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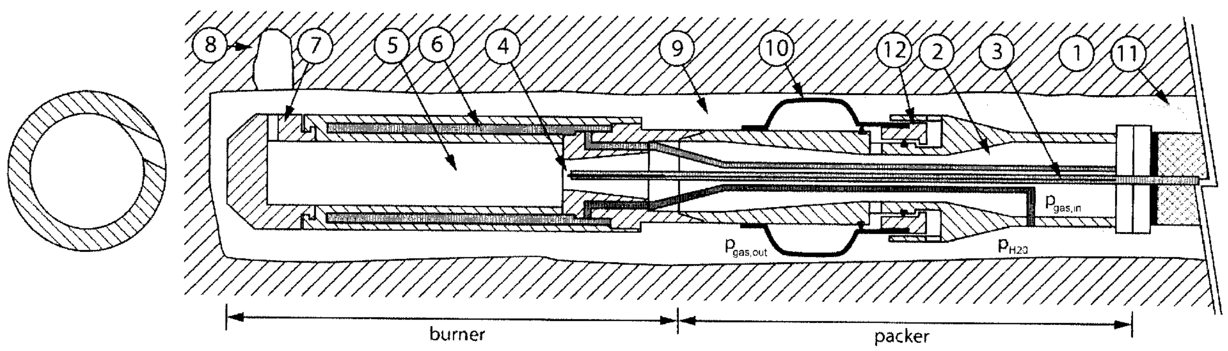
(54) AN APPARATUS FOR THERMAL SPALLATION OF A BOREHOLE

(57) The present invention refers to an apparatus for thermal spallation of a borehole, wherein the borehole comprises a proximal region with a borehole fluid with a pressure p_{H2O}, and a distal region filled with a fluid, in particular filled with an exhaust gas, with a pressure $p_{gas,out}$. The apparatus comprises at least one section with a thermal spallation system having a predetermined weight adapted for insertion down into the distal region of the borehole, and at least one barrier section, comprising at least one element that is designed to form a barrier between the distal region of the borehole filled with a gas and the proximal region of the borehole filled with the borehole fluid, and that is arranged adjacent to the at least one section with the thermal spallation system. The at least one element, forming a barrier between the distal and proximal region, is designed to adapt in a dynamic manner to changing pressure p_{H2O} of the borehole fluid in the proximal region and/or to changing pressure $p_{gas,out}$ of the fluid, in particular gas in the distal region of the borehole such that a flow of the borehole fluid from the proximal region of the borehole towards the distal end of the borehole is prevented, and/or a pressure accumulation of the fluid, in particular gas in the distal region beyond a certain pressure threshold, which corresponds to the weight of the section with the thermal spallation system, is prevented.

FIG 2A



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Description

[0001] The present invention relates to an apparatus for thermal spallation of a borehole and a method of using the same.

Description

[0002] Deep wells for geothermal or oil and gas purposes require intensive financial efforts. Nevertheless, the failure rate of e.g. a geothermal well lays at around 25%. One major issue is the insufficient access to fractures, which can be directly used for heat production or oil/gas extraction or further enhanced via hydraulic stimulation. Due to near well bore impedances (e.g. clogging of the fractures by drilling mud), insufficient access to naturally existing fractures or an unfavorably located well end, insufficient fluid can be transported through the open fractures making the well unproductive.

[0003] Formation damage can be recovered by hydraulic stimulation. Here, high pressure water is injected in the borehole and fractures are re-opened or newly created (Reinicke et al., Hydraulic fracturing stimulation techniques and formation damage mechanism, 2010, Chemie der Erde 70, S3, 107-117). The direction and extension of the created fracture network in the formation are not precisely controllable. Therefore, it is challenging to correctly establish a new fracture network beyond the damage zone, connecting the injection and production boreholes. Further, the occurring induced seismicity hampers the use of hydraulic stimulation methods to recover near wellbore impedance.

[0004] Hydraulic radial jetting is another method to recover unproductive wells which uses a highpressure water jet to enlarge the borehole diameter or to drill multilaterals into the formation. This technology works well in rather soft formations as sandstones, bentonite, clay or silt. Therefore, it is used in the oil and gas industry where the target formation often consists of the mentioned rock types. However, the technology outperforms in hard rock formations such as granite or basalt, which are encountered in geothermal systems and also in new oil and gas resources.

[0005] The main difference between the two technologies is the working principle. Hydraulic radial jetting destroys the rock, due to high pressure impact of the water jet (potentially enhanced by adding abrasive or acidic materials into the jet). On the other hand, radial jetting uses the thermal spallation effect, which has shown its efficiency for hard rock formations (Kant et al., Thermal Spallation Drilling - an Alternative Drilling Technology for Hard Rock Drilling, Oil Gas European Magazine, 2017).

[0006] Perforation guns make use of radially placed-explosive charges to blast holes in the casing and the cement, up to several centimeters in the formation. The penetration is due to the high impact energy exerted on the targeted material by the jet (Lawerence et al., Effect of Perforation Job on Formation Damage; Journal of Engineering Research & Technology 2013, 2-10). In this case, as the export mechanism is high pressure-impact based, the resulting rock material shows permeability reductions, implying reduced wellbore productivity.

[0007] Another remedial to near-wellbore drilling mud damage is to use acidic solutions at low pressure (matrix acidizing) to remove the mineral impairment down hole and re-establish the permeability network required for a correct circulation of production fluids (Portier et al., Review on chemical stimulation techniques in oil industry and applications to geothermal systems; Technical Report - Deep Heat Mining Association, 2007). Moreover, acid fracturing can also be designed to stimulate the formation above the formation fracturing pressure. In geothermal wells, the prevailing temperatures and the low porosity of the rock material considerably limit the penetration in the well bore, resulting in shorter flow paths of the acidic solution.

[0008] Thus, different systems exist, which aim to minimize near well bore impedances to increase the diameter in the production section of the well and to improve the communication between bore hole and formation. Nevertheless, these technologies are limited to soft rocks or are only able to insufficiently increase the diameter of the well. Therefore, in order to improve the efficiency of oil and gas extraction and to enhance the development of deep geothermal energy, solutions have to be found to significantly increase the downhole diameter in the production zone.

[0009] Thermal borehole enlargement is a technique, which increases the well diameter by utilizing the thermal spallation process to excavate rock on the sidewalls of an existing borehole. One or multiple nozzles are placed at the circumference of a burner assembly, creating a hot fluid jet. If this hot fluid jet impinges on the rock, high thermal stresses are induced, which lead to the disintegration of the rock surface. As these flame nozzles can be placed freely around the surface of the burner and a rotation of the system around its axis is possible, a nearly arbitrary geometry of the enlarged borehole, as e.g. slots, notches or complete hole openings, can be created with this technology.

[0010] By opening the well bore diameter, near well bore impedances are removed and the created notch serves as an initial fracture source. Additionally, the hydraulic connection between well and rock is improved, the access to more pre-existing natural fractures can be attained and the initial extent of the reservoir is increased. These measures will enhance the hydraulic stimulation process, as lower pressures to achieve initial breakdown of the rock mass are required and a larger network of fractures can be obtained by stimulation, facilitating fluid circulation and subsequent resource extraction.

[0011] Thermal spallation can be used to locally increase the well diameter by a factor of 3-4. Additionally providing an arbitrary borehole geometry as e.g. slots, notches or complete hole opening, which would further enhance the following hydraulic stimulation process. With the resulting borehole geometry, formation damage is reduced, more natural fractures can be accessed and lower pressure rates of the injection fluid would be required during the stimulation phase, making the process more safe and less cost demanding.

[0012] Thermal spallation allows to precisely define the enlargement shape, orientation and radial depth in the sidewalls of the borehole, therewith ensuring the complete recovery of the damaged section and reducing the stimulation efforts.

[0013] However, one of the problems associated with the use of thermal spallation for enlarging a borehole is maintaining a hot environment in the distal cutting region of the borehole, while keeping the relatively cold liquids or fluids in the proximal region of the borehole.

[0014] One approach for separating the hot distal end of the borehole from the colder proximal end of the borehole is the use of a suitable barrier system that prevents the flow from the cold fluid from the proximal end of the borehole into the hot distal borehole end.

[0015] A suitable barrier system can comprise one or more rigid elements as part of a packer system.

[0016] The disadvantage of such a rigid packer system is however, that it cannot adapt to changing borehole geometries, causing for example drastic pressure increases in the borehole.

[0017] It is therefore an object of the present invention to overcome this and other disadvantages of the prior devices and techniques for borehole enlargement.

[0018] Accordingly, an apparatus for thermal spallation of a borehole is provided. The borehole comprises a proximal region with a borehole fluid with a pressure p_{H2O}, and a distal region filled with a fluid, in particular filled with an exhaust gas with a pressure $p_{gas,out.}$

[0019] The apparatus according to the invention comprises

- at least one section with a thermal spallation system having a predetermined weight adapted for insertion down into the distal region of the borehole,

- at least one barrier section, comprising at least one element that is designed to form a barrier (when inserted into the borehole) between the distal region of the borehole filled with the fluid, in particular gas, and the proximal region of the borehole filled with the borehole fluid and that is arranged adjacent to the at least one section with the thermal spallation system,

[0020] The apparatus is characterized in that the at least one element, forming a barrier between the distal and proximal regions, is designed to adapt in a dynamic manner to changing pressure p_{H2O} of the borehole fluid in the proximal region and/or to changing pressure $p_{gas,,out}$ of the fluid, in particular gas, in the distal region of the borehole such that

a flow of the borehole fluid from the proximal region of the borehole towards the distal end of the borehole is prevented, and/or

a pressure accumulation of the fluid, in particular gas, in the distal region beyond a certain pressure threshold, which corresponds to the weight of the section with the thermal spallation system, is prevented.

[0021] The barrier forming element of the present apparatus allows a dynamic adaptation of the pressure in the borehole, depending on the pressure built up within the borehole. The barrier forming element prevents a flow of the borehole fluid from the colder proximal region of the borehole into the hotter distal region of the borehole.

[0022] At the same time the barrier forming element forms a bypass path adapted to allow material from the distal end of the borehole to penetrate into the proximal region of the borehole. The material that may bypass the barrier forming element may comprise at least one of an output of the thermal spallation jet nozzle and material excavated from the borehole, such as rock materials or a gas or fluid containing drilling mud, water, chemical additive, foaming agent, buffer, etc..

[0023] As will be described in detail further below, the thermal spallation section may comprise, in a conventional manner, a combustion chamber for providing hot gases (obtained from igniting one or more reactant gases in the presence of an oxidizer, such as air) for thermal spallation, and the corresponding nozzles for emitting the jet of hot gases.

[0024] Different embodiments of the barrier section with the barrier element will be described in the following.

[0025] In a first variant of the present apparatus the at least one element, forming a barrier between the distal region and the proximal region, comprises a system that adapts the width d of a gap formed between said element and the wall of the borehole, depending on the pressure. Such a system may also be described as an adaptable packer.

[0026] In this adaptable packer system, the width d of the gap is adjusted such that it is small enough to prevent any flow of the borehole fluid from the proximal region of the borehole towards the distal end of the borehole, and/or the width d of the gap is adjusted such that it is large enough to prevent a pressure accumulation of the gas in the distal region beyond a certain pressure threshold, which corresponds to the weight of the section with the thermal spallation system.

[0027] In one embodiment of the adaptable system, the gap width d between the at least one element forming a barrier between the distal and proximal borehole region and the borehole wall, is reduced in case the pressure p_{H2O} of the borehole fluid in the proximal borehole region increases.

[0028] In another embodiment of the adaptable system, the gap width d between the at least one element, forming a barrier between the distal and proximal borehole region and the borehole wall, is enlarged in case the pressure $p_{gas,out}$ of the gas in the distal borehole region increases.

[0029] Thus, such an adaptable (packer) system avoids water penetration from the proximal borehole region into the enlargement zone in the distal end of the borehole, by creating a small, adjustable gap between its circumference and the borehole wall. Due to the small gap, the combustion products are accelerated until they push out the water by fulfilling a counter-current flow limitation (CCFL) condition. Thereby, the packer can adapt the size of the gap to avoid high pressure accumulations and to provide a sufficiently small gap.

[0030] In one further embodiment, the at least one element forming a barrier between the distal and proximal borehole region, comprises at least one ring element that is designed to move in response to any pressure changes and which is operatively connected to at least one barrier supporting structure. The shape of the ring element can be adapted for different configurations and can assume different shapes.

[0031] In one example, the at least one ring element is designed to move axially downwards when the pressure p_{H2O} of the borehole fluid increases and simultaneously pushes the at least one barrier supporting structure towards the borehole wall, thereby reducing the gap width d. The gap widths for different water pressures are exemplarily calculated in the example section.

[0032] In another example, the at least one ring element is designed to move axially upwards when the pressure $p_{gas,out}$ in the distal borehole region increases and simultaneously retracts the at least one barrier supporting structure away from the borehole wall, thereby enlarging the gap width d.

[0033] The barrier supporting structure interacts with the moveable ring element such that depending on the position of the movable ring element, the barrier supporting structure widens or reduces the gap between the barrier section and the borehole wall. Thus, it is preferred, if the at least one barrier supporting structure is made of a flexible, high temperature resistant material, for example a corrugated metal hose. The material of the barrier supporting structure should be flexible enough to adapt to different pressures but robust enough to withstand the hot corrosive environment.

[0034] The geometry of the barrier supporting structure can vary. In a preferred embodiment the barrier supporting structure is a U shaped element with a flange-like edge. In this variant the bulge of the element points towards the borehole wall. One edge of the U-shaped element that points towards the proximal end is operatively connected to the movable ring element.

[0035] This ring element consists of at least two opposing surfaces. A volume below one surface of the ring element is in contact with the fluid inside the barrier system, by e.g. several holes in the structure of the system. The volume opposite to the first mentioned surface of the ring element is in contact with the borehole fluids. The gap between the ring element and the structure of the barrier system, separating the air and borehole fluid volume is sealed by e.g. an O-ring. The ring element can move axially by a specified distance, whereas its movement is restricted in any other direction. The volume inside the barrier supporting structure is sealed from the fluid inside the barrier system and from the borehole fluids.

[0036] The working principle of the adaptable (packer) system is based on the high momentum of the combustion gases (or any other fluid or gas), when they flow through the gap between the barrier element and the borehole wall, which prevents water from flowing in the counter direction. This phenomenon has been extensively investigated as the counter-current flow limitation (CCFL). Thereby, the gap has to be small enough to enhance the CCFL condition and, on the other hand, large enough to prevent significant pressure accumulations in the distal treatment zone. If the forces, due to the pressure accumulation in the distal zone, exceed the provided weight of the bottom hole assembly, the whole system is lifted up, which could lead to the destruction of the system and makes the process uncontrollable.

[0037] Therefore, an adaptable packer system is required, which can fulfil both criteria: at low operating conditions, it closes the gap to enable the CCFL condition and with increasing mass flows of the burner, the gap opens to avoid pressure accumulations.

[0038] In a second variant of the present apparatus, the at least one element forming a barrier between the distal region and the proximal region comprises a system that is designed to create an air shield between the barrier section of the apparatus and the borehole wall. Such a system may also be described as an air shield packer.

[0039] An air-shield packer keeps the borehole fluids out of the distal borehole zone by providing fluid-jets using, for example, part of the oxidizer, such as air, supplied inside the apparatus for combustion with further reactants (see also below). These fluid-jets have a sufficiently high momentum to penetrate into the water zone until they reach the borehole wall. Therewith, they create a barrier between packer and borehole wall, which the water cannot penetrate. Due to the flexibility of the length of these fluid-jets, the packer system can adapt to irregular borehole geometries such as breakouts. Additionally, non-return valves are integrated into each fluid nozzle with the aim of preventing an inflow of formation fluids into the packer.

[0040] In one embodiment the air shield is generated by a fluid jet emitted by a plurality of nozzles spaced circumferentially around the central axis of the apparatus. The barrier between the distal and the proximal region of the borehole is adjusted by the penetration length x_p of the fluid-jets.

[0041] The fluid-jet velocity and nozzle diameter can be designed for achieving different penetration lengths x_p of the fluid-jets, which define the length before the hydrostatic pressure of the water overcomes the momentum of the jet and water will penetrate into the barrier zone. The calculation of nozzle diameter and jet velocity is described in the example section in more detail.

[0042] As previously mentioned, the thermal spallation system, used in combination with each of the barrier element variants, comprises at least one combustion chamber with at least one igniter. In the combustion chamber the oxidizer is mixed with one or two reactants and is ignited thereby generating the hot gases used for the thermal spallation process.

[0043] The one or more reactants such as hydrocarbons e.g. methane, hydrogen, air, oxygen, hydrogen peroxide, hybergolic fuels e.g. unsymmetrical dimethylhydrazine (UDMH) with N_2O_4 are supplied to the combustion chamber by means of at least one tubing assembly. Said tubing assembly may comprise at least one line for transporting at least one reactant through the proximal section to the at least one combustion chamber in the distal section. There may be one line or two lines depending on the number of reactants supplied.

[0044] The oxidizer, such as air, is supplied from the proximal end of the apparatus through the barrier section into the combustion chamber. The oxidizer, such as air, is guided through the hollow space within the apparatus from the proximal end into the combustion chamber. The oxidizer may also be guided through a tubing system. Both variants are additionally connected to the described control volume below the ring element. The hollow space may comprise also tubing systems for at least one reactant, such as methane, cooling water and cables for igniter and sensors.

[0045] It is furthermore preferred, if the at least one thermal spallation system comprises at least one cooling system, surrounding the at least one combustion chamber. The cooling fluid, preferably cooling water, is supplied through one line from the proximal end of the apparatus. After cooling, the water is released above the barrier system into the borehole fluid to improve the circulation of the produced rock cuttings.

[0046] The thermal spallation system that is used in combination with each of the barrier element variants comprises furthermore at least one or multiple nozzles forming a jetting area for thermal spallation. A plurality of nozzles may be spaced circumferentially around the central axis of the apparatus to emit a jet of hot gases having a directional component that is radial or perpendicular with respect to said central axis, in order to create the desired bore hole enlargement geometry

[0047] The jet system may also comprise one or more rotating nozzles. In this variant the nozzle rotates around the main axis of the apparatus. The rotation of the nozzle assembly around the main axis of the apparatus can be established by the momentum of the combustion gases, exiting through a radially angled nozzle. The rotating nozzle is connected to the remaining structure of the burner by a bearing system (plain or roller bearing), enhancing the rotation. Due to the constant rotation of the nozzle, a rotationally symmetrical and homogenous geometry along the sidewalls of the bore hole is excavated.

[0048] Different configurations for the nozzle can be conceived. In one embodiment, several nozzles are placed at different axial positions and rotated around the central axis, in order to obtain an axial extension of the circumferential enlargement.

[0049] The hot reacted gas may exit the thermal spallation jet nozzle at a temperature of up to 2000°C with sub- or supersonic velocities. Different sensors integrated into the thermal spallation system measure the nozzle temperature and indicate if the borehole fluids could be removed from the treatment zone.

[0050] In one embodiment the hot reacted gas may exit the thermal spallation jet nozzle at a temperature higher than 1000°C, preferably higher than 1300°C at a flow rate lower than 50 g / second, preferably lower than 20 g/second. The output of the thermal spallation jet nozzle and the material excavated from the borehole creates a dynamic pressure.

[0051] The apparatus as described above may be used in a thermal spallation process (or enlargement process).

[0052] Thus, the apparatus may be used in a process for enlarging a borehole by thermal spallation comprising the steps of:

- directing the apparatus as described above down a borehole;
- providing a barrier between the distal and proximal region of the borehole such that

    a flow of the borehole fluid from the proximal region of the borehole towards the distal end of the borehole is prevented, and/or

    a pressure accumulation of the gas in the distal region beyond a certain pressure threshold, which corresponds to the weight of the section with the thermal spallation system is prevented, and

- providing hot gases for forming a jetting area in the distal region of the borehole for enlarging the borehole by thermal spallation.

[0053] The invention is explained in more detail by means of examples with reference to the Figures. They show:

Figure 1 a schematic illustration of the thermal spallation (jetting) process;

Figure 2A a schematic illustration of a first embodiment of the apparatus according to the invention;

Figure 2B an enlargement of a section of the first embodiment shown in Fig. 2A;

Figure 3A a schematic illustration of a second embodiment of the apparatus according to the invention; and

Figure 3B an enlargement of a section of the first embodiment shown in Fig. 3A.

[0054] The thermal spallation process (or thermal enlargement process) is conducted as illustrated in Fig. 1.

[0055] (step 1) The bottom part of the apparatus (or bottom hole assembly BHA), comprising the at least one section with a thermal spallation system and the at least one barrier section is tripped down into the well until the interval to be enlarged is reached.

[0056] (step 2) The targeted region in the production zone is sealed off from the rest of the borehole with the barrier or packer system. The borehole fluids are then removed from the spallation zone by pumping air through the thermal spallation apparatus, as entrainment of the high density aqueous fluids into the hot flame jet will lead to quenching and therefore to a short, cold exhaust jet with insufficient treatment power.

[0057] (step 3) As a next step, the thermal spallation system is driven up by starting the flow of reactants and initiating their combustion, commencing the radial jetting process. The combustion of the reactants is started, creating one or more hot-fluid jets, which impinge on the sidewall of the borehole, initiating the thermal spallation process.

[0058] (step 4) During excavation at the borehole wall, the device is moved axially or rotated around the borehole axis to create the desired enlargement geometry. The turning can be initiated from the surface with a drill rig, with a downhole motor or with a self-propelling nozzle.

[0059] (step 5) After the process is finished, the whole apparatus is removed. The outcome is an enlarged borehole section of arbitrary shape in the production zone of the well. The enlargement process can be repeated in other sections of the well or the BHA is retrieved to the surface.

[0060] In order to enable the process as described in Figure 1, a suitable bottom hole assembly, consisting of a section with a thermal spallation system (burner) and a barrier section (packer system), is required as depicted in Figure 2A.

[0061] The complete system is firstly lowered into the borehole 1. The oxidizer 2 (for example air) with the pressure $pg_{as,in}$ is mixed with one or more reactants 3 (for example methane) and ignited by an igniter 4 in a combustion chamber 5.

[0062] The combustion chamber 5 is cooled by circulating water or drilling mud in the surrounding mantle 6. After cooling, the water is ejected into the annulus between packer and borehole to flush up the produced cuttings.

[0063] After combustion, the product gases are accelerated and radially deviated through one or multiple nozzles 7, with a fixed position or rotating, due to the momentum of the combustion gases, exiting through a radially angled nozzle.

[0064] The hot jet, which impinges on the sidewalls of the borehole, induces the thermal spallation effect and creates the required borehole enlargement shape 8.

[0065] The exhaust gases are then forced out of the treatment zone 9 and through a barrier system or packer system 10. This ensures that the borehole fluids 11 are removed from the enlargement zone 9 and kept above the barrier system 10, as entrainment of the high density aqueous fluids into the low dense setting of the flame jet will lead to a short, cold exhaust jet with insufficient treatment power.

[0066] The embodiment of the apparatus shown in Figure 2A comprises an adaptable barrier system (or adaptable packer system), which is illustrated in more detail in Figure 2B.

[0067] The adaptable packer system of Figure 2B avoids borehole fluid 11 penetration in the enlargement zone 9, by creating a small, adjustable gap 10a between its circumference and the borehole wall 1. Due to the small gap 10a, the combustion gases are accelerated until they push out the water by fulfilling a CCFL condition. Thereby, the packer can adapt the size of the gap to avoid high pressure accumulations and to provide a sufficiently small gap to enable the CCFL condition.

[0068] The adaptable packer system of Figure 2B comprises a barrier forming element in form of a ring element 12. This ring element 12 consists of at least two opposing surfaces 12a, 12b. A volume below one surface 12a of the ring element 12 is in contact with the fluid 2 inside the barrier system, by e.g. several holes in the structure of the system. The volume 12b opposite to the first mentioned surface of the ring element 12 is in contact with the borehole fluids 11.

[0069] The gap between ring element 12 and the structure of the barrier system, separating the air and borehole fluid volume is sealed by e.g. an O-ring. The ring element can move axially a specified distance, whereas its movement is restricted in any other direction. The volume inside the barrier supporting structure is sealed from the fluid inside the barrier system and from the borehole fluids. Ring element 12 is operatively connected to an U-shaped metallic element.

[0070] The ring element 12 is designed to move in response to any pressure changes. In one example, the ring element 12 moves axially downwards when the pressure p_{H2O} of the borehole fluid increases and simultaneously pushes the metallic element towards the borehole wall thereby reducing the gap width d.

[0071] In another example the ring element 12 moves axially upwards when the pressure $p_{gas,out}$ in the distal borehole region increases and simultaneously retracts the metallic element away from the borehole wall thereby enlarging the gap width d.

[0072] The metallic element interacts with the moveable ring element 12 such that depending on the position of the movable ring element 12, the metallic element widens or reduces the gap between the packer system and the borehole wall.

[0073] Thus, the regulation relies on a self-adaptable mechanism, which will be described in the following.

[0074] The relationship between the pressure $p_{gas,out}$ of the combustion gases in the distal region of the borehole (treatment zone), the pressure $p_{gas,in}$ of the air inside the apparatus (that is mixed with reactants in a combustion chamber and ignited for providing the hot gases for thermal spallation as described further below in detail) and the pressure p_{H2O} of the borehole fluid above the barrier gap, which is proportional to the depth of the treatment zone, can be approximated with a quasi-steady pressure balance, as depicted below,

$$p_{H_2O} = p_{gas,out} - \Delta p \quad (1a)$$

$$p_{gas,out} = k \cdot p_{gas,in} - c \quad (1b)$$

where Δp is the pressure drop over the barrier gap, k is a factor accounting for the change in pressure due to the combustion, c accounts for pressure losses between the inside of the packer and the treatment zone.

[0075] Pressure $p_{gas,in}$ and pressure $p_{gas,out}$ interact with each other such that if the pressure $p_{gas,out}$ in the distal borehole region increases, a back pressure on the pressure $p_{gas,in}$ inside the apparatus is created. Thus, the higher $p_{gas,out}$, the higher $p_{gas,in}$ or vice versa. The pressure $p_{gas,in}$ acts on the ring element of the adaptable system, causing an according radial contraction or widening of the barrier support structure. The gap is reduced or enlarged depending on the pressure (see also below).

[0076] Thereby, the pressure drop over the barrier gap can be calculated, as displayed below,

$$\Delta p = \frac{\xi}{\rho}\left(\frac{\dot{m}}{\pi(r_{bore}^2 - r_{pack}^2)}\right)^2 \quad (2)$$

[0077] Where ξ is a positive empirical parameter, ρ the density of the combustion gases, $\dot{m}$ the mass flow of combustion gases, r_{bore} the borehole radius and r_{pack} the packer radius. It can be seen that, with increasing mass flow of combustion gases, the pressure drop increases quadratically, which would lead to significant pressure accumulations in the treatment zone with the consequences discussed above.

[0078] The Δp value is controlled by changing the radius of the barrier support structure or packer r_{pack}, increasing or decreasing the area between the packer and the borehole wall. Thereby, the radius regulates itself by the occurring pressure differences at the ring element.

[0079] A force balance along the axial direction at the ring element yields Eq. (3):

$$p_{gas,in} \cdot A_1 - p_{H_2O} \cdot A_2 = 0 \quad \Rightarrow \quad \frac{A_2}{A_1} = \frac{p_{gas,in}}{p_{H_2O}} \quad (3)$$

where A_1 and A_2 are the surface in contact with the gas inside the packer and the surface in contact with the bore hole fluids outside, respectively.

[0080] Combining Eq. (1) and (3), an expression for the required surface ratio at different water column levels is obtained, as shown in Eq. (4) and Eq. (5):

$$\frac{A_2}{A_1} = \frac{1}{k} + \frac{c + \Delta p}{k \cdot p_{H_2O}} = \quad (4)$$

$$\frac{A_2}{A_1} = \frac{1}{k} + \frac{c+\Delta p}{k \cdot \rho_{H_2O} \cdot g \cdot z} \quad (5)$$

where ρ_{H2O} is the density of water and z the borehole depth. Therefore, any overpressure or underpressure at one of the two sides is accounted for by an according axial movement of the ring element, re-establishing the equilibrium between the two phases.

[0081] As an example, two opposite operating conditions may be distinguished. When the air pressure increases, the higher force acting below the ring element leads to its upwards movement and therefore a decrease of the packer radius, which reduces the pressure drop Δp, releasing the overpressure. On the other hand, when the water pressure suddenly increases (because, of e.g. an increased flow of (heavier) liquids), the ring element is pushed down, leading to a smaller annular gap, which can still enable the required CCFL condition.

[0082] The embodiment of the apparatus shown in Figure 3A and Figure 3B has a similar design of the thermal spallation section but differs in the design of the barrier section. Here the barrier section (or packer system) is designed in form of an air-shield.

[0083] Differently to the adaptable packer, a fixed annulus gap 14 is present. The packer includes several nozzles 15 placed at the circumference of the packer. A part of the oxidizer inside the packer 3, flows through the nozzles 15 and creates several fluid-jets.

[0084] These fluid-jets have a sufficiently high momentum to penetrate into the borehole fluids 11 until they reach the borehole wall 1. Therewith, they create a barrier between packer and borehole wall, which the water cannot penetrate.

[0085] Due to the flexibility of these fluid-jets, the packer system can adapt to irregular borehole geometries, such as breakouts. Additionally, non-return valves are integrated into each nozzle with the aim of preventing an inflow of formation fluids into the packer.

[0086] The penetration length of the fluid-jets X_p can be calculated, as displayed below (K. Harby et al., An experimental investigation on the characteristics of submerged horizontal gas jets in liquid ambient, Experimental Thermal and Fluid Science, 53 (2014) 26-39),

$$x_p = \varphi d_N \ln\left(\frac{u_o}{\sqrt{g\,\Delta\rho/\rho_g d_N}}\right) + \beta\, d_N \quad (6)$$

where d_N is the diameter of the nozzle, u_o the velocity of the fluid at the outlet, $\Delta\rho = \rho_g - \rho_l$, the density difference between the fluid and water, and φ and β positive correlation factors.

[0087] Thereby, the nozzle velocity is a function of the pressure difference between the fluid in the packer and the borehole fluids and the occurring pressure drop along the nozzle.

[0088] Therefore, in order to maintain the desired nozzle velocity, an appropriate nozzle diameter has to be selected or the pressure drop in the burner system has to be adjusted. The penetration length has to be larger than the gap between borehole wall and packer circumference to ensure a functioning fluid-barrier. If a larger penetration length is provided, the fluid-barrier can compensate for sudden changes in the distance between borehole wall and packer circumference, caused by e.g. breakouts.

Examples

A) Adaptable packer system:

[0089] Considering a 3000 m-deep geothermal well and an exemplary situation where, due to a sudden inflow of formation fluids, the pressure of the formation fluids (assume water) in the proximal region p_{H2O} increases from about 300 bar to 400 bar. The system has a surface ratio at the ring element of $\frac{A_2}{A_1} = 1.2,$ a mass flow of air $\dot{m}$ = 0.02 *kg/s* with a density ρ_{air} = 12 kg/m^3, a geometry factor ξ = 0.07 and k and c values are set to 1 and 5 bar, respectively. The increased water pressure in the proximal region is linked to the pressure losses Δp at the gap by Eq. (5).

[0090] Further, from Eq. (2), it can be seen that the pressure losses vary as $\frac{1}{A_{gap}^2}$, where $A_{gap} = \pi(r_{bore}^2 - r_{pack}^2)$ is the surface at the gap between packer and borehole wall.

[0091] Combining Eq. (2) and Eq. (5), the gap area can be calculated for the two water pressure values:

$$p_{H_2O} = 300\,bar \quad \Rightarrow \quad A_{gap} = \frac{\dot{m}}{\sqrt{\frac{\rho_{air}}{\xi}\left[\left(\left(\frac{A_2}{A_1} - \frac{1}{k}\right) \cdot k \cdot p_{H_2O}\right) - c\right]}} = 0.65\,mm^2 \qquad (7)$$

$$p'_{H_2O} = 400\,bar \quad \Rightarrow \quad A_{gap} = \frac{\dot{m}}{\sqrt{\frac{\rho_{air}}{\xi}\left[\left(\left(\frac{A_2}{A_1} - \frac{1}{k}\right) \cdot k \cdot p'_{H_2O}\right) - c\right]}} = 0.56\,mm^2 \qquad (8)$$

[0092] This decrease in gap width leads to higher velocities of the upwards flowing air and therefore improving the CCFL condition and avoiding water to penetrate the distal region of the borehole. Therefore, the packer adapts automatically the gap width in order to accommodate any pressure change at the proximal (water side) or distal (air side) regions. An analogous situation would occur when air pressure is accumulated in the distal region; here an increase of the gap width would allow a release of overpressure.

B) Air-shield packer:

[0093] In order to seal off a gap of 10 mm between packer circumference and bore hole wall, which would be a sufficiently large gap to avoid any pressure accumulations in the treatment zone, a jet velocity at each nozzle (d_N=2 mm) of about 23 m/s would be required (according to Eq. (9). Thereby, a density of the water of 1000 kg/m^3, an air density of 12 kg/m^3 are considered and the empirical parameters are set to β = -48.7 and φ = 18.61. Therefore, a mass flow rate of air of 0.86 g/s through each nozzle is required. Thus, a total air mass flow rate of 17.2 g/s would allow for 20 holes to penetrate the water gap and help sustaining the water column above the packer system.

$$u_0 = \sqrt{\frac{g\,\Delta\,\rho}{\rho_g} d_N} \cdot e^{\frac{x_p - \beta d_N}{\varphi d_N}} \qquad (9)$$

Claims

1. An apparatus for thermal spallation of a borehole,

wherein the borehole comprises a proximal region with a borehole fluid with a pressure p_{H2O}, and a distal region filled with a fluid, in particular filled with an exhaust gas with a pressure $p_{gas,out}$,

wherein the apparatus comprises

- at least one section with a thermal spallation system having a predetermined weight adapted for insertion down into the distal region of the borehole,
- at least one barrier section comprising at least one element that is designed to form a barrier between the distal region of the borehole filled with a gas and the proximal region of the borehole filled with the borehole fluid and that is arranged adjacent to the at least one section with the thermal spallation system,

characterized in that

the at least one element, forming a barrier between the distal and proximal region, is designed to adapt in a dynamic manner to changing pressure p_{H2O} of the borehole fluid in the proximal region and/or to changing pressure $p_{gas,out}$ of the fluid, in particular gas in the distal region of the borehole such that
a flow of the borehole fluid from the proximal region of the borehole towards the distal end of the borehole is prevented, and/or
a pressure accumulation of the fluid, in particular gas in the distal region beyond a certain pressure threshold,

which corresponds to the weight of the section with the thermal spallation system, is prevented.

2. Apparatus according to claim 1, **characterized in that** the at least one element, forming a barrier between the distal region and the proximal region, comprises a system that adapts the width d of a gap formed between said element and the wall of the borehole depending on the pressure.

3. Apparatus according to claim 2, **characterized in that** in case the pressure p_{H20} of the borehole fluid in the proximal borehole region increases, the gap width d between the at least one element, forming a barrier between the distal and proximal borehole region and the borehole wall, is reduced.

4. Apparatus according to claim 2 or 3, **characterized in that** in case the pressure $p_{gas,out}$ of the fluid, in particular the gas, in the distal borehole region increases, the gap width d between the at least one element, forming a barrier between the distal and proximal borehole region and the borehole wall, is enlarged.

5. Apparatus according to one of the preceding claims, **characterized in that** the at least one element forming a barrier between the distal and proximal borehole region comprises at least one ring element that is designed to move in response to pressure changes and which is operatively connected to at least one barrier supporting structure.

6. Apparatus according to claim 5, **characterized in that** the at least one ring element is designed to move axially downwards when the pressure p_{H2O} of the borehole fluid increases and simultaneously pushes the at least one barrier supporting structure towards the borehole wall, thereby reducing the gap width d.

7. Apparatus according to claim 5, **characterized in that** the at least one ring element is designed to move axially upwards when the pressure $p_{gas,out}$ in the distal borehole region increases and simultaneously retracts the at least one barrier supporting structure away from the borehole wall, thereby enlarging the gap width d.

8. Apparatus according to any one of the claims 5 to 7, **characterized in that** the at least one barrier supporting structure is made of a flexible, high temperature resistant material, for example a corrugated metal hose.

9. Apparatus according to claim 1, **characterized in that** the element forming the barrier between the distal and proximal region of the borehole comprises a system that is designed to create an air shield between the barrier section of the apparatus and the borehole wall.

10. Apparatus according to claim 9, **characterized in that** the air shield is generated by a gas jet emitted by a plurality of nozzles spaced circumferentially around a central axis of the apparatus.

11. Apparatus according to claim 10, **characterized in that** the barrier between the distal and the proximal region of the borehole is adjusted by the penetration length X_p of the gas-jets.

12. Apparatus according to one of the preceding claims, **characterized in that** the at least one thermal spallation system comprises at last one or multiple nozzles, in particular at least one rotating nozzle, forming a jetting area for thermal spallation,

13. Apparatus according to one of the preceding claims, **characterized in that** the at least one thermal spallation system comprises at least one combustion chamber with at least one igniter.

14. Apparatus according to one of the preceding claims, **characterized in that** the at least one thermal spallation system comprises at least one cooling system surrounding the at least one combustion chamber.

15. Apparatus according to one of the preceding claims, **characterized by** at least one tubing assembly for supplying at least one reactant to the combustion chamber.

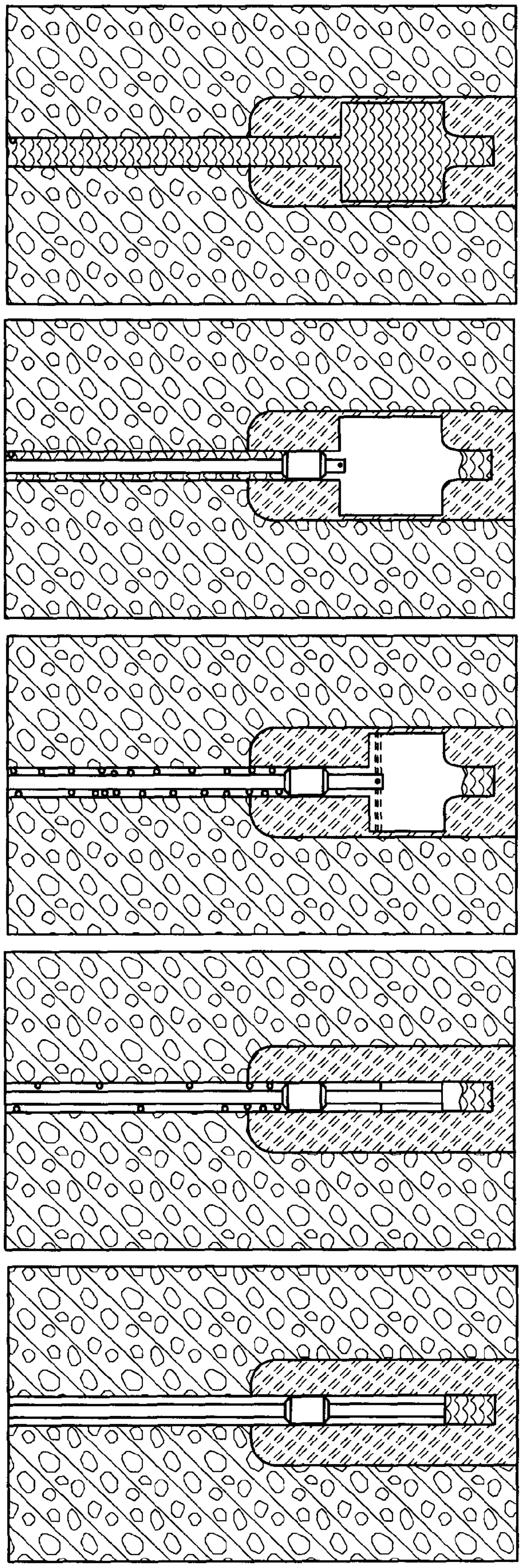


FIG 1

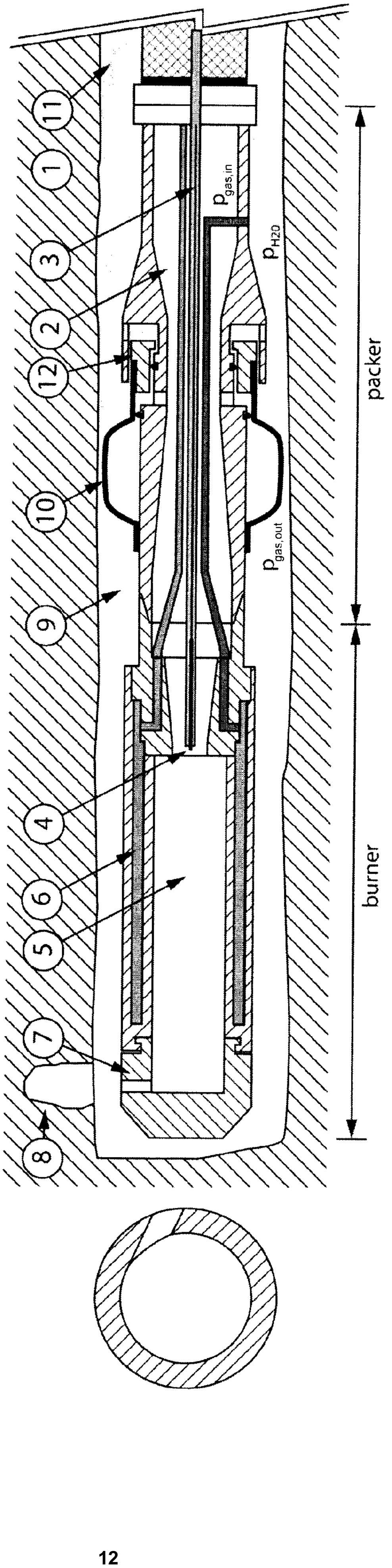


FIG 2A

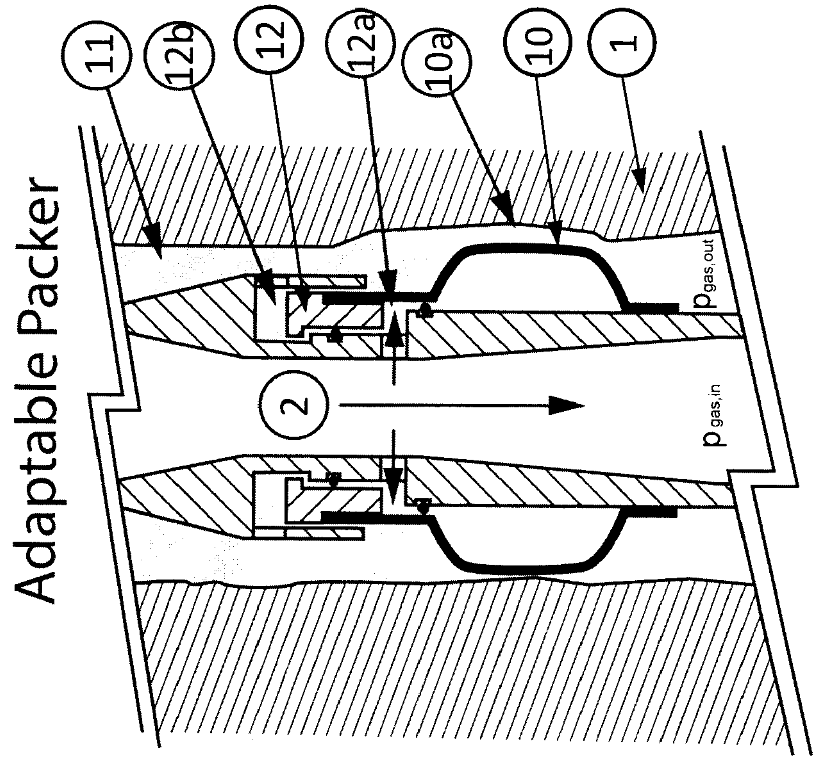


FIG 2B

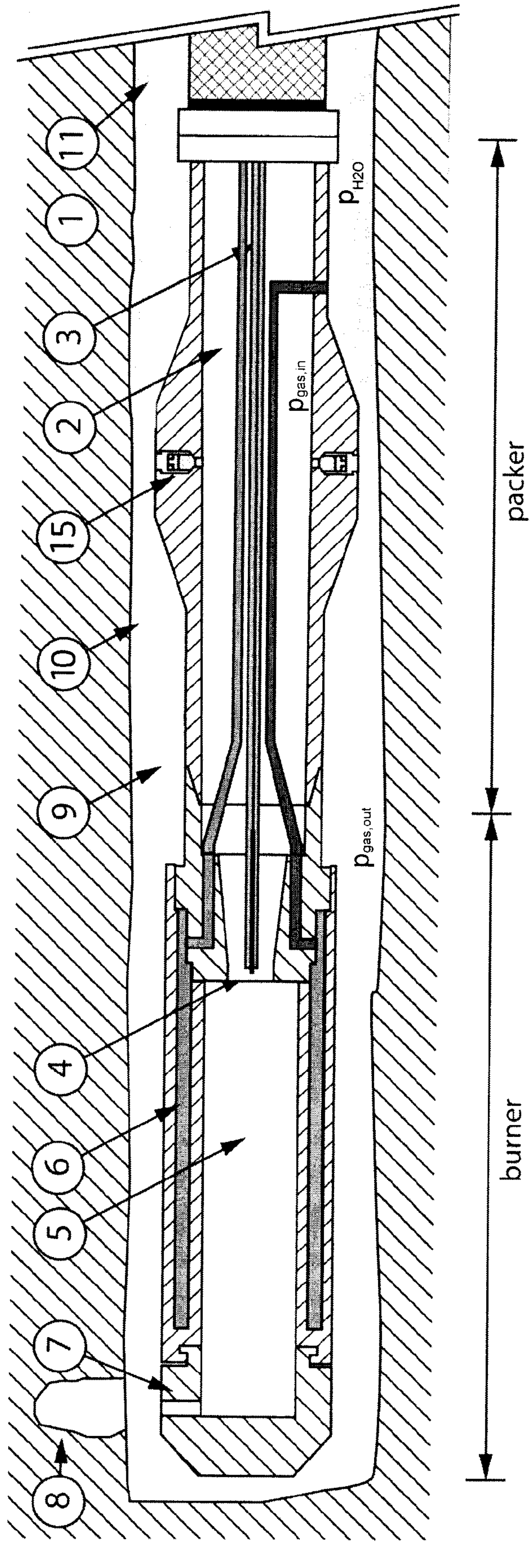
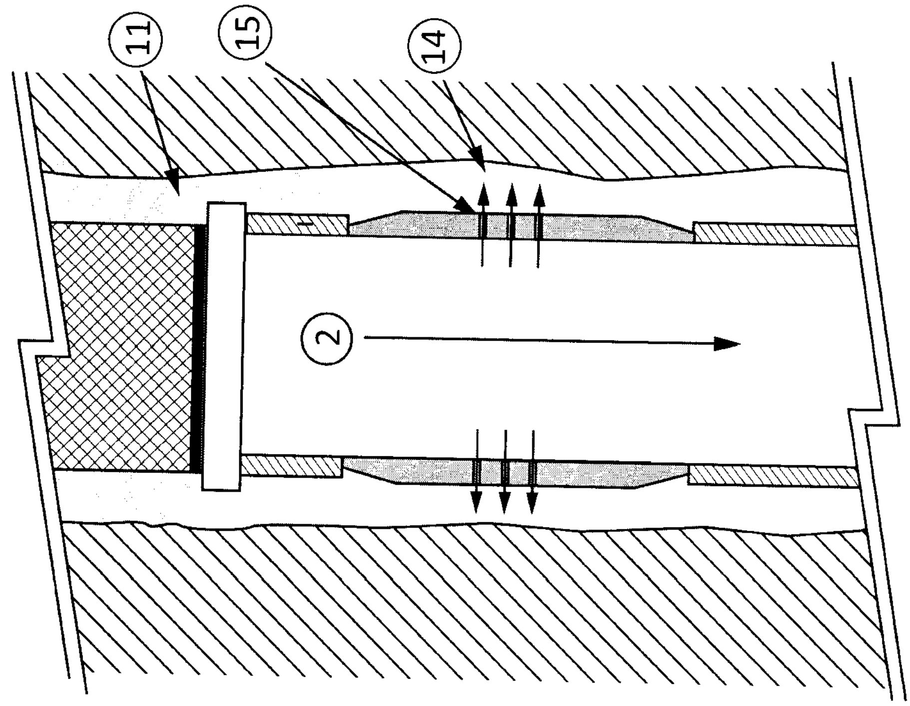


FIG 3A

FIG 3B

Air-Shield Packer



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EUROPEAN SEARCH REPORT

Application Number
EP 17 18 8149

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X	WO 2012/018830 A1 (POTTER DRILLING INC [US]; SAZDANOFF NICHOLAS [US]; POTTER ROBERT M [US) 9 February 2012 (2012-02-09) * paragraph [0005] - paragraph [0009] * * paragraph [0089] - paragraph [0094] * * paragraph [0104] - paragraph [0108] * * paragraph [0117] * * paragraph [0121] - paragraph [0128] * * paragraph [0139] - paragraph [0144] * * figures * -----	1,2,5, 8-15	INV. E21B7/14 E21B7/18 E21B7/28 E21B33/12 E21B33/128 E21B33/127
A	US 5 771 984 A (POTTER ROBERT M [US] ET AL) 30 June 1998 (1998-06-30) * abstract * * figures 9, 15 * * column 9, line 59 - column 11, line 26 * * column 26, line 21 - line 36 * -----	1-15	
A	US 2010/089574 A1 (WIDEMAN THOMAS W [US] ET AL) 15 April 2010 (2010-04-15) * paragraph [0125] * * paragraph [0203] - paragraph [0205] * * claim 39; figures * -----	1-15	TECHNICAL FIELDS SEARCHED (IPC) E21B

The present search report has been drawn up for all claims

1

Place of search	Date of completion of the search	Examiner
Munich	13 December 2017	Pieper, Fabian

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