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(71) Applicant:  
MHWIRTH AS [NO/NO]; Postboks 413  
Lundsiden, N-4639 Kristiansand S (NO).  
(72) Inventor:  
VAYIK, Dag; Odderhei Platå 60, N-4639 Kristiansand (NO).  
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(54) Title: METHOD FOR PREDICTING HYDRATE FORMATION

(57) Abstract: The present invention relates to a method for predicting formation of hydrates in a wellbore or riser annulus, given that gas is present, where the method comprises the following steps: - logging of actual mud properties, - continuously measuring and/or calculating actual sets of pressure data and temperature data at given locations/intervals in the wellbore or riser annulus, - determining a theoretical temperature profile for formation of hydrates $T_{thd}$ dependent on mud properties and pressure as a function of true vertical depth (TVD) in the well, and storing said temperature profile for formation of hydrates $T_{thd}$ in a control system, - utilizing said measured and/or calculated actual set of temperature data and comparing with the temperature profile for formation of hydrates $T_{thd}$, - a signal being given from the control system if said measured and/or calculated actual set of temperature data (153) is getting below or lower than a predefined safety margin for the temperature profile for formation of hydrates $T_{thd}$ (154). The present invention also relates to a control system for predicting formation of hydrates in a well as a function of true vertical depth, wherein the control system comprises means for measuring or calculating actual sets of pressure data and temperature data based on received logged and continuously measured data for actual mud properties and pressure and temperature in the well, and means for comparing the actual set of temperature data with a theoretical temperature profile for formation of hydrates $T_{thd}$ and a signal generator generating a signal to an operator if said actual set of temperature data is getting below or lower than a predetermined safety margin for the temperature profile for formation of hydrates $T_{thd}$ (154).
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HYDRATE FORMATION

Background of the invention

The offshore drilling industry is going to deeper water, introducing new challenges. Deep water with low water temperature in combination with high pressure increases the risk of hydrates. Some fields like the pre-salt reservoir outside Brazil and the Gulf of Mexico have got challenging wells with very little drilling margin, (difference with pore pressure and fracture pressure). Drilling in fractured carbonate is also a challenge for the industry. These types of wells often experience lost circulation cases and sometimes in combination with gas kicks. When lost circulation is experienced, lost circulation material (LCM) or other sacrificial fluids can be pumped down the well in large quantities which will cool down the well, increasing the hydrate risk. Use of pressurized mud cap drilling or dual mud cap drilling increase also risk of hydrates since often large amount of water is used to pump down the well. The introduction of managed pressure drilling (MPD) increase also the risk of hydrates in riser, since the riser will see a higher pressure compared with conventional drilling.

Hydrates may plug subsea BOP (typically below annular preventer) and subsea kill and choke lines. Several case histories and papers about plugged kill and choke lines and other hydrate issues have been published. With introduction of special dual gradient managed pressure drilling MPD system with annular preventer installed subsea in the drilling riser and conventional MPD with riser drilling device (RDD), the risk of plugging outlets from the drilling riser also increases.

An objective of the present invention is to overcome the shortcoming of today’s well monitoring systems, with respect to predicting hydrate formation risk while drilling, tripping and after periods with low or no circulation.

Another objective is to give guidelines for correct remedial action(s) to be taken to avoid incidents with hydrate plugs.

The invention is set forth in the independent claims, while the dependent claims describe other characteristics of the invention.

Summary of the invention
The present invention relates to a method for predicting formation of hydrates in a wellbore or riser annulus, given that gas is present, where the method comprises the following steps:

- logging of actual mud properties,
- continuously measuring and/or calculating actual sets of pressure data and temperature data at given locations/intervals in the wellbore or riser annulus,
- determining a theoretical temperature profile for formation of hydrates $T_{\text{Hyd}}$, dependent on mud properties and pressure as a function of true vertical depth (TVD)
  in the well, and storing said theoretical temperature profile for formation of hydrates $T_{\text{Hyd}}$ in a control system,
- utilizing said measured and/or calculated actual set of temperature data and comparing with the theoretical temperature profile for formation of hydrates $T_{\text{Hyd}}$.
- a signal being given from the control system if said measured and/or calculated actual set of temperature data is getting below or lower than a predefined safety margin for the theoretical temperature profile for formation of hydrates $T_{\text{Hyd}}$.

In an aspect, the method according to the present invention may further comprise the use of at least a first pressure transmitter ($P_{\text{ini}}$) and at least a first temperature transmitter ($T_{\text{ini}}$) arranged in a first position in a well, and at least a second pressure transmitter ($P_{\text{ini}}$), in order to measure and/or calculate the actual set of pressure data and temperature data.

The at least first temperature transmitter ($T_{\text{ini}}$) and the at least first pressure transmitter ($P_{\text{ini}}$) may be arranged in an open hole section of the well.

In an aspect of the method according to the present invention, the method may use a plurality of pressure transmitters ($P_1, P_2, \ldots, P_n$) in fixed vertical distance in the well, wherein the method further comprises measuring an/ or calculating the temperature at different locations in the well.

The method according to the present invention may further comprise the step of:
- always displacing the riser if temperature in riser is below the theoretical temperature profile for formation of hydrates $T_{\text{Hyd}}$,
- pumping fresh mud down at least one booster line and circulating out gas cut mud,
- monitoring possible rapid gas expansion as hydrates melt at low pressure
- be prepared to divert overboard to avoid riser blow-out on drill floor.

The method according to the present invention may further comprise, in case a wellbore influx has inadvertently passed a subsea blowout preventer (BOP), pumping mud down at least one booster line and circulating out gas cut mud, and monitoring possible rapid gas expansion and be prepared to divert overboard to avoid “riser blow-out” on drill floor.

The method according to the present invention may further comprise the steps of filling at least one kill line with hydrate inhibitor fluid, injecting said hydrate inhibitor fluid present in the at least one kill line in the blow out preventer (BOP),
and, simultaneously pumping fresh mud down the drill string to circulate out the wellbore fluids and inhibitor up at least one choke line and divert to a mud gas separator.

The method according to the present invention may further comprise the steps of identifying a stuck pipe situation as a possible result of hydrate formation, by observing increased drag trend or torque oscillation during connections and/or abnormal pressure increase or pressure oscillation during circulation, and confirming that all of the following conditions are fulfilled: then

- drilling in a permeable formation, which permeable formation is identified to have the ability to act as a reservoir rock as well as having a pressure close to or higher than a bottom hole pressure or measured pressure at a pressure transmitter \( (P_r-P_a) \) in the well,
- observing that the temperature in the wellbore is below the hydrate formation temperature \( T_{H_2O} \) and
- observing circulation restriction or pressure peak.

In an aspect of the method according to the present invention, in case of a stuck pipe situation caused by hydrate formation, the method may further comprise the steps of:

- injecting hydrate inhibitor fluid close to a wellhead,
- stop circulation allowing the temperature in the formation to increase the temperature of the fluids in the well thereby melting or dissociating the hydrates into water and dense gas,
- perform flow check to verify hydrate dissociation process has started,
- shut-in the well if well starts to flow and monitor shut-in pressure increase to determine size of hydrate plug/kick.

The present invention also relates to a control system for predicting formation of hydrates in a well as a function of true vertical depth (TVD), wherein the control system comprises means for measuring or calculating actual sets of pressure data and temperature data based on received logged and continuously measured data for actual mud properties and pressure and temperature in the well, and means for comparing the actual set of temperature data with a theoretical temperature profile for formation of hydrates \( T_{H_2O} \) and a signal generator generating a signal to an operator if said actual set of temperature data is getting below or lower than a predetermined safety margin for the theoretical temperature profile for formation of hydrates \( T_{H_2O} \).
Brief description of the drawings

Figure 1 is a schematic showing the gas influx volume expansion as it travels up the wellbore and riser;

Figure 2 is a simplified schematic of a subterranean well and drilling riser showing multiple sensors for transmitting downhole information such as pressure and temperature to the rig;

Figure 3 discloses schematically how hydrate formation temperature between natural gas and water increases with increased pressure;

Figure 4 discloses schematically a method for determining the correct remedial action to be taken based on hydrate warning;

Figure 5 discloses schematically a method for determining the correct remedial action to be taken based on wellbore influx alarm;

Figure 6 discloses schematically a method for determining the correct remedial action to be taken based on stuck pipe warning; and

Figure 7 discloses schematically an embodiment of the present invention;

Detailed description of a preferential form of embodiment

Figure 1 shows how a specific volume of gas influx will expand as it travels up the wellbore and riser towards a floating drilling unit, e.g. a rig. The X-axis indicates travel distance, or more correctly pressure reduction, as the influx travels from bottom of the wellbore where influx may enter the wellbore at a position A, to the floating drilling unit at a position D. The pressure used in the simulated gas influx at position A is 1000 bara. Position B indicates the seabed and the subsea BOP located at 3000 meter water depth, where the pressure is reduced to 500 bara due to reduction of static column of mud with specific gravity SG 1,5 (ρ = 1500 kg/m³, density). Position C is in the drilling riser annulus 100 meters below sea level where the pressure is reduced to 31 bara. Position D is onboard the drilling unit upstream the managed pressure drilling (MPD) choke, where the pressure is approximately 16 bara. Boyle's law (line 1) says that when the pressure of a gas is reduced by 50% the volume will expand by 100%. In other words, if the pressure is reduced from 1000 bara (position A) to 500 bara (position B), the volume should increase from 1,0 m³ to 2,0 m³, according to Boyle’s law (line 1). However, under these high pressures currently experienced in deep water, the natural gas influx will be in dense phase and have a density behavior similar to a liquid. The real gas expansion (line 2) below the subsea BOP located at seabed at position B is insignificantly higher than the mud expansion (line 3). For this reason early kick detection based on changes in density or volume as the undetected kick travels up the wellbore will not work. In deep water it is also another challenge that the annulus fluid in the wellhead, subsea blow out preventer BOP and lower part of the riser has a temperature that often are well below the temperature where hydrates form (T_{hydr}). When the gas influx then reach the wellhead (position B) it will be cooled by the
cold surrounding seawater and hydrates may form in the riser (line 4). For kick
detection, based on gas expansion (line 2), this will be catastrophic because when
hydrates are forming in the riser (line 4), the total volume will decrease rather than
increase. When the hydrates is transported to upper part of the riser C, they may
dissociate (melt) into water and gas as the pressure in the riser get lower, causing a
rapid gas expansion. However, the dissociation time (how rapid the hydrates melt)
is very uncertain, and depends on many factors. The most important factor is how
much applied surface back pressure ($P_{ASBP}$) that the riser annulus will see upstream
the managed pressure drilling MPD choke (position D). In the worst case scenario
the hydrate dissociation time will be so long that there is a risk that the outlets from
the drilling and top of the riser plugs up with hydrates before the hydrates dissociate
when the riser is equipped with managed pressure drilling MPD or riser gas
handling (RGH) choke (MPD/RGH choke) capable of applying back pressure to the
riser annulus. For conventional drilling with atmospheric riser and conventional
flow line, a rapid gas expansion associated with hydrates dissociate in the upper part
of the riser, with a possible gas and mud “blow-out” on drill floor or through the
diverter system most likely to be the scenario. This shows how important it is to
have a method for predicting hydrate formation risk while drilling.

Figure 2 shows a simplified schematic of a subterranean well and lower part of a
drilling riser 20. The well is cased with casing 12 in the upper part and a liner 13 in
the middle part, which are cemented 14 to the earth formation 22. A lower part of
the well is an open-hole section 15. A drill string 10 extends from the top of the
riser 20 to the bottom of the well having a drill bit 11 in its lowermost end for
drilling into the earth formation 22. Drilling fluids flow on the inside of the drill
string 10 down to the drill bit 11 and flows back up towards the surface in the
annulus 16 formed between the drill string 10 and the formation 15, liner 13 or the
casing 12. A larger annulus 21 is formed between the drill string 10 and the marine
drilling riser 20. A first pressure transmitter $P_{BH}$ is arranged in the open hole section
15. At least a second pressure transmitter $P_{BOP}$ is arranged in the blow out preventer
BOP stack 19 or the wellhead 18 above the seabed 17. At least a first temperature
transmitter $T_{BH}$ is arranged close to the pressure transmitters $P_{BH}$. A plurality of
temperature transmitters $T_1, T_2, \ldots, T_n$ can be arranged in the wellbore and drilling
riser to obtain a better temperature profile of the annulus fluid temperature. As
should be understood, a plurality of pressure transmitters $P_1, P_2, \ldots, P_n$ may also be
arranged in the wellbore and drilling riser. Above the seabed 17 a wellhead 18 and a
subsea BOP 19 is connected to the marine drilling riser 20. At least an additional
temperature transmitter $T_R$ and pressure transmitter $P_R$ are recommended to be
installed in the lower or middle part of the marine drilling riser, where the annulus
temperature is expected to be lowest during circulation. Note that in the event of
pressure and temperature transmitters are not present, an annulus pressure and
temperature profile can be calculated using advanced algorithms and surface
measurements, however especially the temperature profile will be very transient after periods with low or no circulation and hence difficult to predict accurately for any given time during these transient phases.

Figure 3 discloses schematically how hydrate formation temperature between natural gas and water increases with increased pressure 50. At atmospheric pressure the hydrate formation temperature (T_Hyd) will be less than -20 °C, while at 100 bara T_Hyd will be +21 °C, 51. At the seabed (cf. B in figure 1) the ambient seawater temperature will be 3 to 4 °C, and the pressure inside the riser can be as high as 500 bara, corresponding to a hydrate formation temperature T_Hyd of up to +29 °C, 52. This shows how important it is to make sure that the kill and choke line, which main purpose is to circulate out gas influx in case of a well control event, are prepared with hydrate inhibitor to prevent them blocking up when gas is circulated out. The amount of salt used in the mud, and if oil based mud (OBM) are used, the hydrate formation temperature T_Hyd will be slightly lower. However, it should be noted that the use of OBM will not eliminate the hydrate risk, because even oil based mud OBM contains water to a certain extent, typically 20%. When calculating the hydrate formation temperature T_Hyd it is therefore important that details about the mud properties are taken into consideration.

In the Figures 4-6, it is made reference to the specific boxes in the decision trees, i.e. the text and required actions identified in these boxes shall be considered as a part of this written detailed description. Figures 4-6 are self-explanatory.

Figure 4 shows schematically a method for determining the correct remedial action to be taken based on hydrate warning. In deep water it is not unusual to have low temperature below the hydrate formation temperature T_Hyd in the wellhead, subsea BOP and lower part of the riser annulus (box 90). In these cases it is important that a dedicated chemical injection line or, if this is not available, the kill line can be used for injecting hydrate inhibitor (fluid), e.g. ethylene glycol (MEG). The amount of MEG required for hydrate suppression must be calculated based on mud type in use and ambient seawater temperature or worst case scenario for annulus mud temperature. It is important that the chemical injection line (or kill line) is filled up with MEG prior to drilling in formation that potentially can give gas influx (box 92), since hydrates may form quickly and potentially plug the subsea BOP and choke line when the kick is circulated out through the kill and choke (K&C) manifold. It should also be noted that under normal drilling operation the fluid in the kill and choke lines will normally be stagnant (continuous circulation not possible) and the temperature is therefore permanently below the hydrate formation temperature T_Hyd in these lines (box 91). Hydrate inhibitor for hydrate suppression is therefore required in these kill and choke lines to reduce risk of plugging the lines when they are used for circulating out gas in a kick scenario.
After longer periods without circulation in the wellbore annulus, typically after a casing cement job and tripping operation, it is not unusual for the fluid temperature in the wellhead annulus to drop below the hydrate formation temperature $T_{\text{hydr}}$. Prior to drilling ahead the driller shall perform the following actions; Start circulation and perform dynamic flow check (box 94), is dynamic flow check indicating gain OR loss? (box 95), if no; Continue to circulate until hydrate formation temperature in wellhead and marine drilling riser, is above hydrate formation temperature $T_{\text{hydr}}$ (box 96). If the dynamic flow check (box 94) indicates gain OR loss (box 95), these signals must not be ignored. Hydrates may form when the gas mixes with the colder fluids in the upper part of the wellbore, so even if the flow check or shut-in pressure test (box 97), apparently shows normal values (box 98), it is important that circulation is continued (box 94), until temperature is above hydrate formation temperature $T_{\text{hydr}}$ (box 96) and “bottoms-up” has been circulated out. Any abnormal pressure, increase or decrease after shut-in pressure test (box 98), is a strong indication that the well is taking a kick (box 99).

In the open wellbore deep down in the earth formation it is not usual to have low temperature below the hydrate formation temperature $T_{\text{hydr}}$ (box 70), because of the general high formation temperature. However, since pressure also generally increase with depth, the hydrate formation temperature $T_{\text{hydr}}$ can be above 30°C, so with high mud circulation the annulus fluid might not get time to heat up enough to get above these temperatures (box 71). To drill ahead with permanent temperature below the hydrate formation temperature $T_{\text{hydr}}$ deep down in the well should be avoided (details in boxes 73, 75, 78, 77, 79, 82, 82 and 84).

Even more likely is it that the temperature deep down in the well drops below the hydrate formation temperature $T_{\text{hydr}}$ due to cold fluid from the riser area after tripping, being pumped down or in the case of mud cap drilling where large amount of relative cold sacrificial fluids is pumped down both in the annulus and drill string in large quantities (box 72). These are more temporary events and prior to drilling ahead it is important that “bottoms up” operations while performing dynamic flow check is carried out, to check for any abnormalities (box 74).

Figure 5 shows schematically a method for determine the correct remedial action to be taken after a kick is detected (box 100). If managed pressure drilling (MPD) or riser gas handling (RGH) equipment is installed (box 101), it is important that applied surface back pressure $P_{\text{ASBP}}$ to increase bottom hole pressure BHP and stop the influx is activated as quickly as possible (box 102). After the blow out preventer BOP is closed (box 103), it is important that hydrate inhibitor is injected immediately into the wellhead (box 106), if the temperature in wellbore, wellhead or riser is below the hydrate formation temperature $T_{\text{hydr}}$ (box 104). There is also a special concern
that hydrates may form. In such cases the actions identified in boxes 107, 108, 109 and 110 should be followed.

If the influx already has past the blow out preventer BOP (box 111), the riser gas needs to be handled depending on the available equipment topside (cf. boxes 114, 115, 116 and 117). Even if there is no sign for gas in riser, special consideration should be taken if the annulus temperature in the riser is below the hydrate formation temperature $T_{\text{hyd}}$ (see boxes 112 and 113 for details).

Figure 6 discloses schematically a method for determining the correct remedial action to be taken based on stuck pipe warning. The novel part of this decision diagram is that it introduces hydrate plugging as a possible cause for stuck pipe (box 120). If permeable formation are being drilled or exposed (boxes 121 and 122), indication of a kick is observed (box 123), temperature in the wellbore is below the hydrate formation temperature $T_{\text{hyd}}$ (box 128), circulation restricted or pressure peaks observed (box 129), then this is a strong indication that hydrates may are about to create a stuck pipe event (box 131).

Further measurements and/or steps regarding the stuck pipe warning are apparent from Figure 6.

Figure 7 discloses schematically an embodiment of the present invention. The hydrate formation temperature $T_{\text{hyd}}$ is plotted schematically relative to the true vertical depth (TVD) 154. $T_{\text{hyd}}$ is compared with the real measured (or calculated) temperature in the annulus 153. Risk of hydrate forming if hydrocarbon influx is present, can be seen as the shaded area 155 and 156. A typical embodiment of the present invention will be to show only the hydrate formation temperature $T_{\text{hyd}}$ profile 154 and annulus temperature profile 153, together with the seabed and blow out preventer BOP location 157. The other curves are added only for information and understanding of the present invention. Seawater temperature profile 150, decreases quite rapidly, to typically around 5 °C at approx. 1500 meter water depth, and then slowly decreases to 3-4 °C at seabed 157. Earth formation temperature 151 increases rapidly with increasing depth. The drilling fluid being pumped down the drill string decreases slightly in temperature 152, as it is being cooled by the colder annulus fluid coming back to the rig in the riser. However below the seabed 157 the annulus fluid 153 is warmer than the drill string fluid 152, and the relative cold drill string fluid 152 prevent the annulus fluid for being heated any further although the surrounding earth formation temperature 151 is very hot. It should however be noted that this situation as shown in figure 7 is showing a situation with a large circulation rate. During periods with low or no circulation the annulus fluid 153 deep down in the wellbore will rabidly increase in temperature and the annulus fluid in the lower part of the riser 153, will decrease due to the colder seawater temperature 150.
The invention has been described in non-limiting embodiments. It is clear that a person skilled in the art may make a number of alterations and modifications to the described embodiments without diverging from the scope of the invention as defined in the attached claims.
CLAIMS

1. Method for predicting formation of hydrates in a wellbore or riser annulus, given gas is present, the method comprising the steps of;
   - logging of actual mud properties,
   - continuously measuring and/or calculating actual sets of pressure data and temperature data (153) at given locations/intervals in the wellbore or riser annulus,
   - determining a theoretical temperature profile for formation of hydrates, $T_{Hyd.}$ (154) dependent on mud properties and pressure as a function of true vertical depth (TVD) in the well, and storing said $T_{Hyd.}$ (154) in a control system,
   - utilizing said measured and/or calculated actual set of temperature data (153) and comparing with the $T_{Hyd.}$ (154),
   - a signal being given from the control system if said measured and/or calculated actual set of temperature data (153) is getting below or lower than a predefined safety margin for the $T_{Hyd.}$ (154).

2. Method according to claim 1, wherein the method comprises using at least a first pressure transmitter ($P_{BH}$) and at least a first temperature transmitter ($T_{BH}$) arranged in a first position in a well, and at least a second pressure transmitter ($P_{BH}$), in order to measure and/or calculate the actual set of pressure data and temperature data (153).

3. Method according to claim 2, wherein the at least first temperature transmitter ($T_{BH}$) and the at least first pressure transmitter ($P_{BH}$) are arranged in an open hole section (15) of the well.

4. Method according to any of the preceding claims 2, 3, using a plurality of pressure transmitters ($P_1$, $P_2$, ..., $P_n$) in fixed vertical distance in the well, wherein the method further comprising measuring and or calculating the temperature at different locations in the well.

5. Method according to claims 1-4, comprising the step of:
   - always displacing the riser if temperature in riser is below $T_{Hyd.}$,
   - pumping fresh mud down at least one booster line and circulating out gas cut mud,
   - monitoring possible rapid gas expansion as hydrates melt at low pressure
   - be prepared to divert overboard to avoid riser blow-out on drill floor.

6. Method according to claim 1-4, comprising, in case a wellbore influx has inadvertently passed a subsea blowout preventer (BOP), pumping mud down at least one booster line and circulating out gas cut mud, and monitoring possible rapid gas
expansion and be prepared to divert overboard to avoid "riser blow-out" on drill floor.

7. Method according to any of the preceding claims 1-6, comprising the steps of filling at least one kill line with hydrate inhibitor fluid, injecting said hydrate inhibitor fluid present in the at least one kill line in the blow out preventer (BOP), and, simultaneously pumping fresh mud down the drill string to circulate out the wellbore fluids and inhibitor up at least one choke line and divert to a mud gas separator.

8. Method according to any of the preceding claims 1-7, comprising the step of deciding that a choke line shut-in pressure \( P_S \) is showing abnormal pressure decrease, and generate a wellbore influx and hydrate alarm.

9. Method according to claims 1-8, comprising the steps of identifying a stuck pipe situation as a possible result of hydrate formation, by observing increased drag trend or torque oscillation during connections and/or abnormal pressure increase or pressure oscillation during circulation, and confirming that all of the following conditions are fulfilled:

- drilling in a permeable formation, which permeable formation is identified to have the ability to act as a reservoir rock as well as having a pressure close to or higher than a bottom hole pressure or measured pressure at a pressure transmitter \( (P_T-P_R) \) in the well,
- observing that the temperature in the wellbore is below hydrate formation temperature \( T_{Hyd} \),
- observing circulation restriction or pressure peak.

10. Method according to claim 9, wherein, in case of a stuck pipe situation caused by hydrate formation, the method further comprising the steps of:

- injecting hydrate inhibitor fluid close to a wellhead,
- stop circulation allowing the temperature in the formation to increase the temperature of the fluids in the well thereby melting or dissociating the hydrates into water and dense gas,
- perform flow check to verify hydrate dissociation process has started,
- shut-in the well if well starts to flow and monitor shut-in pressure increase to determine size of hydrate plug/kick.

11. Control system for predicting formation of hydrates in a well as a function of true vertical depth (TVD), wherein the control system comprises means for measuring or calculating actual sets of pressure data and temperature data \((153)\) based on received logged and continuously measured data for actual mud properties and pressure and temperature in the well, and means for comparing the actual set of
temperature data (153) with a theoretical temperature profile for formation of hydrates, $T_{H_{yd}}$ (154), and a signal generator generating a signal to an operator if said actual set of temperature data (153) is getting below or lower than a predetermined safety margin for the $T_{H_{yd}}$ (154).
Figure 1
HYDRATE WARNING
Temperature ($T_i$) below hydrate formation temperature ($T_{f,w}$) observed in lower part of the wellbore.

- **Is $T_i$ below $T_{f,w}$ due to high circulation rate ($Q_{in}$)?**
  - **Yes:** Evaluate to reduce $Q_{in}$ or $P_i$ or add inhibitor. Check effect on $T_i$ and hydrate margin ($T_i - T_{f,w}$).
  - **No:** Stop drilling ahead and circulate "bottoms up" while performing dynamic flow check.

- **Is $T_i$ still below $T_{f,w}$?**
  - **Yes:** Evaluate to change mud properties. Salt and OBM decrease $T_{f,w}$. Increased viscosity allow lower $Q_{in}$.
  - **No:** Has mud properties been changed?
    - **Yes:** If $T_i$ below $T_{f,w}$ can not be avoided, drilling ahead may be continued but with increased risk of stuck pipe or kick.
    - **No:** Drilling ahead may be continued but be aware that $T_{f,w}$ increases with increasing TWW and increasing $P_i$.

- **WARNING**
  - Increasing drag trend or torque oscillation during connection.
  - Positive indication of wellbore influx (kick).
  - Abnormal pressure increase or pressure oscillation during circulation.

- **ALARM**
  - Wellbore influx detected. Necessary action to be taken, ref. figure 5.
  - Stuck pipe warning! Evaluate action to prevent stuck pipe, ref. figure 6.
  - Abnormal pressure in wellbore, the well may be taken a kick, ref. figure 5.

HYDRATE WARNING
Temperature ($T_i$) below hydrate formation temperature ($T_{f,w}$) observed in wellhead and/or marine drilling riser.

- **Is temp. permanently below hydrate formation temp.?**
  - **Yes:** Start circulation and perform dynamic flow check.
  - **No:** Is dynamic flow check indicating gain OR loss?
    - **Yes:** Close BOP annular and stop circulation, monitor choke line shut-in pressure ($P_{sc}$).
    - **No:** Is $P_{sc}$ showing abnormal pressure, increase or decrease?

**Figure 4**
Figure 5

**WELLBORE INFUX ALARM**
Wellbore influx detected or positive indication that the well is taking a kick.

100

101
Is drilling operation performed with RGH or MFD?

102
Increase Applied Surface Back Pressure ($P_{app}$) to increase BHP, and stop the influx.

103
Close BOP annular and stop circulation; monitor choke line shut-in pressure ($P_{s}$).

104
Is temp in wellbore, wellhead or riser below $T_{f}$?

105
Wellbore influx should be handled according to conventional well control procedures.

106
Inject hydrate inhibitor through kill line or other dedicated injection line for hydrate inhibitor to BOP.

107
Is $P_{s}$ showing abnormal pressure decrease?

108
No

109
Yes

110
Decreasing annulus pressure after a wellbore influx and temperature below $T_{f}$ may indicate that hydrates already have formed in the wellbore.

111
Has the influx inadvertently passed the BOP into the riser?

112
Is temp in the riser below $T_{f}$?

113
Yes

114
No

115
Displace the riser by pumping "fresh" mud down the booster line, circulating out the gas cut mud through the RGH/MFD choke with constant $P_{app}$ to the MGS.

116
Is drilling operation performed with RGH or MFD?

117
Be prepared for rapid gas expansion as the gas influx and potential hydrates reach surface and pressure are getting close to atmospheric pressure. For this reason the RGH/MFD choke should always be automatically regulated by a constant value of $P_{app}$. If any risk of hydrates the $P_{app}$ should be set as low as possible and hydrate inhibitor should be injected in the riser below the RCD.

118
Although influx apparently has not reached the riser, gas may be hiding as hydrates and can be very difficult to detect because the hydrates density is almost the same as the water it is replacing. For that reason always displace the riser by pumping mud down the booster line. Be prepared for rapid gas expansion as the potential hydrates reach surface and pressure are getting close to atmospheric pressure.

119
To prevent possible hydrate plugging of choke line, hydrate inhibitor should be injected down through the kill line or other dedicated injection line, simultaneously with "fresh" mud being pumped down the steel string. The wellbore fluids is then circulated together with inhibitor up the choke line and via the K&C manifold to the MGS. The choke to be adjusted to give a constant BHP during circulation. Always circulate "bottoms up" even if well is not flowing.
**STUCK PIPE WARNING**

Procedure for determine possible cause of potential stuck pipe scenario:
- **Formation related**
- **Hydrates**
- **Mechanical or Differential Sticking**

133 Formation related stuck pipe scenarios can also be associated with non-permeable formation such as reactive Montmorillonite, fractured or faulted carbonates and shales and "mobile formations" like salt and plastic shales.

120 Yes

121 Is permeable formation being drilled or exposed?

122 No

121 Yes

123 In order for hydrates to build up in the wellbore a permeable formation with ability to act as a reservoir rock must be exposed to the open hole. Addition the BHP or $P_e$ must be below or close to the pore pressure ($P_{pore}$) of the permeable formation.

124 No

132 Possible cause can be:
- **Formation related**
  - High pore pressure in the formation can blow apart rock particles filling the borehole.

135 Is water loss experienced?

136 Yes

137 Possible cause can be:
- **Reactive formation**
  - Montmorillonite clay can hydrate and swell in contact with water based mud (WBM).

131 No

138 Possible cause of stuck pipe can be:
- **Hydrates**
  - Forming in the wellbore and gradually building up and plugging the wellbore annulus around the drillstring.
  - To reduce the risk of hydrates being transported up the wellbore and potentially plugging BOP and C&K lines, hydrate inhibitor should be injected in the wellhead. Low down in the wellbore the heat from the formation will normally increase $T_h$ to above $T_{hyd}$ when circulation stops. Also lowering $P_{slip}$ will speed up the process of "melting" the hydrates.

125 Yes

126 Can drillstring be moved?

127 No

128 Is temp in the wellbore below $T_{hyd}$?

129 Yes

130 Possible cause can be:
- **Formation related**
  - Unconsolidated sandstone can collapse forming a bridge around the drillstring.

133 No

134 Is $P_1 < P_{pore}$ or any indication of kick observed?

135 Yes

136 Possible cause of stuck pipe can be:
- **Mechanical**
  - Junk, cement related, wellbore geometry, etc.

123 Yes

124 Is $P_1 < P_{pore}$ or any indication of kick observed?

125 Can drillstring be moved?

126 No

127 Possible cause of stuck pipe can be:
- **Differential Sticking**
  - It will normally still be possible to circulate and the pipe will be easier to get loose if the BHP is lowered by reducing mud weight or in the case of MPD reduce the $P_{slip}$ in order to minimise the differential pressure $P_1 - P_{pore}$.
Figure 7

- 150: Seawater temperature
- 151: Earth formation temp.
- 152: Drillstring temperature
- 153: Annulus temperature
- 154: Hydrate formation temp.
INTERNATIONAL SEARCH REPORT

A. CLASSIFICATION OF SUBJECT MATTER

INV. E21B41/00 E21B44/00 E21B47/06

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
E21B

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic database consulted during the international search (name of data base and, where practicable, search terms used)
EPO-Internal, WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

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<th>Citation of document, with indication, where appropriate, of the relevant passages</th>
<th>Relevant to claim No.</th>
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<td>X</td>
<td>STEVE HODGES ET AL: &quot;Application of Optical Sensors in Deepwater Environments&quot;, OTC, 6 May 1999 (1999-05-06), pages 3-6, XP055214699, Teas abstract figure 2 page 3, columns 1,2 page 5, column 1, line 1 -----</td>
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Further documents are listed in the continuation of Box C.

See patent family annex.

Date of the actual completion of the international search
21 September 2015

Date of mailing of the international search report
01/10/2015

Name and mailing address of the ISA/
European Patent Office, P.B. 5818 Patentlaan 2 NL-2280 HV Rijswijk
Tel. (+31-70) 340-2040, Fax. (+31-70) 340-3016

Wehland, Florian

Form PCT/ISA/210 (second sheet) (April 2005)

page 1 of 2
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<td>A</td>
<td>BENJAMIN HERZHAFT ET AL: &quot;Gas Hydrate Formation in Drilling Mud Characterized With DSC Technique&quot;, SPE ANNUAL TECHNICAL CONFERENCE AND EXHIBITION, 30 SEPTEMBER-3 OCTOBER, NEW ORLEANS, LOUISIANA, 3 October 2001 (2001-10-03), XP055214587, Texas, USA DOI: 10.2118/71379-MS ISBN: 978-1-55-563154-3 abstract page 2, column 1, paragraph 3-5 page 5, column 2, paragraph 2-4 page 4, column 2, paragraph 3-4</td>
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