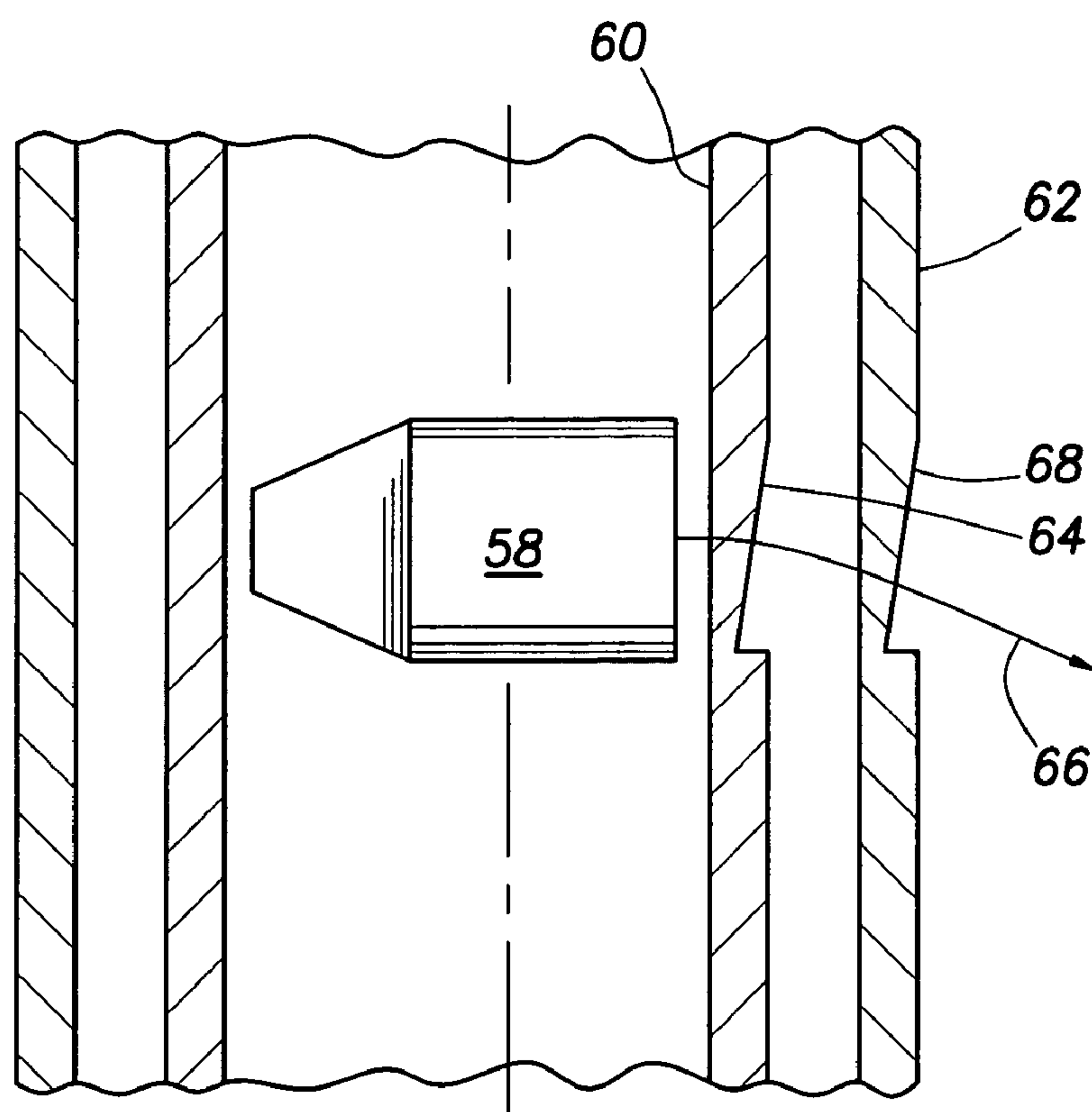


FIG. 6

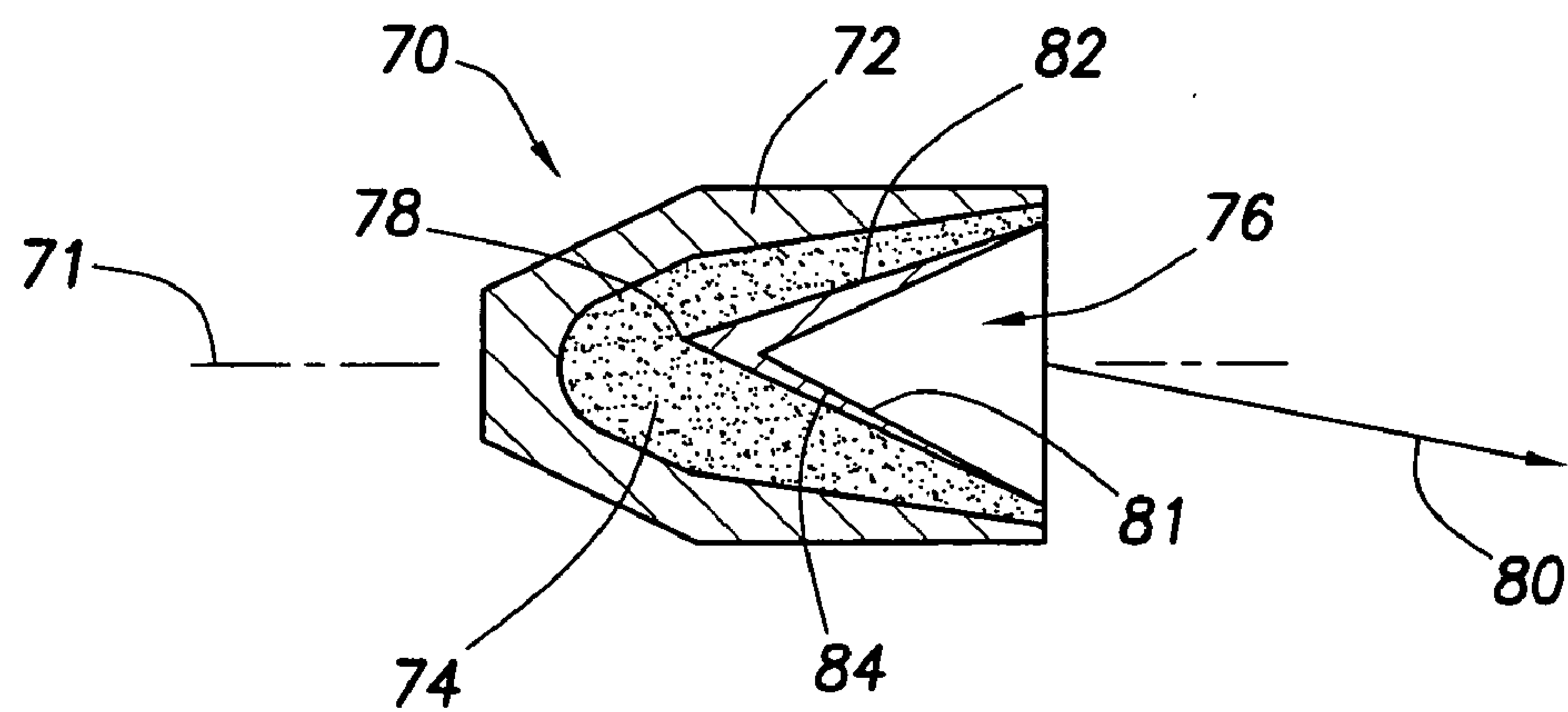


FIG. 7

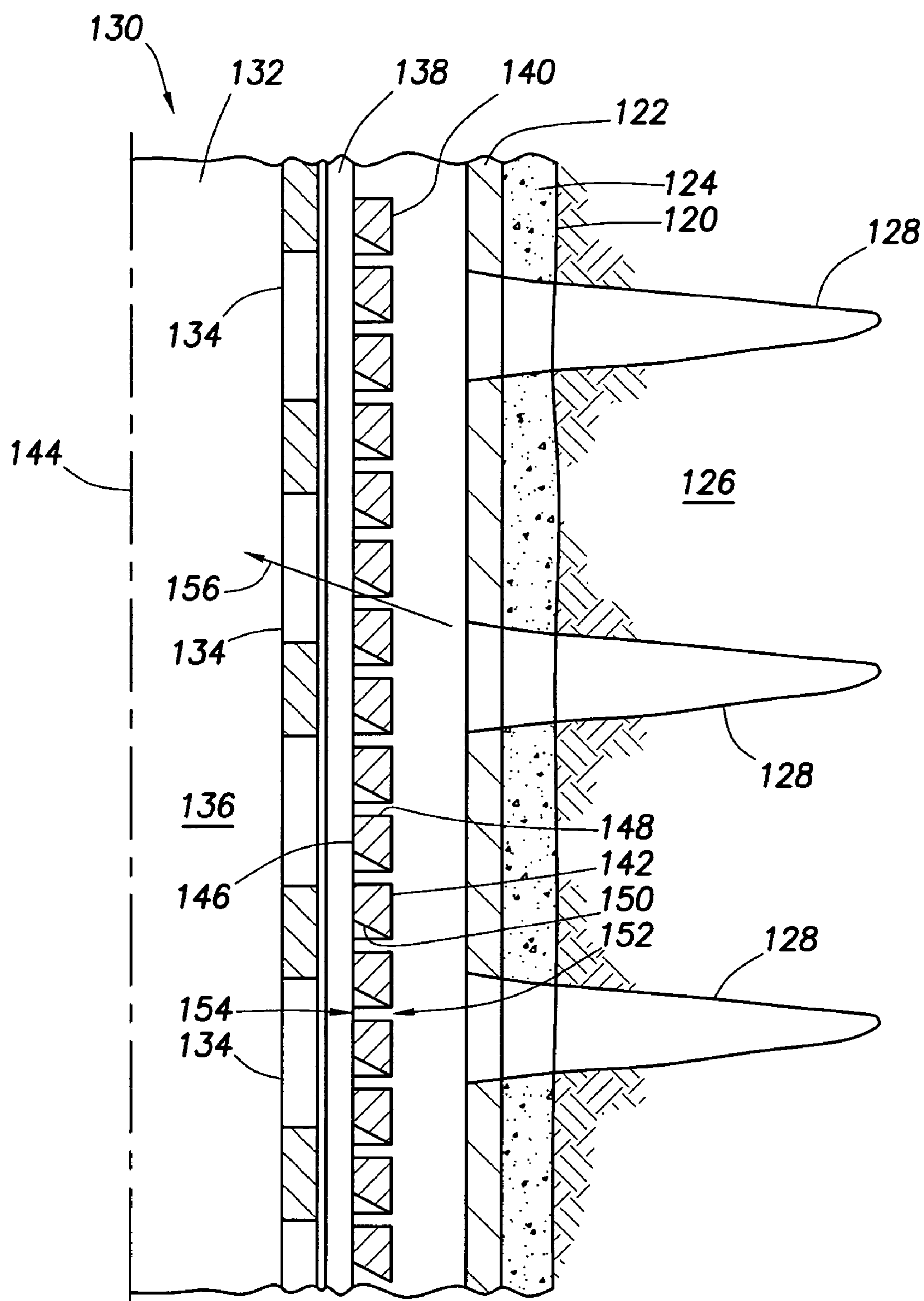


FIG. 10

WELL PERFORATING FOR INCREASED PRODUCTION

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] None.

STATEMENT REGARDING FEDERALLY SPONSORED RESEARCH OR DEVELOPMENT

[0002] Not applicable.

REFERENCE TO A MICROFICHE APPENDIX

[0003] Not applicable.

FIELD OF THE INVENTION

[0004] The present invention relates to flow of fluids between an earth formation and a well and more particularly to well structures and equipment that flow fluids between an earth formation and a well in a direction that reduces pressure drop in the fluid as it moves between an earth formation and a well.

BACKGROUND OF THE INVENTION

[0005] Oil and gas wells are drilled from the surface of the earth to and through subsurface formations from which fluids such as oil and gas may be produced. The wells are often lined with steel casing from the surface location of the well down to and through the productive formation or formations. The annulus between the casing and the well-bore is normally filled with cement. The casing and cement form a stable well structure and avoid undesirable flow of fluids, e.g. flow of oil or gas into an aquifer. The casing and cement also seal off the productive formation.

[0006] In order to produce fluids from the productive formation, it is common practice to perforate the casing and cement in the productive formation. Perforations have been formed by tools commonly referred to as perforating guns. Early perforating guns included the equivalent of firearm barrels and cartridges and actually fired projectiles through the casing and cement into the formation. Currently, the most common perforating guns use shaped charges to form perforations. Shaped charges typically include a cup shaped housing containing a quantity of explosive. The explosive typically has a conical recess and a conical liner carried in the recess. The liner is typically a metal, such as copper, or a metal alloy. When the explosive is fired, the liner is fluidized into a jet of liquid metal which flows from the open end of the charge at very high velocity and is very effective at forming holes through steel casing and concrete and into the formation rock. The perforations allow oil, gas and other fluids in the formation to flow into the well casing, through which it may flow to the surface location of the well.

[0007] Some wells, often horizontal wells, are completed without casing and cement and are often referred to as open hole completions. Such wells often are not perforated, but may be if desired to increase production. Fluids flowing from the productive formations in open hole completions often include produced particulates, typically referred to as sand. To prevent the flow of the sand to the surface with produced fluids, it is common to use filtering elements, referred to as screens or sand screens, to filter out the sand

and allow only fluids to flow into the production stream in the well. Annular space between such screens and the well bore may be filled with particulate material as a filtering material and to support uncased well bores in an operation typically referred to as gravel packing. In some cases the screen is expandable into contact with the well bore and can provide mechanical support without gravel packing.

SUMMARY OF THE INVENTION

[0008] The present invention provides well structures that flow fluids from a productive earth formation into a production stream in a well in a manner or direction that conserves natural formation pressure and enhances the flow of produced fluids.

[0009] In one embodiment, the present invention provides a perforation structure which allows increased production of fluids from a well. The perforation structure flows fluids into the well in a direction having a component parallel to the central axis of the well and/or having a component which does not pass through the central axis of the well.

[0010] In one embodiment, at least some of the perforations in a productive zone are slanted downward relative to the central axis of the well, thereby directing flow of fluids into the well in a direction having a component up the well toward the surface location.

[0011] In one embodiment, at least some of the perforations are tangentially deviated away from the central axis of the well so that fluid flowing from the perforation has a direction somewhat tangential to the well casing and circular motion is generated in fluids in the well.

[0012] In one embodiment, perforations may be both slanted and tangentially deviated to both provide a flow component up the well and to generate circular motion in the well fluids.

[0013] The present invention also includes methods and systems for producing perforations that flow produced fluids into a well in a direction having a component parallel to the central axis of the well and/or having a component which does not pass through the central axis of the well.

[0014] The present invention includes methods for producing fluids from wells including forming at least some perforations in a producing zone that flow produced fluids in a direction having a component parallel to the axis of the well and/or having a component which does not pass through the central axis of the well, and producing fluids through the perforations.

[0015] In yet another embodiment, the invention provides a filtering element in a well that flows fluids into a production stream in the well in a direction having a component parallel to the central axis of the well and/or having a component which does not pass through the central axis of the well.

BRIEF DESCRIPTION OF THE DRAWINGS

[0016] **FIG. 1** is a partially cross sectional view of a perforated portion of a well showing slanted perforation structures and a shaped charge arrangement for forming the structures.

[0017] **FIG. 2** is a partially cross sectional view of a perforated portion of a well showing a tangentially deviated perforation structure and a shaped charge arrangement for forming the structure.

[0018] **FIG. 3** is a plot of model test results which illustrate benefits of the invention.

[0019] **FIG. 4** is a table of calculated flow rates for conventional perforations and slanted perforations and indicating improved flow rates which may be achieved by the present invention.

[0020] **FIG. 5** is a partially cross sectional illustration of an alternative perforation structure and method of forming such structure.

[0021] **FIG. 6** is an illustration of a perforating gun and casing structure for producing slanted perforations with a horizontal shaped charge.

[0022] **FIG. 7** illustrates a shaped charge modified to generate a slanted perforating jet while the charge is in a horizontal position.

[0023] **FIG. 8** illustrates a well casing modification allowing an effectively slanted perforation to be produced by a horizontal perforating jet.

[0024] **FIG. 9** illustrates a perforating gun in a well casing and various arrangements for reducing reaction forces produced when shaped charges are fired.

[0025] **FIG. 10** illustrates a well having a filtering element through which produced fluids flow from a producing formation into a production stream in one embodiment of the invention.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

[0026] Various elements are described herein with reference to their position relative to a well or the central axis of a well. The terms up and down, or up hole and down hole, are used with reference primarily to the surface location of a well. Up or up hole means toward the surface location, while down or down hole means away from the surface location and toward the bottom hole location of the well. For vertical wells, up and down have their common meanings. For slanted or horizontal wells, a first element which is down hole from a second element will not be directly below the second element and may actually be at the same elevation. However, the first element will be farther from the surface location in distance through the well than the second element. A well and its central axis may be shown in the drawings to be in a vertical orientation. However, it is understood that the well, or at least portions of the well, may be deviated or slanted and some portions of a well may be horizontal and therefore the central axis will also be slanted or horizontal.

[0027] An annulus, as used in the embodiments, is generally a space between two generally cylindrical elements formed when a first generally cylindrical element is positioned inside a second generally cylindrical element. For example, a casing is a cylindrical element which may be positioned in a wellbore, the wall of which is generally cylindrical forming an annulus between the casing and the wellbore. While drawings of such arrangements typically show the inner element centrally positioned in the second, it should be understood that inner element may be offset and may actually contact a surface of the outer element at some radial location, e.g. on the lower side of a horizontal well. The width of an annulus is therefore typically not the same in all radial directions.

[0028] As noted in the background section, it is conventional to perforate wells so that fluids may be produced from productive formations or zones. A common perforating practice is to position a shaped charge, or other perforating device, at about the central axis of a well and directed perpendicular to the central axis of the well. This location and direction has a number of advantages. It has generally been considered desirable to produce the deepest possible perforation, measured in terms of distance into the producing formation, in order to increase the flow of fluids from the formation. Larger charges may produce deeper perforations. As charge size is increased, geometric considerations dictate that the charge be positioned in the center of a perforating gun and therefore on the central axis of the well. For a perforation to extend the greatest distance into the formation, geometric considerations dictate that the charge be aimed directly at, i.e. perpendicular to, the inner surface of the casing and therefore perpendicular to the central axis of the well. The conventional perforations produced by such charges therefore have a central axis perpendicular to the central axis and the wall of the casing and well.

[0029] Formation fluids flowing from conventional perforations generated as described above have a flow direction perpendicular to the central axis of a well and passing through the central axis. The flow direction is therefore aimed directly at the opposite side of the well and the flow impinges upon the opposite side of the well at a ninety degree angle. To travel up the well, the fluids must make a ninety degree turn. The fluids entering the well from one perforation are also flowing perpendicular to the direction of the stream of fluids produced through perforations located farther downhole. These crossing flow paths generate a large amount of turbulence and increase the pressure loss of fluids flowing through the perforations. A part of the energy of the fluids in the formation as a result of natural formation pressure is lost in flowing the fluids through the perforations into the well.

[0030] In the present invention, perforations are formed and arranged to reduce the loss of energy of the fluids flowing from the formation into the well as compared to conventional perforations. As a result, the fluid pressure in the well is increased allowing more flow of fluids up the casing or production tubing placed in the casing. The reduction in energy loss through the perforations reduces the pressure drop across the perforations, thereby reducing sand production and/or allowing production rate to be increased without increasing sand production.

[0031] **FIG. 1** illustrates one embodiment of the present invention. A well **10** has been drilled through a productive formation **12**. A casing **14** has been positioned in the well **10** and cement **16** has been placed in the annulus between casing **14** and well **10**. A number of perforations **18** have been formed through casing **14** and cement **16** into the formation **12** to allow fluids to flow from the formation **12** into the casing **14** and therefore into a stream of produced fluids in the casing **14**. Each perforation **18** is slanted downward at a slant angle **20** relative to the central axis **22** of the well **10**. Fluids flowing from perforations **18** into the casing **14** flow in a direction **24** which has a component parallel to the central axis **22**. As indicated by the curved arrow **24**, the flow from each perforation **18** will encounter an upward flowing stream of produced fluids from down hole perforations and turn upward to become part of the total

uphole stream of produced fluids. The slant angle **20** may desirably be as great as possible. The maximum angle is limited by various practical considerations discussed below, which vary depending upon the system used to form the perforations. It is believed that slant angles from ten to eighty degrees will provide advantages in producing fluids from a well bore.

[0032] In this embodiment, the perforations **18** were formed by a number of shaped charges **26**. To simplify **FIG. 1**, only one charge **26** is shown in **FIG. 1**. The charge **26** may be any conventional shaped charge. Charge **26** may be carried into the well as part of a conventional shaped charge assembly, for example as a capsule charge on an open strip carrier or in a sealed charge carrier. In either case, the charge **26** may be located generally on the axis **22** of the well **10** and may be slanted downward at the slant angle **20**. The slanted charge **26** therefore produces a downward slanted explosive jet directed along the path **28** to form a slanted perforation **18**. As is well known in the perforating art, the charge **26** disintegrates upon detonation and any debris either falls down the well **10** or, if the charge is in a sealed carrier, is returned to the surface of the well with the carrier. As with conventional charge carriers, the charges **26** may be arranged in a spiral pattern as indicated by the pattern of perforations **18** in **FIG. 1**. A spiral pattern may improve use of space in a perforating gun and may shorten the length of detonating cord between adjacent charges.

[0033] **FIG. 2** illustrates a second perforation structure according to the invention. In **FIG. 2**, the well **10**, casing **14**, cement **16**, and formation **12** are viewed down the axis **22** of the well **10**. A shaped charge **30**, which may be identical to charge **26**, is positioned in the well **10** offset from the central axis **22**, in this case positioned about half way between the central axis **22** and the casing **14**. The charge **30** produces an explosive jet which travels along path **32** deviated at an angle **34** from the conventional radial direction **36** from the central axis **22**. A jet following path **32** forms a tangentially deviated perforation **38**. It should be understood that a plurality of other perforations may be formed in the casing **14** spaced above and/or below perforation **38** as shown in **FIG. 1**, for example in a spiral pattern.

[0034] Fluids flowing from the formation **12** through perforation **38** into the casing **14** will be directed along the path **32**, in the opposite direction of the jet from charge **30**, and along the path **40**. The path **40** shows that the flow from perforation **38** has a directional component tangential to the wall of casing **14**. As noted above, conventional perforations direct the flow of produced fluids directly across the central axis **22** so that they impinge upon the inner surface of the casing **14** at about a ninety degree angle generating turbulence as the flow redirects itself to flow up hole. The flow path **40** not only produces less turbulence, but also may induce a circular flow in the casing **14**.

[0035] Circular flow of a production stream in a well may have a number of advantages. Circular flow may be used to at least partially separate produced fluids, i.e. gas, water and oil, down hole. Circular flow may have a hydrocyclone effect to separate water from oil based on gravity, i.e. density, of the fluids. Such partial separation may be part of a first stage separator in a system such as the "Down hole Oil and Water Separator and Method" disclosed in U.S. patent application Ser. No. 10/924,161 (Attorney docket number

2002-IP-008005) filed on Aug. 23, 2004 and assigned to the assignee of this application, which application is hereby incorporated by reference for all purposes. Circular flow may help produce condensate in gas wells, which condensate may otherwise tend to form on the well casing or tubing. Circular flow may also help prevent scale formation on the casing. In horizontal wells, circular flow may help prevent undesirable separation of phases that can result in collection of water on the lower side of the horizontal well and undesirable nonuniform production with flow of water slugs.

[0036] The perforation **38** is tangentially deviated by the angle **34**. Fluids produced from formation **12** through the perforation **38** will enter the well **10** with a tangential deviation equal to the angle **34**. The terms tangentially deviated and tangential deviation are used herein to indicate that a fluid flow path is at least partially tangential to the casing at the point at which the flow impinges upon the casing as opposed to perpendicular as in conventional perforations.

[0037] In **FIG. 3**, tangential deviation angle **34** is about thirty degrees. This angle positions the charge **30** about half way between the well axis **22** and the well casing **14**. It is desirable for angle **34** to be as great as practical. Practical considerations include space to position the charge **30**, reduction in depth of penetration as angle is increased, and possible deflection of the perforating jet off the casing **14**. These considerations indicate that the deviation angle **34** is desirable from about five degrees to the maximum angle based on the diameter of the well, or a charge carrier, and the diameter of the charge itself. Preferred angles are between ten and forty degrees and more preferably from about twenty to thirty-five degrees. In a perforating gun, multiple charges **30** preferably are all deviated in the same direction so that circular motion generated by produced fluids is the same for all perforations. It is also desirable to select the deviation angle **38** so that torsional reaction forces from firing charges **30** tend to tighten, rather than loosen, threaded connections in a work string and perforating gun assembly.

[0038] While **FIG. 1** illustrates slanted perforations **18**, and **FIG. 2** illustrates tangentially deviated perforation **38**, various combinations of these structures may be used in the present invention. For example, any perforation may be both slanted and tangentially deviated. In a given completion, some perforations may be slanted while others are tangentially deviated. A completion may also include some conventional perforations which are not slanted or tangentially deviated.

[0039] Four one-twelfth scale models were built and operated with water to test the embodiments described above. The models simulated a sixty-foot interval with six inch internal diameter casing. In a conventional model, the simulated perforations were not slanted and had no tangential deviation. In a tangent only model, the perforations were not slanted, but were tangentially deviated so that the angle **34** was 30 degrees, which directs the flow at a point half way between the central axis **22** and the wall of the casing **14**. In an angled only model, the perforations were slanted so that the angle **20** was about 45 degrees. In a combination model, the perforations were both slanted at about 45 degrees and tangentially deviated at about 30 degrees.

[0040] **FIG. 3** shows plots of model test results which illustrate benefits of the present invention. The plots are of

pressure in pounds per square inch on the vertical axis required to flow the test fluid at the flow rate in gallons per minute on the horizontal axis. The curve **42** for the conventional model shows that conventional perforations require more pressure at all flow rates than any of the above described embodiments. For example, at twenty-five gallons per minute, the conventional perforations model, curve **42**, required about twenty-eight pounds pressure, the tangent only model, curve **44**, required about twenty-six pounds, the combination model, curve **46**, required about seventeen pounds, and the slanted only model, curve **48**, required only fifteen pounds. These results indicate that the slanted only embodiment provides the most flow at a given pressure drop and the least pressure loss at a given flow rate. The tangentially deviated embodiment provides better flow than the conventional perforations, but not as good as the slanted only embodiment. The combination model provides better flow than the tangentially deviated only model, but is not as good as the slanted only model. These results indicate that to achieve the maximum flow rate from a well, perforations should be slanted, but not tangentially deviated. However, if it is desired to obtain a benefit of circular flow in the casing **14**, it may be desirable to use the combination embodiment or tangential only embodiment even though the flow rate characteristics may not be as good as the slanted only embodiment.

[0041] Using the test model results, calculations were made to determine the flow rate improvements that may be possible by use of the slanted perforation embodiment as compared to conventional perforations. The calculations were based on 3.5 inch production tubing of various length, six inch casing at the perforations, a twenty foot perforated interval and the properties of water. All combinations of flow rate, available pressure drop and tubing length indicated production rate improvement ranging from about five to fifty percent. A set of calculated results are set out in **FIG. 4**.

[0042] As noted above, one aspect of the present disclosure addresses conservation of available formation pressure. Pressure drop of fluids flowing through the perforations is reduced so that pressure in the well is increased and is available to drive fluid through the casing, and/or production tubing, at a greater flow rate. The improvement is believed to be due primarily to the direction of flow of produced fluid as it flows into the casing and interacts with the casing and the flow of produced fluids in the casing. Thus, it may not be necessary to slant all of the perforations in a given completion as shown in **FIGS. 1 and 2**. Other perforation structures or geometries may provide a desirable fluid flow direction that reduces turbulence and other causes of pressure loss.

[0043] **FIG. 5** is an illustration of an alternative perforation structure and method of forming such structure. Two shaped perforating charges **50** and **52** are shown positioned in the well **10** at about the same location and directed at about the same location on the casing **14**. Charge **50** may be a conventional deep penetrating shaped charge, which is designed to produce a deep perforation **54** extending into the formation **12**. Charge **52** may be a charge designed to produce a wide but relatively shallow perforation **56**. In this embodiment, both charges **50** and **52** may be located on the central axis **22**, positioned at a right angle to the central axis **22**. Charge **52** may be positioned above charge **50** by a short distance that causes a lower portion of perforation **56** to

overlap the perforation **54**. The two charges may be fired simultaneously or sequentially. The combined perforation is a deep perforation **54** with an opening at the casing **14** which is slanted and directs the flow of fluids upwards as indicated by the arrow **58**, like the slanted perforations **18** of **FIG. 1**. It will be appreciated that the charges **50** and **52** may be closely spaced as indicated or may be spaced apart and fired at different times or from different perforating guns which have been positioned to provide the overlapping double perforation as illustrated. If desired, the shallow charge **52** may be slanted to provide more space between the charges **50**, **52** while providing the desired overlap of the perforations **54**, **56**. This embodiment allows use of horizontal perforating charges and their deeper penetration potential instead of slanted charges as in the **FIG. 1** embodiment.

[0044] **FIG. 6** illustrates another embodiment in which a conventional horizontal shaped charge **58** may be used to produce a slanted perforation. The charge **58** is shown positioned in a sealed charge carrier housing **60** that is positioned inside a well casing **62**. Charge carrier housings typically have thinned areas adjacent the jet firing end of shaped charges, commonly referred to as scallops. The thinned areas reduce the energy required for the jet to exit the housing, thereby providing more energy for perforating the casing **62**, etc. In this embodiment, a scallop **64** may be provided with a nonuniform thickness that causes the jet from charge **58** to turn in a downhole direction as indicated by the arrow **66**, thereby producing a slanted perforation. The casing **62** is also illustrated with a similar nonuniform thickness scallop on its outer surface that may also cause deflection of the jet from charge **58**. Either or both of the nonuniform scallops **64** or **68** may be used as desired. The scallops **64** and **68** may also be formed in the inner surfaces of housing **60** and casing **62** if desired, although it may be easier to machine the outer surfaces.

[0045] **FIG. 7** illustrates a modification to a conventional shaped charge that may allow the shaped charge **70** to have a central axis **71** positioned perpendicular to a central axis of a well, but to fire a penetrating jet at an angle other than perpendicular to the well axis. The charge **70** includes a conventional cup shaped metal housing **72**. A quantity of explosive **74** is carried in the housing **72**. A generally conical shaped recess **76** is provided in the output or jet firing end of the charge **70**. In conventional shaped charges, the recess **76** is centrally located in the housing **72**. In this embodiment, the innermost end or bottom **78** of the recess **76** is not centered in the housing **72**. The offset in the recess **76** may cause a jet fired by charge **70** to be angled or deviated from the normal horizontal direction **71** as indicated by the arrow **80**. The charge **70** also includes a generally conical liner **81**, e.g. copper, lining the recess **76**. The liner material fluidizes to form the jet produced by firing charge **74**. Conventional liners have symmetrical thickness around central axis **71** of the charge **70**, but may vary in thickness from the innermost end **78** to the open end of the charge. In this embodiment, one side **82** of liner **81** is made thicker than an opposite side **84**. The nonsymmetrical liner **81** may also cause the jet to exit the charge along the path **80** deviated from the central axis **71** of the charge housing **72**. Such a charge may be carried into a well and fired from an otherwise conventional charge carrier and may produce desirable slanted perforations.

[0046] **FIG. 8** illustrates another embodiment that allows use of conventional shaped charges fired perpendicularly to a well central axis to produce a perforation **86** that may flow fluids into a well in a direction having a component aligned with the well central axis. A well casing **88** has been modified by expanding a portion **90** to provide a curved inner surface **92**. A conventional shaped charge has been fired in a conventional direction perpendicular to a well axis **94** producing the perforation **86** into a productive formation. However, the charge was positioned near the lower edge of the inner curved area **92** so that the perforation opening in the casing **88** is slanted upward to some extent. Produced fluids from perforation **86** may flow into the casing **88** in a direction **96** having a desirable upward component. The curved section **90** may extend around the casing **88** as indicated to facilitate alignment with a perforating gun or may be formed as a circular area on only one side of casing **88**. Alternatively, equivalent casing shapes may be formed by cutting a hole in the casing **88** and welding on the outside a spherical or conical member providing an upward slanted surface through which a perforation may be formed as shown in **FIG. 8**.

[0047] In **FIG. 1**, all the perforations **18** slant down at about the same angle **20**. The model for slanted perforations used an angle **20** of about 45 degrees. For maximum flow improvement, it may be desirable to select the angle **20** to be as large as practical. As noted above, angles **20** from ten to eighty degrees should enhance production. The angle of the test model was selected according to this criteria. Positioning of slanted shaped charges in a perforating gun becomes more difficult as the slant angle is increased. It is possible that the perforating jet may deflect off the inner surface of the casing if the slant angle is too large. As the slant angle **20** is increased, the radial depth of the perforation is reduced. The slanted perforating charges also produce a reaction force that will tend to drive a perforating gun up hole, possibly damaging the work string on which the gun is conveyed into the borehole. For these various practical considerations, when using shaped charges a practical range of slant angles **20** may be from about fifteen to fifty degrees, preferably from about fifteen degrees to thirty degrees and it may be desirable to select the slant angle **20** to be about 25 degrees. It may also be desirable to provide additional elements in the perforating system to accommodate or reduce reaction forces generated by firing a perforating gun carrying slanted shaped charges. **FIG. 9** illustrates various elements and arrangements of elements which may accommodate or reduce the reaction forces.

[0048] In **FIG. 9**, a perforating gun **100** is shown positioned in a well casing **102** in preparation for perforating the casing. The gun **100** has been conveyed into this position by a work string **104**, which may be a wireline, coiled tubing, drill string, or other work string known in the art. Between the work string **104** and the gun **100** is a shock absorbing or reducing section **106**.

[0049] A plurality of arrows **108**, **110**, **112**, and **114** indicate the directions of perforating jets which may be produced by shaped charges carried within the perforating gun **100**. In this embodiment, the jets **108** at the upper end of the gun **100** have a larger slant angle **20** than intermediate jets **110**. The jets **108** would generate a larger uphole reaction force than the jets **110**. Modeling has indicated that the slant angle **20** of upper perforations is more effective in

reducing perforation pressure loss and therefore more effective at increasing production, possibly because flow from upper jets encounters more total flow of produced fluids in the casing **102**. As a result, it may be desirable to provide upper perforations with the greatest practical slant angle and lower perforations with smaller slant angles **20**. The total reaction force may be reduced by the smaller angles in the lower perforations. Perforations **112** near the bottom of a producing zone may actually be at a zero slant angle as illustrated. In addition it may be desirable to provide one or more shaped charges **114** at the bottom of the gun **100** with a large uphole slant to provide a downhole reaction force to counter some of the reaction forces from the upper charges. As the upward slant of charges **114** is increased, the downward reaction force is increased and if the angle is large enough, the jets **114** may not actually penetrate the casing **102**. If the jets **114** actually produce downward slanted perforations, they will be at the bottom of the productive zone and should not interfere with the fluids produced from up hole perforations.

[0050] The shock absorbing or reducing section **106** may include one or more mechanisms for preventing reaction forces from the gun **100** from damaging the work string **104**. The work string may be attached to the section **106** by a sliding piston **116**. This arrangement may allow the section **106** to slide up the work string **104** without transferring energy to the work string **104**. Fluid in the borehole and gravity may absorb sufficient energy to stop the gun **100**. The sliding piston arrangement may also allow rotation of the perforating gun relative to the work string **104**, to accommodate rotation of the gun **100** if it contains tangentially deviated charges as illustrated in **FIG. 2**.

[0051] The shock absorbing or reducing section **106** may include one or more slips **118** which may be deployed to engage the casing **102** and resist upward movement of the gun **100**. The slips **118** may be deployed before firing the gun **100** by a signal from the surface location of the well and an energy source in the section **106**. Alternatively, the slips may be actuated by weights and levers within section **106**, similar to braking systems which prevent elevators from falling. In one embodiment, section **106** may be used to anchor the gun **100** in position in the casing **102** and the work string **104** may be disconnected and moved up hole a safe distance. After firing of the gun **100**, the work string may be reconnected and used to remove the gun **100** from the well.

[0052] Alternatively, the section **106** may simply be a collapsible cylinder which may be crushed by gun **100** if it is driven up hole with sufficient force.

[0053] In the above description of the **FIG. 9** embodiment, the angles of various perforating charges **108**, **110**, **112** were selected to provide improved flow rate with minimum reaction force. In general this resulted in the upper charges having greater slant angles **20** than the lower charges. The slant angles may be varied along the length of a perforation gun and possibly from one side to the other to accommodate other parameters. For example, in horizontal boreholes, it may be desirable for the perforations on the top of the well bore to be more or less slanted than the perforations on the bottom. Due to pressure drop along the length of a horizontal well section, the production from the toe, i.e. the portion farthest from the vertical portion of the well, is often less

than desired. To increase production from the toe, it may be desirable to provide greater slant angle for perforations in the toe portion of a slanted cased well, than in the heel portion, i.e. the portion adjacent the vertical portion of the well. The slant angles may be selected and varied to accommodate other formation characteristics.

[0054] It is believed to be desirable to fire charges in a perforating gun from the top down to minimize the total reaction force. This firing sequence is consistent with available perforating guns that normally have a firing head at the top connected to a work string for receiving a firing signal. The firing head normally is connected to an upper end of a length of detonating cord which extends down through the perforating gun and is coupled to each charge carried in the gun. While the charges all fire within a very short time, the top charges are fired first in this arrangement. As discussed above, the gun 100 may move up hole as a result of reaction forces from firing the guns 108, etc. It is possible that the lower guns 110, 112 may move before they actually fire. When firing is performed with conventional detonation cord, the detonation speed is faster than the speed of sound in the perforating gun and essentially no movement should occur between firing of the charges. Low speed detonation cords are known and, if used, it may be desirable to adjust the spacings between successive charges to account for movement of the gun 100 during firing.

[0055] The above described embodiments preferably include the use of shaped charges to form the perforation structures in boreholes. Shape charges may be preferred because they are the current standard devices used to form well perforations. The charges and systems for handling and firing the charges are readily available. However, as noted above, certain characteristics of shaped charges may limit the practical maximum slant angle 20 and may require additional system elements to control reaction forces. As a result, it may be desirable to use alternative perforating systems. Various alternatives may have certain advantages for forming slanted perforations. Alternatives include lasers, mechanical boring, e.g. mills and drills, and hydraulic jetting. None of these alternatives produces large reaction forces. Lasers and mechanical boring are more suited to producing highly slanted perforations than conventional horizontal perforations, due to the shapes of the tools themselves. That is, they tend to work best with a long central working axis and may be able to form perforations extended a great distance into the productive formation. When using these alternative perforating systems, the upper end of the desirable range of angles 20 from ten to eighty degrees is possible and preferred. Thus the preferred range may be from forty-five to eighty degrees and more preferably from fifty to seventy degrees. Hydraulic jetting may have an advantage in producing perforations with a desirable slant angle of about 45 degrees. Hydraulic jetting has been found to abrade and form holes in steel most effectively which the hydraulic jet is applied to the steel surface at from about 35 degrees to about 55 degrees and preferably at about 45 degrees.

[0056] The above description of embodiments is with respect to production of fluids from wells. In many cases, waste or treating fluids are injected into earth formations through perforated well casings. For example, produced water is often separated from produced oil and the water is often injected into a disposal zone. Producing zones are

often fractured after perforating and before the well is put on production. During the fracturing process it is common to pump fluids down a well and out the perforations at very high pressure and high flow rate. It is desirable to achieve sufficient pressure in the producing formation to cause fracturing without exceeding safe working pressure in the pumping equipment, tubing, casing, etc. used to convey the fracturing fluids to the formation. Treating fluids other than fracturing fluids may also be pumped down a well and through perforations into an earth formation. It is believed that just as the above described perforation structures reduce pressure drop of fluid flowing from the formation into the well bore, they will also reduce the pressure loss across the perforations when fluids are pumped from the well into the formation. As a result, the pressure in the well bore may be reduced while achieving a desirable fracturing pressure in the formation or a desirable injection pressure in a disposal zone. For injected fluids that are pumped down the well and into the formation, the downward slanted perforations of FIG. 1 may provide a benefit. If waste fluids are separated down hole at or near a producing formation, they may be flowed up hole for injection in a disposal formation located above the producing formation. In that case, it may be desirable for perforations in the disposal formation to be slanted upward relative to the central axis of the well to improve flow of fluids flowing up hole and into the disposal zone.

[0057] FIG. 10 illustrates an alternative embodiment that may be useful in open hole wells or in wells that are cased, but produce sand and require sand screens and possibly gravel packing. A well 120 is shown as including a casing 122 and cement 124 between the casing 122 and a productive formation 126. A number of conventional perforations are shown extending through the casing 122 and cement 124 into the formation 126. If desired, the casing 122 and cement 124 may be omitted and the well 120 may be completed as an open hole. If completed as an open hole, the perforations 128 may also be omitted if desired.

[0058] In this embodiment, a filtering element 130 is positioned inside the well 120, and, if casing 122 is used, within the casing 122. The filtering element 130 is a somewhat conventional wire wrapped screen that has been modified according to the invention. The screen 130 includes a base pipe 132 having slots or perforations 134 that allow free flow of fluids into the interior 136 of the screen 130. The interior 136 is coupled to a production string that carries a produced fluid stream up hole to the surface location of the well. The base pipe 132 is surrounded, or wrapped, by several layers of elongated metal elements, commonly referred to as wires or ribs. A number of longitudinally extending ribs 138 may be attached to the outer surface of the base pipe 132. A spiral wrap of wires, or one continuous wire, 140 may be attached around the ribs 138. The wire 140 has a rectilinear cross section designed to provide a sand filtering function. The outer edge 142, relative to the axis 144 of the screen 130, of the wire 140 has a longer dimension than the inner edge 146 that is connected to the ribs 138. An upper edge 148 of the wire 140 may be about perpendicular to the outer and inner edges 142, 146. A lower edge 150 of the wire 140 is slanted so that the spacing 152 between adjacent wraps of wire 140 is smaller on the outer edge than the spacing 154 on the inner edge. The spacing 152 is selected to be small enough to restrict the flow of sand produced from the formation 126, or to restrict the flow of

aggregate used to form a gravel pack around the screen 130. By slanting the lower edge 150 of wire 140 but not the upper edge 148, an up hole slanted flow path 156 is generated between adjacent wraps of the wire 140. This up hole slanted flow path 156 directs fluids produced from the formation 126 into the produced fluid stream in screen 130 in a direction having a component in alignment with the central axis 144 and conserves available formation pressure to enhance production.

[0059] As noted above, the space between the screen 130 and the well 120 may be gravel packed with particulates to filter out produced sand and support the formation 126. A gravel pack is more likely to be used if casing 122 and cement 124 are omitted, but may also be used in cased and perforated wells. If a gravel pack is used, especially in an open hole completion, flow through the gravel pack may be primarily in a radial direction. As a result, use of slanted perforations as shown in FIG. 1 may provide little advantage in a gravel packed completion, but may be used if desired. But when the radial flow of produced fluids passes through the screen 130, it will be directed along the flow path 156 having an upward component. The openings 134 through base pipe 130 are normally much wider than the thickness of the base pipe 130, and should not substantially redirect fluid flowing in the direction produced by flow path 156. In contrast, the flow path 156 has a length at least as large as its width, and preferably at least twice as large as its width, so that it may impart a desired direction to fluids flowing through the path 156.

[0060] Conventional gravel packs have little directional affect on produced fluids and the fluids normally flow in a radial direction from the higher pressure in the formation to the lower pressure in the well. However, systems, referred to as pumpable screens, have been developed in which a settable mixture may be pumped into an annulus between a production tubing and a borehole and allowed to set into a rigid, but porous, mass that functions as a sand filter. Porosity may be generated by including elements that dissolve, leaving open spaces in the mixture after it has set. By selecting the sizes, shapes and orientations of these dissolvable elements possibly in combination with some other aligning force, such as a magnetic field, the rigid mass may direct fluids in a desired direction in accordance with the present invention.

[0061] While the present invention has been illustrated and described with reference to various perforation structures and methods of forming such structures, it is apparent that various changes to the structures may be made and other systems and methods for forming such structures may be used within the scope of the present invention as described in the appended claims.

1. A method for completing a cased well having a central axis, comprising:

forming perforations through the casing, the perforations shaped to flow fluids into the well in a direction that reduces pressure drop across the perforations relative to conventional perforations.

2. The method of claim 1, wherein the perforations flow fluids in a direction having a component parallel to the direction of flow of fluids in the well.

3. The method of claim 1, wherein the perforations flow fluids in a direction that does not pass through the central axis of the well.

4. The method of claim 1, wherein the perforations flow fluids in a direction having a component parallel to the axis of the well and not passing through the central axis of the well.

5. The method of claim 1, wherein the perforations extend through the casing into a producing formation at a downward angle of from ten to eighty degrees relative to the perpendicular to the central axis of the well.

6. The method of claim 1, wherein the perforations extend through the casing into a producing formation at a downward angle of from 15 degrees to 50 degrees relative to the perpendicular to the central axis of the well.

7. The method of claim 1, wherein the perforations extend through the casing into a producing formation at a downward angle of from 15 degrees to 30 degrees relative to the perpendicular to the central axis of the well.

8. The method of claim 1, wherein the perforations extend through the casing into a producing formation at a tangentially deviated angle of at least five degrees relative to the central axis of the well.

9. The method of claim 1, wherein the perforations extend through the casing into a producing formation at a tangentially deviated angle of from 10 degrees to 40 degrees relative to the central axis of the well.

10. The method of claim 1, wherein the perforations extend through the casing into a producing formation at a tangentially deviated angle of from 20 degrees to 35 degrees relative to the central axis of the well.

11. The method of claim 1, further comprising using shaped charges to form the perforations.

12. The method of claim 11, further comprising positioning shaped charges in the well and slanted relative to the central axis of the well to fire a perforating jet at a downward angle relative the perpendicular to the central axis.

13. The method of claim 11, further comprising positioning shaped charges in the well between the central axis and the casing.

14. The method of claim 1, further comprising forming a perforation by:

positioning a first shaped charge in a cased well and directed at the casing, the first shaped charge adapted to produce a first perforation,

positioning a second shaped charge in the cased well directed at an area on the casing at least partially overlapping the first perforation, and

firing said first shaped charge and said second shaped charge in either order.

15. The method of claim 1, further comprising forming a perforation by:

positioning a first shaped charge in a cased well and directed at the casing, the first shaped charge adapted to produce a first perforation having a center, a lower edge, a first diameter and a first depth,

positioning a second shaped charge in the cased well directed at a point on the casing between the center and lower edge of the first perforation, the second shaped charge adapted to produce a perforation having a second diameter smaller than said first diameter and a second depth greater than said first depth, and

firing said first shaped charge and said second shaped charge in either order.

16. The method of claim 1, further comprising forming a perforation by:

deforming a portion of said casing to provide a slanted area on an inner surface of the casing that is not parallel to the central axis,

positioning a shaped charge in the casing directed at the slanted area, and

firing the shaped charge.

17. The method of claim 1, further comprising forming a perforation by:

deforming a portion of said casing to provide an upward facing area on an inner surface of the casing,

positioning a shaped charge in the casing directed at the upward facing area, and

firing the shaped charge.

18. The method of claim 1, further comprising using one of laser and mechanical boring to form the perforations.

19. The method of claim 18, wherein the perforations extend through the casing into a producing formation at a downward angle of from about 50 degrees to about 80 degrees relative to the perpendicular to the central axis of the well.

20. The method of claim 1, further comprising using hydraulic jetting to form the perforations.

21. The method of claim 20, wherein the perforations extend through the casing into a producing formation at a downward angle of about 35 degrees to about 55 degrees relative to the perpendicular to the central axis of the well.

22. A completion in a cased well, comprising:

a plurality of perforations through the casing shaped to flow produced fluids into the casing in a direction that reduces pressure drop across the perforations relative to conventional perforations.

23. A completion according to claim 22, wherein the perforations are shaped to flow fluids in a direction having a component parallel to the axis of the well and in the direction of flow of fluids in the well.

24. A completion according to claim 22, wherein the perforations are shaped to flow fluids in a direction that does not pass through the central axis of the well.

25. A completion according to claim 22, wherein the perforations are shaped to flow fluids in a direction having a component parallel to the axis of the well and not passing through the central axis of the well.

26. A completion according to claim 22, wherein the perforations extend through the casing into a producing formation at a downward angle of from about 10 degrees to about 80 degrees relative to the perpendicular to the central axis of the well.

27. A completion according to claim 26, wherein the plurality of perforations are vertically spaced along a length of the casing and the downward angle of the perforations varies along the length of the casing.

28. A completion according to claim 27, wherein upper perforations are slanted at greater angles than lower perforations.

29. A completion according to claim 27, further comprising at least one perforation extending through the casing into

a producing formation at an angle of about ninety degrees relative to the central axis of the well.

30. A completion according to claim 22, wherein the perforations extend through the casing into a producing formation at a downward angle of from 15 degrees to 50 degrees relative to the perpendicular to the central axis of the well.

31. A completion according to claim 22, wherein the perforations extend through the casing into a producing formation at a tangentially deviated angle of from 15 degrees to 30 degrees relative to the perpendicular to the central axis of the well.

32. A method for increasing production of fluids from a cased well, comprising:

flowing fluids into the well through perforations shaped to flow fluids into the well in a direction that reduces pressure drop across the perforations relative to conventional perforations.

33. The method of claim 32, further comprising flowing fluids in a direction having a component parallel to the axis of the well and in the direction of flow of fluids in the well.

34. The method of claim 32, further comprising flowing fluids in a direction that does not pass through the central axis of the well.

35. A perforating gun assembly, comprising:

a charge carrier having a central axis, an upper end and a lower end,

a plurality of downward directed shaped charges carried on the carrier and positioned to fire perforating jets at a downward angle relative to the perpendicular to the central axis, and

a reaction force absorber coupled to the carrier.

36. A perforating gun assembly according to claim 35, wherein the reaction force absorber comprises a cylinder coupled to the charge carrier and a piston carried within the cylinder and adapted for coupling to a work string.

37. A perforating gun assembly according to claim 35, wherein the reaction force absorber comprises one or more slips adapted for engagement with a well casing.

38. A perforating gun assembly according to claim 35, wherein the reaction force absorber comprises a crushable member having a first end coupled to the charge carrier and a second end adapted for coupling to a work string.

39. A perforating gun assembly according to claim 35, further comprising at least one upward directed shaped charge carried on the carrier and positioned to fire a perforating jet at an upward angle relative to the perpendicular to the central axis.

40. A perforating gun assembly according to claim 39, wherein the downward directed shaped charges comprise more than half of the shaped charges carried on the carrier and the at least one upward directed shaped charge is carried proximate the lower end of the carrier.

41. A hydrocarbon production well, comprising:

a borehole in a hydrocarbon producing formation,

a conduit in the borehole flowing produced fluids up the well,

a flow path from the producing formation to the conduit, the flow path shaped to direct fluids entering the conduit in a direction having a component in the direction of flow of produced fluids in the well.

42. A well according to claim 41, wherein the flow path comprises a perforation extending into the producing formation at a downward angle of less than ninety degrees relative to a perpendicular to a central axis of the well.

43. A well according to claim 41, further comprising:

a filter element in the well and coupled to the conduit, the filter element having a flow path slanted at a downward angle of less than ninety degrees relative to a perpendicular to a central axis of the well.

44. A well according to claim 41, wherein the flow path has a length at least as large as its width.

45. A filtering device for use in a producing hydrocarbon well, comprising:

a base pipe having an interior space defining a conduit for produced fluids, and having perforations allowing produced fluids to flow from the exterior of the base pipe into the conduit,

a filter layer carried on the outer surface of the base pipe and having flow paths sized to allow flow of produced fluids and to restrict flow of particulate material, the flow paths shaped to direct fluids flowing through the filter layer into the conduit in a direction having a component parallel to the direction of flow of produced fluids in the conduit.

46. A filtering device according to claim 45, wherein the filter layer comprises a wire wrapped screen.

47. A filtering device according to claim 45, wherein the filter layer comprises a settable mixture.

48. A method for separating multiple fluids in a stream of fluids in a well, the fluids produced from an earth formation, comprising:

forming a flow path between the formation and the well directing fluids from the formation into the well in a direction that does not pass through a central axis of the well,

whereby circular motion is induced in the stream of fluids in the well and the multiple fluids at least partially separate due to density differences.

49. The method of claim 48, further comprising:

forming tangentially deviated perforations into the formation.

50. A method for completing a cased well in an earth formation, comprising:

forming perforations through the casing, the perforations shaped to flow fluids between the earth formation and the well in a direction that reduces pressure drop across the perforations relative to conventional perforations.

51. A method according to claim 50 wherein the well has a central axis and the perforations have a downward angle of from ten to eighty degrees relative to the perpendicular to the central axis, further comprising flowing fluids from the earth formation into the well.

52. A method according to claim 50, further comprising flowing fluids from the well into the formation.

53. A method according to claim 52 wherein the well has a central axis and the perforations have a downward angle of from ten to eighty degrees relative to the perpendicular to the central axis, further comprising flowing the fluid down the well and into the formation.

54. A method according to claim 53 further comprising flowing waste fluids down the well and into the formation.

55. A method according to claim 53 further comprising treating fluids down the well and into the formation.

56. A method according to claim 53 further comprising flowing fracturing fluids down the well and into the formation.

57. A method according to claim 52 wherein the well has a central axis and the perforations have an upward angle of from ten to eighty degrees relative to the perpendicular to the central axis, further comprising flowing the fluid up the well and into the formation.

58. A perforating gun assembly, comprising:

a charge carrier having a central axis, an upper end and a lower end,

a plurality of downward directed shaped charges carried on the carrier and positioned to fire perforating jets at a downward angle relative to the central axis, and

at least one upward directed shaped charge carried on the carrier and positioned to fire a perforating jet at an upward angle relative to the central axis.

59. A perforating gun assembly according to claim 58, wherein the downward directed shaped charges comprise more than half of the shaped charges carried on the carrier and the at least one upward directed shaped charge is carried proximate the lower end of the carrier.

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