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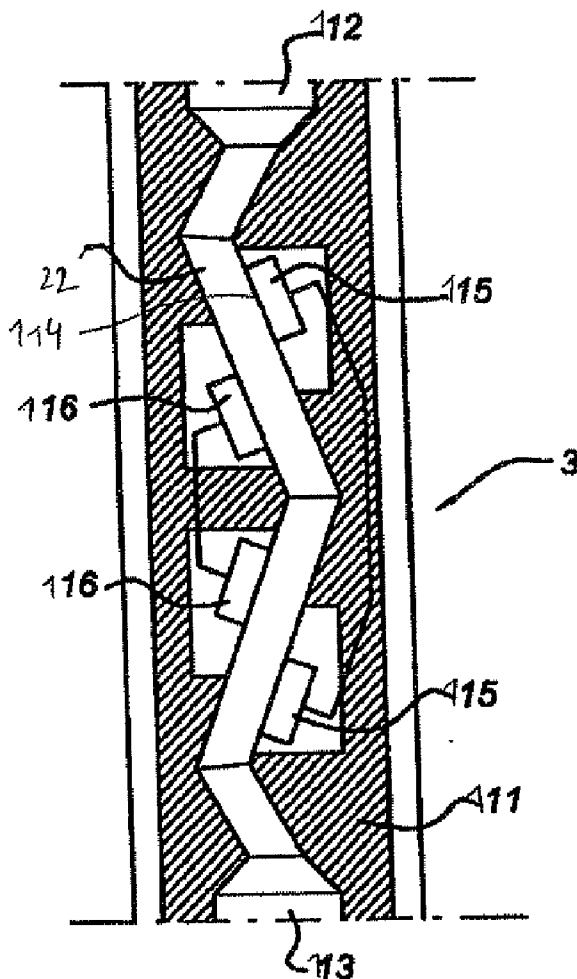
(19) **United States**(12) **Patent Application Publication**
Blangé et al.(10) **Pub. No.: US 2012/0255791 A1**(43) **Pub. Date: Oct. 11, 2012**(54) **METHOD OF DRILLING AND ABRASIVE JET
DRILLING ASSEMBLY****Publication Classification**

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(57) **ABSTRACT**

(76) **Inventors:** **Jan-Jette Blangé**, Rijswijk (NL);
Pieter Van Nieuwkoop, Rijswijk
(NL)(21) **Appl. No.:** **13/517,445**(22) **PCT Filed:** **Dec. 22, 2010**(86) **PCT No.:** **PCT/EP2010/070496**§ 371 (c)(1),
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A method of drilling comprises providing a drill string in a borehole, the drill string comprising an abrasive jet drill head including a jet nozzle, and providing a fluid passageway between the object's surface and the jet nozzle; supplying a fluid mixture comprising magnetic particles to the abrasive jet drill head and blasting from the nozzle an abrasive jet into impingement with the object; and modulating a jetting concentration of magnetic particles in the abrasive jet by modulating a magnetic field a first value, at which magnetic particles are collected from the fluid mixture, and a second value, at which magnetic particles are released into the fluid mixture. Further, an abrasive jet drilling assembly comprising a modulation means for modulating the concentration of the magnetic abrasive particles in the fluid jet a modulation control means for selectively changing a magnetic field between first and second values.



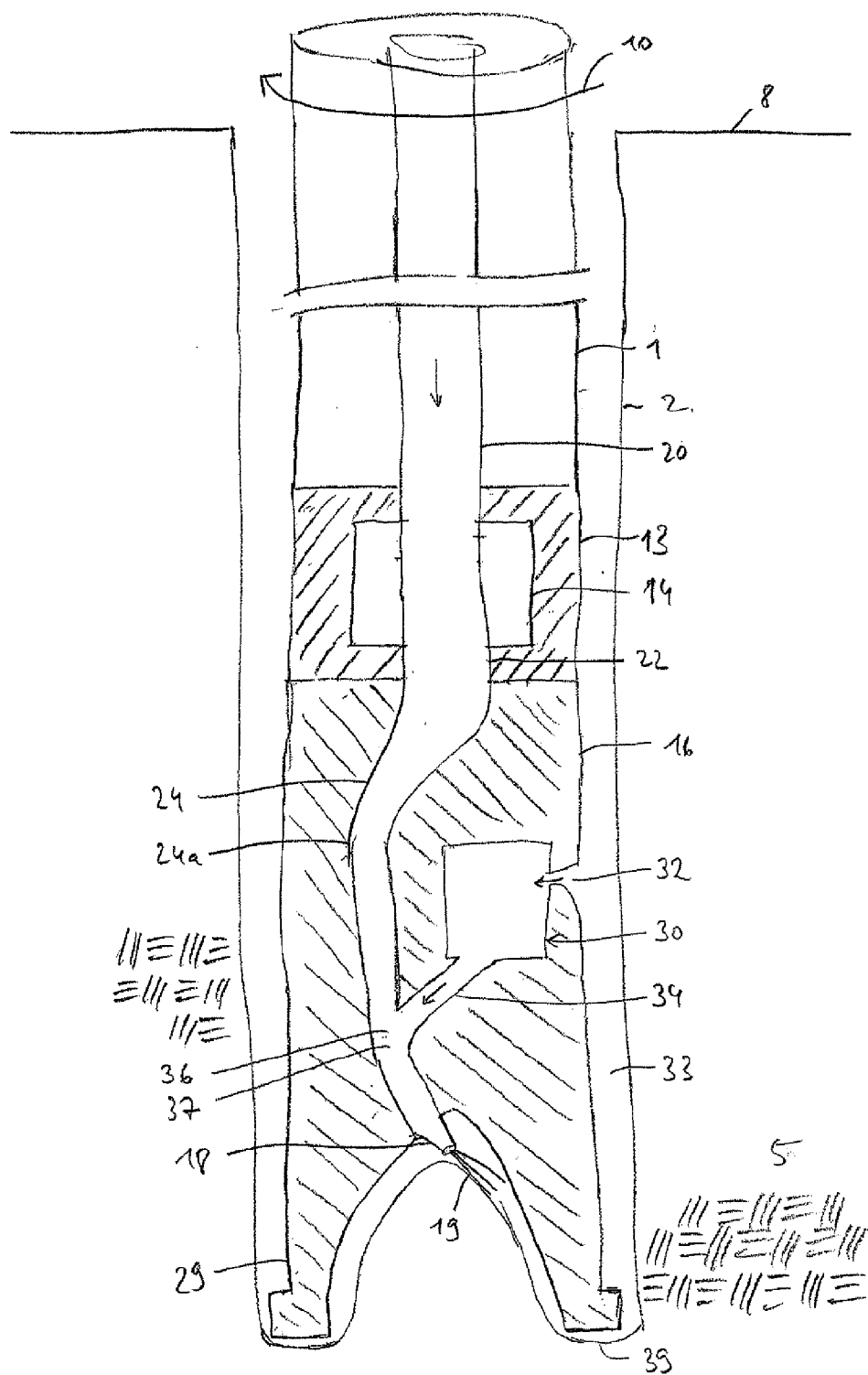
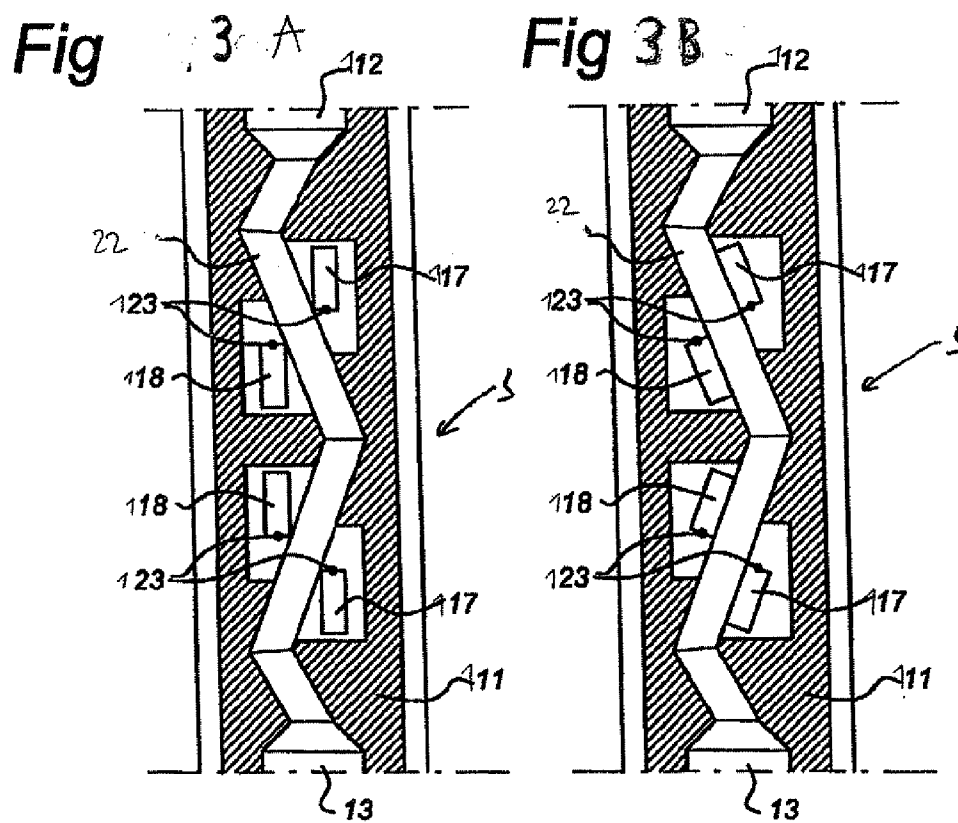
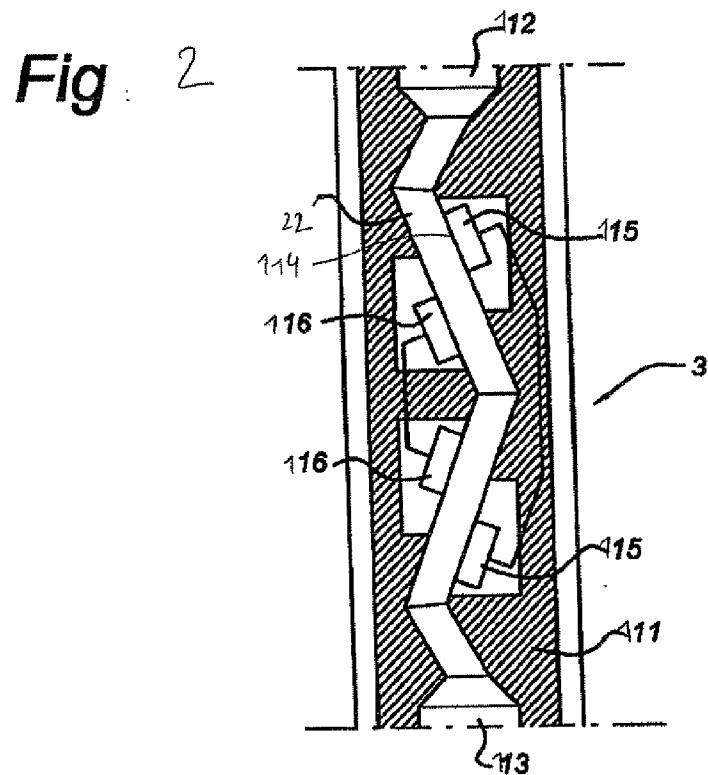


Fig. 1



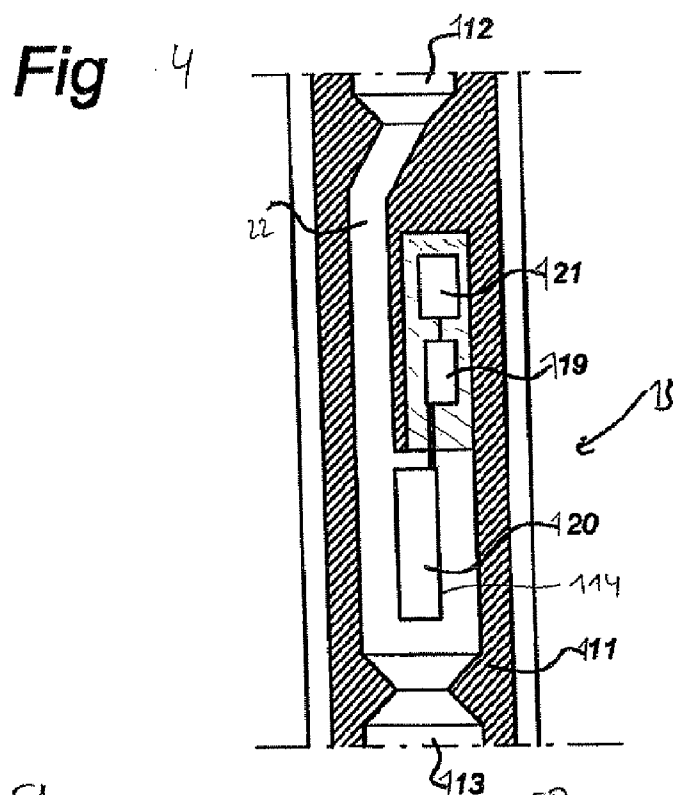


Fig 5A

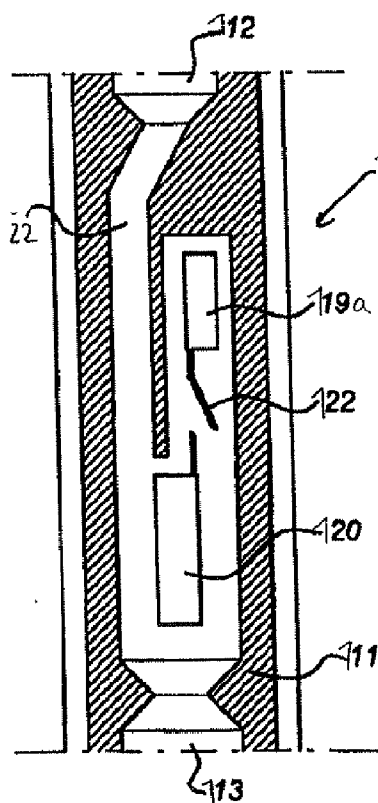


Fig 5B

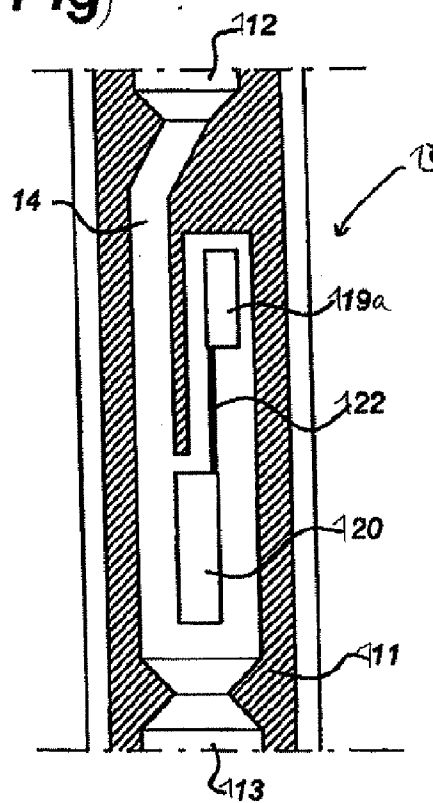


Fig 6A

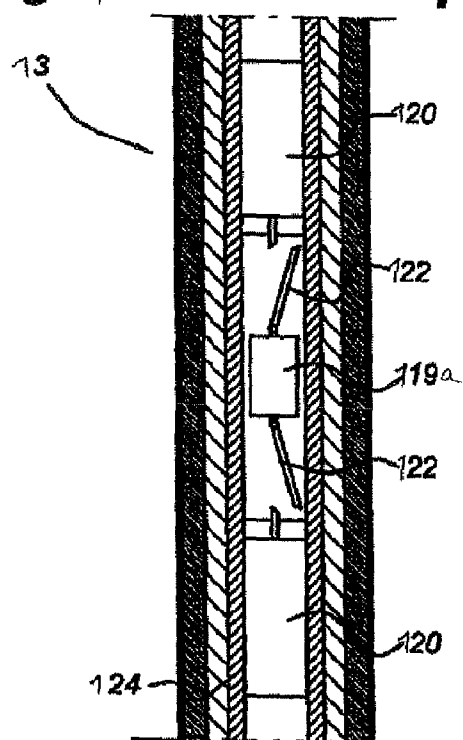
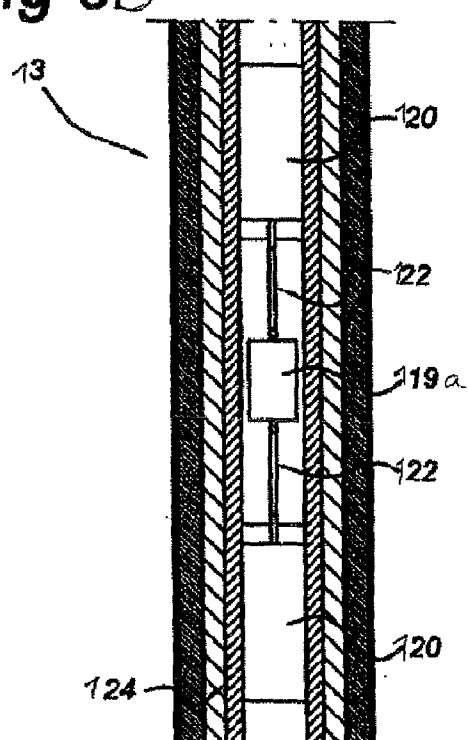


Fig 6B



METHOD OF DRILLING AND ABRASIVE JET DRILLING ASSEMBLY

[0001] The invention is related to a method of drilling into an object and to an abrasive jet drilling assembly. The object can in particular be an earth formation.

[0002] An abrasive jet drill system and method of making a hole in an object is disclosed in WO-A-2005/005767. Said prior art system comprises an excavating tool, herein also referred to as abrasive jet drill head, mounted on a lower end of a drill string that is inserted from the surface into a hole in a subterranean earth formation. The drill string is provided with a longitudinal passage for transporting a drilling fluid mixture comprising abrasive particles to the drill head. The drill head comprises jet means arranged to generate an abrasive jet in a jetting direction into impingement with the earth formation in an impingement area. The abrasive jet contains magnetic abrasive particles (steel shot). A recirculation system is provided, which captures abrasive particles from the return stream to surface, after erosive impingement by means of a magnet, and re-mixes the abrasive particles at a mixing location with the mixture received via the drill string. The magnet is arranged as a rotatable conveyor, attracting particles to be recycled and conveying them towards a mixing location with fresh fluid from surface. The conveyor means has a magnet arrangement forming high-field bands and low-field bands in a helical arrangement. Magnetic particles are attracted by both bands onto a support surface, and are rearranged to the high-field bands. The distance between magnet arrangement and support surface decreases in the direction of an inlet to a mixing chamber, therefore the magnetic field at the support surface due to both high-field and low-field bands increases. During rotation of the conveyor means the particles are transported along the support surface to an inlet to a mixing chamber, where they are entrained by drilling fluid streaming along. A modulation means in form of a controllable drive means for the conveyor is arranged so as to modulate the recirculation rate, and in this way the quantity of particles in the abrasive jet at the jet means is modulated. When the abrasive jet is moved along a trajectory in the hole, in particular in a rotating motion, the amount of erosion in each impingement area along the trajectory can be varied, and directional control is achieved. Reference is also made in this regard to WO 2005/05766.

[0003] In another abrasive jet drill system and method, described in WO-A-2008/119821, a recirculation system device is arranged, which can operate without a moving action of the magnet. As much as it is advantageous not to have moving parts or at least not continuously moving parts operating downhole, such static magnet cannot modulate the recycle rate of abrasive particles.

[0004] There is a need for an improved abrasive jet drilling assembly and method of drilling, wherein modulation of the abrasive particle concentration in the abrasive jet can be provided with a minimum of moving parts or without moving parts.

[0005] In accordance with the invention there is provided a method of drilling into an object, the method comprising

[0006] providing a drill string in a borehole in the object, the drill string comprising an abrasive jet drill head at its lower end, the drill head including a jet nozzle, the drill string providing a passageway for fluid from the object's surface to the jet nozzle;

[0007] supplying a fluid mixture comprising magnetic particles via the drill string towards the abrasive jet drill head and blasting from the jet nozzle an abrasive jet with an erosive power into impingement with the object;

[0008] modulating a jetting concentration of magnetic particles in the abrasive jet;

wherein modulating the jetting concentration of magnetic particles in the abrasive jet comprises modulating a magnetic field at a collection surface arranged along a flow path of fluid towards the jet nozzle between a first value of the magnetic field, at which magnetic particles are collected from the fluid mixture at the collection surface, and a second value, at which magnetic particles are released into the fluid mixture from the collection surface.

[0009] Modulating magnetic field strength between a high value at which particles are attracted to a collection surface that is arranged along the passage of fluid with particles towards jet nozzle, and a low value at which particles are released from the collection surface, provides an efficient and elegant way to avoid moving parts in the modulation system.

[0010] The magnetic field can be modulated by moving a magnet relative to the collection surface, and/or by modulating a drive current of an electromagnet. Modulating the magnetic field can comprise moving a magnetic connector for magnetically connecting a magnet and the collection surface between a connecting position and a non-connecting position.

[0011] Preferably for directional drilling operation, the particle concentration is controlled so as to be modulated in relation with the position of the impingement area on the selected trajectory. The jet nozzle can in particular be rotated, and the modulation of the magnetic field can be controlled in dependence of the rotation of the jet nozzle.

[0012] In one embodiment, a supply concentration of abrasive particles in the fluid mixture received at an upstream side of the abrasive jet drill head is modulated in order to modulate a jetting concentration in the abrasive jet. The jetting concentration can be different, in particular on average higher, but still dependent on the supply concentration, if a recirculation system

is provided, to recirculate abrasive particles after their discharge from the jet nozzle to a mixing location with the supply fluid mixture along the passageway, and wherein the supply concentration is modulated upstream of the mixing location. It is in principle also possible to use the modulation of the present invention inside a recirculation system, alternatively or in addition to modulating the supply concentration. Preferably, when a downhole recirculation system is provided, it is not used for modulating the recycle rate.

[0013] The invention also provides an abrasive jet drilling assembly connectable to a tubular drill string part, and comprising an abrasive jet drill head with a jet nozzle, a passageway for fluid comprising magnetic abrasive towards the jet nozzle,

and a modulation means for modulating the concentration of the magnetic abrasive particles in fluid flowing, during operation, through the jet nozzle;

the modulation means comprising

a collection surface,

a magnetic holdup device for exerting a magnetic field at the collection surface, comprising a magnet arrangement and a modulation control means for selectively changing the magnetic field at the collection surface between a first value, at which magnetic particles are collected at the collection sur-

face, and a second value, at which magnetic particles are released from the collection surface.

[0014] The modulation means can be integrated with the abrasive jet drill head, or can be separate, such as connectable as part of a bottomhole assembly into the drill string.

[0015] In one embodiment the abrasive jet drilling assembly further comprises a control unit for controlling the particle concentration of the abrasive jet in relation with a position of an impingement area of the abrasive jet drill head during operation. Preferably, when a downhole recirculation system is provided, it is not adapted for modulating the recycle rate, and/or the control means is not adapted to control the recycle rate of the recirculation system.

[0016] The magnet arrangement can comprise at least one electromagnet, and then preferably modulation control means is arranged to modulate a drive current of the electromagnet. Alternatively or in addition, the magnet arrangement can comprise at least one permanent magnet, preferably then the at least one permanent magnet is movable with respect to the collection surface. It can e.g. be translationally and/or rotationally movable.

[0017] The magnetic holdup device can comprise an actuator for changing the relative position of the magnet arrangement and the collection surface.

[0018] Alternatively or in addition, the magnet arrangement can further comprise a selectively movable magnetic connector.

[0019] The passageway can be at least partially an annular passageway having inner and outer annular walls, and the collection surface can be at least partially arranged on the inner annular wall. E.g. a magnet can be enclosed by the inner wall, or the magnet arrangement can be surrounded by the inner annular wall.

[0020] The magnet arrangement can comprise at least two magnets which are positioned at different angular positions with respect to flow direction along the passageway.

[0021] The magnet arrangement can be positioned outside the passageway.

[0022] The abrasive jet drilling assembly can further comprise a downhole recirculation system arranged to recirculate abrasive particles during operation after their discharge from the jet nozzle to a mixing location along the passageway, and wherein the collection surface is arranged along the passageway upstream of the mixing location. In a particular embodiment the modulation means can form part of the recirculation system.

[0023] However, by arranging the modulation means along the fluid passageway from surface to the drill nozzle, upstream of a mixing location with a return stream from a recirculation system, i.e. so that it has effect in this passageway and not in a return path of the recirculation system, the modulation becomes independent of the presence of and precise function of the recirculation system.

[0024] The expressions upper, above, upstream, uphole, lower, below, downstream, downhole, and the like, are used with reference to a drill string with abrasive jet drill head in a borehole, wherein upper or above is closer to surface than lower or below; and upstream and downstream are with respect to drilling fluid flowing generally downwards through the drill string, and upwards to surface through the annulus with the borehole wall.

[0025] The abrasive jet drilling assembly can be part or a drilling system including part or all of a drill stream, e.g. an entire drill string to surface or a conventional component of a

drill string such as drill string element, jointed pipe, bottom hole assembly, special function sub such as for measurement while drilling (MWD), stabilizer, etc.

[0026] The modulation means can be integrated with the abrasive jet drill head, such as at an upper or upstream end thereof, in particular upstream of the mixing location with abrasive particles from a recirculation system. It is however also possible to arrange the modulation means separate from the abrasive jet drill head, e.g. as part of the drill string above the abrasive jet drill head, such as in a separate drill string element or sub. Suitably the distance along the drill string between the modulation means and the jet nozzle is not too large, otherwise a modulation of particle concentration in the supply fluid can be partially or fully smeared out when arriving at the abrasive jet drill head. It will be understood that a certain time lag between the modulation at an upstream position in the passageway and the nozzle can occur. Suitably the distance is 100 m or less, preferably 50 m or less, more preferably 20 m or less, so that the supply concentration received at the abrasive jet drill head is well-defined. The modulation means can be provided just upstream of the abrasive jet drill head or as part of a bottomhole assembly.

[0027] The abrasive jet drilling assembly can further comprise a measurement device for detecting the angular orientation of the jet nozzle in the borehole, and the modulation control means can be arranged to control the magnetic holdup device in dependence on the detected angular orientation.

[0028] In one embodiment the modulation means is positioned in the drill string above or at a lower outlet connection towards the abrasive jet drill head. When connected, a flow of drilling fluid with modulated abrasive particles supply concentration enters an upper inlet connection of the drill head. In one embodiment, the modulation means is contained in a collar positioned in the drill string, said collar having a through going channel forming part of the passageway of the drill string. In one embodiment the through going channel comprises an annulus and a magnetic holdup device is positioned within the area surrounded by the innermost wall of the annulus. In one embodiment the modulation means comprises at least two magnets which are positioned on opposite sides of the through going channel. In one embodiment the magnet(s) comprise at least one permanent magnet and the activating means is provided comprising a mover, said mover being carried out for displacing the permanent magnet with respect to the through going channel. In one embodiment the magnet(s) are mounted in a rotatable fashion between a position parallel to the through going channel and an oblique position with respect to the through going channel. In one embodiment the modulation means is provided with a paramagnetic collector and the mover is arranged so as to establish respectively break a magnetic contact between the magnet(s) and the collector.

[0029] In one embodiment of the invention, a method for operating the abrasive jet drilling assembly comprises the steps of obtaining a flow mixture comprising a drilling fluid and abrasive particles, and varying the operation of the activation device so as to obtain a controlled attraction and/or release of the paramagnetic abrasive particles. In particular the modulation means is operated so as to hold an amount of particles within the through going channel, and subsequently making the modulation means operate in a pulsating manner so as to release a part and only a part of the abrasive particles held within the through going channel during each pulsation. In one embodiment the method comprises providing at least

two modulation devices in series, activating said modulation means so as to hold a batch of abrasive particles each, deactivating said modulation devices such that a time difference is obtained in the arrival time at the jet nozzle of said batches of abrasive particles.

[0030] The invention will now be described by way of example with reference to the drawings, wherein

[0031] FIG. 1 shows schematically an abrasive jet drilling system with abrasive jet drill assembly according to the invention;

[0032] FIG. 2 shows a first embodiment of a modulation means;

[0033] FIG. 3 A, B show a second embodiment of a modulation means;

[0034] FIG. 4 shows a third embodiment of a modulation means;

[0035] FIGS. 5 A, B show a fourth embodiment of a modulation means; and

[0036] FIGS. 6 A, B show a fifth embodiment of a modulation means.

[0037] In the Figures, like reference numerals are used to designate the same or similar objects.

[0038] As shown in FIG. 1, an abrasive jet drilling system including an abrasive jet drilling assembly according to the invention comprises a drill string 1 in a borehole 2 in an object. This object is here a subterranean earth formation 5, in particular to provide a borehole for the manufacture of a well for production of mineral hydrocarbons. The drill string 1 is which at its upper end at surface 8 connected to a rotational drive device (not shown, but indicated by arrow 10) and at the other, lower, end to a collar 13 comprising a modulation means 14 in accordance with the invention. The collar 13 can also be provided with a controller unit, such that the controller unit is located inside the hole.

Alternatively, the controller unit can be positioned at a different position in the drill string with abrasive jet drill head, or at the surface 8.

[0039] At the lower end of the collar 13 an abrasive jet drill head 16 with jet nozzle 18 is connected to or integrated with collar 13. The drill string 1 has a passageway 20 for fluid, which is in fluid communication with the jet nozzle, via passages 22,24 of the collar 13 and abrasive jet drill head 16. The nozzle 18 is obliquely oriented in a central area so that the impingement area is located eccentric with respect to the rotary axis of the drill head 16, and in this case rotating the abrasive jet in the hole results in the jet 19 and the impingement area moving along an essentially circular trajectory in the hole. Preferably, the eccentric impingement area overlaps with the centre of rotation, so that also the middle of the bore hole is subject to the erosive power of the abrasive jet.

[0040] The jet nozzle 18 is arranged above an optional foot part 29, and is inclined relative to the longitudinal direction of the system at an inclination angle of 15-30° relative to the rotary axis, but other angles can be used. Preferably the inclination angle is about 21° which is optimal for abrasively eroding the bottom of the bore hole by axially rotating the complete tool inside the bore hole.

[0041] The abrasive jetting drill head in this embodiment moreover comprises a recirculation system for abrasive particles, which is generally indicated as 30, with an inlet 32 in fluid communication with the annulus 33 between abrasive jet drill head 16 and the borehole 2, and an outlet 34 to a mixing chamber 36 arranged at a mixing location 37 of the passageway 24.

[0042] The optional foot part provides for a distance from the borehole bottom and suitably contains slots for drilling fluid and cuttings to flow via the annulus 33 upwardly. The abrasive jet drill head 18 can for example be a head as described in e.g. WO2008/113843, WO 2008/113844.

[0043] In operation, the system works as follows. A stream of drilling fluid including abrasive particles such as steel shot, is pumped from the object's surface (e.g. earth's surface) by a suitable pump (not shown) through the longitudinal passage 20 of the drill string 2. Part or all of the drilling fluid is led to the jet nozzle 18 where an abrasive jet 19 is generated. The abrasive jet is blasted into impingement with the formation. The formation is eroded in the impingement area as a result of the abrasive jet 19 impinging the formation 5, thereby deepening the borehole 2.

[0044] Simultaneously, the abrasive jet is rotated about the rotary axis. Thus, the impingement area is moved along a circular trajectory in the hole so that the formation can be eroded at all azimuths. By modulating the erosive power of the abrasive jet a high degree of directional control can be achieved.

[0045] By keeping the erosive power of the abrasive jet constant, the formation is eroded evenly on all sides of the hole and consequently the hole is excavated straight. When the erosive power is modulated, in particular by modulating the concentration of abrasive particles, a modulation that is not synchronized with the moving of the impingement area of the jet such as by rotation, is not going to give rise to a directional effect. Thus, straight borehole sections can in principle be drilled by modulation that is asynchronous with respect to the rotation. Nevertheless, distortions in the rotating of the excavation tool, or variations in rock formation properties in the hole region, or other causes may result in uneven erosion in the hole. A directional correction may be required by modulating the erosive power to compensating for the unintentional uneven erosion. The erosive power of the abrasive jet can also be modulated in order to deliberately excavate a curved hole. When the abrasive jet is oriented to impinge the formation in an area that requires more erosion in order to establish the directional correction, the erosive power of the abrasive jet can be periodically increased resulting in a higher erosion rate in that area. Alternatively, or in combination, the erosive power of the abrasive jet can be reduced when the abrasive jet is oriented to impinge the formation in an area that requires less erosion.

[0046] A directional effect can be obtained by making the abrasive particles emanate from the jet nozzle 10 at a higher concentration at the same specific spot at each rotation of the drill string 2 and the drill head 16. Thereby, the borehole bottom 39 is eroded unevenly, which makes that the further progression of the borehole 9 will continue deviated with respect to the longitudinal direction of the borehole 1.

[0047] The flow of drilling fluid with abrasive particles can be modulated so as to obtain a pulsating effect. That is to say, at each full rotation of the drill string 1 and the drill bit 4 the jet can contain one phase with a relatively high concentration of abrasive particles and at least one phase with a relatively low concentration of abrasive particles. It would also be possible to provide a higher concentration only once every selected integer number of rotations. Other schemes of preferential erosion can be used in case more than one jet nozzle is arranged. When more than one jet nozzle is arranged they suitably provide an asymmetric distribution of impact on the borehole.

[0048] Modulation of a concentration c means that the concentration depends on time, $c=c(t)$. The modulation can have a period of repetition after 1, 2, 3, up to 10, or 20, or more rotations. The time scale considered for a particular modulation can be the duration of one or several, say 10, 100 or more, 1000 or more, rotations of the drill string. Over longer times the modulation can be modified, or even stopped during certain periods, so as to drill along a desired trajectory which may include straight parts.

[0049] It is thus preferred that the modulation means comprises modulation control means arranged to control the modulation means such that the erosive power of the abrasive jet is modulated in relation with the position of the impingement area on the selected trajectory.

[0050] In order to establish the position of the impingement area, the system can be provided with a positional sensor, for instance a measurement while drilling sensor, for providing a signal indicative of the position of the abrasive jet. In order to establish the current drilling direction through the formation, the system can be provided with a navigational sensor, for instance a measurement while drilling sensor, for providing a signal indicative of the direction under which the making of the hole in the earth formation progresses.

[0051] Such a navigational sensor can be provided in the form of one of or a combination of a directional sensor providing a signal indicative of the direction of the device relative to a reference vector; a positional sensor providing a signal indicative of one or more positional coordinates relative to a reference point; a formation density sensor providing information on a distance to a change of formation type or formation content nearby; or any other suitable sensor.

[0052] The mechanical forces on the drilling system that is based on abrasive jetting are much smaller than is the case for systems based on mechanical rock removal. This has the advantage that the sensors can be located very close to the excavating tool, making early and accurate signal communication possible to the modulation control means. The sensors can for instance be provided in the same chamber as the modulation control means.

[0053] Alternatively, the position and/or the direction of progress through the formation of the abrasive jet can be determined on the basis of parameters available on the surface **8**, including torque on the drill string **2** and azimuthal position of the drill string **2**, and axial position and velocity of the drill string **2**.

[0054] A decision to change or correct drilling direction may also be taken via the operator of the directional system at surface. In case of the signal originating from a down-hole measurement while drilling sensor, a mud-pulse telemetry system or any other suitable data transfer system can be employed to transfer the data to the surface. Via similar means of data transfer a control signal can be sent to the down hole control means triggering a series of control actions required for the desired direction drilling correction.

[0055] A thruster (not shown) is advantageously provided for pressing the abrasive jetting system upon the bottom **39** of the hole **2**. Best results are obtained when the pressing force is not much higher than what is required to keep the abrasive jet drill head **16** at the bottom, in order to avoid unnecessary wear on the abrasive jet drill head **6**, bending of the system, and loss of directional control. Thus, the pressing force is preferably just sufficient to counteract the axial recoil force of the abrasive jet and the friction forces in the thruster and

between the abrasive jet system and the hole wall. Typically, the pressing force is well below 10 kN.

[0056] A suitable abrasive jet comprises a mixture containing a fluid, such as the drilling fluid, and a certain controlled concentration of abrasive particles. The erosive power of the jet correlates with the total power vested in the abrasive particles entrained in the mixture. This depends on the mass flow rate of abrasive particles and on the square of the velocity of the abrasive particles.

[0057] Modulating the erosive power of the abrasive jet can be achieved by modulating the mass flow rate of the abrasive particles in the abrasive jet. This can most advantageously be achieved by modulating the concentration of abrasive particles in the mixture. When the quantity of similar particles impinging on an area per unit of time is higher, the total erosive power of the abrasive jet increases in that more of the formation will be eroded. Modulation of the concentration of abrasive particles in the mixture does not influence the mechanical contact forces between the drilling system and the formation.

[0058] A relatively small variation in the concentration of abrasive particles can be sufficient to achieve a directional effect, such as 20 wt % of the particles or less, 10 wt % or less, 5 wt % or less between maximum and minimum concentration of particles during modulation. When the particles have substantially the same size/weight and/or density, these figures can likewise be expressed in vol % of abrasive particles.

[0059] Still referring to FIG. 1, the abrasive particles will be entrained in a return stream of drilling fluid through the excavated hole, running for instance through an annular space **33** between the hole **1** and the drilling system (**2**, **13**, **16**).

[0060] In order to reduce the concentration of abrasive particles to be transported all the way back to the surface, the drilling system, in particular the abrasive jet drill head **16**, can be provided with recirculation means **30** arranged to recirculate at least a part of the abrasive particles from the return stream downstream from impingement with the formation, back into the abrasive jet **10** again. The abrasive particles to be recirculated can be mixed with the fresh stream of drilling fluid containing a supply concentration of abrasive particles, for instance in a mixing chamber to which both the fresh stream of drilling fluid and the recirculated abrasive particles are admitted, to obtain a jetting fluid mixture comprising a jetting concentration of abrasive particles.

[0061] The abrasive particles preferably comprise or consist of magnetisable material, i.e. paramagnetic or ferromagnetic material, such as for instance steel shot or steel grit. This will herein also be referred to as "magnetic material" or "magnetic particles", although it does not need to have a permanent magnetization. The recirculation system can comprise a magnet attracting magnetic particles from the drilling fluid flowing upwardly in annulus **33**, and conveying the particles via outlet **34** to the mixing chamber **36**. Generally suitable recirculation systems are for example described in WO 2002/034653, WO 2005/005766, WO2008/119821, WO 2008/113844.

[0062] In accordance with the invention the supply concentration of abrasive particles is modulated, upstream of the mixing location **37**, i.e. in the passageway **20**, **22**, **24a** above the mixing chamber **36**. Thereby the jetting concentration of abrasive particles in the jet **19**, which depends on the supply concentration, is modulated.

[0063] The modulation means 14 is therefore arranged along the passageway 20, 22, 24 of the drill string, in the embodiment of FIG. 1 at the upper end or just upstream of the abrasive jet drill head 16.

[0064] In the embodiment of FIG. 1 the modulation is obtained in the collar 13, several embodiments of which are shown in FIGS. 2-6.

[0065] In the embodiment of FIG. 2, the collar 13, which has a non-magnetic housing 111, has an upper inlet 112, for fluid communication with the passage 20 of the upper part of the drill string and a lower outlet 113 for fluid communication with the passage 24 of the abrasive jet drill bit. Between this inlet and outlet, the through going channel 22 extends. Alongside this through going channel 22, two pairs of electric holdup devices, electromagnets 115, 116, are positioned. Each pair of electromagnets 115, 116 is situated along a somewhat obliquely oriented part of the through going channel 22. The modulation of the concentration of abrasive particles which pass through this through going channel 22 is obtained by controlled activation and de-activation of these electromagnets. This is obtained by starting or stopping the current which is fed to the electromagnets. The current can also be varied more smoothly and/or between various non-zero values, but the latter is less preferred as a constant energizing from a power source would be required.

[0066] Thus, at collection surfaces at the wall of the passage 22 the magnetic field is modulated between a first value, at which at least some magnetic particles are collected from the fluid mixture at the collection surface, and a second value, at which magnetic particles are released into the fluid mixture from the collection surface. The first value is a higher value and the second value is a lower value of the magnetic field. It will be understood that particles on the collection surface can move along the surface under the influence of the streaming fluid, but in periods of higher magnetic field strength more particles are present on the collection surface than in periods of lower or zero magnetic field strength. Only one collection surface is indicated at 114. Preferably, magnetic particles are collected by a substantial part of the support surface, preferably at least 25% of the area or the support surface, more preferably at least 50% of the area, even more preferably at least 75% of the area, such as substantially all area, when the magnetic field is at its first value. Preferably, magnetic particles are released from substantial part of the support surface, preferably at least 25% of the area or the support surface, more preferably at least 50% of the area, even more preferably at least 75% of the area, such as substantially all area, when the magnetic field is at its second value. Preferably, when the magnetic field is at the first value, no or only an insignificant part of magnetic particles is re-entrained by fluid streaming along the support surface, such as less than 25% of the particles collected on the support surface are re-entrained then during a period at which the magnetic field is at its first value.

[0067] In the embodiment shown in FIGS. 3A, B, permanent magnets 117, 118 have been applied as magnetic holdup devices alongside the through going channel 22. These magnets can be swung around the swing axis 123, so as to obtain the different positions shown in FIG. 3A and in FIG. 3B. In the position shown in FIG. 3A, the magnets 117, 118 are swung away from the through going channel 22, which means that a relatively large part of the paramagnetic abrasive particles will pass along the passage 22. Conversely, in the position shown in FIG. 3B, the magnets 117, 118 are swung

towards and against the collection surfaces 114 at the wall of the through going channel 22, in such a way that the magnetic field at the collection surfaces is higher and a portion of the magnetic abrasive particles are collected at said surfaces. By changing between the position is shown in FIGS. 3A, B, such as by means of a mechanic actuator (not shown), modulating effects can be obtained in that the drilling fluid flow will show different concentrations of abrasive particles.

[0068] The embodiment of FIG. 4 contains an electromagnet 119, which is connected to a so-called paramagnetic collector 120, together forming a magnetic holdup device. Furthermore, the box 121 contains a battery or connection to external power source and an electronic control unit. Under the influence of the control unit, the electromagnet is energized by the battery/power source in such a way that the magnetic field at the paramagnetic collector becomes strong enough so that magnetic abrasive particles will collect on the paramagnetic collector 20. By varying the activation of the electromagnet, the concentration of the magnetic particles in the through going channel 14 can be varied so as to obtain the modulation required. The paramagnetic collector can comprise a permanent magnet providing a relatively low magnetic field strength, which is just insufficient to collect particles at the collection surface 114, in this case surrounding the collector 120. So a moderate increase of field strength at the collection surface provided by electromagnet 119 is sufficient for collection.

[0069] The embodiment shown in FIGS. 5A, B comprises a permanent magnet 119a, which by means of the magnetic connector 122 can be disconnected (FIG. 2A) from or connected (FIG. 2B) to the paramagnetic collector 120, together forming a magnetic holdup device. By changing between the disconnected and the connected state of the connector 22, the concentration of the abrasive particles in the through going channel 14 can be varied.

[0070] The embodiment shown in FIGS. 6A, B contains a permanent magnet 119a which by means of the connectors 122 can be connected to the double paramagnetic collectors 120, together forming a magnetic holdup device. The area or annulus 124 on the outside of the collectors 120 should be large enough to collect a sufficiently large volume of abrasive particles, so as to significantly vary the concentration of the abrasive particles which is fed to the bit within a single rotation of the string. Instead of permanent magnet 119a a selectively energizable electromagnet can be used (not shown).

[0071] Instead of moving paramagnetic connectors in FIGS. 5 and 6, the permanent magnets themselves could be moved up and down to connect/disconnect with the paramagnetic collector. Alternatively or in addition, only one of the two paramagnetic collectors 120 shows can be arranged. It might also be advantageous to mount an additional magnetic guide (not drawn) parallel to the magnet in order to form a magnetic shortcut with the open connectors. This is to avoid that when the connectors are open the magnetic field coming from the open end of the connectors disturb the particle flow in the surrounding annulus.

[0072] So, modulation can be e.g. obtained by selectively energizing electromagnets, by physical movement of the permanent magnets to or from the collection surface, by repositioning a magnetic conductor between the magnet and the wall of the fluid channel, and/or by creating (or removing) a magnetic shortcut at the magnet(s). If possible, the magnets are preferably permanent magnets, e.g. rare earth permanent

magnets like NdFeB, or SmCo magnets in order to avoid the continuous supply of current to the magnets when they have to be activated.

[0073] Advantages of the embodiments of FIGS. 5 and 6 are that only one chamber with electronics is required; the fluid pass through area at the height of the paramagnetic collector is large which reduces the average fluid and particle velocity around the device; only the switching between activation or deactivation of the collector requires power and not the (de-)activation itself. In the embodiment of FIG. 5 the magnetic holdup device is coaxial with the housing. This can be advantageous for manufacturing and for connecting to other (electronic) devices like surveying sensors and electronic control units.

[0074] The design and material of the magnet, the magnetic connector and the collector should match each other so that magnetic flux is not wasted and the strength of the magnetic field on the outside of the collector is big enough to collect temporarily the ferromagnetic particles in the drilling fluid stream along the collector. The collection surface should be large enough to collect a sufficiently large volume of abrasive particles to be able to significantly vary the concentration of the particles to the bit within one rotation of the string.

[0075] In an illustrative example, the rotation of the string can typically take 1 sec. In the case a downhole recirculation device is used, the concentration of particles pumped through the drill string is typically in the range of 0.1 to 4% by volume, such as 0.4 to 2 vol %, considering steel shot in an aqueous fluid, e.g. water. Each 100 litres of drilling fluid pumped to the bit per minute then contains up to 0.017 litres/s of abrasives. A collector for a particle flow rate of 1 vol % at 200 L/min fluid flow rate and a 1 sec modulation typically needs to be able to collect for 0.017 L during 0.5 sec and release it during the other half of the second.

[0076] When a recirculation system is used, the drilling fluid in the abrasive jet may contain a jetting concentration of up to 10% by volume, typically up to 5 vol % of magnetic abrasive particles, and is on average higher than the supply concentration. When there is no recirculation system, the supply concentration via the drill string is typically the same as the jetting concentration, apart from a possible time lag of changes, and can e.g. be in the range of 0.5 to 10 vol %, such as 2-5 vol %, e.g. 3 vol %. The recycle frequency preferably exceeds the rotational frequency of the drill string. The recycle frequency can for example be between 10 and 40 Hz. The rotation of the drill string, or at least the abrasive jet drill head excavating tool, is typically between 0.3 and 3 Hz.

[0077] The intended bending radius of the drilled trajectory can be increased by modulating not continuously, but, for instance, only two or every three subsequent rotations.

[0078] In order to obtain directional control, the activation and deactivation of the collector are suitably triggered by a measurement of the angular orientation of the jet nozzle of the drilling bit with respect to the desired drilling direction. The power for the (de-)activation could e.g. come from a down hole battery pack or a turbine generator or a combination thereof. In an example bottom hole configuration, a battery pack or turbine, control unit and memory, and a sensor package, are arranged, e.g. in this order, between the modulation means (cf. 14 in FIG. 1), and the mixing location 37, either all integrated in an abrasive jet drill head or in several connected components. It is however also possible that no recirculation system is arranged.

[0079] It can be desired to avoid release of all collected particles at the same time, i.e. to avoid a spike. To this end it can be considered to use:

[0080] a modulation means comprising more than one modulation device in series with each other that have deactivation times that are chosen such that there is a time difference between the arrival time of the released particle batches at the jet nozzle; for example, the collection surface closest to the bit could be deactivated first and possibly also be activated first;

[0081] a by-pass channel that ensures that a constant fraction of the particles in the flow reaches the abrasive jet drilling device;

[0082] a pulsed release of particles from the collector; by deactivating the collector only very briefly the particles that were released at the top of the collector will be recollected, and this way a few pulses with varying number of particles can be released within a short time frame;

[0083] design of the collector such that it saturates after a fraction such as a quarter of the duration of the modulation cycle and releases particles half a cycle later duration of the modulation cycle later;

[0084] a combination of the options mentioned above.

[0085] A variation in the amount of magnetic flux that goes from a selected magnet, e.g. 119, 119a, to the paramagnetic collector. By varying the contact area between the magnetic connector and the magnet or the connector and the collector the flux to the collector can be regulated and thereby the number of particles that can be collected by the collector.

[0086] Preferably, the toolface and direction of the drill head are measured close to the bit and may require the measurement of the earth magnetic field. To avoid influence of the magnet(s) in the modulator on this measurement it is preferred to have the modulator at a distance of typically at least 1 meters away from the magnetic sensors. To match the modulation of the abrasive concentration with the orientation of the abrasive jet nozzle, i.e. the toolface of the abrasive jet drill head, the timing of the modulation has to compensate for the travel time of the particles from the modulator to the bit. In the case of stationary permanent magnets in both the modulator and the abrasives recycling device the relative position of the magnets with respect to the magnetic sensors only changes by the bending of the assembly and by its rotation. These effects can largely be eliminated by a calibration.

[0087] If it is found that the passage of the particles along the magnetic field sensors disturbs their measurement, it can be considered to do a magnetic field measurement after activating de collector and before the collector is saturated with abrasive particles. Again, a time delay (in this case for the particles to travel from the collector to the magnetic sensors) should be taken into account.

[0088] The correlation between the particle concentration and drill string rotation can be arranged by taking into account several parameters. First of all, the rotational position of the drill bit is of importance. Furthermore, the rotational speed of the drill bit plays a role. Also, by measuring the flow rate or by calibrating the system for a specific flow rate the travel time of the particles between their time of release and their time of arrival at the drill bit may be corrected for.

[0089] When the modulation means is accommodated in the drill string above the abrasive jetting drill head, it is possible to deliver a supply flow of drilling fluid with modulated abrasive particle concentrations so as to obtain a certain

desired eroding effect at the downhole bottom. Therefore, it is no longer necessary to rely on the modulation of the downhole recirculation circuit.

[0090] In one embodiment the modulation means is contained in a collar positioned in the drill string, said collar having a through going channel along which the modulation means is positioned. Said collar can be positioned at specific desired positions along the drill string. Best results of the modulation effect are however obtained in case the collar is positioned close to the drill bit.

[0091] The modulation means may comprise at least one magnet as well as activating means for influencing the magnetic field of the magnet(s) at the location of and outside the through going channel. By properly varying the magnetic field, the paramagnetic abrasive particles are influenced in such a way that concentration differences can be obtained. Thus, the drill bit is supplied with a drilling fluid flow having varying concentrations of abrasive particles over time, without the necessity to recirculate the abrasive particles downhole.

[0092] The magnets and the through going channel may be positioned according to several possibilities. For instance, the through going channel may comprise an annulus, in which case the magnet is positioned within the area surrounded by the innermost wall of the annulus. According to yet another possibility, the modulation means may comprise at least two magnets which are positioned on opposite sides of the through going channel.

[0093] With the aim of obtaining the required modulation, it is possible to apply a magnetic conductor which is displaceable between the magnet and the through going channel. The magnetic conductor influences the magnetic field experienced by the abrasive particles, depending on the position of said conductor. Other possibilities exist as well. For instance, the magnet(s) may comprise at least one permanent magnet and the activating means may comprise a mover. Said mover is carried out for displacing the permanent magnet with respect to the through going channel. The physical movement of the magnet with respect to the wall of the through going channel makes that the magnetic field experienced by the abrasive particles passing by in the through going channel varies, such that some particles are held and other particles are passed through. This different behavior of the abrasive particles in the through going channel evokes a modulation of the particle concentration in the drilling fluid.

[0094] The magnet(s) may be mounted in a rotatable fashion between a position parallel to the through going channel and an oblique position with respect to the through going channel. Other displacement mechanisms are possible as well, such as slides.

[0095] According to a further alternative, the collar may be provided with a paramagnetic collector in which case the mover is operated for establishing respectively breaking a contact between the magnet(s) and the collector.

[0096] Further, the magnet may comprise an electromagnet. By energizing respectively de-energizing such electromagnet, the modulation effect is obtained.

[0097] The invention is also related to a method for operating the abrasive jet drilling described before, comprising the step of varying the operation of the activation device so as to obtain a controlled attraction and/or release of the paramagnetic abrasive particles. In this way, batches of abrasive particles may be generated in the drilling fluid flow which provide a pulsating effect.

[0098] According to a further possibility, the method according to the invention may comprise the step of:

[0099] operating the modulation means so as to hold an amount of particles within the through going channel,

[0100] subsequently making the modulation means operate in a pulsating manner so as to release a part and only a part of the abrasive particles held within the through going channel during each pulsation.

[0101] By means of a quick pulsation, some of the particles will be released and also be attracted again, depending on the duration of the pulses. In this way, a limited amount of abrasive particles is freed each time, resulting in batches the size of which can be determined accurately.

[0102] Alternatively, the method according to the invention may comprise the step of:

[0103] providing at least two modulation means in series,

[0104] activating said modulation means so as to hold a batch of abrasive particles each,

[0105] de-activating said modulation means such that a time difference is obtained in the arrival time at the drill bit of said batches of abrasive particles.

[0106] As an example, the modulation means which is closest to the drill bit can be de-activated before the other modulation means is de-activated.

[0107] Furthermore, the method according to the invention may comprise the steps of:

[0108] measuring the flow rate of the flow mixture or calibrating the drilling system for a specific flow rate,

[0109] applying a correction for the time of travel of the particles from the time of release thereof by the modulation means and the time of arrival thereof at the drill bit.

[0110] Down hole power systems used in conjunction with the present invention can extract power from the pressurised drilling fluid stream. Only a small fraction of the hydraulic energy present in the fluid circulating through the hole, typically less than 5% needs to be extracted. Thus, the generator can be made much smaller than, for instance, a down hole turbine or positive displacement motor (PDM) that aims at converting a large fraction of the available energy for driving a conventional drill bit.

[0111] A first type of down hole power system comprises an electric generator drivable by the drilling fluid flow for instance by means of a turbine or a PDM section. The electric power generated can be supplied to an electric motor. The electric motor 23 may be controlled by an electronic control system.

[0112] More than one turbine/generator module can be mounted in series in order to convert the required power. This can improve the directional flexibility of the down hole power system, because such modular approach can be constructed mechanically less stiff than a non-modular turbine assembly with a similar power rating.

[0113] A second, alternative, type of down hole power system comprises a passive hydraulic motor, such as for instance a turbine or a positive displacement motor (PDM) section, drivable by the drilling fluid flow. Means are provided for controlling the power on the output shaft. Such means can be provided in the form of flow control means controlling the flow of drilling fluid through the passive hydraulic motor, such as an adjustable valve.

[0114] Alternatively, a generator can be mounted around the output shaft and act as a controlled brake that is electroni-

cally adjustable by adjusting the load in the generator circuit. The electronically adjustable valve or load may be controlled by an electronic control system.

[0115] The erosive power of the abrasive jet with the abrasive jet can be modulated via an electronic control system. The electronic control system may be arranged to receive a signal indicative of the position of the impingement area of the abrasive jet along its trajectory on the bottom of the borehole, which it can then use to modulate the erosive power of the abrasive jet in dependence on the position along the trajectory. The signal can be received directly from a downhole positional sensor located in the vicinity of the abrasive jet drill head. The positional sensor can suitably be housed together with the electronic control system.

[0116] The electronic control system may include an electronic memory module that stores data including one or more of motor voltage, current, rotational frequency, temperature and other data. A selection of this data may be transmitted to the surface via a measurement while drilling MWD system when provided. Such measurement while drilling system can be electronically connected to the electronic control system by means of a male stabber. The electronic control system may be programmable, such that selected conditions can be maintained or achieved. Any electronic components can be placed in an atmospheric chamber or a pressure-balanced chamber.

1. A method of drilling into an object, the method comprising

providing a drill string in a borehole in the object, the drill string comprising an abrasive jet drill head at its lower end, the drill head including a jet nozzle, the drill string providing a passageway for fluid from the object's surface to the jet nozzle;

supplying a fluid mixture comprising magnetic particles via the drill string towards the abrasive jet drill head and blasting from the jet nozzle an abrasive jet with an erosive power into impingement with the object;

moving an impingement area of the abrasive jet along a selected trajectory in the borehole; and

modulating a jetting concentration of magnetic particles in the abrasive jet while the impingement area is being moved;

wherein modulating the jetting concentration of magnetic particles in the abrasive jet comprises modulating a magnetic field at a collection surface arranged along a flow path of fluid towards the jet nozzle between a first value of the magnetic field, at which magnetic particles are collected from the fluid mixture at the collection surface, and a second value, at which magnetic particles are released into the fluid mixture from the collection surface.

2. The method according to claim 1, wherein the magnetic field is modulated by moving a magnet relative to the collection surface.

3. The method according to claim 1, wherein the magnetic field is modulated by modulating a drive current of an electromagnet.

4. The method according to claim 1, wherein modulating the magnetic field comprises moving a magnetic connector for magnetically connecting a magnet and the collection surface between a connecting position and a non-connecting position.

5. The method according to claim 1, wherein the particle concentration is controlled so as to be modulated in relation with the position of the impingement area on the selected trajectory.

6. The method according to claim 1, wherein a supply concentration of abrasive particles in the fluid mixture is modulated in order to modulate the jetting concentration in the abrasive jet.

7. The method according to claim 1, wherein a downhole recirculation system is provided, to recirculate abrasive particles after their discharge from the jet nozzle to a mixing location with the supply fluid mixture along the passageway, and wherein the supply concentration is modulated upstream of the mixing location.

8. An abrasive jet drilling assembly connectable to a tubular drill string part, and comprising:

an abrasive jet drill head with a jet nozzle,

a passageway for fluid comprising magnetic abrasive towards the jet nozzle,

and a modulation means for modulating the concentration of the magnetic abrasive particles in fluid flowing, during operation, through the jet nozzle;

the modulation means comprising

a collection surface, and

a magnetic holdup device for exerting a magnetic field at the collection surface, comprising a magnet arrangement and a modulation control means for selectively changing the magnetic field at the collection surface between a first value, at which magnetic particles are collected at the collection surface, and a second value, at which magnetic particles are released from the collection surface.

9. The abrasive jet drilling assembly according to claim 8, wherein the magnet arrangement comprises at least one electromagnet, preferably wherein the modulation control means is arranged to modulate a drive current of the electromagnet.

10. The abrasive jet drilling assembly according to claim 8, wherein the magnet arrangement comprises at least one permanent magnet, preferably wherein the at least one permanent magnet is movable with respect to the collection surface.

11. The abrasive jet drilling assembly according to claim 8, wherein the magnetic holdup device comprises an actuator for changing the relative position of the magnet arrangement and the collection surface.

12. The abrasive jet drilling assembly according to claim 8, wherein the magnet arrangement further comprises a selectively movable magnetic connector.

13. The abrasive jet drilling assembly according to claim 8, wherein the passageway is at least partially an annular passageway having inner and outer annular walls, and wherein the collection surface is at least partially arranged on the inner annular wall.

14. The abrasive jet drilling assembly according to claim 8, wherein the magnet arrangement comprises at least two magnets that are positioned at different angular positions with respect to flow direction along the passageway.

15. The abrasive jet drilling assembly according to claim 8, wherein the abrasive jet drilling assembly further comprises a downhole recirculation system arranged to recirculate abrasive particles during operation after their discharge from the jet nozzle to a mixing location along the passageway, and wherein the collection surface is arranged along the passageway upstream of the mixing location.