Abstract: A distributed flow metering system using a heating component and a temperature measuring system is disclosed. The rate of temperature change in the cable is related to a flow rate through the wellbore. The system includes a combination fiber optic and heating element cable configured to measure flow using temperature and without a direct flow measuring component.


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DISTRIBUTED THERMAL FLOW METERING

CROSS-REFERENCE TO RELATED APPLICATIONS:

[0001] This application claims priority to U.S. Provisional Patent Application No. 61/973,038 entitled DISTRIBUTED THERMAL FLOW METERING filed March 31, 2014 which is incorporated herein by reference in its entirety.

BACKGROUND:

[0002] Hydrocarbon fluids such as oil and natural gas are obtained from a subterranean geologic formation, referred to as a reservoir, by drilling a well that penetrates the hydrocarbon-bearing formation. Once a wellbore is drilled, various forms of well completion components may be installed in order to control and enhance the efficiency of producing the various fluids from the reservoir. One piece of equipment which may be installed is a monitoring system, to monitor wellbore conditions. Some monitoring systems may include distributed sensor systems, such as fiber optic distributed sensors.

SUMMARY

[0003] Embodiments of the present disclosure are directed to a distributed flow metering system, including a cable positioned in a wellbore. The cable can include a fiber optic component configured to measure temperature at specific locations along the cable in the wellbore, and a heating component configured to periodically direct heat into the wellbore. The system also includes a fluid inducing component configured to induce fluid flow in heated areas of the wellbore. The system still further includes a monitoring component configured to monitor temperature when the heating component is active and to deduce fluid flow rates from a monitored temperature.

[0004] In other embodiments the present disclosure is directed to a method of metering flow in a wellbore. The method includes heating select portions of a wellbore by directing energy to the select portions, and measuring a temperature at the select portions using a fiber optic cable. The method also includes interpreting a flow rate from a temperature at the select portions as a function of the energy directed to the selected portions.
BRIEF DESCRIPTION OF THE DRAWINGS:

[0005] Figure 1 is a schematic illustration of a distributed flow metering system according to embodiments of the present disclosure.

[0006] Figure 2 is a cross-sectional view of a cable of a distributed flow metering system according to embodiments of the present disclosure.

[0007] Figure 3 is a schematic illustration of a distributed flow metering system having varying flow rates according to embodiments of the present disclosure.

[0008] Figure 4 is a graph of time and temperature using a curve-fitting technique according to embodiments of the present disclosure.

[0009] Figure 5 is a chart of time and phase for various configurations of the distributed flow metering system according to embodiments of the present disclosure.

[0010] Figure 6 illustrates two cable configurations for use with the distributed flow metering system according to embodiments of the present disclosure.

DETAILED DESCRIPTION:

[0011] Certain embodiments of the disclosure will hereafter be described with reference to the accompanying drawings, wherein like reference numerals denote like elements. It should be understood, however, that the accompanying drawings illustrate only the various implementations described herein and are not meant to limit the scope of various technologies described herein. The drawings show and describe various embodiments of the current disclosure. In the following description, numerous details are set forth to provide an understanding of the present disclosure. However, it will be understood by those skilled in the art that the embodiments of the present disclosure may be practiced without these details and that numerous variations or modifications from the described embodiments may be possible.

[0012] Figure 1 illustrates a cable 10 in a well 12 with fluid 14 being injected through a casing 16 into reservoir zones 18 according to embodiments of the present disclosure. A similar arrangement can be implemented during production with the direction of flow being reversed. In some embodiments, it may be desirable to monitor flow into and out of the wellbore 12. In particular, it is desired to identify regions 18 of a
reservoir accepting injected fluids or emitting production fluids. The cable 10 cable is run into the well 12 and is interrogated from surface to determine the flow rate or velocity past the cable 10 at several points along the length of the cable 10. The flow generally decreases along the cable 10 with increasing distance from the surface as flow enters the reservoir from the well 12.

[0013] In some embodiments, temperature may be measured at points along the cable 10 using an optical fiber contained within it. Such a system may be referred to as a Distributed Temperature Sensor (DTS). Such a system may be used to determine flow rates during production by comparison to the background geothermal temperature distribution. However, this mode of operation may be less effective when injecting fluid or when the well is highly deviated.

[0014] Figure 2 is a cross-sectional view of a cable 10 according to embodiments of the present disclosure. The cable 10 includes multiple lines, such as a fiber line 20, a heating line 22, and a communication line 24. Any combination of lines can be used in a given embodiment. The cable 10 can include insulation 26 and an outer cover 28. In some embodiments, the heating line 22 can be used to heat the cable to monitor flow. The cable 10 may be heated by electrical, chemical or other means. The embodiments of this disclosure describe several methods to interrogate a heated cable, and several refinements to the heated cable concept. These may be used to improve the reliability of the measurement and increase its feasibility in an operational environment.

[0015] In some embodiments, a cable 10 may be placed into a well 12 as shown in Figure 1. The cable 10 may also be permanently installed on production tubing, attached to the casing 16 or otherwise placed in the well 12. The heating line 22 of the cable 10 can be used to heat the line, and the fiber 20 is used to make distributed measurements. Fluid flows past the cable 10 during production, injection, stimulation or cross-flow in the well 12. The heating line 22 may be pulsed on and off using an electrical power supply placed at surface.

[0016] Figure 3 is a schematic representation of a distributed temperature sensing (DTS) system according to embodiments of the present disclosure. In some embodiments, the flow velocity past the cable 10 may be estimated by measuring the
temperature difference between the condition when the heating is off and when it is on. The greater the flow velocity the smaller will be the temperature rise upon heating and, to a lesser extent, the faster the temperature rise. When flow rates are high, more of the thermal energy is carried away from the cable 10 during heating, resulting in a lower temperature at the site of the cable 10. The size of the arrows in Figure 3 represents rates of flow and heat transfer. Energy 30, in the form of electrical power or another suitable type, is directed down the cable 10 and into the formation. The first site 31 results in a relatively low temperature 32, which is evidence of a high flow 34. The second site 33 results in a relatively high temperature 36, evidencing a relatively lower flow rate 38.

**Distributed Temperature Sensing (DTS)**

[0017] In some embodiments, the temperature rise due to heating can be measured using DTS. This may be achieved by establishing the equilibrium temperatures with the heating off and with the heating on. The DTS typically has a relatively low temporal resolution, outputting a temperature distribution several times a minute. In many conditions there will be background temperature variations in addition to those caused by the cable heating. The effect of these can be removed by fitting a pair of curves 39 and 41, for example polynomials, to a section of the temperature data of limited duration as shown in Figure 4. The two curves can have identical parameters, except for a constant term which takes one of two values depending on whether the heating was on or off; the fitting procedure may be operated to adjust both these values independently in addition to the common parameters. The fitted curves are used to detrend the data and also to determine the equilibrium temperature difference between the heating off and heating on conditions.

[0018] In some embodiments, instead of or in addition to measuring the equilibrium temperature difference between heating on and heating off conditions, it is possible to measure the rate of temperature rise or fall, or both and to measure the flow velocity using these rates. To achieve this with DTS it may be desirable to synchronize the pulsing on and off of the heating with the measurements made by the DTS. The temperature change after a fixed number of DTS timesteps may be used to give a measure of the rate of temperature rise or fall.
DVS/DAS/Coherent Rayleigh

[0019] In some embodiments, distributed vibration (DVS) and distributed acoustic (DAS) OTDR sensors based upon Coherent Rayleigh backscatter are sensitive to both changes in strain (vibration) and temperature. Such systems may have much greater temporal and temperature resolution than DTS. However, they may not give absolute value of temperature. The term "DVS" refers to all measurements based upon Coherent Rayleigh backscatter.

[0020] In some embodiments of DVS, the phase of the reflected light is measured and differentiated over distance along the fiber. At high frequencies this may give a measure of vibration while at low frequencies it may give a measure of temperature change. Figure 5 shows an example of DVS data influenced by changes in temperature. In this case, an increase in temperature causes a negative change in phase.

[0021] In some embodiments, measurements based on Coherent Rayleigh backscatter may give no absolute value of temperature. Instead they may give a measure of the temperature change. In some embodiments according to this disclosure, we combine DTS and DVS measurements to determine the absolute temperature at known times with detail regarding the temperature change between these points. This approach effectively gives an interpolated measurement between times at which the absolute cable temperature is known.

[0022] In some embodiments, the heating may preferably be repeatedly pulsed on and off with a known period. The DVS data may then be segmented to match the pulse period and stacked. The coherent Rayleigh measurement contributions due to vibration are generally random and of high frequency, and will be substantially removed by the stacking leaving only the effect of temperature changes. Preferably, the pulse on/off time will be related to the time constant of the heating/cooling process, for example a full on/off cycle may take place over 4 time constants.

[0023] In some embodiments, the potentially high temporal and temperature resolutions of the DVS measurement may allow it to be used as a measure of transient flow. The heating may be rapidly pulsed on and off and the resulting small temperature changes monitored using the DVS. From these the flow velocity and/or fluid type
surrounding the cable may be determined at high temporal resolution. One possible application of this is the tracking of gas slugs moving past or along the cable.

**Distributed Strain**

[0024] In some embodiments, cable heating may cause thermal expansion which may be detected using a distributed strain measurement. In this case, a higher flow velocity will cause a smaller temperature rise and hence a smaller thermal expansion.

**Cable Refinements**

[0025] In some embodiments, a number of refinements are possible to the general concept of distributed thermal flow metering. In some embodiments a length of cable may remain on the deployment drum for anchoring. An additional length of cable is in the upper part of the well and unlikely to measure flow of interest. It is therefore optimal to place maximum heating in the lower (far) section of cable. We can achieve this by changing the material of the heating element along its length. A low resistance material may be used for the first section, followed by a high resistance material in the far section.

[0026] In other embodiments, the cable may be designed so as to allow electrical connection of the heating power to be made at or near the wellhead. The connection may be galvanic, inductive or capacitive in nature.

[0027] In some embodiments, for greatest measurement resolution maximum heating power per unit length of cable may be sought. To maximize this the cable may be equipped with alternating sections of high and low resistance heating element, so focusing heating power in short sections. Additionally, such a cable will heat fluid as it passes the high resistance sections and then allow it to cool as it passes the low resistance sections. In another mode of operation the variation of temperature with distance is used to track the advection of warmed fluid along the cable, giving another measure of flow velocity. Such a method may be desirable when the flow velocity is very low and hence there is minimum fluid mixing.

[0028] In some embodiments, it may also be possible to vary the heating along the cable by not only changing the conductor material but also changing the lay length of
the resistive materials. Shorter lay lengths will give a higher density of resistive material and so more heating. Longer lay lengths will give a lower density of resistive material and so less heating. This approach could be used to give alternating high and low heating regions, and also to create a longer zone of increased heating within the cable.

[0029] In some embodiments of this disclosure, we describe a further configuration with the heating element on the outside of the cable, structure or device. This may allow the maximizing of the dependence upon convection and minimizing the dependence on conduction, so maximizing the sensitivity of the cable to variations in flow velocity.

[0030] Figure 6 illustrates further embodiments in which a cable is modified to accommodate heating and measurement techniques disclosed herein. In some embodiments, a cable 40 has a heating element 44 on the outside of the cable 40 in the form of a metal tube through which current is passed. A fiber 42 is placed inside the tube, measuring the temperature. The temperature will be generally uniform within the tube. In still further embodiments, a cable 50 includes an outer coating 52, a heating element 54, armour wires 56, a return current path 58, and an optical fiber 60. In this embodiment, the heating element is included in the outer layers of the cable 50. The heating element 54 can be in addition to the armour wires 56, or the armor wires 56 themselves could be used as the heating element.

[0031] In the specification and appended claims: the terms "connect", "connection", "connected", "in connection with", and "connecting" are used to mean "in direct connection with" or "in connection with via one or more elements"; and the term "set" is used to mean "one element" or "more than one element". Further, the terms "couple", "coupling", "coupled", "coupled together", and "coupled with" are used to mean "directly coupled together" or "coupled together via one or more elements". As used herein, the terms "up" and "down", "upper" and "lower", "upwardly" and "downwardly", "upstream" and "downstream"; "above" and "below"; and other like terms indicating relative positions above or below a given point or element are used in this description to more clearly describe some embodiments of the disclosure.
While the present disclosure has been disclosed with respect to a limited number of embodiments, those skilled in the art, having the benefit of this disclosure, will appreciate numerous modifications and variations therefrom. It is intended that the appended claims cover such modifications and variations as fall within the true spirit and scope of the invention.
What is claimed is:

1. A distributed flow metering system, comprising:
   a cable positioned in a wellbore, the cable having
   a fiber optic component configured to measure temperature at specific
   locations along the cable in the wellbore; and
   a heating component configured to periodically direct heat into the
   wellbore;
   a fluid inducing component configured to induce fluid flow in heated areas of the
   wellbore; and
   a monitoring component configured to monitor temperature when the heating
   component is active and to deduce fluid flow rates from a monitored
   temperature.

2. The distributed flow metering system of claim 1 wherein the fluid inducing
   component is configured to inject fluid into the well.

3. The distributed flow metering system of claim 1 wherein the fluid inducing
   component is configured to move fluid out of the well.

4. The distributed flow metering system of claim 1 wherein the heating component
   comprises at least one of resistive electrical heating and chemical heating.

5. The distributed flow metering system of claim 1 wherein the heating component
   is configured to direct heat substantially evenly along the cable.

6. The distributed flow metering system of claim 1 wherein the heating component
   is configured to direct heat to discrete regions of the cable.

7. The distributed flow metering system of claim 6 wherein the heating component
   includes portions of higher electrical resistance which are configured to direct more
   thermal energy into the well at the portions.
8. The distributed flow metering system of claim 1 wherein the heating component is configured to connect to a power source at a wellhead.

9. The distributed flow metering system of claim 8 wherein the heating component is configured to couple to the power source through galvanic, inductive, or capacitive connection means.

10. The distributed flow metering system of claim 1 wherein the cable comprises a fiber component at a center of the cable and the heating component is also located at a center of the cable.

11. The distributed flow metering system of claim 1 wherein the fiber optic component is at a center of the cable and the heating component comprises a shell at an outer portion of the cable.

12. The distributed flow metering system of claim 1 wherein the heating component comprises at least one of an outer coating, a heating element, or armour wires.

13. The distributed flow metering system of claim 1 wherein the cable also includes a return current path to return current used to heat the heating component.

14. A method of metering flow in a wellbore, comprising:
   heating select portions of a wellbore by directing energy to the select portions;
   measuring a temperature at the select portions using a fiber optic cable; and
   interpreting a flow rate from a temperature at the select portions as a function of the energy directed to the selected portions.

15. The method of claim 14 wherein heating select portions comprises passing an electrical current through a cable in the wellbore.

16. The method of claim 14 wherein measuring the temperature comprises using at least one of distributed acoustic sensors
17. The method of claim 14, further comprising measuring a vibration at the select portions.

18. The method of claim 14, further comprising varying the energy directed at the select portions.

19. The method of claim 18 wherein varying the energy directed at the select portions comprises carrying a lay length of a resistive material.

20. The method of claim 14, further comprising coupling the fiber optic cable and to a power source at a wellhead.
A. CLASSIFICATION OF SUBJECT MATTER

GOIF l/68(2006.01)i, GOIF l/688(2006.01)i, G01K 11/32(2006.01)i

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)

GOIF 1/68; G06F 19/00; G01J 4/00; G01J 1/04; E21B 36/04; G01L 9/04; G01L 11/02; G02B 6/00; G01F l/688; G01K 11/32

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

Korean utility models and applications for utility models

Japanese utility models and applications for utility models

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

eKOMPASS(KIPO internal) & Keywordsxable, fiber optic, temperature, heating, fluid, velocity and rate

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category* Citation of document, with indication, where appropriate, of the relevant passages Relevant to claim No.

X US 2008-0185138 Al (HERNANDEZ-SOLIS et al.) 07 August 2008
See abstract, para; graphs [0003], [0023]-[0033] and figures 2-5.

See abstract, para; graphs [0023]-[0028], claims 1-4 and figures 1.2.

A US 2006-0071158 Al (VAN DER SPEK, ALEXANDER MICHAEL) 06 April 2006
See abstract, para; graphs [0043]-[0050], claim 13 and figures 1-5.

A US 2012-0277995 Al (HARTOG et al.) 01 November 2012
See abstract, para; graphs [0037]-[0042] and figures 1A-3.

A US 2011-0048136 Al (BIRCH et al.) 03 March 2011
See abstract, para; graphs [0044]-[0056], claim 1 and figures 1-5.

Further documents are listed in the continuation of Box C.

See patent family annex.

* Special categories of cited documents:
  "A" document defining the general state of the art which is not considered to be of particular relevance
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<th>Patent document cited in search report</th>
<th>Publication date</th>
<th>Patent family member(s)</th>
<th>Publication date</th>
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<tbody>
<tr>
<td>US 2008-0185138 Al</td>
<td>07/08/2008</td>
<td>CA 2679994 Al</td>
<td>14/08/2008</td>
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<tr>
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<td></td>
<td>CN 101311493 A</td>
<td>26/11/2008</td>
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<tr>
<td></td>
<td></td>
<td>US 7730936 B2</td>
<td>08/06/2010</td>
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<tr>
<td></td>
<td></td>
<td>WO 2008-096287 Al</td>
<td>14/08/2008</td>
</tr>
<tr>
<td>US 2007-0110355 Al</td>
<td>17/05/2007</td>
<td>AU 2004-263671 Al</td>
<td>17/02/2005</td>
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<td></td>
<td>AU 2004-263671 B2</td>
<td>03/01/2008</td>
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<td>BR PI0413422 A</td>
<td>10/10/2006</td>
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<td>CA 2534386 Al</td>
<td>17/02/2005</td>
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<td>CA 2534386 C</td>
<td>21/02/2012</td>
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<td>CN 100516460 C</td>
<td>22/07/2009</td>
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<td>EP 1664487 Al</td>
<td>07/06/2006</td>
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<td>EP 1664487 B1</td>
<td>20/08/2008</td>
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<td>NO 20061147 A</td>
<td>04/05/2006</td>
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<td>US 7561771 B2</td>
<td>14/07/2009</td>
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<td>WO 2005-014976 Al</td>
<td>17/02/2005</td>
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<td>BR PI0407981 A</td>
<td>07/03/2006</td>
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<td>CA 2518033 Al</td>
<td>23/09/2004</td>
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<td>CA 2518033 C</td>
<td>23/10/2012</td>
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<td>EA 007244 B1</td>
<td>25/08/2006</td>
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<td>EP 1604181 Al</td>
<td>14/12/2005</td>
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<td>EP 1604181 B1</td>
<td>24/08/2011</td>
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<td></td>
<td>NO 20054564 A</td>
<td>04/10/2005</td>
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<tr>
<td></td>
<td></td>
<td>US 7315666 B2</td>
<td>01/01/2008</td>
</tr>
<tr>
<td>US 2012-0277995 Al</td>
<td>01/11/2012</td>
<td>CA 2702313 Al</td>
<td>07/05/2009</td>
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<td>EP 2205999 Al</td>
<td>14/07/2010</td>
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<td>US 2009-0114386 Al</td>
<td>07/05/2009</td>
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<td>US 2011-0188344 Al</td>
<td>04/08/2011</td>
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<td>US 7946341 B2</td>
<td>24/05/2011</td>
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<td>US 8225867 B2</td>
<td>24/07/2012</td>
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<td></td>
<td>US 8347958 B2</td>
<td>08/01/2013</td>
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<tr>
<td></td>
<td></td>
<td>WO 2009-056855 Al</td>
<td>07/05/2009</td>
</tr>
<tr>
<td>US 2011-0048136 Al</td>
<td>03/03/2011</td>
<td>AU 2008-320812 Al</td>
<td>07/05/2009</td>
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<td>AU 2008-320812 B2</td>
<td>12/01/2012</td>
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<td></td>
<td>CA 2701773 Al</td>
<td>07/05/2009</td>
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<td></td>
<td>GB 2468221 A</td>
<td>01/09/2010</td>
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<td>US 8176790 B2</td>
<td>15/05/2012</td>
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<td>WO 2009-056623 Al</td>
<td>07/05/2009</td>
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