Abstract: The present disclosure relates to an apparatus and method for estimating a parameter of interest in a downhole fluid using a fluid analysis module. The fluid analysis module may include: a first transducer configured to generate a surface wave in a fluid. The first transducer may include one or more of: a piezoelectric crystal, an electromagnetic transducer, and a surface acoustic wave crystal. The apparatus may use the first transducer or a second transducer to generate a signal indicative of the dissipation of the surface wave in the fluid. The apparatus may include a compensator configured to reduce mechanical pressure on the transducer. The method may include estimating a parameter of interest of the fluid using a signal indicative of the dissipation of the surface wave.
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SURFACE WAVE SENSOR FOR DOWNHOLE APPLICATIONS

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FIELD OF THE DISCLOSURE

[0001] This disclosure generally relates to estimating properties of downhole fluids. In certain aspects, the disclosure relates to analysis of fluids using surface waves.

BACKGROUND OF THE DISCLOSURE

[0002] Fluid evaluation techniques are well known. Broadly speaking, analysis of fluids may provide valuable data indicative of formation and wellbore parameters. Many fluids, such as formation fluids, production fluids, and drilling fluids, contain a large number of components with a complex composition.

[0003] The complex composition of such fluids may be sensitive to changes in the environment, e.g., pressure changes, temperature changes, contamination, etc. Thus, retrieval of a sample may cause unwanted separation or precipitation within the fluid. Additionally, some components of the fluid may change state (gas to liquid, or liquid to solid) when removed to surface conditions. If precipitation or separation occurs, it may not be possible to restore the original composition of the fluid.

SUMMARY OF THE DISCLOSURE

[0004] In aspects, this disclosure generally relates to analysis of fluids. More specifically, this disclosure relates to analysis of fluids using a device configured to respond to a dissipation of surface waves.

[0005] One embodiment according to the present disclosure includes an apparatus for estimating a parameter of interest of a fluid downhole, comprising: a first transducer responsive to a dissipation of at least one surface wave in the
fluid and configured to generate an electrical signal indicative of the parameter of interest.

[0006] Another embodiment according to the present disclosure includes a method of estimating a parameter of interest in a fluid downhole, comprising: estimating the parameter of interest using an electrical signal indicative of a dissipation of at least one surface wave in the fluid, the electrical signal being generated using a first transducer.

[0007] Examples of certain features of the disclosure have been summarized rather broadly in order that the detailed description thereof that follows may be better understood and in order that the contributions they represent to the art may be appreciated.

**BRIEF DESCRIPTION OF THE DRAWINGS**

[0008] For a detailed understanding of the present disclosure, reference should be made to the following detailed description of the embodiments, taken in conjunction with the accompanying drawings, in which like elements have been given like numerals, wherein:

- **Fig. 1** shows a schematic of a fluid analysis module deployed in a borehole along a wireline according to one embodiment of the present disclosure;

- **Fig. 2** shows a schematic of a fluid analysis module according to one embodiment of the present disclosure;

- **Fig. 3** shows a schematic of a fluid analysis module according to another embodiment of the present disclosure;

- **Fig. 4** shows a schematic of a fluid analysis module according to another embodiment of the present disclosure;

- **Fig. 5** shows a schematic of a fluid analysis module according to another embodiment of the present disclosure; and

- **Fig. 6** shows a flow chart of a method for analyzing a fluid using a fluid analysis module according to one embodiment of the present disclosure.
DETAILED DESCRIPTION

[0009] This disclosure generally relates to analysis of fluids. In one aspect, this disclosure relates to analysis of fluids using a transducer responsive to a dissipation of at least one surface wave and configured to generate an electric signal indicative of the dissipation. Herein, the term "surface wave" relates to a mechanical wave that propagates along the interface between differing media.

[0010] A surface wave may be introduced to a fluid by a transmitter. The resulting vibrations may begin to dissipate due to resistance to motion due to the fluid. Herein, the term "dissipation" relates to damping, reduction, or attenuation of the amplitude or energy of a wave. The time and manner of the dissipation may be related to properties of the fluid, such as, but not limited to, viscosity, density, and viscosity-density product. A receiver may be configured to generate a signal in response to the dissipation of the surface waves in the fluid. The transmitter and receiver may be separate devices or a single device may be configured to operate as transmitter and receiver. The surface wave transmitted into the fluid may be, but is not limited to, a square pulse or a sinusoid (continuous or stored in memory). The modification of the signal in amplitude, frequency, or phase may be used individually or together to estimate the viscosity and density of the fluid using suitable analytical and empirical models known to those of skill in the art. In embodiments where the same transducer may be used as both transmitter and receiver, the transmitter may be switched off during a period for the reflected signal from a metal-liquid interface.

[0011] Different configurations of transmitters may be used for different types of surface waves. A lamb wave transmitter may include a wedge configured to couple lamb waves with a body in contact with the fluid. Herein, the term "couple" relates to channeling the energy from a transducer to a structure from which surface waves may propagate. In some embodiments, the wedge may be configured to reduce undesired wave components. A love wave transmitter may use a transducer directed to generate a wave in a thin layer surrounding, at least in part, a solid body in communication with the fluid. The solid body may include a
crystal, such as, but not limited to, one of: i) an XY-cut quartz crystal, ii) an ST-quartz crystal, and iii) a Y-rotated quartz crystal. The thin layer may include a metal configured to act as a waveguide for love waves. In some embodiments, the love wave transmitter may include a solid body of lithium tantalite with a thin layer that includes silica. Finally, a Rayleigh wave sensor may include a surface acoustic crystal disposed in the fluid. Transducers that may be used to generate lamb, love, and Rayleigh waves, may also be used to generate flexural plate waves and skimming bulk waves. Several non-limiting embodiments of an apparatus configured to use the proposed technique are described below.

[0012] Referring initially to FIG. 1, there is schematically represented a cross-section of a subterranean formation 10 in which is drilled a borehole 12. Suspended within the borehole 12 at the bottom end of a carrier 14, such as a wireline, is a downhole assembly 100. In some embodiments, the carrier 14 may be rigid, such as a coiled tube, casing, liners, drill pipe, etc. In other embodiments, the carrier 14 may be non-rigid, such as wirelines, wireline sondes, slickline sondes, e-lines, drop tools, self-propelled tractors, etc. The term "carrier" as used herein means any device, device component, combination of devices, media and/or member that may be used to convey, house, support, or otherwise facilitate the use of another device, device component, combination of devices, media and/or member. The carrier 14 is often carried over a pulley 18 supported by a derrick 20. Wireline deployment and retrieval is performed by a powered winch carried by a service truck 22, for example. A control panel 24 interconnected to the downhole assembly 100 through the carrier 14 by conventional means controls transmission of electrical power, data/command signals, and also provides control over operation of the components in the downhole assembly 100. The data may be transmitted in analog or digital form. Downhole assembly 100 may include a fluid analysis module 112. Downhole assembly 100 may also include a sampling device 110. Herein, the downhole assembly 100 may be used in a drilling system (not shown) as well as a wireline. While a wireline conveyance system has been shown, it should be understood that
embodiments of the present disclosure may be utilized in connection with tools conveyed via rigid carriers (e.g., jointed tubular or coiled tubing) as well as non-rigid carriers (e.g., wireline, slickline, e-line, etc.). Some embodiments of the present disclosure may be deployed along with Logging While Drilling/Measurement While Drilling tools. In some embodiments, downhole assembly 100 may be configured for installation in a borehole 12.

[0013] FIG. 2 shows an exemplary embodiment for a fluid analysis module 112 for testing one or more fluids. Fluid analysis module 112 may include an actuator 210 configured to generate waves in a body 230. The body 230 may include, at least in part, one of: i) a metal, ii) a ceramic, and iii) a composite material. The actuator 210 may generate waves using techniques known to those of skill in the art. The actuator 210 may include one or more of: i) a piezoelectric crystal, ii) a fine point contact transducer, iii) an air-coupled ultrasonic transducer, iv) a laser wave generator, and v) a wedge transducer. The actuator 210 may be in contact with a wedge 220 configured to couple lamb waves to body 230. The wedge may have an angle 225 selected to enhance the coupling of lamb waves to the body. The angle 225 may be selected to adjust the degree of coupling of the lamb waves using techniques known to those of skill in the art. The body 230 may be positioned within a housing 250 such that part of the body 230 may be in contact with the fluid 240 for analysis. In some embodiments, body 230 may include multiple sub-bodies (not shown) such that at least one sub-body is in contact with fluid 240, at least one sub-body is in contact with wedge 220, and each of the multiple sub-bodies is in physical communication with at least one other sub-body.

[0014] After a lamb wave is introduced to the fluid 240, the dissipation of the lamb wave may be detected by a transducer. The actuator 210 may be configured to serve as the transducer and thus receive the dissipating vibrations from the lamb waves in the fluid 240. In some embodiments, a separate transducer (not shown) may be placed in communication with the lamb waves in the fluid 240 to generate an electrical signal in response to the dissipating waves.
The use of a separate transducer may enable wave generation and dissipation measurement to take place simultaneously. In some embodiments, the actuator 210 may be used to both transmit the surface waves and measure the dissipation of the surface waves, separately. When using the actuator 210 to transmit and receive, the actuator 210 may use a duty cycle where the transmission aspect of actuator 210 is active to transmit and inactive to receive. In some embodiments, fluid analysis module 112 may include multiple transducers disposed to estimate the dissipation of surface waves at several points along housing 250. The transducers may be configured to transmit, receive, or transmit/receive. The estimates from multiple locations may compensate for variations in dissipation estimates due to differences in environmental conditions along housing 250. The environmental conditions may include, but are not limited to, one or more of: i) temperature and ii) pressure. In some embodiments, one or more of flexural plate waves and skimming bulk waves may be substituted for lamb waves.

[0015] FIG. 3 shows another embodiment for the fluid analysis module 112. In this embodiment, fluid analysis module 112 may include an electromagnetic transducer (eMAT) 320 configured to generate an alternating magnetic field. The eMAT 320 may include a permanent magnet 340 and coil 310. The module 112 may include a metallic plate 330 positioned in wave communication with fluid 240 under investigation. The metallic plate 330 may be configured to generate lamb waves and/or love waves when exposed to the magnetic field from magnetic field source 320. In some embodiments, the magnetic field source 320 may include an electromagnet coil. In some embodiments, the eMAT 320 may include one or more of: i) a permanent magnet, ii) an array of permanent magnets, iii) a DC electromagnet, and iv) a pulsed current electromagnet.

[0016] After a lamb/love wave is introduced to the fluid 240, the dissipation of the wave may be detected by vibrations of the fluid causing vibrations in metallic plate 330. The dissipation of the waves may be estimated from an electrical signal generated by the magnetic field interaction between the
metallic plate and the magnetic field source 320. In some embodiments, a separate transducer (not shown) may be in communication with the fluid 240 to estimate the dissipation of the surface waves in the fluid 240. The use of a separate transducer may enable wave generation and dissipation measurement to take place simultaneously. In some embodiments, the magnetic field source 320 may be used to both transmit the surface waves and measure the dissipation of the surface waves, separately. When using the magnetic field source 320 to transmit and receive, the magnetic field source 320 may use a duty cycle where the transmission aspect of magnetic field source 320 is active to transmit and inactive to receive. In some embodiments, one or more of flexural plate waves and skimming bulk waves may be substituted for lamb/love waves.

[0017] FIG. 4 shows another embodiment for the fluid analysis module 112. This embodiment may be configured to generate a Rayleigh wave using a surface acoustic wave (SAW) crystal 410 as a transducer. In some embodiments, the SAW crystal 410 may include an interdigitated transducer 450 configured to excite a surface wave in a crystal 460. The fluid analysis module 112 may include a SAW crystal 410 disposed within the fluid 240. The SAW crystal 410 may be disposed in a holder 420 to insulate the SAW crystal 410 from the housing 250. The SAW crystal 410 may further have patterns on its surface which can be used to perform additional measurements of density of the fluid.

[0018] The crystal 460 may include a piezoelectric crystal that may be configured to generate a Rayleigh wave, such as by being cut along a specific plane of the piezoelectric crystal. Techniques for cutting crystals to generate different types of waves are known to those of skill in the art. The crystal 460 may include, but is not limited to, one or more of: quartz, langasite, GaP0 4 , and lithium niobiate. The interdigitated transducer 450 may be configured to convert acoustic waves into electric signals and vice versa.

[0019] After the Rayleigh wave is introduced to the fluid 240, the dissipation of the wave may be detected by vibrations of the fluid causing vibrations in SAW crystal 410. The dissipation of the waves may be estimated
from an electrical signal generated due to the vibrations in the SAW crystal 410. In some embodiments, a sound speed sensor 430 may be configured to estimate the speed of sound in the fluid 240 and/or compressibility of the fluid 240. The sound speed sensor 430 may be separated from the fluid by a metallic plate 440. The sound speed sensor 430 may include an ultrasonic transducer. In some embodiments, a separate transducer (not shown) may be in communication with the fluid 240 to estimate the dissipation of the surface waves in the fluid 240. The use of a separate transducer may enable wave generation and dissipation measurement to take place simultaneously. In some embodiments, the SAW crystal 410 may be used to both transmit the surface waves and measure the dissipation of the surface waves, separately. When using the SAW crystal 410 to transmit and receive, the SAW crystal 410 may use a duty cycle where the transmission aspect of SAW crystal 410 is active to transmit and inactive to receive. In some embodiments, one or more of flexural plate waves and skimming bulk waves may be substituted for Rayleigh waves.

One example of a SAW crystal 410 is a shear-horizontal SAW crystal, wherein the crystal may be configured to generate surface waves with a shear-horizontal propagation. The shear-horizontal SAW crystal may be configured to concentrate wave energy on the surface in contact with lower attenuation than a bulk acoustic wave sensor.

FIG. 5 shows another embodiment for the fluid analysis module 112. This embodiment may be configured to generate a Rayleigh wave using a SAW crystal 510. The fluid analysis module 112 may include a SAW crystal 510 in contact with the fluid 240. The SAW crystal 510 may also be in contact with a compensator 520. The compensator 520 may be configured to reduce a pressure difference between the fluid side 530 of the SAW crystal 510 and the compensated side 540 of the SAW crystal 510. The use of pressure compensator 520 may reduce the thickness of SAW crystal 510 used in high pressure fluids, since the differential pressure across the SAW crystal 510 may be maintained within a range which is not detrimental to the SAW crystal 510. The
compensator 520 may be disposed in housing 250. In some embodiments, the compensator 520 may include a pressurized fluid. In other embodiments, the compensator 520 may include a mechanical compensation device, such as, but not limited to, a piston or a mechanical spring.

[0022] After the Rayleigh wave is introduced to the fluid 240, the dissipation of the wave may be detected by vibrations of the fluid causing vibrations in SAW crystal 510. The dissipation of the waves may be estimated from an electrical signal generated due to the vibrations in the SAW crystal 510. In some embodiments, a separate transducer (not shown) may be in communication with the fluid 240 to estimate the dissipation of the surface waves in the fluid 240. The use of a separate transducer may enable wave generation and dissipation measurement to take place simultaneously. In some embodiments, the SAW crystal 510 may be used to both transmit the surface waves and measure the dissipation of the surface waves, separately. When using the SAW crystal 510 to transmit and receive, the SAW crystal 510 may use a duty cycle where the transmission aspect of SAW crystal 510 is active to transmit and inactive to receive. In some embodiments, one or more of flexural plate waves and skimming bulk waves may be substituted for Rayleigh waves.

[0023] FIG. 6 shows a flow chart of a method 600 for estimating fluid properties in the fluid 240 using embodiments of the fluid analysis module 112. In step 610, a surface wave may be introduced to the fluid 240. In step 620, an electrical signal may be generated by a transducer in module 112 in response to the dissipation of the surface wave in the fluid 240. The transducer responsive to the dissipation of the surface waves may be the actuator 210, coil 310, SAW crystal 410, SAW crystal 510, or a separate transducer (not shown). In step 630, at least one fluid property may be estimated using the electrical signal. The at least one fluid property may include, but is not limited to, at least one of: i) viscosity, ii) density, and iii) density-viscosity product. In some embodiments, step 630 may include using information from an additional sensor, such as a sound speed sensor.
While the present teachings have been discussed in the context of hydrocarbon producing wells, it should be understood that the present teachings may be applied to geothermal wells, groundwater wells, subsea analysis, etc. Also, the present teachings may be applied to downhole installations for wellbore fluid monitoring and surface-based fluid recovery and analysis.

While the foregoing disclosure is directed to the one mode embodiments of the disclosure, various modifications will be apparent to those skilled in the art. It is intended that all variations be embraced by the foregoing disclosure.
CLAIMS

We claim:

1. An apparatus for estimating a parameter of interest of a fluid downhole, comprising:
   a first transducer responsive to a dissipation of at least one surface wave in the fluid and configured to generate an electrical signal indicative of the parameter of interest.

2. The apparatus of claim 1, the first transducer being disposed downhole and in communication with the fluid.

3. The apparatus of claim 1, wherein the first transducer is configured to generate the at least one surface wave in the fluid.

4. The apparatus of claim 1, further comprising:
   a second transducer configured to generate the at least one surface wave in the fluid.

5. The apparatus of claim 4, wherein the generation of the electrical signal and the generation of the at least one surface wave take place simultaneously.

6. The apparatus of claim 1, wherein the at least one surface wave includes at least one of: i) a Lamb wave, ii) a Love wave, iii) a Rayleigh wave, iv) a flexural plate wave, and v) a skimming bulk wave.

7. The apparatus of claim 1, wherein the parameter of interest includes at least one of: i) a density of the fluid, ii) a viscosity of the fluid, and iii) a density-viscosity product of the fluid.

8. The apparatus of claim 1, wherein the first transducer includes:
   an element configured to generate an alternating magnetic field when energized; and
a plate disposed between the element and the fluid and configured to generate the at least one surface wave when exposed to the alternating magnetic field.

9. The apparatus of claim 8, wherein the plate is, at least in part, metallic.

10. The apparatus of claim 8, wherein the element includes at least one of: a permanent magnet and an electromagnet coil.

11. The apparatus of claim 1, wherein the first transducer includes:

   a piezoelectric crystal; and

   a wedge configured to couple lamb waves to a body in communication with the fluid.

12. The apparatus of claim 1, wherein the first transducer includes a surface acoustic wave crystal.

13. The apparatus of claim 12, further comprising:

   a second transducer in communication with the fluid.

14. The apparatus of claim 12, further comprising:

   a compensator configured to reduce a physical stress from the fluid on the first transducer.

15. The apparatus of claim 14, wherein the compensator includes at least one of: i) a pressurized fluid, ii) a piston, and iii) a mechanical spring.

16. A method of estimating a parameter of interest in a fluid downhole, comprising:

   estimating the parameter of interest using an electrical signal indicative of a dissipation of at least one surface wave in the fluid, the electrical signal being generated using a first transducer.

17. The method of claim 16, the first transducer being disposed downhole and in communication with the fluid.
18. The method of claim 16, further comprising:

   generating the at least one surface wave in the fluid.

19. The method of claim 18, wherein the at least one surface wave is generated using one of: the first transducer and a second transducer.

20. The method of claim 16, wherein the first transducer includes:

   an element configured to generate an alternating magnetic field when energized; and

   a plate disposed between the element and the fluid and configured to generate the at least one surface wave when exposed to the alternating magnetic field.

21. The method of claim 16, wherein the estimation of the parameter of interest includes using at least one of: a sound speed in the fluid and a compressibility of the fluid.

22. The method of claim 16, wherein the first transducer includes a surface acoustic wave crystal; and

   further comprising reducing a physical stress from the fluid on the surface acoustic wave crystal.
1. Introduce a surface wave to the fluid.
2. Generate an electrical signal indicative of the dissipation of the surface wave in the fluid.
3. Estimate at least one fluid property using the signal.

FIG. 6