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(54) **PULSE DETONATION TOOL, METHOD AND SYSTEM FOR FORMATION FRACTURING**

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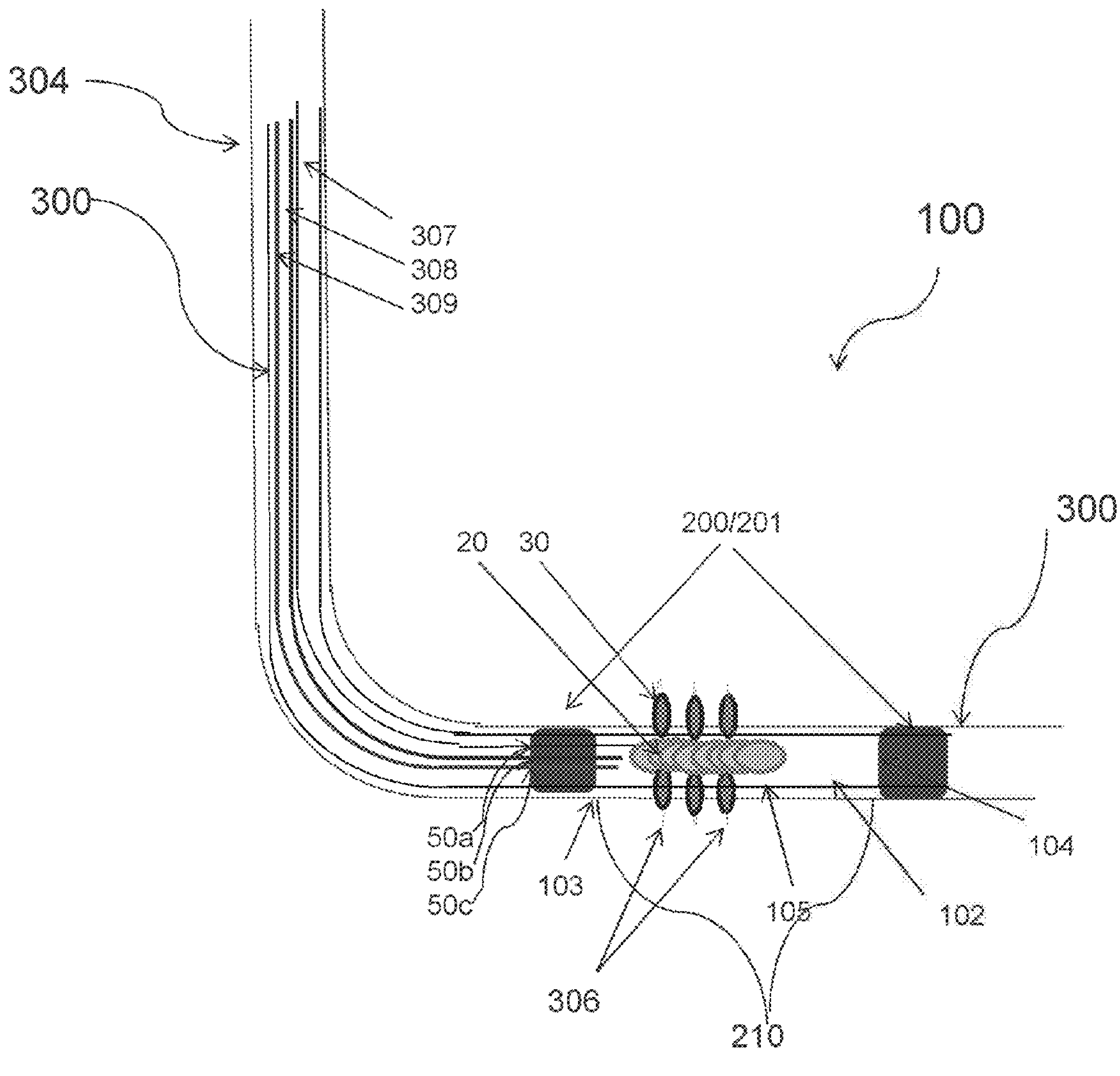
(57) **ABSTRACT**

According to one aspect of the invention, a pulse detonation tool is provided for fracturing subterranean formations. The pulse detonation tool includes a pulse detonation combustor and creates an isolated zone within a wellbore. The tool generate a series of repeating supersonic shock waves that are directed into the subterranean formation to cause propagation of multiple fractures into the formation. According to another aspect of the invention, a method and system for fracturing a subterranean formation using pulse detonation is provided.



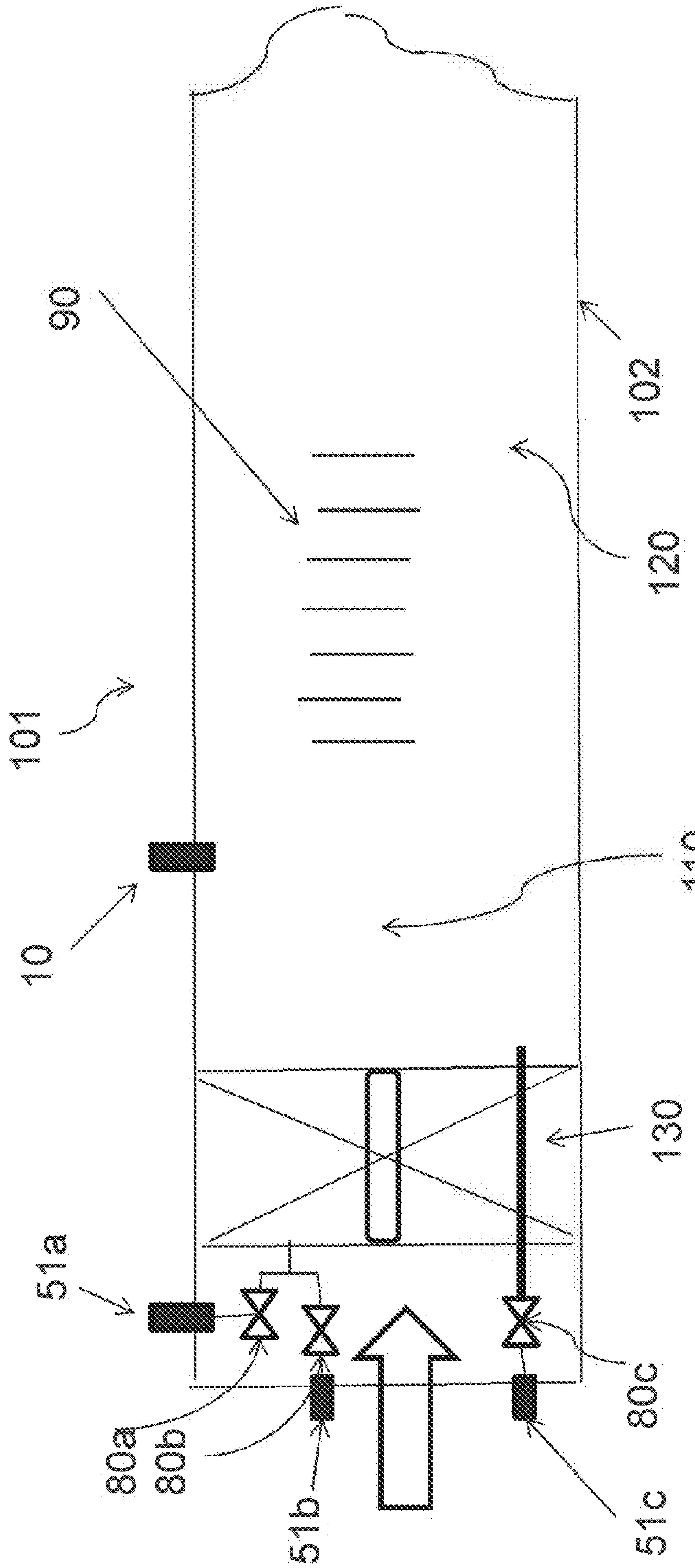
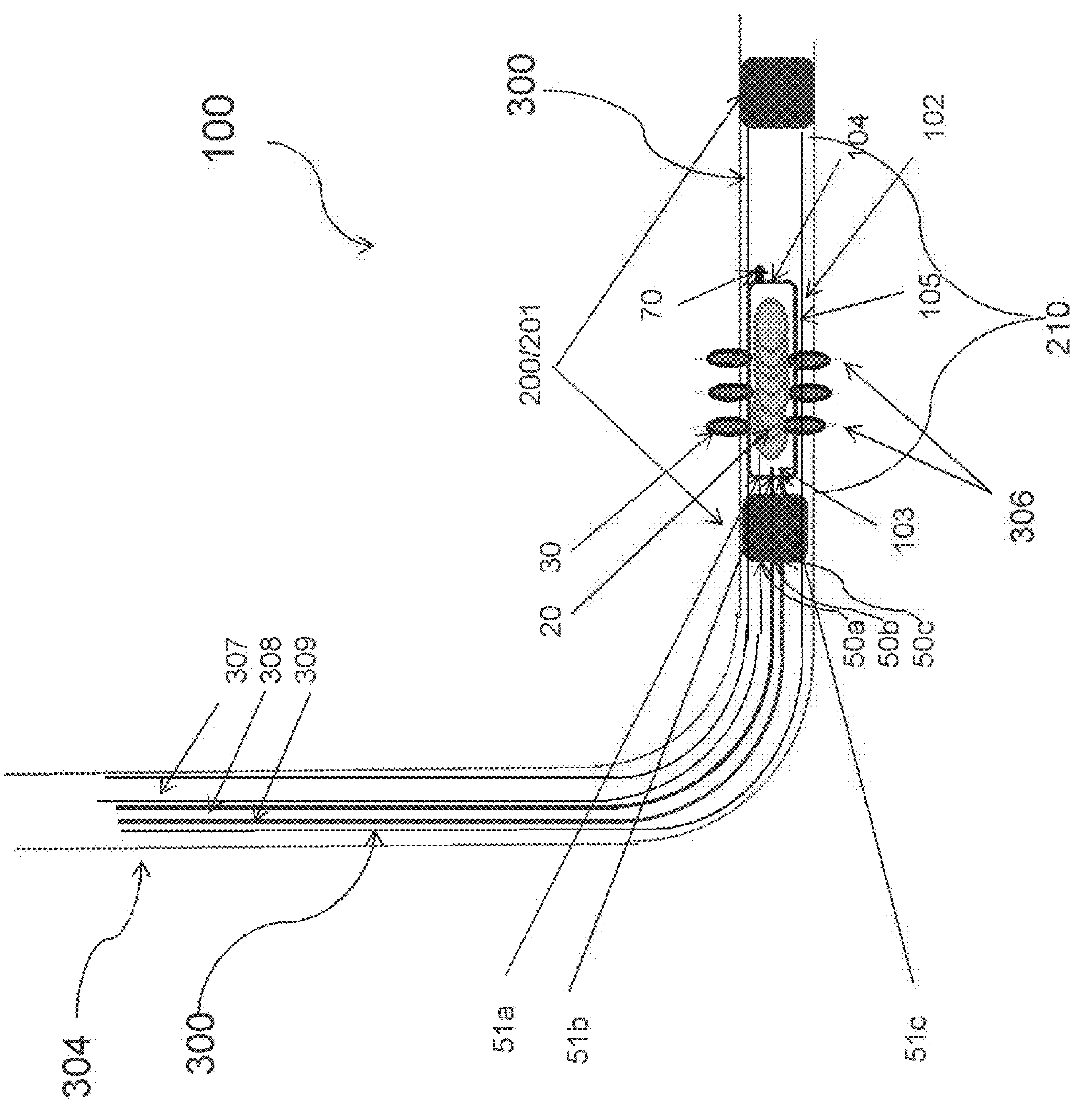


Figure 1

Figure 2


100
300
104
102
70
105
210
200/201
306
103
30
20
50a
50b
50c
307
308
309
304
300
51a
51b
51c

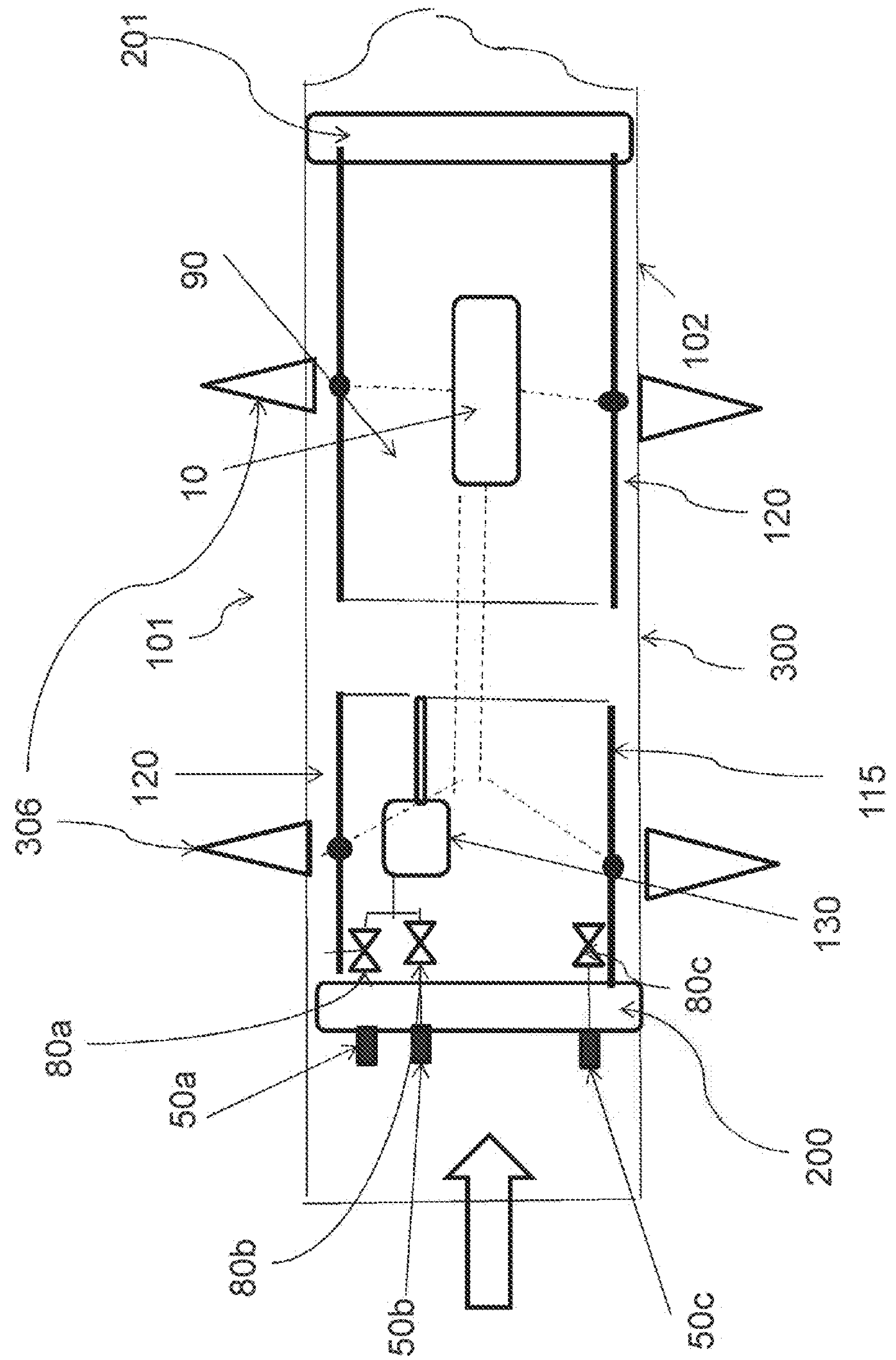

201
90
10
102
120
101
300
306
120
115
130
80a
80c
50a
200
80b
50b
50c

Figure 3

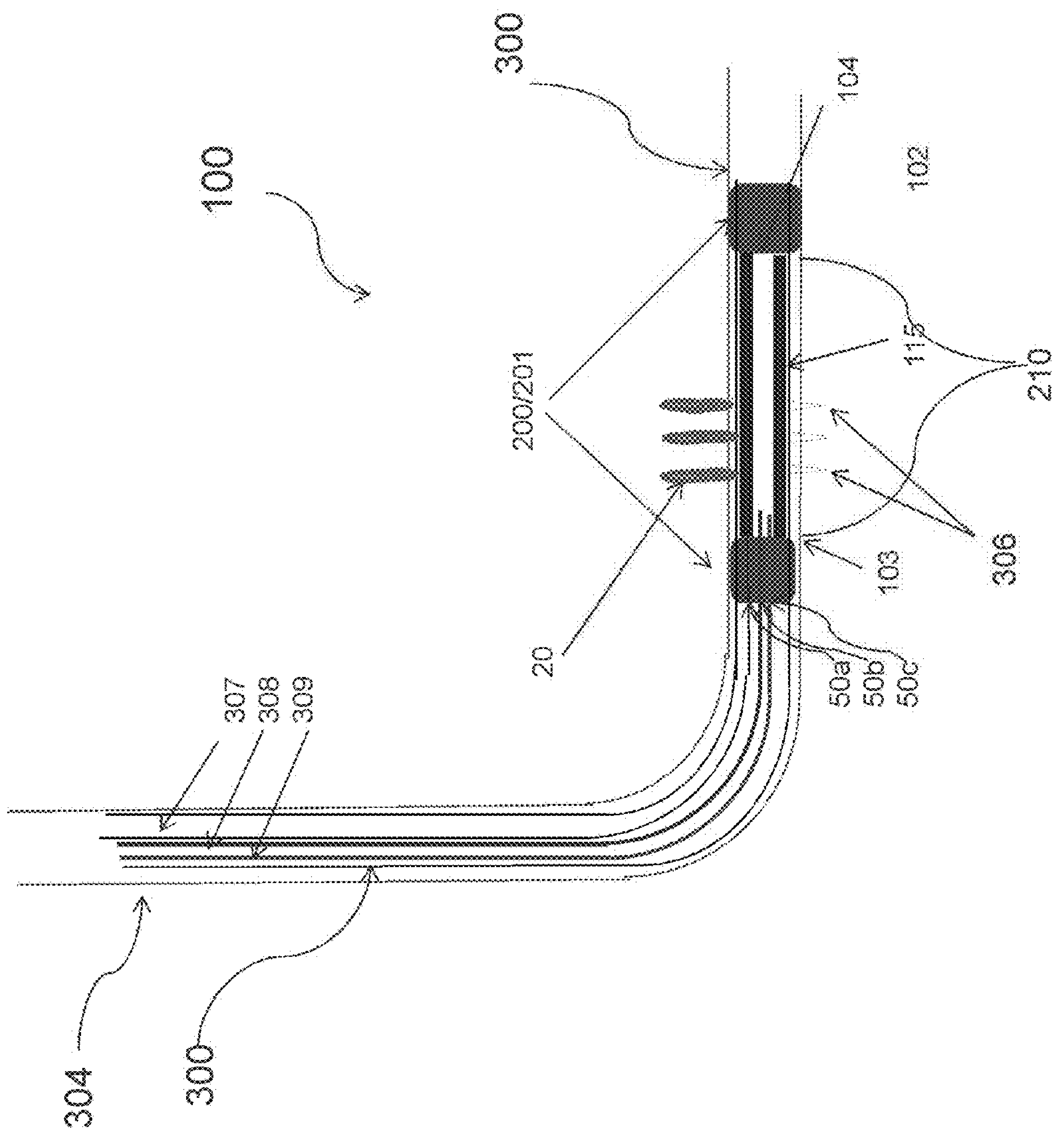

100
300
104
102
200/201
115
210
20
306
103
50a
50b
50c
307
308
309
304
300

Figure 4

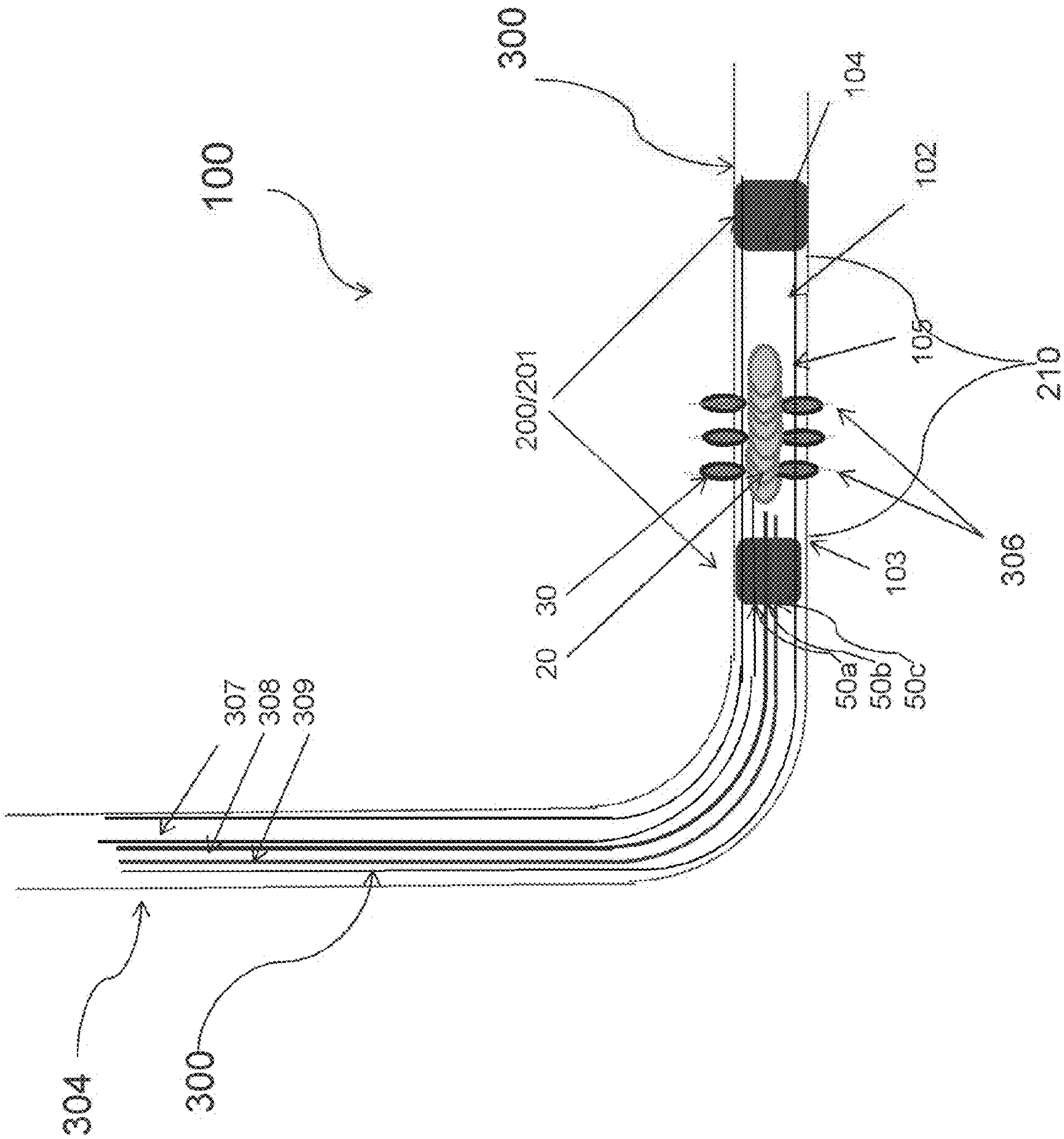

100
300
104
102
105
210
200/201
306
103
30
20
50a
50b
50c
307
308
309
304
300

Figure 5

PULSE DETONATION TOOL, METHOD AND SYSTEM FOR FORMATION FRACTURING

BACKGROUND

[0001] Formation fracturing is becoming an important tool for hydrocarbon production. There is an increasing need to produce hydrocarbons from wells in subterranean formations that contain a sufficient volume of hydrocarbon fluids, but have low permeability or restricted flow near the wellbore so that production is slow or difficult and, thus, not economical. In addition to oil and/or gas producing wells, formation fracturing is also an important tool for injection wells, storage wells, brine or water production wells, and disposal wells.

[0002] Flow of a fluid, such as oil or gas, through a porous medium, i.e. a subterranean formation, is directly related to the permeability of the formation. A formation with low permeability can occur naturally due to the geological conditions of the formation. Low permeability can also be caused by damage to the formation from drilling, cementing and perforating operations. Further, mature wells can incur damage from the buildup of fine particulates and contaminants. If permeability can be increased in these formations, more fluid can be recovered.

[0003] It is known that one way to increase production and permeability within a formation is artificial stimulation through "well fracturing." Various fracturing procedures have been introduced and used, including: (1) hydraulic fracturing; (2) explosive fracturing; (3) various chemical treatments (usually acids); (4) high energy gas fracturing or controlled pulse fracturing; and (5) combinations of the above.

[0004] Originally, devices and materials such as nitroglycerin, dynamite or other high energy materials that produce "explosive" events were used to increase fluid flow around the wellbore of an oil or gas production well. This method of formation fracturing is called explosive fracturing and is associated with a rapid pressure rise over a short time period. The success of this method has been limited, however, due to safety hazards and because frequently the explosive compaction of the formation opposite to the explosion fracture causes formation and wellbore damage, which results in a decrease rather than increase of permeability.

[0005] Currently, the most common method of formation fracturing is hydraulic fracturing. Hydraulic fracturing increases formation permeability by slowly pumping a fluid into the formation, which in turn creates a slow pressure rise in the formation. Fluid pressure is steadily increased until the tensile strength of the rock formation is exceeded. At that point, a fracture will be initiated that propagates from opposite sides of the wellbore into the formation. Because the increased fluid pressure flows to the point of least resistance, a single bidirectional fracture typically is formed. Although this method is successful, the equipment and labor involved in hydraulic fracturing is extensive and expensive. There are also growing concerns regarding the environmental consequences associated with hydraulic fracturing due, in part, to the huge amounts of water that are required and the variety of chemicals that are used in connection with hydraulic fracturing.

[0006] The third type of well fracturing used in lieu of hydraulic fracturing or explosive fracturing is called "high energy gas fracturing" or "propellant fracturing." This method employs propellant deflagration technology to create a more rapid pressure rise than that seen in hydraulic fracturing, but less rapid than during an explosive fracturing regime. "Deflagration" refers to the rapid burning of a material at faster rate than normal combustion, but at a rate slower than detonation. Propellant deflagration produces a good distribution of radial fractures around a wellbore and can be employed in lieu of hydraulic fracturing techniques as a more cost effective manner to create and propagate fractures. The resulting radial fractures, however, do not penetrate deep enough into the formation (i.e only 50-75 feet) and thus it is often necessary to combine them with, for example, hydraulic fracturing or chemical treatments.

[0007] Each of the current methods of formation fracturing thus have drawbacks. Pulse detonation devices, in general, are known and have been considered for use in jet aircrafts for propulsion, coal gasification, impulsive cleaning systems and medical cleaning devices. A pulse detonation device is an apparatus which produces high pressure exhaust from a series of repetitive detonations within a detonation chamber. The process is a constant volume heat addition process. The gaseous fuel is detonated within a chamber, causing a pulse detonation wave which propagates at supersonic speeds. The detonation wave compresses the fluid within the chamber, increasing its pressure, temperature and density, and producing a series of high-intensity, high-decibel blasts.

[0008] In pulse detonation combustors, a mixture of fuel and oxidizer, such as air, is ignited and either transitioned from deflagration to detonation, or detonated via direction initiation (DI), so as to produce detonation waves. The deflagration to detonation transition (DDT) or DI of detonation typically occurs in a tube or pipe structure.

BRIEF DESCRIPTION OF THE INVENTION

[0009] In one aspect of the invention, a pulse detonation tool for fracturing subterranean formations is adapted to be lowered into a production tubing disposed within a wellbore and comprises a first and second sealing mechanism configured to create an isolated zone having an axis parallel to and extending through the production tubing, wherein the first sealing mechanism has at least one inlet port configured to allow a fuel and an oxidizer to flow into a pulse detonation combustor disposed within the isolated zone and wherein the first sealing mechanism is further configured to connect to an oxidizer and a fuel source by way of a fluid injection line extending from the surface through the tubing; at least one valve assembly to achieve controlled delivery of the fuel and oxidizer to the pulse detonation tool; the pulse detonation combustor comprising: a combustion region defining a fluid flow path; a mixing region for producing a flammable mixture comprising a controlled volume of fuel and oxidizer, wherein the mixing region is in fluid communication with the at least one inlet port and the combustion region; an ignition device configured to periodically ignite the flammable mixture; and means for initiating a series of repeating detonations that generate a series of repeating supersonic shock waves, wherein the shock waves are directed into the subterranean formation to cause propagation of multiple fractures into the formation.

[0010] Another aspect of the invention includes a method of fracturing subterranean formations comprising the steps of: (a) deploying at least one pulse detonation combustor into production tubing disposed within a wellbore; (b) positioning the pulse detonation combustor in an isolated zone within the wellbore, wherein the isolated zone is adjacent to a portion of the formation to be fractured; (c) commencing a pulse detonation cycle by, (i) creating a flammable mixture comprised of a fuel and oxidant mixture in the pulse detonation combustor by injecting a controlled amount of fuel from a fuel source and controlled amount of oxidant from an oxidant source into the pulse detonation combustor, wherein both the fuel source and oxidant source are located at the surface; (ii) igniting the fuel and oxidant mixture to cause a detonation, wherein the detonation within the pulse detonation combustor generates a supersonic shockwave; and (iii) purging combustion products of the detonation from the pulse detonation combustor; (d) directing the shockwave into the subterranean formation; and (e) repeating steps (i)-(iii) at a selected time and frequency sufficient to generate a series of repeating supersonic shock waves, thereby causing propagation of multiple fractures in the formation.

[0011] In another aspect of the invention, a method of fracturing subterranean formations comprises the steps of establishing a wellbore extending to the subterranean formation; and deploying a pulse detonation apparatus for generating repeating, supersonic shockwaves within the interior of the wellbore at a selected time and frequency sufficient to produce multiple fractures in the subterranean formation without causing damage to the wellbore and further extend the fractures until at least one hydrocarbon fluid fracture is intersected.

[0012] Another aspect of the invention includes a system for fracturing a subterranean/subterranean/geologic formation, comprising: means for establishing a wellbore extending to the subterranean formation; and a pulse detonation apparatus for generating repeated, supersonic pulses within the interior of the wellbore with a total number of pulses to produce multiple fractures in the subterranean formation and further extend the fractures until at least one hydrocarbon fluid fracture is intersected.

BRIEF DESCRIPTION OF THE DRAWINGS

[0013] The nature and various additional features of the invention will appear more fully upon consideration of the illustrative embodiments of the invention which are schematically set forth in the figures. Like reference numerals represent corresponding parts.

[0014] FIG. **1** illustrates a cross-sectional view of a pulse detonation combustor according to an exemplary embodiment of the present invention;

[0015] FIG. **2** is a schematic illustration of a pulse detonation tool disposed within a wellbore according to an exemplary embodiment of the present invention as shown in FIG. **1**;

[0016] FIG. **3** illustrates a cross-sectional view of a pulse detonation combustor according to yet another exemplary embodiment of the present invention;

[0017] FIG. **4** is a schematic illustration of a pulse detonation tool disposed within a wellbore according to the exemplary embodiment of the present invention as shown in FIG. **3**;

[0018] FIG. **5** illustrates a cross-sectional view of a pulse detonation combustor according to yet another exemplary embodiment of the present invention.

DETAILED DESCRIPTION

[0019] Embodiments of the present invention will be explained in further detail by making reference to the accompanying drawings, which do not limit the scope of the invention in any way.

[0020] FIG. **1** depicts a cross-sectional side view of an illustrative pulse detonation tool **100**, hereinafter referred to as “tool **100**,” for formation fracturing according to various exemplary embodiments of the present invention. In FIG. **2**, tool **100** is shown suspended within a wellbore **304** that should be understood as extending from ground level into a subterranean formation **305**.

[0021] Turning now to FIG. **1** in which an embodiment of the present invention is depicted. In one or more embodiments, tool **100** contains at least one pulse detonation combustor **101**. As used herein, a “pulse detonation combustor” PDC is understood to mean any device or system that produces both a pressure rise and velocity increase from a series of repeated detonations or quasi-detonations within the device. A “quasi-detonation” is a supersonic turbulent combustion process that produces a pressure rise and velocity increase higher than the pressure rise and velocity increase produced by a deflagration wave. As used herein, “detonation” includes both detonations and quasi-detonations.

[0022] Embodiments of PDCs include a means of igniting a fuel/oxidizer mixture, for example a fuel/air mixture, and a detonation chamber, in which pressure wave fronts initiated by the ignition process coalesce to produce a detonation wave. Each detonation or quasi-detonation is initiated either by external ignition, such as spark discharge or laser pulse, or by gas dynamic processes, such as shock focusing, autoignition or by another detonation (i.e. cross-fire). Pulse detonation may be accomplished in a number of types of chambers including detonation tubes, shock tubes, resonating detonation cavities and annular detonation chambers, for example. In addition, a PDC can include one or more detonation chambers. The structure and construction of the pulse detonation combustor **101** is that of any known pulse detonation combustor type device, and the present invention is not limited in this regard.

[0023] In one or more embodiments, pulse detonation combustor **101** includes an ignition chamber **110** and a combustion region, or detonation chamber, **120**. The ignition chamber **110** and the detonation chamber **120** can be formed as a contiguous region, as in FIG. **1**, or discrete chambers (not illustrated).

[0024] In the embodiment shown in FIGS. **1-2**, pulse detonation combustor **101** includes a tubular housing **102**, an ignition device **10** disposed within ignition chamber **110**, detonation chamber **120** formed within tubular housing **102**, a fuel/oxidizer mixing region or chamber **130**, at least one fuel inlet port **50** that supplies oxidizer and fuel to pulse detonator combustor **101**, and at least one valve assembly **80**. The diameter of tubular housing **102** can be varied to fit and preferably generally fills up the diameter of production tubing **300** or wellbore **304**.

[0025] As used herein, “wellbore”, “borehole” and “well” are used interchangeably and should not be considered of varying scope.

[0026] Tubular housing **102** is preferably fabricated from a steel or like material having sufficient wall thickness and strength that it will not be destroyed during the pulse detonation cycle. Similarly, each of the components of tool **100** described herein should be formed from strong, durable materials and securely mounted so as to withstand the high pressures, repeated shock waves and thermal deformations from the repeated detonations and to resist fluid pressure in the wellbore during the pulse detonation cycle.

[0027] In the embodiment shown in FIGS. **1-2**, tubular housing **102** has a first end **103** and a second end **104** and a circular side wall **105**. For example, and as shown in FIG. **2**, tubular housing **102** is an elongated, cylindrical shock tube closed at both ends (**103**/**104**). Circular side wall **105** of tubular housing **102** has an outside diameter smaller than the inside diameter of the production tubing **300**, and is adapted to be lowered into and subsequently removed from a wellbore **304**. In the embodiment shown here, tubular housing **102** also has discharge port **70** for venting combustion products or excess fuel or oxidant. One of ordinary skill in the art would recognize that port **70** could be eliminated or modified if the fuel/oxidizer mixture results in combustion products that condense into water or can readily dissolve into the water within the wellbore , or that other means for venting known in the art could be used to vent combustion products back to the surface or downhole.

[0028] Configured as a shock tube, tubular housing **102** contains and isolates the flammable mixture from production tubing **300** so as to confine combustion, or detonation, waves **20** generated by the repeating detonations to within tubular housing **102**. Tubular housing **102** further comprises a plurality of spaced nozzles **80** along the length of the circular side wall **105**. Nozzles **80** are located at spaced intervals. Each nozzle **80** extends radially outward and is configured to direct or aim the shock waves **30** generated by the repeating detonations in a substantially axial direction into the subterranean formation **305**. Nozzles **80** are adapted so that tubular housing **102** can be lowered into and subsequently removed from wellbore **304**. For example, in one embodiment, nozzles **80** can be telescoping.

[0029] In the embodiment shown here, fuel inlet port **50** is also configured to supply a buffer to pulse detonator combustor **101**, wherein the buffer is any nonflammable fluid. In this embodiment, the buffer is different from the fuel and oxidant and introduced separately. One of ordinary skill in the art would recognize, however, that a buffer and buffer inlet is not required if there is sufficient time between detonation cycles to allow the combustion products remaining in the pulse detonation combustor **101** to cool below autoignition temperature of the fuel-oxidizer mixture for the next detonation cycle. Furthermore, even if a buffer is required, one of ordinary skill in the art would recognize that either the fuel or oxidizer could be used as the buffer by configuring and adjusting valve assembly **80**, thereby eliminating the need for a separate buffer and buffer inlet.

[0030] Referring now to FIG. **2**, tool **100** also includes a first sealing mechanism **200** and a second sealing mechanism **201**. Sealing mechanisms **200**/**201** are configured to create an isolated zone **210** having an axis parallel to and extending through wellbore **304**. Sealing mechanisms **200**/**201** comprise any suitable means for sealing, such as an expandable packer shown in FIG. **2** or tubing (not illustrated). First sealing mechanism **200** is located uphole of tubular housing **102** and second sealing mechanism **201** is located downhole of tubular housing **102**. First and second sealing mechanisms **200**/**201** are positioned to align isolated zone **210** with perforations **306** in the production tubing **300**, well casing (not shown), or both.

[0031] First sealing mechanism **200** has at least one first inlet port **50** configured to allow a fuel, an oxidizer and a buffer to flow into pulse detonation combustor **101** disposed within isolated zone **210**. In the embodiment shown in FIG. **2**, the at least one first inlet port **50** comprises fuel inlet port **50***a*, oxidizer inlet port **50***b*, and buffer inlet port **50***c*. First inlet ports **50***a-c* are configured in accordance with technology known to a skilled artisan in pulse detonation technology. Furthermore, one of ordinary skill in the art could configure a single inlet port **50** to achieve flow communication with the fuel source **302**, oxidizer source **301** and/or buffer source **303** (not shown). Although not shown in FIGS. **1-2**, in certain embodiments, oxidizer source **301** is the same as buffer source **303**. For example, in practicing the invention, one skilled in the art could utilize air as both the oxidant and the buffer. Accordingly, in certain embodiments oxidizer inlet **50***b* and buffer inlet **50***c* are one and the same.

[0032] Additionally, in the embodiment shown in FIGS. **1-2**, tubular housing **102** has at least one second inlet, or injection, port **51** configured to allow a fuel, an oxidizer and a buffer to flow into combustor **101**. As shown in FIG. **1**, the at least one second inlet port **51** comprises multiple inlet ports, more specifically fuel inlet port **51***a*, oxidizer inlet port **51***b*, and buffer inlet port **51***c*. Second inlet ports **51***a-c* are configured in accordance with technology known to a skilled artisan in pulse detonation technology. For example, in other embodiments, fuel is introduced co-axially through fuel inlet port **50***a* (see FIG. **3**), or oxidizer is supplied to combustor **101** downstream of the fuel injection via inlets **50***b* (not shown). As used herein, "downstream" refers to a direction of flow of at least one of fuel, or oxidizer or buffer. Accordingly, the inlet ports, or injectors, can be arranged in various other locations such as perpendicular to the flow, at a tangential angle to the flow (to induce swirl), or at an angle in conjunction with a suitably shaped wall to help promote mixing. Any known mechanism for injection can be used such as air-blast atomization, pressure-atomization, etc. By way of further example, one of ordinary skill in the art could configure a single inlet port to achieve injection of the fuel, oxidizer and/or buffer into combustor **101**. Additionally, as discussed above, in certain embodiments wherein oxidizer source **301** is the same as buffer source **303**, oxidizer inlet **51***b* and buffer inlet **51***c* are the same inlet port.

[0033] Referring again to FIG. **2**, tool **100** is further configured to connect to an oxidizer source **301**, fuel source **302** and buffer source **303** by way of multiple fluid injection lines **307**, **308**, **309** extending from the surface through the wellbore **304** or production tubing **300**. In practicing the invention, fuel source **302** can be a liquid fuel or a gaseous fuel. Furthermore, tool **100** is operable with a plurality of different fuels including, but not limited to, gaseous fuels, such as, hydrogen, ethylene, natural gas, or propane, liquid fuels, such as, gasoline, kerosene, or aviation fuels, and a plurality of oxidizers including, but not limited to, air. Examples of suitable fuel/oxidizer combinations, or flammable mixtures, would include hydrogen/oxygen or methane/oxygen, both of which would be delivered in gaseous form only. Another example of a suitable flammable mixture would be propane/oxygen, wherein the propane would be in liquid form. Liquid rocket propellants using nitrous oxide or liquid oxygen as an oxidizer can also be used. Likewise, liquid explosives could be used as a fuel source, such as nitromethane mixed with dietylenetriamine or ethylenediamine. It should be noted, however, that the specific fuel/oxidizer combination selected will be dictated by operational parameters and characteristics within the wellbore **304** and subterranean formation **305**, as well as the desired characteristics of fractures **400** within the formation, in order to optimize performance and limit damage within the formation or wellbore. The invention is not limited to the use of the above-identified fuel/oxidizer combinations and any suitable flammable mixture known to those skilled in the art of pulse detonation technology can be used in order to achieve the desired shock waves and resulting fracture geometry within the formation.

[0034] Tool **100** also comprises at least one valve assembly disposed within tubular housing **102**. The at least one valve assembly is configured to achieve controlled delivery of the fuel, oxidizer and buffer to tool **100**. In the embodiment shown in FIG. **1**, the at least one valve assembly comprises fuel valve **80***a,* oxidizer valve **80***b,* and buffer valve **80***c.*

[0035] As used herein, the term "valve" or "valve assembly" is intended to describe any device that turns on and off a flow at a high frequency, namely, faster than or equal to the time scale of one pulse detonation combustion cycle. Valves **80***a-c* are configured in accordance with pulse detonation technology known to one of ordinary skill in the art, and may be either a passive check valve or active valve, or a combination of both. Furthermore, one of ordinary skill in the art could configure a single valve to achieve controlled delivery of the fuel, oxidizer and/or buffer. As shown in FIG. **1**, fuel valve **80***a* and oxidizer valve **51***b* are positioned within tubular housing **102** downstream of fuel inlet port **51***a* and oxidizer port **51***b,* and both are configured to only allow fuel and oxidizer to flow into the mixing chamber **130** periodically.

[0036] Although not shown, in other embodiments, the valve assembly is located outside of tubular housing **102** but within isolated zone **210**. In still further embodiments, the valve assembly is located upstream of the isolated zone **210** defined by sealing mechanisms **200/201**. For example, in these embodiments, fuel valve **51** a is disposed between the fuel source and inlet port **51***a,* and oxidizer valve **51***b* is disposed between the oxidizer source and inlet port **51***b*. In exemplary embodiments, tool **100** also comprises means for preventing backflow of the fuel or flammable mixture towards the surface within the production tubing **300**.

[0037] Pulse detonation combustor **101** is detonated by suitable detonation means connected to ignition device **10**. In this embodiment, ignition device **10** is located within ignition chamber **110** and is arranged downstream from the fuel and oxidizer inlets. Ignition device **10** comprises at least one ignition point, as shown in FIG. **1**, or may comprise multiple ignition points (as shown in FIG. **3**). Ignition device **10** can be, but is not limited to being, a spark plug, a plasma igniter, and/or a laser source, or any suitable device. Ignition device **10** is configured to periodically ignite the flammable mixture and, as such, is fabricated from suitable materials to allow device **10** to achieve multiple ignition events without being destroyed or consumed during the repeating detonation cycles.

[0038] In further embodiments, ignition device **10** comprises an external power source, timing device and remote signaler configured to remotely ignite the flammable mixture exiting mixing chamber **130**, wherein the timing of ignition is predetermined and controlled via one of ordinary by one skill in the art. In an embodiment where there is no separate mixing chamber, the location of the ignition device **10** is arranged based upon the optimum ignition location for fuel-oxidizer mixing. For example, the ignition device **10** can be placed downstream of the fuel inlet port to provide time for the fuel to mix with the oxidizer. Ignition device **10** should also be placed upstream of any detonation-creating obstacles that may be located in the detonation chamber.

[0039] Ignition chamber **110** and detonation chamber, or combustion region, **120** define a fluid flow path in flow communication with mixing chamber **130**, as illustrated in FIG. **1**. Mixing chamber **130** is also in fluid communication with the at least one inlet port and the detonation chamber **120**. Mixing chamber **130** is configured to produce a flammable mixture comprising a controlled volume of fuel and oxidizer and to promote uniform flow into the ignition chamber **110**. For example, the geometry of mixing chamber **130** can be a cylindrical chamber wherein the fuel and oxidizer mix as a result of turbulence created by the fuel and oxidant jet inlet interaction. Mixing chamber **130** can also comprise a perforated plate or a geometry to induce swirl or other turbulence for example. In practicing the invention, any suitable flow mixing element can be used to promote the uniform flow of the fuel/oxidant mixture into the ignition chamber **110** and additional geometry known to those skilled in the art can function to enhance mixing and uniform flow if desired.

[0040] Pulse detonator combustor **101** also comprises means for initiating a series of repeating detonations that in turn generate a series of repeating supersonic, high impulse shock waves **30**. In one embodiment, as shown in FIG. **1**, the means for initiating a series of repeating detonations comprise a series of obstacles disposed along the fluid flow path within detonation chamber **120**. More specifically, in the embodiments shown herein, detonation chamber **120** includes an obstacle field or center body **90** to promote turbulence within the detonation chamber **120**. The center body **90** is often referred to as deflagration to detonation transition (DDT) geometry. DDT geometry enhances the deflagration to detonation transition process by increasing turbulence in the detonation chamber **120**. There are a variety of DDT geometries. The overall length and diameter of the center body **90** will be dictated by operational parameters and characteristics within the wellbore **304** and subterranean formation **305**, as well as the desired characteristics of fractures **400** within the formation, in order to optimize performance.

[0041] It is to be noted that the invention is not limited to the use of a particular DDT geometry. Any suitable DDT geometry can be used to increase turbulence. Similarly, detonation chamber **120** can be arranged without DDT geometry or with other means for initiating a series of repeating supersonic shock waves known to those skilled in the art. For example, in alternate embodiments, the means for initiating a series of repeating detonations comprises direct initiation (DI) detonation methods, such as a high energy laser, spark, or other shock-to-detonation methods suitable for achieving direction initiation (DI) of detonation. In practicing the invention, one of ordinary skill in the art would recognize that DI of detonation is preferable over DDT if circumstances allow for lower frequency requirements, high pressure in the well bore, and the appropriate fuel-oxidizer mixtures. In addition, the fuel-oxidizer ratio can be supplied so that there is a slightly fuel-rich mixture in the ignition chamber **110** to improve the selected means for initiating a series of repeating detonations . This can be accomplished by controlling the flow of fuel and oxidizer into the ignition chamber **110** via valve assembly **80**.

[0042] Referring to FIG. **2**, the resulting shock waves **30** are directed into the subterranean formation **305** and create propagation of multiple fractures **400** (not shown) into formation **305** without causing damage to the surrounding wellbore **304**. In the embodiment shown here, combustion or detonation waves **20** are confined to tubular housing **102**. In practicing the invention, the resulting shock waves **30** are in the range of about 10 to 16-times the initial pressure in the formation. For example, in one embodiment with an initial pressure of 100,000 psi-160,000 psi. If the initial pressure in the wellbore is lower, the shock waves could be approximately in the range of about 10,000 psi to 24,000 psi, and preferably 15,000 psi. The frequency of operation of the particular embodiment of pulse detonation combustor **101** shown in FIGS. **1-2** is in the range from about 0.1 millihertz to 100 Hertz. It should be noted, however, that the firing frequency, in part, is determined by the time required to purge and refill the volume within pulse detonation combustor **101** with the fuel/oxidant flammable mixture. As such, in certain embodiments (see, for example, see FIGS. **3-5**), the firing frequency will be in the range of about 0.1 millihertz to 5 Hz, preferably 0.01-0.2 Hz. After the requisite number of firing cycles, multiple fractures **400** will extend into formation **305** at a distance in the range of about 50 meters to about 300 meters, and in certain embodiments a distance of about 100 meters.

[0043] In practice, and referring again to FIG. **2**, to fracture a subterranean formation and recover hydrocarbons, a wellbore **304** is drilled vertically and/or horizontally into subterranean formation **305** to some depth below the surface. The wellbore **304** can be lined with production tubing or casing, to strengthen the walls of the well, or not. For example, individual lengths of metal tubing can be secured together to form a casing string which is positioned within a well bore, thus increasing the integrity of the wellbore and providing a path for hydrocarbons to flow to the surface. If casing is used, and to further strengthen the walls of the wellbore **304**, the annular area formed between the casing and the borehole **304** can be filled with cement to permanently set the casing in the wellbore. The casing can then be perforated at a location where fracturing is to take place using a perforation tool that is lowered into the wellbore from the surface.

[0044] Tool **100**, which includes sealing mechanism **200/201**, is then lowered into the wellbore **304** to a depth adjacent to the particular section of subterranean formation **305** to be fractured. In the example shown in FIG. **2**, tool **100** is positioned adjacent to perforations **306**. Tool **100** can be lowered and positioned into a wellbore **304** by conventional means, such as on a wireline, slickline, production tubing, pipe tubing, coiled tubing, or any combination thereof, or any other technique known or yet to be discovered by a skilled artisan.

[0045] Prior to lowering the tool **100** into the wellbore **304**, the location, distance and direction of the at least one natural hydrocarbonaceous fluid fracture is determined. Furthermore, the characteristics of the subterranean formation **305** are determined and used to construct a pulse detonation combustor **101** with the desired pulse detonation characteristics for the particular formation such that optimum radial fractures can be achieved within the subterranean formation **305**. These determinations can be made by geologists and others skilled in the art.

[0046] Once tool **100** is properly positioned within the well to create an isolated zone **210** adjacent to both the perforations **306** and the portion of the formation to be fractured, the pulse detonation cycle is commenced. A controlled amount of fuel from fuel source **302** located on the surface, and a controlled amount of oxidizer from oxidizer source **303** located on the surface, are injected into mixing chamber **130** via fuel supply line **308**, oxidizer supply line **309**, and the respective inlet ports, to create a flammable mixture comprised of a predetermined fuel and oxidant mixture in the pulse detonation combustor **101**.

[0047] The flammable mixture flows from the mixing chamber **130** to the ignition chamber **110** and is ignited. The flame then propagates into the detonation chamber and detonates within the detonation chamber **120**, which in turn generates a supersonic shockwave. In the embodiment shown in FIGS. **1-2**, the shockwave is then directed radially into the subterranean formation via nozzles **80** that are aligned with perforations **306**. Following the first detonation cycle, the combustion products of the detonation are then purged from detonation chamber **120** and, if necessary, a buffer is introduced into the pulse detonation combustor **101** before commencing the next pulse detonation cycle.

[0048] As illustrated in FIG. **2**, the generated shock waves **30** resulting from pulse detonation are at supersonic velocities (for example, approximately 2000 m/s), and high pressure in the range of about 10 to 16 times the initial pressure of the formation. The shock waves **30** are directed radially into the formation through nozzles **80** formed in tubular housing **102**. The generated shock waves **30** pass through perforations **306** formed in the well casing to open and extend existing fractures. The shock waves also may clear out blockages of materials that have been deposited in existing fractures.

[0049] These same steps are repeated at a predetermined, calculated time and frequency sufficient to generate a series of repeating, high impulse supersonic shock waves that cause propagation of multiple fractures **400** to extend further and further into the formation with each cycle. In practice, the precise number of repeated detonation "pulses", or cycles, required to reach the desired fracture length will depend on the nature and characteristics of the formation. More specifically, in one example rock formation, the propagation of a fracture 1 cm in length requires 1000 detonation cycles. Therefore, in order to extend the fracture out 100 m into the formation, the pulse detonation cycle will require 10,000,000 pulses or cycles.

[0050] The repeating, high impulse shock waves have a pressure above the maximum fracture extension pressure but below that which would cause casing, wellbore or formation damage. In other words, the shock waves create a pressure loading rate sufficient to fracture the rock and create multiple radial fractures at the wellbore and extending into the formation, but low enough to avoid crushing the formation or casing adjacent to the wellbore. As such, the repeated "pulses" will allow fractures to continue their extension into the formation to obtain the required distances to reach the hydrocarbons in the formation.

[0051] In another embodiment, shown in FIGS. **3-4**, circular side wall **105** of tubular housing **102** is formed by the production tubing **300**, and the first and second end of the tubular housing (**103/104**) are formed by the first sealing mechanism **200** and second sealing mechanism **201**, located uphole and downhole respectively. As further shown in FIG. **3**, concentric liner **115** is positioned within tubular housing **102** with an outside wall that has a diameter smaller than the diameter of production tubing **300**, and wherein the uphole and downhole seal **200/201** are adapted to be mounted to each end of the cylindrical tube to form an annular combustion region **120** between the outside wall of concentric liner **115** and production tubing **300**. In this embodiment, mixing region **130** is disposed in fluid communication with the at least one inlet port **50** and annular combustion region **120**.

Furthermore, annular combustion region **120** is aligned with the perforations **306** to provide direct flow of the flammable mixture into the fractures of the subterranean formation **305**. Pulse detonation combustor **101**, according to this exemplary embodiment, includes multiple ignition sources **10**.

[0052] In this embodiment, both the combustion waves **20** and shock waves **30** generated by the repeating detonations extend into the fractures **400**. More specifically, the flammable mixture is pushed into perforations **306** and thus into the subterranean formation. In one embodiment (not shown), combustion can be initiated in the production tubing and then transition into the fueled perforations or fractures within the formation. Alternatively, and as shown in FIG. **3**, multiple ignition devices **10** can be positioned so that combustion is initiated directly into the formation. With this embodiment, both the detonation waves and shock waves will occur directly in the rock formation, resulting in a higher pressure loading.

[0053] FIG. **5** illustrates another exemplary embodiment of tool **100**. In this embodiment, circular side wall **105** of tubular housing **102** is once again formed by the production tubing **300**, and the first and second end of the tubular housing (**103**/**104**) are formed by the first sealing mechanism **200** and second sealing mechanism **201**, located uphole and downhole respectively.

[0054] As shown in FIG. **5**, isolated zone **210** within the production tubing forms the detonation, or combustion, region **120** of pulse detonation combustor **101** and the entire volume between the first and second sealing mechanisms **200**/**201** will be filled with the flammable mixture. In contrast to the embodiment shown in FIGS. **3**-**4**, because the flammable mixture is contained within production tubing **300**, combustion waves **20** will be confined to production tubing **300** and will not extend into the formation. Shock waves **30** extend radially into the formation. The arrangement of the ignition device **10** and fuel and oxidizer inlet ports and valve assembly are similar to those in the previous embodiments, and a mixing region is provided to promote uniform flow. Even more significantly than the other embodiments, the firing frequency will largely be determined by the time required to purge and refill the volume within tubular housing.

[0055] As used herein, the terms "tubular housing" and "concentric liner" include tubes having a circular or alternatively non-circular cross-section. Exemplary hollow carriers or concentric liners include cylindrical tubes and tubes having polygonal cross-sections, such as, for example, hexagonal tubes. Each of the circular and non-circular cross-sections identified above may have a continuous cross sectional area, or the cross sectional area may vary. For example, in the exemplary embodiments shown in FIGS. **1**-**2**, the cross-section of the ignition chamber **110** can be larger than the cross section of the detonation chamber **120**. Likewise, the volume of the detonation chamber **120** can be larger than that of the ignition chamber **110**, wherein the specific ratio is set to optimize the performance based upon the characteristics of the subterranean formation or wellbore. Cross-sectional area variations in the ignition chamber **110** and the detonation chamber **120** allow for control of the bulk flow velocity, which in turn enhances fuel-air mixing, initial flame growth, DDT turbulence, minimizes loads on the upstream components in tool **100**, and can reduce the requisite length of pulse detonator combustor **101**, for example. By reducing the length of the combustor, the run-up time for DDT will be reduced, which will then enable combustor **101** to operate at higher frequencies. Higher frequency will generate more pressure rise and increase the usable output of tool **100** in the subterranean formation.

[0056] In further embodiments, tool **100** comprises means to introduce a proppant into the fractures. Fractures have a tendency to close or collapse once the pressure in the formation is relieved. To prevent such closing when the fracturing pressure is relieved, fracturing techniques often employ a granular or particulate material, referred to as a "proppant," that is left behind in the fractures. The proppant is used to keep the fracture open and thus provide a flow path through which hydrocarbons can flow. In one or more of the embodiments disclosed herein, the means to introduce proppants include mixing the proppant with the fuel, the oxidizer or both and the introduction of the proppant would start with the deflagration event pushing the proppant into the formation. In other embodiments, proppants could be entrained with the fracturing fluid or introduced via other means as is known in the art. A variety of proppants can be used depending on the geological conditions of the formation, including particulate materials, such as sand, glass beads and ceramic pellets, which create a porous structure.

[0057] It is noted that the above embodiments have been shown with respect to a single pulse detonation combustor. However, the concept of the present invention is not limited to single pulse detonation combustor. Furthermore, it should be expressly understood that any desired number of pulse detonation combustors could be employed in series, and that the dimensions, configurations, and compositions of tool **100** is within the discretion of the skilled artisan to meet the needs of a particular well.

[0058] Finally, in exemplary embodiments, a computer program can be used to model the pulse detonation cycle to predict the resulting generation of fracture propagation, and thereby determine a suitable configuration of tool **100** for fracture propagation in the surrounding formation. Tool **100** may also be equipped with remote pressure and temperature sensors, transducers, acoustic sensors, accelerometers (vibration sensors), chemical sensors such as oxygen sensor to confirm presence or absence of oxidizer] or other means known in the art to accurately monitor the pulse denotation cycle within the wellbore.

[0059] Although the apparatus and method of the invention is disclosed with examples that incorporate a cased well with production tubing that has been perforated, the apparatus and method of the invention are equally applicable to an open hold completion of a well.

[0060] This written description uses examples to disclose the invention, including the best mode, and also to enable any person skilled in the art to practice the invention, including making and using any devices or systems and performing any incorporated methods. The patentable scope of the invention is defined by the claims, and may include other examples that occur to those skilled in the art. Such other examples are intended to be within the scope of the claims if they have structural elements that do not differ from the literal language of the claims, or if they include equivalent structural elements with insubstantial differences from the literal languages of the claims.

What is claimed is:

1. A pulse detonation tool for fracturing subterranean formations, adapted to be lowered into production tubing within a wellbore, and comprising:

a first sealing mechanism and a second sealing mechanism configured to create an isolated zone having an axis parallel to and extending through the production tubing, wherein the first sealing mechanism has at least one inlet port configured to allow a fuel and an oxidizer to flow into a pulse detonation combustor disposed within the isolated zone and wherein the first sealing mechanism is further configured to connect to an oxidizer and fuel source by way of a fluid injection line extending from the surface through the tubing;

at least one valve assembly to achieve controlled delivery of the fuel and oxidizer to the pulse detonation combustor, the pulse detonation combustor comprising:

a combustion region defining a fluid flow path;

a mixing region for producing a flammable mixture comprising a controlled volume of fuel and oxidizer, wherein the mixing region is in fluid communication with the at least one inlet port and the combustion region;

an ignition device configured to periodically ignite the flammable mixture; and means for initiating a series of repeating detonations that generate a series of repeating supersonic shock waves, wherein the shock waves are directed into the subterranean formation to cause propagation of multiple fractures into the formation.

2. The apparatus of claim **1** wherein the first sealing mechanism and second sealing mechanism are positioned to align the isolated zone with perforations in the production tubing, a well casing, or both.

3. The apparatus of claim **1** wherein the shock waves are about 10 to about 16 times the initial pressure in the wellbore.

4. The apparatus of claim **3** wherein the shock waves are in the range of about 10,000 psi to 24,000 psi, and preferably 15,000 psi.

5. The apparatus of claim **1** wherein the frequency of operation of the pulse detonation combustor is at a frequency in the range from about 0.1 millihertz to 100 hertz, preferably 0.2 millihertz to 5 hertz, and more preferably 0.01-0.2 Hertz.

6. The apparatus of claim **1** wherein the means for initiating a series of repeating detonations comprise a series of obstacles disposed along the fluid flow path of the combustion region.

7. The apparatus of claim **1** wherein the at least one inlet port comprises a fuel inlet port and an oxidizer inlet port.

8. The apparatus of claim **1** wherein the at least one inlet port and the at least one valve assembly are further configured to introduce a buffer into the pulse detonation combustor after each detonation to purge the combustor of combustion products.

9. The apparatus of claim **8** wherein the buffer is non-flammable and selected from the group consisting of the oxidant, the fuel or air .

10. The apparatus of claim **8** wherein the at least one inlet port further comprises a buffer inlet port.

11. The apparatus of claim **1** wherein the at least one valve assembly comprises a plurality of valves and valve-actuating means.

12. The apparatus of claim **1** wherein the at least one valve assembly comprises a fuel valve disposed between the fuel source and inlet port, the fuel valve configured to only allow fuel to flow into the combustion chamber periodically.

13. The apparatus of claim **1** further comprising means for preventing backflow of the fuel or flammable mixture towards the surface within the tubing.

14. The apparatus of claim **1** wherein the pulse detonation combustor comprises a tubular housing having a first end and a second end and a circular side wall.

15. The apparatus of claim **14** wherein the tubular housing is formed by an elongated, cylindrical shock tube closed at both ends and disposed within the production tubing, wherein the shock tube has an outside diameter smaller than the inside diameter of the production tubing and is adapted to be lowered into and subsequently removed from the wellbore.

16. The apparatus of claim **15** wherein the shock tube contains and isolates the flammable mixture from the production tubing surrounding the shock tube so as to confine combustion waves generated by the repeating detonations to within the shock tube.

17. The apparatus of claim **15** wherein the shock tube further comprises a plurality of spaced nozzles along the length of the circular side wall, each nozzle extending radially outward and configured to aim the shock waves in a substantially axial direction into the formation.

18. The apparatus of claim **17** wherein the nozzles are adapted so that the shock tube can be lowered into and subsequently removed from the wellbore.

19. The apparatus of claim **14** wherein the circular side wall of the tubular housing is formed by the production tubing.

20. The apparatus of claim **19** wherein the first and second end of the tubular housing are formed by the first and second sealing mechanisms, respectively.

21. The apparatus of claim **20** wherein the flammable mixture is contained within the production tubing so as to confine combustion waves generated by the repeating detonations to the production tubing.

22. The apparatus of claim **20** further comprising a cylindrical tube with an outside wall, wherein the outside wall has a diameter smaller than the diameter of the production tubing, and wherein the first and second sealing mechanisms are adapted to be mounted to each end of the cylindrical tube to form an annular combustion region between the outside wall of the cylindrical tube and the production tubing.

23. The apparatus of claim **22** wherein the mixing region is disposed in fluid communication with the at least one inlet port and the annular combustion region, and wherein the annular combustion region is aligned with the perforations in the well casing to provide direct flow of the flammable mixture into the fractures of the subterranean formation.

24. The apparatus of claim **23** wherein the combustion wave generated by the repeating detonations extends into the fractures of the formation.

25. The apparatus of claim **1** wherein the structural components of the pulse detonation combustor are made of materials sufficient to withstand repeated shock waves and thermal deformations from the repeated detonations and to resist fluid pressure in the wellbore.

26. The apparatus of claim **1** wherein the ignition device comprises at least one ignition point.

27. The apparatus of claim **1** wherein the ignition device comprises multiple ignition points.

28. The apparatus of claim **1** wherein the ignition device comprises electrical ignition means or chemical ignition means.

29. The apparatus of claim **1** wherein the ignition device comprises a remote signaler to remotely ignite the flammable mixture.

30. The apparatus of claim **1** wherein the fuel is a liquid fuel or a gaseous fuel.

31. The apparatus of claim **1** adapted to be lowered into a wellbore on a wireline, production tubing, coiled tubing, or any combination thereof.

32. The apparatus of claim **1** wherein the at least one inlet port is configured to provide a continuous supply of air to the pulse detonation combustor during the operation of the combustor.

33. The apparatus of claim **1** wherein the first and second sealing mechanisms comprise a pair of expandable packers.

34. The apparatus of claim **1** further comprising means to introduce a proppant into the fractures.

35. A method of fracturing subterranean formations comprising the steps of:

(a) deploying at least one pulse detonation combustor into production tubing disposed within a wellbore;

(b) positioning the pulse detonation combustor in an isolated zone within the wellbore, wherein the isolated zone is adjacent to a portion of the formation to be fractured;

(c) commencing a pulse detonation cycle by,

(i) creating a flammable mixture comprised of a fuel and oxidant mixture in the pulse detonation combustor by injecting a controlled amount of fuel from a fuel source and controlled amount of oxidant from an oxidant source into the pulse detonation combustor, wherein both the fuel source and oxidant source are located at the surface;

(ii) igniting the fuel and oxidant mixture to cause a detonation, wherein the detonation within the pulse detonation combustor generates a supersonic shockwave; and

(iii) purging combustion products of the detonation from the pulse detonation combustor;

(d) directing the shockwave into the subterranean formation; and

(e) repeating steps (i)-(iii) at a selected time and frequency sufficient to generate a series of repeating supersonic shock waves, thereby causing propagation of multiple fractures in the formation.

36. The method according to claim **35** wherein the isolated zone is formed by a first and second sealing mechanism secured within the wellbore.

37. The method according to claim **35** wherein the isolated zone is aligned with perforations in the production tubing, well casing, or both.

38. The method according to claim **35** wherein the pulse detonation combustor comprises:

a combustion region defining a fluid flow path;

a mixing region for producing the flammable mixture comprising a controlled volume of fuel and oxidizer, wherein the mixing region is in fluid communication with the at least one inlet port and the combustion region;

an ignition device configured to periodically ignite the flammable mixture; and means for initiating a series of repeating detonations.

39. The method of claim **35** wherein the step of purging the pulse detonation combustor comprises introducing a buffer into the pulse detonation combustor after igniting a fuel and oxidant mixture from a previous cycle and before commencing a next pulse detonation cycle.

40. The method of claim **35** further comprising the step of introducing a proppant into the fractures.

41. The method according to claim **35** further comprising the step of controlling the time and frequency of the pulse detonation cycle by a programmable digital signal processor.

42. The method according to claim **35** wherein the pulse detonation combustor provides shockwaves at a frequency in the range from about 0.1 millihertz to 100 hertz, preferably 0.2 millihertz to 5 hertz, and more preferably 0.01-0.2 Hertz.

43. The method according to claim **35** wherein two or more pulse detonation combustors are connected in series.

44. A method of fracturing subterranean formations comprising the steps of:

establishing a wellbore extending to the subterranean formation; and

deploying a pulse detonation apparatus for generating repeating, supersonic shockwaves within the interior of the wellbore at a selected time and frequency sufficient to produce multiple fractures in the subterranean formation without causing damage to the wellbore and to further extend the fractures until at least one hydrocarbon fluid fracture is intersected.

45. A system for fracturing a subterranean/subterranean/geologic formation, comprising:

means for establishing a wellbore extending to the subterranean formation; and a pulse detonation apparatus for generating repeating, supersonic pulses within the interior of the wellbore with a total number of pulses sufficient to produce multiple fractures in the subterranean formation and further extend the fractures until at least one hydrocarbon fluid fracture is intersected.

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