



- (51) International Patent Classification:
G01R 33/24 (2006.01) *G01R 33/02* (2006.01)
- (21) International Application Number:
PCT/US2015/020131
- (22) International Filing Date:
12 March 2015 (12.03.2015)
- (25) Filing Language: English
- (26) Publication Language: English
- (30) Priority Data:
61/954,365 17 March 2014 (17.03.2014) US
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(54) Title: TOMOGRAPHY OF MULTIPHASE MIXTURES CONTAINING SOLIDS

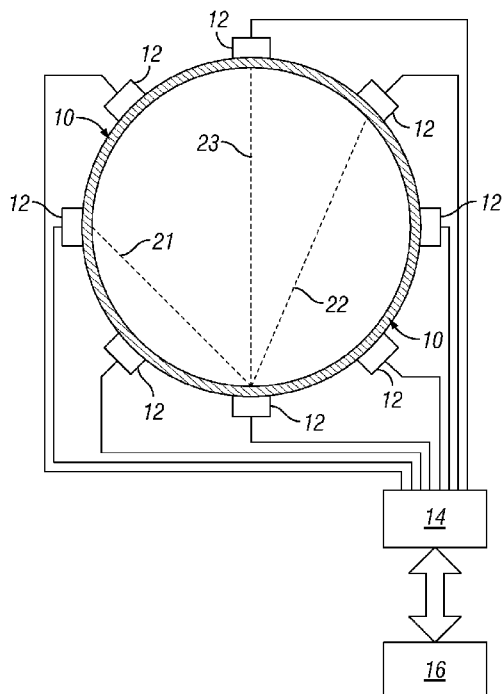


FIG. 1

(57) Abstract: A tomography system for determining properties of flowing gas-solids, liquid-solids and/or gas-liquid-solids multiphase fluid. A duct wall and interior space within the duct wall carries a flow of the multiphase fluid and a plurality of sensors are used to make measurements of electrical or magnetic properties through the duct wall and the multiphase fluid, at single or a plurality of operating frequencies in the range of 1 MHz to 400 MHz. A processor computes quantitative values of at least one property selected from permittivity, conductivity, magnetic permeability, complex permittivity and complex-conductivity of the multiphase fluid from the measured properties. The processor uses the quantitative values to compute the phase fraction and phase velocity of the multiphase fluid.



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(81) **Designated States** (*unless otherwise indicated, for every kind of national protection available*): AE, AG, AL, AM, AO, AT, AU, AZ, BA, BB, BG, BH, BN, BR, BW, BY, BZ, CA, CH, CL, CN, CO, CR, CU, CZ, DE, DK, DM, DO, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT, HN, HR, HU, ID, IL, IN, IR, IS, JP, KE, KG, KN, KP, KR, KZ, LA, LC, LK, LR, LS, LU, LY, MA, MD,

ME, MG, MK, MN, MW, MX, MY, MZ, NA, NG, NI, NO, NZ, OM, PA, PE, PG, PH, PL, PT, QA, RO, RS, RU, RW, SA, SC, SD, SE, SG, SK, SL, SM, ST, SV, SY, TH, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, ZA, ZM, ZW.

(84) **Designated States** (*unless otherwise indicated, for every kind of regional protection available*): ARIPO (BW, GH, GM, KE, LR, LS, MW, MZ, NA, RW, SD, SL, ST, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, RU, TJ, TM), European (AL, AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HR, HU, IE, IS, IT, LT, LU, LV, MC, MK, MT, NL, NO, PL, PT, RO, RS, SE, SI, SK, SM, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, KM, ML, MR, NE, SN, TD, TG).

Published:

— with international search report (Art. 21(3))

TOMOGRAPHY OF MULTIPHASE MIXTURES CONTAINING SOLIDS

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application claims priority to U.S. Provisional Patent Application having Serial No. 61/954,365, filed on March 17, 2014, entitled “Tomography Of Multiphase Mixtures Containing Solids,” the entirety of which is incorporated by reference herein.

BACKGROUND

[0002] Embodiments of the present invention relate to a tomography system for determining the properties of flowing gas-solids, liquid-solids, and/or gas-liquid-solids multiphase fluids. In some embodiments, a method for measuring the properties of the fluids is provided.

[0003] Performing tomography on multiphase mixtures is a way to determine properties of the multiphase mixture, where the properties may be measured in a pipeline, conduit, wellbore or other structure carrying flow of the multiphase mixture.

[0004] The challenge with gas-solids, liquid-solids and/or gas-liquid-solids multiphase flow measurement is that both the phase distribution and the phase velocity profile vary significantly in time and space, typically as a function of pipe deviation, gas-solids or liquid-solids superficial velocities, solids density and/or particle-size distributions. At an oilfield wellsite, solids additives may be screw-feeder fed or gravity-dropped, pneumatically conveyed or hydraulically conveyed, before or after being mixed with liquid (water).

[0005] As an example, fracturing fluids may be made at the wellsite by adding various liquid and dry solid chemicals to water. Though there are multiple systems available to measure online the amount of liquid additives added to water, there is no equivalent system for measuring in real time, or online, the dry powder additives. For example, U.S. Patent Pub. No. 2013/0144548 A1 discloses several techniques for analyzing gas-liquid multiphase fluids or oil/water/gas continuous flow. Currently, dry powder is commonly added to the liquid systems by using auger-based metering screw feeders (calibrated based on bucket tests). Measuring

accurately in real time the ‘dry’ powder flow, *i.e.*, the parameters associated with the flow rate of the solid powder, is critical for the production of a fracturing fluid that meets useable requirements – especially ‘dry’ guar powder used to mix with liquid water to create a linear gel of a desired viscosity to suspend fully subsequently-mixed solids-proppant pressure-pumped downhole.

[0006] Process tomography has been conceived to have the potential of measuring dynamic multiphase processes such as multiphase flows of complex regimes through a pipeline or in a process vessel. The basic concept is to mathematically reconstruct, from appropriate multiple measurements made at a pipe/vessel periphery, the phase holdup and/or phase velocity profiles, at a sufficient spatial and temporal resolution.

[0007] The term “holdup” denotes the fraction of a particular fluid present in a cross-section of pipe. Because each fluid moves at a different speed due to different gravitational forces and other factors, the holdup of a particular fluid is not the same as the volumetric-flow-rate proportion of the total volumetric flow rate due to that fluid. Individual volumetric flow rates can be derived by integrating phase holdup and phase velocity profiles over the pipe cross-section.

[0008] A lot of academic and industrial research efforts have been devoted to imaging multiphase flow phase holdup and velocity profile based on electrical capacitance tomography (ECT) (for instance for imaging gas-solids fluidized bed as disclosed in U.S. Patent No. US8461852B2; for measuring gas-solids flows, Hunt A, Pendleton J and Byars M. ‘*Non-Intrusive Measurement Of Volume And Mass Using Electrical Capacitance Tomography*’, ESDA 2004-58398, 7TH BIENNIAL ASME CONFERENCE ON ENGINEERING SYSTEM DESIGN AND ANALYSIS, Manchester, UK. July 19-22, 2004), electrical resistance tomography (ERT) (*e.g.* for measuring water-solids slurry flows, Wang M, Jones TF and Williams RA ‘*Visualization Of Asymmetric Solids Distribution In Horizontal Swirling Flows Using Electrical Resistance Tomography*’, *CHEMICAL ENGINEERING RESEARCH & DESIGN*, vol. 81, pp.854-861, 2003). Processing of the experimental data to derive solids holdup has been problematic for gas-solids flows with varying moisture (bound water) content, and/or for slurry flows with varying water

salinity. A single-modality electrical impedance tomography (EIT) system capable of rapidly measuring, using the same set of sensors (e.g. electrodes), both electrical capacitance and resistance (or conductance) at single or a plurality of operating frequencies in the range of 1 MHz to 400 MHz or in some aspects in the range of 1 MHz to 200 MHz, hence suitable for measuring non-conducting or weakly-conducting gas-solids flows (e.g. powder flow with varying moisture content), or oil-based solids flows (e.g. an oil-based mud OBM), and for measuring conducting water-based solids flows (e.g. a water-based mud WBM, fracturing or cementing fluids) is desirable for oilfield applications.

SUMMARY

[0009] A summary of certain embodiments disclosed herein is set forth below. It should be understood that these aspects are presented merely to provide the reader with a brief summary of these certain embodiments and that these aspects are not intended to limit the scope of this disclosure. Indeed, this disclosure may encompass a variety of aspects that may not be set forth.

[0010] In some aspects, the present disclosure describes a tomography system for rapid measurement of gas-solids, liquid-solids and/or gas-liquid-solids multiphase flow in which a processor such as a computer is configured to compute quantitative values of permittivity, conductivity, magnetic permeability and/or complex-permittivity/-conductivity of the multiphase flow from the measured properties representative of capacitance, conductance (which may be measured as its reciprocal which is resistance), inductance and/or admittance (which may be measured as its reciprocal which is impedance), at a single frequency or a plurality of frequencies in the range of 1 MHz to 400 MHz or in some aspects in the range of 1 MHz to 200 MHz. Electrical or magnetic tomography as disclosed here can provide robust determination of properties of the flow, such as values representative of mixture permittivity and/or conductivity. For example, the permittivity and/or conductivity components of the electrical admittance measurements at single frequency or a plurality of frequencies may relate to the moisture content of the conveyed solids, and used to make solids holdup measurement independent of moisture or density variations.

[0011] In some embodiments, measurements may be made over a plurality of frequencies, thereby providing a plurality of images conveying different information. For instance, as the chosen frequency increases, the visibility of the contents of the pipe, or rather the constituents therein, may become greater. Not only does this provide an indication of several parameters of the complex system in general, but it may also offer information on any highly conductive fluid, such as water, present in the system. This may be realised by measuring the characteristics of the multiphase fluid over a plurality of frequencies; that is, measuring the image visibility or contrast with respect to frequency (a frequency response curve) can provide information on highly conductive fluids.

[0012] In one aspect, there is disclosed an electrical or magnetic tomography system for determining properties of flowing gas-solids, liquid-solids and/or gas-liquid-solids multiphase fluid, comprising:

a duct for carrying a flow of a multiphase fluid;

a plurality of sensors which are electrodes and/or coils at positions distributed around the duct on at least one planar cross section through the duct, for measuring properties of the multiphase fluid at a single or a plurality of frequencies in the range of 1 MHz to 400 MHz, or in some embodiments in the range of 1 MHz to 200 MHz; and

a processor receiving measurement data from the sensors and configured to determine quantitative values of permittivity, conductivity, magnetic permeability and/or complex-permittivity/conductivity of the multiphase fluid from the measured properties representative of capacitance, conductance, inductance and/or admittance.

[0013] Providing a measurement system adapted to operate at high-frequencies, i.e., frequencies in the range up to several-hundred MHz, enables a more universal realisation of a true electrical impedance measurement system for the simultaneous measurements of capacitance and conductance components, owing to the fact that measurements in the conductivity and permittivity contributions can be of a more comparable magnitude or detectable by the use of a wide-dynamic range measurement system. This is particularly useful during simultaneous measurements of different properties of the multiphase fluid. A

conventional low-frequency ERT system is typically designed to operate up to a few hundred KHz to measure the conductance component of *e.g.* a conductive water-continuous solids-containing flow; it may not be able to measure the quadrature capacitance component of such a multiphase flow (or of a non-conductive gas-solids multiphase flow). Similarly, a conventional ECT system (typically operating at low frequencies up to a few MHz) will only be able to measure the capacitance component of *e.g.* a gas-solids flow; it will not be able to measure a relatively conductive water-continuous solids-containing flow where the conductance component overwhelms the capacitance one. Neither a conventional low-frequency ERT nor a conventional ECT system can measure accurately a mixed water-continuous and gas/solids-continuous flow, such as a horizontal stratified gas/water/solids flow (where the top gas-rich layer is non-conductive and the bottom water-rich solids-containing layer is water continuous and conductive). The use of a high-frequency-band EIT system with the same set of sensors (electrodes) may overcome such a measurement difficulty.

[0014] The processor may be configured to determine a distribution of one or more of the quantitative values representative of permittivity, conductivity, magnetic permeability and/or complex-permittivity/conductivity within the at least one planar cross-section.

[0015] In some aspects, the system may comprise groups of sensors, with the sensors in one group distributed around one cross section through the duct and the sensors in other groups distributed around respective different cross-sections through the duct. In such a case, the sensors in each group may be used to make in-plane measurements but it is also possible that sensors in different groups could be used to make cross-plane measurements.

[0016] The processor may also be configured to determine a distribution of solids velocity by cross correlating the solids distributions over two planar cross-sections of one or more of the quantitative values representative of permittivity, conductivity, magnetic permeability and/or complex-permittivity/conductivity.

[0017] The duct may be circular in cross-section, but it is also possible that it will have some other cross-section such as square or rectangular. In some configurations, the sensors are adapted to measure, online, complex permittivities or complex conductivities of at least one

liquid-rich and/or at least one solid-rich part of the multiphase fluid flowing within the duct based upon liquid-rich region and/or solid-rich region tomographic sensing. The liquid-rich region and/or solid-rich region sensing may be, for example, near-wall sensing that includes sensing a region between at least two near-by or adjacent sensors.

[0018] In this regard, near-by or adjacent sensors are defined according to the thickness of the solid or liquid rich part. A sensor that is near-by to another sensor is one such that the sensing volume between the two sensors is occupied predominately by one phase of the multiphase fluid. That is, two sensors are near-by if the solid phase (which may contain moisture), for example, is disposed between the sensors and within the sensing volume of the two sensors. A physical distance defining the near-by sensors, therefore, depends upon the volume of the solid/liquid phase with respect to the sensing volume covered by the sensors. Note that in some situations the ‘near-by’ sensors may also include a pair of cross-pipe-diameter sensors when their sensing volume is full of solids/liquid phase.

[0019] In further embodiments, the processor is adapted to control a feedback means, the feedback means altering the component flow proportion and/or velocity of the multiphase fluid within the duct. The processor may be adapted to operate the feedback means to provide desired parameters of the multiphase fluid on the basis of the measured permittivity, conductivity, magnetic permeability, complex-conductivity, and/or complex-permittivity, and/or on the basis of the measured pipe cross-section distribution of the desired parameters, and/or the derived solids velocity (distribution).

[0020] In other words, the processor may, for example, calculate the solid fraction and velocity of a gas-solids multiphase fluid and, on the basis of either a measured viscosity value of a resulting product (linear gel, for example, which is a product of solids powder mixed with liquid water) or on the basis of measured properties of the multiphase fluid (linear gel mixture-permittivity and/or mixture-conductivity and their uniformity), the processor may determine that the multiphase fluid does not contain the correct fraction of solids powder. Thus, the processor may be adapted to control the feedback means to alter the flow rate of the solids constituent of the multiphase fluid. In some further embodiments, the feedback means may control the flow

rate of the second fluid constituent to be mixed with the first fluid to form the multiphase fluid, such as water, or control the mixing/blending rate of a mixer/storage facility holding the multiphase fluid.

[0021] In a second aspect there is provided a computer implemented method of measuring properties of flowing gas-solids, liquid-solids and/or gas-liquid-solids multiphase fluid, comprising making a plurality of measurements at a single frequency or a plurality of frequencies in the frequency range between 1 MHz and 400 MHz, or in some embodiments in the frequency range between 1 MHz and 200 MHz, representative of capacitance, conductance, inductance, and/or admittance at one or more cross sections through the duct and computing permittivity, conductivity, magnetic permeability and/or complex-permittivity/conductivity of the multiphase fluid from the measurements made.

[0022] In embodiments of this disclosure, the single or multiple-frequency values of permittivity, conductivity, magnetic permeability and/or complex-permittivity/ conductivity may be used to identify fluid type/species, compute phase holdups (or fractions) such as the gas or solids fraction and the solids moisture content of a gas-solids multiphase flow; or the water or solids fraction of a liquid-solids flow. This may for example, be a low solids-loading (lean) flow, a medium solids-loading flow, a high solids-loading (dense) flow or a flow which is a combination of lean, medium and dense solids-loading flow. They may also be used to compute, using a direct and/or iterative algorithm, a quantitative reconstruction of the distribution of permittivity, conductivity, magnetic permeability and/or complex-permittivity/-conductivity of the multiphase flow, in two-dimensional (2D) and/or three-dimensional (3D) space, and/or in time. Such a computed reconstruction may be displayed or otherwise output as a graphic 2D and/or 3D image(s).

[0023] The electrical or magnetic tomographic methods disclosed here may be used together with other measuring methods, such as an electromagnetic flowmeter, Coriolis flow meter, a differential-pressure flowmeter (*e.g.* Venturi) for flow rate measurement of liquid-solids slurry flow, a gamma-ray or X-ray densitometer for fluid density, and in combination with a multi-energy gamma-ray or multi-energy X-ray system.

[0024] In one example, an oilfield fracturing fluid preparation system comprises multiphase fluid (*e.g.* guar-powder or the like) input means, such as a transfer can, an eductor, and the tomography system described above, wherein the multiphase fluid input means is connected to the eductor via the duct and supplies the multiphase fluid to the duct and eductor, and wherein the water-flow driven eductor is configured to draw by suction the multiphase fluid and mix it with a quantity of water and output the multiphase-fluid/water mixture to a mixing/blending vessel to generate a desired linear gel at the outlet pipe of the mixing/blending vessel.

[0025] In some embodiments, the (mass) flow rate mixing ratio of the multiphase-fluid/water mixture may be adjusted depending upon the multiphase-fluid flow rate readings obtained using the tomography system and the eductor-driving water flow rate reading obtained from the other conventional measuring methods, thereby adjusting the desired linear-gel properties of the multiphase fluid mixed with the liquid (water), and subsequently adjusting the desired properties of the final fracturing-fluid product which is a mix of the linear-gel with other solids and/or proppants to be transported and pressure-pumped downhole.

BRIEF DESCRIPTION OF THE DRAWINGS

[0026] The present disclosure is described in conjunction with the appended figures. It is emphasized that, in accordance with the standard practice in the industry, various features are not drawn to scale. In fact, the dimensions of the various features may be arbitrarily increased or reduced for clarity of discussion.

[0027] Fig 1 shows a cross section of a pipe for a multiphase flow, with one plane of sensors;

[0028] Fig 1A shows two cross sections of a pipe for a multiphase flow, with two planes of sensors;

[0029] Figs 2 and 3 diagrammatically illustrate prior art calculation procedures for qualitative image reconstruction and flow measurements from an ECT system;

[0030] Fig 4 diagrammatically illustrates a calculation procedure for quantitative image reconstruction and measurement of a gas-solids flow from an ECT system;

[0031] Fig 5 diagrammatically illustrates a calculation procedure for quantitative image reconstruction and measurements of a liquid (water)-solids flow from an ERT system;

[0032] Fig 6 diagrammatically illustrates a calculation procedure for quantitative image reconstruction and measurements of a gas-solids flow from an EIT system;

[0033] Fig 7 diagrammatically illustrates a calculation procedure for quantitative image reconstruction and measurements of a liquid-solids flow from an EIT system;

[0034] Fig 8 diagrammatically illustrates another calculation procedure for quantitative image reconstruction from EIT measurements of a liquid-solids flow;

[0035] Fig 9 illustrates rapid near-wall measurement of the solids complex-conductivity at pipe underside and that of the gas complex-conductivity at pipe topside from an EIT system for a horizontal gas-solids flow;

[0036] Fig 10 illustrates rapid near-wall measurement of the solids complex-conductivity from an EIT system for a vertical gas-solids flow;

[0037] Fig 11 illustrates rapid near-wall measurement of the solids complex-conductivity at pipe underside and that of the liquid complex-conductivity at pipe topside from an EIT system for a horizontal liquid-solids flow;

[0038] Fig 12 illustrates rapid near-wall measurement of the solids complex-conductivity from an EIT system for a vertical liquid-solids flow;

[0039] Fig 13 illustrates a typical fracturing operation wellsite layout; and

[0040] Fig 14 illustrates possible locations around the hydration unit in Fig.13 of installing an EIT system (1, 2, or 3) for the online measurement of (guar) powder flow rate and/or the

location (4) for the flow rate and/or the viscosity measurement the linear gel (guar mixed with water).

[0041] In the appended figures, similar components and/or features may have the same reference label. Further, various components of the same type may be distinguished by following the reference label by a dash and a second label that distinguishes among the similar components. If only the first reference label is used in the specification, the description is applicable to any one of the similar components having the same first reference label irrespective of the second reference label.

DETAILED DESCRIPTION

[0042] The ensuing description provides exemplary embodiment(s) only, and is not intended to limit the scope, applicability or configuration of the invention. Rather, the ensuing description of the exemplary embodiment(s) will provide those skilled in the art with an enabling description for implementing an exemplary embodiment of the invention. It being understood that various changes may be made in the function and arrangement of elements without departing from the spirit and scope of the invention as set forth in the appended claims.

[0043] Specific details are given in the following description to provide a thorough understanding of the embodiments. However, it will be understood by one of ordinary skill in the art that the embodiments maybe practiced without these specific details. For example, circuits may be shown in block diagrams in order not to obscure the embodiments in unnecessary detail. In other instances, well-known circuits, processes, algorithms, structures, and techniques may be shown without unnecessary detail in order to avoid obscuring the embodiments.

[0044] Also, it is noted that the embodiments may be described as a process which is depicted as a flowchart, a flow diagram, a data flow diagram, a structure diagram, or a block diagram. Although a flowchart may describe the operations as a sequential process, many of the operations can be performed in parallel or concurrently. In addition, the order of the operations may be re-arranged. A process is terminated when its operations are completed, but could have

additional steps not included in the figure. A process may correspond to a method, a function, a procedure, a subroutine, a subprogram, etc. When a process corresponds to a function, its termination corresponds to a return of the function to the calling function or the main function.

[0045] Moreover, as disclosed herein, the term "storage medium" may represent one or more devices for storing data, including read only memory (ROM), random access memory (RAM), magnetic RAM, core memory, magnetic disk storage mediums, optical storage mediums, flash memory devices and/or other machine readable mediums for storing information. The term "computer-readable medium" includes, but is not limited to portable or fixed storage devices, optical storage devices, wireless channels and various other mediums capable of storing, containing or carrying instruction(s) and/or data.

[0046] Furthermore, embodiments may be implemented by hardware, software, firmware, middleware, microcode, hardware description languages, or any combination thereof. When implemented in software, firmware, middleware or microcode, the program code or code segments to perform the necessary tasks may be stored in a machine readable medium such as storage medium. A processor(s) may perform the necessary tasks. A code segment may represent a procedure, a function, a subprogram, a program, a routine, a subroutine, a module, a software package, a class, or any combination of instructions, data structures, or program statements. A code segment may be coupled to another code segment or a hardware circuit by passing and/or receiving information, data, arguments, parameters, or memory contents. Information, arguments, parameters, data, etc. may be passed, forwarded, or transmitted via any suitable means including memory sharing, message passing, token passing, network transmission, etc.

[0047] It is to be understood that the following disclosure provides many different embodiments, or examples, for implementing different features of various embodiments. Specific examples of components and arrangements are described below to simplify the present disclosure. These are, of course, merely examples and are not intended to be limiting. In addition, the present disclosure may repeat reference numerals and/or letters in the various examples. This repetition is for the purpose of simplicity and clarity and does not in itself

dictate a relationship between the various embodiments and/or configurations discussed. Moreover, the formation of a first feature over or on a second feature in the description that follows may include embodiments in which the first and second features are formed in direct contact, and may also include embodiments in which additional features may be formed interposing the first and second features, such that the first and second features may not be in direct contact.

[0048] Fig 1 shows a portion of pipe 10 used to carry a multiphase flow, in particular a multiphase flow containing a solid component. It is seen as an illustration here in one cross section transverse to the pipe axis and it is surrounded by a plurality of sensors, which may be electrodes 12, positioned in the plane of the cross section. These electrodes 12 make measurements in a non-contact manner because they are at the exterior of a portion of pipe 10. This portion of pipe 10 may be made from an electrically insulating and non-magnetic material, possibly a ceramic. The electrodes 12 make measurements through the pipe wall and the multiphase flow within the pipe 10. However, it is also possible to make measurements in a contact manner, with the electrodes 12 being embedded in the insulating material so as to lie flush with its interior surface and in contact with the multiphase flow. The electrodes 12 may be connected to an electronics package 14 for multiplexing among the electrodes 12 to make measurements and the electronics package 14 may in turn be connected to a processor such as a computer 16 for controlling excitation of the electrodes 12, data collection and processing of the data obtained. Similar to Fig 1, Fig 1A shows a portion of the multiphase flow pipe 10, with two planes of pipe cross sections surrounded by a plurality of sensors (electrodes 12) connected to electronics package(s) 14. In one embodiment, one or more planes are provided and, in other aspects, at least two planes of electrodes may be used.

[0049] In at least one of the cross sections, the electrodes 12 are operated at a single or a plurality of high-frequency operating frequencies, typically up to the hundreds of MHz range. In one embodiment, the electrodes 12 are operated at a single or a plurality of operating frequencies in the range of 1 MHz to 400 MHz to measure a property which may be capacitance, resistance (or its reciprocal which is conductance), inductance or impedance (or its reciprocal admittance) between individual pairs of electrodes 12. In some embodiments, the

range is 1 MHz to 400 MHz, but may in some aspects be in the range 1 MHz to 200 MHz. In other embodiments, the frequency or plurality of frequencies is in the range of 20 MHz to 300 MHz. If the total number of electrodes is N , a total of $N(N-1)/2$ independent complex-impedance measurements may be obtained at each frequency by making measurements between each electrode and every other electrode.

[0050] In some embodiments of the present disclosure which will now be explained further by way of example, the electrodes and the electronics package(s) may provide a measure of the capacitance component between electrode pairs and so provide an ECT-mode system for tomographic capacitance measurements of gas-solids or non-conducting liquid-solids multiphase flow in the pipe. The capacitance of the fluid in the pipe is in series with the capacitance of the pipe wall and, as has been disclosed in the literature, the measurements obtained using the electrodes 12 can be processed to obtain multi-view (normalised) capacitance values which do not include the pipe wall capacitance.

[0051] As a preliminary, two calibration measurements may be made. *Low-calibration* raw capacitance measurements C_l (containing $N(N-1)/2$ independent electrode-pair measurements for an N -electrode system) are made using a material with known low-permittivity (ϵ_l) (such as empty-pipe air or dry gas), followed by *high-calibration* capacitance measurements C_h using a material of known high-permittivity (ϵ_h) (such as full-pipe oil or packed dry solids).

[0052] A parallel-capacitance normalization model has been used in prior publications to derive the (measured) normalised capacitances C_n from the raw capacitances C_m

$$C_{n,parallel} = \frac{C_m - C_l}{C_h - C_l} \quad (1)$$

[0053] The effective capacitance of the electrically insulating pipe wall (C_{wall}), seen by each pair of the selected electrodes, is considered to be in series with the (unknown) fluid capacitance C_x . A ceramic material may be used for the insulating pipe wall to provide a stable value of C_{wall} . The measured raw capacitances of the unknown fluid (C_m), of the low-

permittivity calibration material (C_l) and of the high-permittivity calibration material (C_h) are then as follows:

$$\frac{1}{C_m} = \frac{1}{C_{\text{wall}}} + \frac{1}{C_x(\epsilon_m)}; \quad (2a)$$

$$\frac{1}{C_l} = \frac{1}{C_{\text{wall}}} + \frac{1}{C_x(\epsilon_l)}; \quad (2b)$$

$$\frac{1}{C_h} = \frac{1}{C_{\text{wall}}} + \frac{1}{C_x(\epsilon_h)}; \quad (2c)$$

[0054] Substituting Equations (2a) to (2c) into Equation (1), provides:

$$C_{n,parallel} = \frac{\left(\frac{1}{C_{\text{wall}}} + \frac{1}{C_x(\epsilon_m)} \right)^{-1} - \left(\frac{1}{C_{\text{wall}}} + \frac{1}{C_x(\epsilon_l)} \right)^{-1}}{\left(\frac{1}{C_{\text{wall}}} + \frac{1}{C_x(\epsilon_h)} \right)^{-1} - \left(\frac{1}{C_{\text{wall}}} + \frac{1}{C_x(\epsilon_l)} \right)^{-1}} \quad (3)$$

[0055] The (unknown) single-phase or multiphase fluid *only* capacitance C_x can be assumed to be proportional to the dielectric constant ϵ_m of the bulk fluid as follows (where k are proportional/geometrical constants for the different electrode pairs), viz.

$$C_x(\epsilon_m) = k\epsilon_m \quad (4a)$$

$$C_x(\epsilon_l) = k\epsilon_l \quad (4b)$$

$$C_x(\epsilon_h) = k\epsilon_h \quad (4c)$$

And then Equation (3) can be written as:

$$\mathbf{C}_{n,parallel} = \frac{\left(\frac{1}{\mathbf{C}_{wall}} + \frac{1}{\mathbf{k}\epsilon_m}\right)^{-1} - \left(\frac{1}{\mathbf{C}_{wall}} + \frac{1}{\mathbf{k}\epsilon_l}\right)^{-1}}{\left(\frac{1}{\mathbf{C}_{wall}} + \frac{1}{\mathbf{k}\epsilon_h}\right)^{-1} - \left(\frac{1}{\mathbf{C}_{wall}} + \frac{1}{\mathbf{k}\epsilon_l}\right)^{-1}} \quad (5)$$

[0056] Prior publications have disclosed a qualitative image reconstruction method based on the normalized capacitance $\mathbf{C}_{n,parallel}$. This is illustrated in Fig 2, with the linear back-projection (LBP) algorithmic equations (as shown in the figure) as an example. Phase fraction determination in this method is largely based on an empirical model which assumes that $\mathbf{C}_{n,parallel}$ is proportional to ϵ_m . (This is only true if $\mathbf{C}_{wall} \gg \mathbf{k}\epsilon_m$).

[0057] A series-capacitance normalisation model has previously been proposed to derive alternative (measured) normalised capacitances $\mathbf{C}_n$ from the raw capacitances $\mathbf{C}_m$, viz.

$$\mathbf{C}_n = \frac{\frac{1}{\mathbf{C}_m} - \frac{1}{\mathbf{C}_l}}{\frac{1}{\mathbf{C}_h} - \frac{1}{\mathbf{C}_l}} \quad (6)$$

[0058] From Equations (2a) to (2c), and Equations (4a) to (4c), the (measured) normalised capacitances $\mathbf{C}_n$ can be related to the ultimately desired (multiphase fluid-only) mixture permittivity ϵ_m , as follows:

$$\mathbf{C}_n = \frac{\left(\frac{1}{\mathbf{C}_{wall}} + \frac{1}{\mathbf{C}_x(\epsilon_m)}\right) - \left(\frac{1}{\mathbf{C}_{wall}} + \frac{1}{\mathbf{C}_x(\epsilon_l)}\right)}{\left(\frac{1}{\mathbf{C}_{wall}} + \frac{1}{\mathbf{C}_x(\epsilon_h)}\right) - \left(\frac{1}{\mathbf{C}_{wall}} + \frac{1}{\mathbf{C}_x(\epsilon_l)}\right)} = \frac{\frac{1}{\mathbf{C}_x(\epsilon_m)} - \frac{1}{\mathbf{C}_x(\epsilon_l)}}{\frac{1}{\mathbf{C}_x(\epsilon_h)} - \frac{1}{\mathbf{C}_x(\epsilon_l)}} = \frac{\frac{1}{\epsilon_m} - \frac{1}{\epsilon_l}}{\frac{1}{\epsilon_h} - \frac{1}{\epsilon_l}} \quad (7)$$

[0059] Using this approach, the wall-capacitances $\mathbf{C}_{wall}$ (and the sensors' geometrical factors $\mathbf{k}$) are substantially removed in the normalized (measured) capacitances $\mathbf{C}_n$, by the use of the series-capacitance model of Equation (6). However, it can be seen from Equation (7)

that, the resulting normalized capacitances C_n are a nonlinear function of the desired mixture permittivity ϵ_m , which is to be measured and/or to be imaged.

[0060] A qualitative image reconstruction method based on the series-model normalized capacitance C_n has been proposed in prior documents and is illustrated in Fig 3, with the linear back-projection (LBP) algorithm as an example. Phase fraction determination in this method is largely based on C_n and an empirical (calibration) model.

[0061] In embodiments of the present disclosure, and in contrast with prior disclosures, measured multi-view (normalised) capacitances C_n (that are free from the effects of pipe-wall capacitances and the sensors' geometrical factors k) are converted to a fundamental physics parameter – the corresponding multi-view mixture permittivity ϵ_m . These multi-view mixture permittivities ϵ_m (which depend only on what is present in the flow in the pipe 10) may then be used as input to an image reconstruction step, removing the issues of the nonlinearity in the imaging domain and of the empirical correlations/calibrations in the subsequent step(s) of determining phase fractions based on the measured C_n . This may then be used to compute the solids fraction of a gas-solids flow or a gravity-conveyed powder flow or of a non-conducting liquid-solids flow (such as an OBM), with the use of an appropriate dielectric mixing model(s). Based on the multi-view permittivity ϵ_m data, a direct and/or iterative quantitative reconstruction of the mixture-permittivity distribution can be made.

[0062] Rearranging Equation (7) provides:

$$\epsilon_m = \frac{1}{C_n \left(\frac{1}{\epsilon_h} - \frac{1}{\epsilon_l} \right) + \frac{1}{\epsilon_l}} \quad (8)$$

[0063] Quantitative image reconstruction (at time instant t typically of 1-ms resolution), based on this conversion to permittivity more accurately processes capacitance measurements into an image directly representing the permittivity properties of a multiphase mixture. An embodiment is shown by Fig 4. A linear back-projection (LBP) algorithm is modified from that

shown in Fig. 3 to use the measured $\epsilon_m(t)$ as the input and provides the reconstructed image of the mixture-permittivity space-time distribution $\epsilon_m(\mathbf{r}; t)$ as output (here $\mathbf{r}=(x,y,z)$ defines the central positions of the image pixels or image regions consisting of chosen multiple pixels). Iterative image reconstruction algorithm(s) using the measured $\epsilon_m(t)$ as the input may be used in addition to or in place of the LBP algorithm (LBP may be used to provide an initial estimate of the mixture-permittivity space-time distribution $\epsilon_m(\mathbf{r}; t)$ for an iterative algorithm); processing in this way overcomes distribution-dependent ‘softfield’ effects.

[0064] As illustrated in Fig. 4, the output of the reconstruction of mixture-permittivity distribution $\epsilon_m(\mathbf{r}; t)$, which may be processed to indicate the underlying flow-regime information, may be used as input to an appropriate dielectric mixing law(s) (implicit function f_g below for a pixel-wise ‘uniform’ gas-solids flow; or f_l for a pixel-wise ‘uniform’ liquid-solids flow) to calculate the solids-fraction distribution $\alpha_{solids}(\mathbf{r}; t)$:

$$\alpha_{solids}(\mathbf{r}; t) = f_g(\epsilon_m(\mathbf{r}; t), \epsilon_{solids}, \epsilon_{gas}) \quad (9a)$$

$$\alpha_{solids}(\mathbf{r}; t) = f_l(\epsilon_m(\mathbf{r}; t), \epsilon_{solids}, \epsilon_{liquid}) \quad (9b)$$

The above solids-fraction distribution time-averaged over a short (say $\Delta T=100\text{-ms}$) integration interval, $\alpha_{solids}(\mathbf{r}; \Delta T)$, may be obtained as:

$$\alpha_{solids}(\mathbf{r}; \Delta T) = \frac{1}{\Delta T} \int_0^{\Delta T} \alpha_{solids}(\mathbf{r}; t) dt \quad (10a)$$

Some further data processing on the above short-time (over ΔT) solids-holdup distribution may be desirable, e.g. short-time pipe-averaged (over cross-sectional area A) solids holdup:

$$\alpha_{solids}(\Delta T) = \frac{1}{A} \int_A \alpha_{solids}(\mathbf{r}; \Delta T) dA \quad (10b)$$

[0065] The solids-velocity distribution $V_{solids}(\mathbf{r}; \Delta T)$ may be obtained by determining the transit-time distribution $\tau_m(\mathbf{r}; \Delta T)$, which corresponds to the peak values at each pixel-position of the cross-correlation function $R_{12}(\mathbf{r}; \tau)$ between the instantaneous solids-fraction

$\alpha_{solids}(\mathbf{r}; t)$ distributions measured at at least two axially-spaced (by a distance L) planar cross sections (Figs. 9 and 10), viz.

$$V_{solids}(\mathbf{r}; \Delta T) = \frac{L}{\tau_m(\mathbf{r}; \Delta T)} \quad (11)$$

$$\tau_m(\mathbf{r}; \Delta T) \xleftarrow{\text{maximum}} R_{12}(\mathbf{r}; \tau) = \frac{1}{\Delta T} \int_0^{\Delta T} \alpha_{solids,1}(\mathbf{r}; t) \alpha_{solids,2}(\mathbf{r}; t - \tau) dt \quad (12)$$

The solids volumetric flow rate q_{solids} averaged over the pipe cross-sectional area A and the over a long time interval T is therefore:

$$q_{solids} = \left(\frac{1}{A}\right) \left(\frac{1}{T}\right) \int_A \int_0^T \alpha_{solids}(\mathbf{r}; \Delta T) \times V_{solids}(\mathbf{r}; \Delta T) d(\Delta T) dA \quad (13)$$

[0066] Obtaining accurate parameters relating to the solid or the powder flow is critical in accurately calculating the amount of solid or powder that is passing through a particular section of piping. As is discussed later in more detail, typical multiphase solid-containing flows may be mixed with a further fluid, such as water, and/or additional proppants. In order to accurately determine the quantity of solid passing into the mixing unit, in one embodiment of the present invention, the abovementioned ECT-mode measurement system is used simultaneously with the ERT-mode measurement, i.e. in EIT mode.

[0067] In one embodiment, the ECT-mode measurement is operated at one or more operating frequencies selected from the frequency range of 1 MHz to 400 MHz, and in some embodiments in the range of 1 MHz to 200 MHz. Selecting a frequency and/or a plurality of frequencies from this range provides the advantage of being able to detect varying levels of moisture content of the solids being measured, to identify bound-water and free-water in solids.

[0068] Another ECT-mode embodiment of the present disclosure uses the parallel-capacitance normalization model above. The sensing electrodes 12 may be designed with a very thin dielectric coating on the electrodes 12 such that the pipe-wall capacitance is much larger than the expected maximum of the fluid capacitance, which can be expressed as $C_{wall} \gg$

$\max(C_x)$. Then $C_m \cong C_x$ and Equation (5) reduces to $C_{n,parallel} \cong (\epsilon_m - \epsilon_l)/(\epsilon_h - \epsilon_l)$ so that $C_{n,parallel}$ is proportional to ϵ_m . This provides a way to convert to permittivity measurements ϵ_m , where $\epsilon_m = C_{n,parallel}(\epsilon_h - \epsilon_l) + \epsilon_l$. ϵ_m can then be used as input to an LBP algorithm and/or an iterative image reconstruction algorithm so as to obtain the reconstructed image of the mixture-permittivity distribution $\epsilon_m(\mathbf{r})$, and the multiphase-flow solids fraction and solids velocity as outputs.

[0069] In some other embodiments of the present disclosure, the electrodes 12 and the electronics package(s) 14 shown in Fig 1 or Fig 1A may provide measure of the resistance or conductance component between electrode pairs and so provide an ERT-mode system for tomographic resistance measurements of a conducting liquid-solids multiphase flow in pipe 10. (Resistance is the reciprocal of conductance).

[0070] The measured multi-view (normalised) conductances G_n (that are free from the effects of electrode contact conductances) are converted to multi-view mixture conductivities σ_m . These flow-dependent-only conductivities σ_m may then be converted to the solids and/or liquid-fraction, with the use of conductivity mixing model(s). Based on the multi-view σ_m data, a direct and/or iterative quantitative reconstruction of the mixture-conductivity distribution may be made (Fig 5). The mathematical treatment is analogous to that given above for capacitance, as will now be shown.

To perform an appropriate calibration of the ERT-mode system, *low-calibration* raw
[0071] conductance measurements G_l may be made by using a material with known low-conductivity (σ_l) (such as full-pipe fresh water), followed by *high-calibration* ones G_h by using a material of a known high-conductivity (σ_h) (such as full-pipe salty water).

[0072] The effective contact resistance ($R_{contact}$) of the electrodes of an ERT-mode sensor is in series with the fluid (unknown) resistance R_x (the electrode material may be chosen so that $R_{contact}$ is small and/or is stable).

[0073] The measured raw conductances of the unknown fluid (G_m), of the low-conductivity calibration material (G_l) and of the high-conductivity calibration material (G_h) are then as follows (from $R_m = R_{\text{contact}} + R_x$):

$$\frac{1}{G_m} = \frac{1}{G_{\text{contact}}} + \frac{1}{G_x(\sigma_m)}; \quad (102a)$$

$$\frac{1}{G_l} = \frac{1}{G_{\text{contact}}} + \frac{1}{G_x(\sigma_l)}; \quad (102b)$$

$$\frac{1}{G_h} = \frac{1}{G_{\text{contact}}} + \frac{1}{G_x(\sigma_h)}; \quad (102c)$$

[0074] The single-phase or multiphase fluid *only* (unknown) conductance G_x can be assumed to be proportional to the conductivity σ_m of the bulk fluid as follows (where k are proportional/geometrical constants for the different electrode pairs), viz.

$$G_x(\sigma_m) = k\sigma_m \quad (104a)$$

$$G_x(\sigma_l) = k\sigma_l \quad (104b)$$

$$G_x(\sigma_h) = k\sigma_h \quad (104c)$$

[0075] A normalisation model (analogous to the series-capacitance model at Equation (6) above) can be used to derive the measured normalised conductances G_n from the raw conductances G_m , viz.

$$G_n = \frac{\frac{1}{G_m} - \frac{1}{G_l}}{\frac{1}{G_h} - \frac{1}{G_l}} \quad (106)$$

[0076] From Equations (102a) to (102c), and Equations (104a) to (104c), it is then possible to relate the (measured) normalised conductances $\mathbf{G}_n$ to the ultimately desired (multiphase fluid-only) mixture conductivity σ_m , as follows:

$$\mathbf{G}_n = \frac{\left(\frac{1}{\mathbf{G}_{\text{contact}}} + \frac{1}{\mathbf{G}_x(\sigma_m)} \right) - \left(\frac{1}{\mathbf{G}_{\text{contact}}} + \frac{1}{\mathbf{G}_x(\sigma_l)} \right)}{\left(\frac{1}{\mathbf{G}_{\text{contact}}} + \frac{1}{\mathbf{G}_x(\sigma_h)} \right) - \left(\frac{1}{\mathbf{G}_{\text{contact}}} + \frac{1}{\mathbf{G}_x(\sigma_l)} \right)} = \frac{\frac{1}{\mathbf{G}_x(\sigma_m)} - \frac{1}{\mathbf{G}_x(\sigma_l)}}{\frac{1}{\mathbf{G}_x(\sigma_h)} - \frac{1}{\mathbf{G}_x(\sigma_l)}} = \frac{\frac{1}{\sigma_m} - \frac{1}{\sigma_l}}{\frac{1}{\sigma_h} - \frac{1}{\sigma_l}} \quad (107)$$

[0077] In this way, the electrode contact conductances $\mathbf{G}_{\text{contact}} = 1/\mathbf{R}_{\text{contact}}$ and also the sensors' geometrical factors $\mathbf{k}$ are substantially removed. However, it can be seen from Equation (107) that the resulting normalized conductances $\mathbf{G}_n$ are a nonlinear function of the desired mixture conductivity σ_m to be measured and/or to be imaged.

[0078] In embodiments of the present disclosure, the normalised conductances $\mathbf{G}_n$ are converted to the mixture conductivity σ_m which is a fundamental physics parameter and this mixture-conductivity (σ_m) is itself used as the input to the image reconstruction step, removing the issues of the nonlinearity in the imaging domain and of the empirical correlations/calibrations in the subsequent step(s) of determining phase fractions based on the measured $\mathbf{G}_n$.

[0079] Rearranging Equation (107) gives

$$\sigma_m = \frac{1}{\mathbf{G}_n \left(\frac{1}{\sigma_h} - \frac{1}{\sigma_l} \right) + \frac{1}{\sigma_l}} \quad (108)$$

[0080] A quantitative image reconstruction method based on the outcome of the above step is shown in Fig 5. An LBP algorithm (as shown) and/or an iterative image reconstruction algorithm use the measured multi-view $\sigma_m(t)$ as the input and give the reconstructed image of

the mixture-conductivity distribution $\sigma_m(\mathbf{r}; t)$ as output (here $\mathbf{r}=(x,y,z)$ specifies the central positions of the image pixels or image regions consisting of multiple pixels).

[0081] As illustrated in Fig.5, the output of the reconstruction of mixture-conductivity distribution $\sigma_m(\mathbf{r}; t)$ may be used as input to an appropriate conductivity mixing law (function h_l below for a pixel-wise ‘uniform’ liquid-solids flow) to calculate the solids-fraction distribution $\alpha_{solids}(\mathbf{r}; t)$:

$$\alpha_{solids}(\mathbf{r}; t) = h_l(\sigma_m(\mathbf{r}; t), \sigma_{solids}, \sigma_{liquid}) \quad (109)$$

[0082] The solids-fraction distribution time-averaged over a short integration interval ΔT (of say 100-ms) $\alpha_{solids}(\mathbf{r}; \Delta T)$ may be obtained as from Equation (10a). The solids-velocity distribution $V_{solids}(\mathbf{r}; \Delta T)$ may be obtained from Equations (11) and (12) for a horizontal (Fig 11) or vertical (Fig 12) liquid-solids flow (other pipe deviations are also possible). The solids volumetric flow rate q_{solids} averaged over the pipe cross-sectional area A and then over a long time interval T may be similarly calculated from Equation (13).

Further embodiments of this disclosure use the same set of electrodes 12 to provide an electrical impedance tomography (EIT) system which is a more general approach encompassing both ERT-mode conductance and ECT-mode capacitance measurements. At an appropriate operating frequency or a plurality of frequencies (with 1 MHz to 400 MHz range), an EIT system can measure the conductances (**G**) and capacitances (**C**) of different electrode pairs simultaneously, for example by the use of phase-sensitive (in-phase and quadrature-phase) detection methods. The electrical admittances **Y** (admittance is the reciprocal of impedance) can be represented by $\mathbf{Y} = \mathbf{G} + j\omega\mathbf{C}$, where ω is the angular frequency. The fluid mixture complex-conductivity can be expressed $\sigma_m^* = \sigma_m + j\omega\epsilon_o\epsilon_m$ (where $\epsilon_o = 8.854\text{pF/m}$). Alternatively, the fluid mixture complex-permittivity can be used, and is expressed $\epsilon_m^* = \epsilon_m' + j\epsilon_m'' = \epsilon_m + j\sigma_m/(\omega\epsilon_o)$.

[0084] A single frequency or a plurality of different frequencies used to measure or probe the pipe may be selected from the high-frequency range, from a range of 1 MHz to 400 MHz, and in some aspects in the range of 1 MHz to 200 MHz. Other embodiments may use a single

frequency or a plurality of different frequencies from a frequency range of 20 MHz to 300 MHz. Selecting a frequency/frequencies from this range provides the advantageous effect of enabling both the real and imaginary parts of the aforementioned admittance or complex-conductivities/permittivities to be measured simultaneously for a multiphase mixture containing solids, i.e., a gas-solids, liquid-solids, and/or gas-liquid-solids multiphase fluid. This is because the real and imaginary terms are of comparable and/or detectable magnitude when using a frequency/frequencies from the aforementioned range and when measuring a solid-containing multiphase fluid.

[0085] Calibration measurements may again be performed. The measured raw admittances of the unknown multiphase fluid ($\mathbf{Y}_m$), of the low complex-conductivity calibration material ($\mathbf{Y}_l$), and of the high complex-conductivity calibration material ($\mathbf{Y}_h$), are then as follows (from $1/\mathbf{Y}_m = 1/\mathbf{Y}_{\text{contact}} + 1/\mathbf{Y}_x$):

$$\frac{1}{\mathbf{Y}_m} = \frac{1}{\mathbf{Y}_{\text{contact}}} + \frac{1}{\mathbf{Y}_x(\sigma_m^*)}; \quad (202a)$$

$$\frac{1}{\mathbf{Y}_l} = \frac{1}{\mathbf{Y}_{\text{contact}}} + \frac{1}{\mathbf{Y}_x(\sigma_l^*)}; \quad (202b)$$

$$\frac{1}{\mathbf{Y}_h} = \frac{1}{\mathbf{Y}_{\text{contact}}} + \frac{1}{\mathbf{Y}_x(\sigma_h^*)}; \quad (202c)$$

[0086] The single-phase or multiphase fluid *only* (unknown) admittances $\mathbf{Y}_x$ can be assumed to be proportional to the complex-conductivity σ_m^* of the bulk fluid as follows (where $\mathbf{k}$ are proportional/geometrical constants for the different electrode pairs), viz.

$$\mathbf{Y}_x(\sigma_m^*) = \mathbf{G}_x(\sigma_m) + j\omega\epsilon_o \mathbf{C}_x(\epsilon_m) = \mathbf{k}\sigma_m + j\omega\epsilon_o \mathbf{k}\epsilon_m = \mathbf{k}\sigma_m^* \quad (204a)$$

$$\mathbf{Y}_x(\sigma_l^*) = \mathbf{G}_x(\sigma_l) + j\omega\epsilon_o \mathbf{C}_x(\epsilon_l) = \mathbf{k}\sigma_l + j\omega\epsilon_o \mathbf{k}\epsilon_l = \mathbf{k}\sigma_l^* \quad (204b)$$

$$\mathbf{Y}_x(\sigma_h^*) = \mathbf{G}_x(\sigma_h) + j\omega\epsilon_o \mathbf{C}_x(\epsilon_h) = \mathbf{k}\sigma_h + j\omega\epsilon_o \mathbf{k}\epsilon_h = \mathbf{k}\sigma_h^* \quad (204c)$$

[0087] The normalised admittances $\mathbf{Y}_n$ (from the raw admittances $\mathbf{Y}_m$) are derived similarly to the normalised capacitances (Equation 6) or normalised conductances (Equation 106), as follows:

$$\mathbf{Y}_n = \frac{\frac{1}{\mathbf{Y}_m} - \frac{1}{\mathbf{Y}_l}}{\frac{1}{\mathbf{Y}_h} - \frac{1}{\mathbf{Y}_l}} \quad (206)$$

[0088] From Equations (202a) to (202c), and Equations (204a) to (204c), the (measured) normalised admittances $\mathbf{Y}_n$ can then be related to the ultimately desired (multiphase fluid-only) mixture complex conductivity σ_m^* , as follows:

$$\mathbf{Y}_n = \frac{\left(\frac{1}{\mathbf{Y}_{\text{contact}}} + \frac{1}{\mathbf{Y}_x(\sigma_m^*)} \right) - \left(\frac{1}{\mathbf{Y}_{\text{contact}}} + \frac{1}{\mathbf{Y}_x(\sigma_l^*)} \right)}{\left(\frac{1}{\mathbf{Y}_{\text{contact}}} + \frac{1}{\mathbf{Y}_x(\sigma_h^*)} \right) - \left(\frac{1}{\mathbf{Y}_{\text{contact}}} + \frac{1}{\mathbf{Y}_x(\sigma_l^*)} \right)} = \frac{\frac{1}{\mathbf{Y}_x(\sigma_m^*)} - \frac{1}{\mathbf{Y}_x(\sigma_l^*)}}{\frac{1}{\mathbf{Y}_x(\sigma_h^*)} - \frac{1}{\mathbf{Y}_x(\sigma_l^*)}} = \frac{\frac{1}{\sigma_m^*} - \frac{1}{\sigma_l^*}}{\frac{1}{\sigma_h^*} - \frac{1}{\sigma_l^*}} \quad (207)$$

[0089] In this way, the electrode contact/wall impedances $\mathbf{Z}_{\text{contact}} = 1/\mathbf{Y}_{\text{contact}}$ (and the sensors' geometrical factors $\mathbf{k}$) are substantially removed in the normalised (measured) admittances $\mathbf{Y}_n$; the resulting normalized admittances $\mathbf{Y}_n$ are a nonlinear function of the desired mixture-complex conductivity σ_m^* to be measured and/or to be imaged.

[0090] In embodiments of this disclosure, the normalised admittances $\mathbf{Y}_n$ are converted to a fundamental physics parameter which is the mixture complex-conductivity σ_m^* , and this mixture-conductivity (σ_m^*) is the input to the image reconstruction step (Figs 6 and 7), removing the issues of the nonlinearity in the imaging domain and of the empirical correlations/calibrations in the subsequent step(s) of determining phase fractions based on the measured $\mathbf{Y}_n$. Phase fractions may be determined from σ_m^* , based on complex conductivity-mixing models – or based on their real and imaginary parts.

[0091] Rearranging Equation (207) gives:

$$\sigma_m^* = \frac{1}{\mathbf{Y}_n \left(\frac{1}{\sigma_h^*} - \frac{1}{\sigma_l^*} \right) + \frac{1}{\sigma_l^*}} \quad (208)$$

A quantitative image reconstruction method based on the outcome of the above step is shown in Figs 6 and 7. An LBP algorithm (as shown) and/or an iterative image reconstruction algorithm, uses the measured σ_m^* as the input and provides a reconstructed image of the mixture-conductivity distribution $\sigma_m^*(\mathbf{r})$ as output.

[0092] As illustrated in Fig.6, the output of the reconstruction of mixture complex-conductivity distribution $\sigma_m^*(\mathbf{r}; t)$ may be used as input to an appropriate complex-conductivity mixing law (function H_g below for a pixel-wise ‘uniform’ gas-solids flow, Fig 6; function H_l for a pixel-wise ‘uniform’ liquid-solids flow, Fig 7) to calculate the solids-fraction distribution $\alpha_{solids}(\mathbf{r}; t)$:

$$\alpha_{solids}(\mathbf{r}; t) = H_g(\sigma_m^*(\mathbf{r}; t), \sigma_{solids}^*, \sigma_{gas}^*) \quad (209a)$$

$$\alpha_{solids}(\mathbf{r}; t) = H_l(\sigma_m^*(\mathbf{r}; t), \sigma_{solids}^*, \sigma_{liquid}^*) \quad (209b)$$

[0093] The solids-fraction distribution time-averaged over a short integration interval ΔT (of say 100-ms) $\alpha_{solids}(\mathbf{r}; \Delta T)$ may be obtained in a similar manner to Equation (10a). The solids-velocity distribution $V_{solids}(\mathbf{r}; \Delta T)$ may be obtained similarly to Equations (11) and (12) for horizontal (Fig 11) or vertical (Fig 12) liquid-solids flows. The solids volumetric flow rate q_{solids} averaged over the pipe cross-sectional area A and the over a long time interval T may be similarly calculated from Equation (13).

[0094] An EIT measurement system according to the above and operated at a single frequency or a plurality of frequencies within the frequency range of 1 MHz to 400 MHz, or 1 MHz to 200 MHz, is able, not only to provide accurate information on the current solid-containing multiphase fluid flowing through the section of pipe, but also accurate information on a second, different solid-containing multiphase fluid that flows through at a different time. In other words, the system may not require extensive off-line calibration or reconfiguration when the type of multiphase fluid passing through the pipe changes, owing to the use of a wide

frequency range that enables on-line calibration and fluids-typing by making comparable measurements of conductances and capacitances of any type of multiphase fluid containing solids, over the entire and/or chosen regions of the pipe cross section(s).

[0095] Electrical impedance tomography facilitates a rapid imaging of flow complex-conductivity distribution $\sigma_m^*(\mathbf{r}; t) = \sigma_m(\mathbf{r}; t) + j\omega\epsilon_o\epsilon_m(\mathbf{r}; t)$. This is realized by the simultaneous measurement of two electrical parameters (permittivity ϵ and conductivity σ , from the simultaneously measured capacitance C and conductance G) of solids-containing multiphase flow, at a single or a plurality of frequencies (ω).

[0096] As a result, the cross-pipe distribution of the loss-factor $\delta_m(\mathbf{r}; t)$ below may be useful for flow component spectroscopic identification and/or flow diagnosis:

$$\epsilon'(\mathbf{r}; t) = \epsilon_m(\mathbf{r}; t) \quad (210a)$$

$$\epsilon''(\mathbf{r}; t) = \sigma_m(\mathbf{r}; t)/(\omega\epsilon_o) \quad (210b)$$

$$\delta_m(\mathbf{r}; t) = \epsilon''(\mathbf{r}; t)/\epsilon'(\mathbf{r}; t) = \sigma_m(\mathbf{r}; t)/(\omega\epsilon_o\epsilon_m(\mathbf{r}; t)) \quad (210c)$$

[0097] For a dry gas-solids flow (with $\sigma_{gas} = 0$ and $\sigma_{solids} \approx 0$), the loss-factor $\delta_m(\mathbf{r}; t)$ is largely zero; the ϵ_{solids} is typically known for a known dry solids or may be obtained by online (in-situ) calibration from near-wall measurements of solids-rich pipe region (Figs 9 and 10). In other words, a near-wall measurement may be made such that it corresponds to a high bulk density (a low porosity) of the measured solids, i.e., the solid fraction at this near-wall region is relatively the highest. The increase in the solids (bound-water) moisture content (MC) may largely increase both σ_{solids} and ϵ_{solids} .

[0098] A density-independent function based on the Argand-diagram of the complex permittivity divided by the density of the materials has been previously tested with good results (Klaus Kupfer, 'Methods of density-independent moisture measurement', pp.135-68, Klaus Kupfer (Ed.), *Electromagnetic Aquametry*, Springer 2005). From the Argand diagram, obtained from data at a given frequency and temperature, the following linear regression (calibration) equation with slope a_f and intercept k may be obtained:

$$(\varepsilon''/\rho) = a_f((\varepsilon'/\rho) - k) \quad (211)$$

[0099] Equation (211) can also be used for the determination of solids density. The calibration parameter a_f may be used in the following density-independent function, ψ_f :

$$\psi_f = \sqrt{\frac{\varepsilon''}{\varepsilon'(a_f \varepsilon' - \varepsilon'')}} \quad (212)$$

The relation between solids moisture content (MC) and ψ_f is linear; from the linear regression equation with the slope a and the intercept b , the MC is determined as follows:

$$MC = \frac{\psi_f - b}{a} \quad (213)$$

[00100] For gas-solids flows, to determine solids fraction independent of changes in the solids moisture content, it is desirable to track the changes in $\sigma_{solids}^* = \sigma_{solids} + j\omega\varepsilon_o\varepsilon_{solids}$ (an input of an implicit mixing law of Equation (209a)). Processing of time-series data of solids-rich (gas-free) part of the tomographic data or cross-sectional image $\sigma_m^*(\mathbf{r}; t)$, for example the pipe cross-sectional region near the underside of a solids-conveying horizontal pipe (Fig 9) or the near wall region of a vertical pipe (Fig 10), may permit online estimate of σ_{solids}^* (Fig 4, Fig 6 and Fig 8), that is:

$$\sigma_{solids}^* \approx \sigma_m^*(\mathbf{r}; t); (\mathbf{r}; t) \in (near\ wall, solids\ rich) \quad (214)$$

[00101] For liquid (water)-solids flows, to determine the solids fraction independent of changes in the water salinity (conductivity), it is desirable to track the changes in the complex-conductivity of the carrying liquid (water) $\sigma_{liquid}^* = \sigma_{liquid} + j\omega\varepsilon_o\varepsilon_{liquid}$ (an input to an implicit mixing law of Equation (209b)). Time-series data processing of liquid-rich (solids-free) part of the tomographic data or cross-sectional image $\sigma_m^*(\mathbf{r}; t)$, for example the pipe cross-sectional region near the topside of a solids-conveying horizontal pipe (Fig. 11), may permit an online estimate of σ_{liquid}^* (Fig 5, Fig 7 and Fig 8), that is

$$\sigma_{liquid}^* \approx \sigma_m^*(\mathbf{r}; t); (\mathbf{r}; t) \in (near\ wall, liquid\ rich) \quad (215)$$

[00102] Being able to isolate differing regions of the pipe 10 may be useful in providing an accurate representation of the parameters of the solids/liquid. For example, dry powder solids may differ in the amount of bound water or their moisture content, and thus have different conductivity and permittivity values. In such cases, a different value of the parameters, namely σ_{solids}^* or σ_{liquid}^* , may be required to be captured online at single and/or a plurality of frequencies in order to facilitate the calculation of the solids fraction (and the solids moisture content).

[00103] For example, this situation may be realized during batch changes of the multiphase fluid, e.g., the dry powder, whereby the moisture content changes between batches. Correspondingly, a system able to isolate changes in the solids (powder) moisture content by making measurements of the solids-rich (gas free) regions of the pipe or duct is able to track the parameters of the equations used above without performing offline analysis.

[00104] A possibility, in yet further embodiments, is that the electrodes 12 are replaced with coils used as sensors to measure mutual-inductance between pairs of coils. The measurements of inductance may then be processed in a manner analogous to the above described processing of capacitance, conductance or impedance measurements in order to determine magnetic permeability of the multiphase flow and/or eddy-current conductivity of the flow independent of effects arising externally to the fluid flow itself. Conductivity may have general applicability; magnetic permeability may be unable to differentiate between water, oil and gas phases but may be used to observe some metallic solid particles entrained in the multiphase fluid flow.

[00105] The mixture permittivity ϵ_m or mixture conductivity σ_m calculated, for example, from Equation (8) or (108) respectively, or obtained from mixture complex-conductivity σ_m^* from Equation (208), from one or more pair of sensors (electrodes and/or coils), can be used with dielectric mixing models to derive the phase fractions of the constituents of a mixture.

[00106] A large number of theoretical models for effective physical properties of complex multiphase materials have been proposed (Wang M and Pan N, "Predictions of effective

physical properties of complex multiphase materials", *Materials Science and Engineering R* 63 (2008) 1–30). Some of the models have highly specific applications, while others have wider applicability. For instance, a generalized form of the Maxwell-Garnett effective-medium-approximation (EMA) formula may be used to calculate mixture permittivity ε_m of a multiphase mixture comprising N different types of spherical inclusions (the spheres may be of varying sizes but are small compared with the wavelength of the applied electrical field): (Schwank M and Green T, 'Simulated effects of soil temperature and salinity on capacitance sensor measurements', *Sensors* 2007, 7, 548-577, <http://www.mdpi.com/journal/sensors>):

$$\varepsilon_m = \varepsilon_c + 3\varepsilon_c \left(\sum_{i=1}^N v_i \frac{\varepsilon_i - \varepsilon_c}{\varepsilon_i + 2\varepsilon_c} \right) / \left(1 - \sum_{i=1}^N v_i \frac{\varepsilon_i - \varepsilon_c}{\varepsilon_i + 2\varepsilon_c} \right) \quad (14)$$

[00107] In the above, ε_c is the permittivity of the continuous (host) phase; ε_i and v_i are the permittivities and volume fractions of the dispersed phases, respectively. Note that the mixing formula such as Equation (14) may be applicable for *complex* permittivity values ε_c and ε_i .

[00108] Equation (14) may be used to model the permittivity $\varepsilon_m^* = \varepsilon'_m + j\varepsilon''_m = \varepsilon_m + j\sigma_m/(\omega\varepsilon_0)$ of a sensing or imaging region containing (largely uniform) multiphase (gas/liquid/solids) mixture, with region-wise bulk porosity ϕ and (free) water volumetric content α_{water} . For instance, for a liquid-solids multiphase mixture with spherical solid particles (e.g. with $\varepsilon_{solids} = 5.5 + j0.2$ for quartz sand) and entrained gas bubbles (with $\varepsilon_{gas} = 1$) enclosed in the liquid water (with complex permittivity ε_{water}), Equation (14) may be evaluated for $N = 2$ as follows:

$$\varepsilon_m = \varepsilon_{water} + 3\varepsilon_{water} \frac{\alpha_{solids} \left(\frac{\varepsilon_{solids} - \varepsilon_{water}}{\varepsilon_{solids} + 2\varepsilon_{water}} \right) + \alpha_{gas} \left(\frac{\varepsilon_{gas} - \varepsilon_{water}}{\varepsilon_{gas} + 2\varepsilon_{water}} \right)}{1 - \left(\alpha_{solids} \left(\frac{\varepsilon_{solids} - \varepsilon_{water}}{\varepsilon_{solids} + 2\varepsilon_{water}} \right) + \alpha_{gas} \left(\frac{\varepsilon_{gas} - \varepsilon_{water}}{\varepsilon_{gas} + 2\varepsilon_{water}} \right) \right)} \quad (15a)$$

$$\phi = 1 - \rho_b / \rho_{solids} \quad (15b)$$

$$\alpha_{solids} = 1 - \phi \quad (15c)$$

$$\alpha_{gas} = \phi - \alpha_{water} \quad (15d)$$

Here ρ_b is the dry solid bulk density (mass per bulk volume); ρ_{solids} the solid particle density.

[00109] Water complex permittivity ε_{water} may be calculated from a Debye-type dielectric relaxation law, as a function of frequency ω , water temperature and salinity (for an explicit formula, see applicant's US patent number 6,831,470B2):

$$\varepsilon_{water} = \varepsilon_{\infty,water} + \frac{\varepsilon_{s,water} - \varepsilon_{\infty,water}}{1 + j(\omega/\omega_{water})} - j \frac{\sigma_{water}}{\omega \varepsilon_0} \quad (16)$$

where $\varepsilon_{s,water}$ is the static permittivity of water ($\varepsilon_{s,water} \approx 81$ for fresh water at 20°C); $\varepsilon_{\infty,water}$ is the water permittivity at infinite frequency ($\varepsilon_{\infty,water} \approx 4$); the relaxation frequency $f_{water} = \omega_{water}/(2\pi)$ is about 17 GHz for free fresh water at 20°C; σ_{water} is the electrical conductivity of the free water.

[00110] The (complex) dielectric mixing model of Equation (15a) may be suitable for a solids system with relatively high free water contents, where water is the continuous phase (with gas bubbles being dispersed within it).

[00111] For a liquid-solids flow, it is possible to map out the solids fraction distribution $\alpha_{solids}(\mathbf{r}; t)$ from the (complex) permittivity tomographic distribution $\varepsilon_m(\mathbf{r}; t)$, based on a mixing model such as Equation (15a) applied pixel-wise. The required water (complex) permittivity ε_{water} may be estimated from solids-free (water-rich) part of the sensors' time-series data, e.g. measured by the near-wall electrode pair(s) at the periphery of the topside of a horizontal pipe (Fig 11). This may also permit the estimate of the water conductivity σ_{water} (directly from $\sigma_{water} \approx \sigma_m = \omega \varepsilon_0 \text{Im}[\varepsilon_m]$; or indirectly, from both σ_m and ε_m , see applicant's US patent number 6,831,470B2).

[00112] It may be desirable to generate stratified moving liquid-solids flows for the benefits of online ‘calibration’ measurement of the solids and/or the liquid complex permittivities, by controlling the liquid and/or solids flow rates based on tomographic flow mapping (Fig 11).

[00113] However, different dielectric responses may arise for a gas-solids multiphase mixture with bound water (at relatively low moisture content). The dielectric spectrum of the water close to solids particle surfaces is subject to surface forces that hinder its response to an imposed electromagnetic field. This behavior may result in both a lower relaxation frequency (ω_{water} in Equation (16) may reduce to within the MHz range) and a much lower permittivity (depending on water-film thickness) relative to that of free liquid water. Different relaxation frequencies of bound water may be measured to account for the differences in the solids-water interactions among different type of solids. An electrical impedance spectroscopic tomography system may permit the selection of a wide range of optimal operating frequencies for bound-water relaxation frequency effect identification, and for solids typing or identification, when operating within the 1 MHz to 400 MHz range.

[00114] To avoid the modeling difficulties (in terms of relating wet solids permittivity to bound-water content), it may be possible to obtain an estimate of the required solids (complex) permittivity ϵ_{solids} from the gas-free (solids-rich) part of the sensors’ time-series data, e.g. measured by the near-wall electrode pair(s) at the periphery of the underside of a horizontal pipe with moving beds of solids (Fig 9). This may lead to moisture-content immune solids-fraction (α_{solids}) measurement of gas-solids flows, based on a mixing model such as the following (a variation from Equation (14)):

$$\epsilon_m = \epsilon_{gas} + 3\epsilon_{gas} \frac{\alpha_{solids} \left(\frac{\epsilon_{solids} - \epsilon_{gas}}{\epsilon_{solids} + 2\epsilon_{gas}} \right)}{1 - \left(\alpha_{solids} \left(\frac{\epsilon_{solids} - \epsilon_{gas}}{\epsilon_{solids} + 2\epsilon_{gas}} \right) \right)} \quad (17)$$

[00115] For a gas-solids flow, it is possible to map out the solids fraction distribution $\alpha_{solids}(\mathbf{r}; t)$ from the permittivity tomographic distribution $\epsilon_m(\mathbf{r}; t)$, based on a mixing model such as Equation (17) applied pixel-wise.

[00116] It may be desirable to generate stratified moving gas-solids flows for the benefits of online ‘calibration’ measurement of solids and/or gas complex permittivities, by controlling the gas and/or solids flow rates based on tomographic flow mapping (Fig 9).

[00117] Fig. 13 shows a typical fracturing operation wellsite layout; the entire location can be divided into (i) low pressure operations, which include all the fluid blending and frac fluid creation and (ii) high-pressure operations, which is the actual process of pumping the fluid at high pressures and rates into the wellbore.

[00118] The wellsite process starts at the low pressure side, which usually consists of multiple water tanks 221 (also called frac tanks). Water is pumped from these tanks 221 into the hydration unit 223, where the water may be mixed with gelling agents (such as guar powder) to create a gel which is the base fluid of any fracturing operation. This gel then flows into a blending unit 225, where sand or proppants delivered from a storage silo 227 may be blended into the gel along with other additives to create the final frac fluid. This sand-loaded gel may then be fed into the high-pressure pumps 201. The outlet of the blending unit 225 is the end of the low-pressure operations. The gel fed into the frac pumps may then be pumped out at high pressures, up to 15000 psi and at high flow rates, as high as 100 barrels per minute (BPM), into the wellbore 120 via high-pressure manifold 210. The fluid from the manifold flows into the wellbore via high-pressure pipes 215. The sand-loaded gel creates fractures (conductive channels) in formation rocks. When the pumps are turned off after the operation and pressure bled off, the sands in the gel help keep the formation cracks open. The entire fracturing operation may be controlled from the control unit 229.

[00119] The hydration unit 223 in Fig. 13 (which may be a Schlumberger Precision Continuous Mixer* PCM) performs an important function during a fracturing operation that largely determines the service quality. Water pumped from the tanks 221 is mixed with the gelling agent, primarily guar, inside the hydration unit 223. Guar is fine powder made from a leguminous plant; when added to water and allowed to hydrate and mix, guar-water mixture creates a viscous gel solution known as linear gel. The viscosity of the solution, in one aspect, is

determined by the amount of guar, i.e., mass, added to the water. The residence time and flow mixing inside the hydration unit 223 ensures that the guar reacts sufficiently with water to create liner gel of required viscosity, before being delivered to the blending unit (unit 225 in Fig.13) to further mix with sand or proppants and other additives to create the final frac fluid.

[00120] As illustrated in Fig. 14, a hydration unit 223 (such as the PCM) may use an eductor to facilitate adding guar powder to a water stream (a screw-feeder auger installed in a transfer can in the PCM may be used to crudely meter the amount of guar). The transfer can may be considered as multiphase fluid input means. An eductor is a type of jet pump where the energy from one fluid (such as water) may be transferred to another fluid (such as powder) via the Venturi effect. The water (with its flow rate being variable by a centrifugal pump) flowing into the eductor is accelerated, creating a vacuum that sucks dry guar powder into the water stream. This mixed water and guar stream may be diluted further by water and allowed to flow through multiple compartments inside the hydration unit 223, where agitators are used to mix guar powder well with the water.

[00121] The viscosity of the resulting linear gel produced at the outlet of the hydration unit 223 is very critical to a successful fracturing operation; this is dependent on the mixing of the correct amount of guar powder with the correct amount of water. In Fig.14, an on-line viscosity measurement may be made at location 4, rather than an offline lab analysis as is performed in some prior art systems. This may be realized with the use of an inline viscometer or a Coriolis flow meter which may provide online viscosity measurements, in addition to flow rate, density and temperature. This online measurement capability is important; improper viscosity of sand-laden gel leads to settling of the sand particle during the high-pressure pumping operation. The sand particles may fill the wellbore and surface equipment, resulting in operational failure or shut-down (or screen out). If a screen out were to happen, then a costly and time-consuming sand clean-out operation using coiled tubing will be required before resuming the operation.

[00122] The quality of the linear gel may be ensured by accurately measuring and adjusting online the desired amount of guar powder in relation to that of the mixing water. In

Fig. 14, the online monitoring of the delivery of the amount of guar from the transfer-can to the eductor may be performed by the use of the electrical impedance tomography system located at horizontal transport-pipeline locations (1 or 3 in Fig. 14), or at a vertical transport-pipeline location (2 in Fig. 14). The water flow rate may be measured by an electromagnetic flow meter (not shown), and may be varied by changing the rotational speed of the water centrifugal pump. The guar powder flow regime may be varied (for the purpose of facilitating periodic online calibration of guar powder permittivity for moisture-content tracking) by varying the flow rate of the water that feeds the eductor (which in turn changes the suction rate or uptake rate of the guar powder).

[00123] There are several design considerations for the pipe/duct incorporating tomography sensors. The same design considerations are applicable to other flow-measurement sensors such as electromagnetic flowmeters, or coriolis flowmeters in order to survive abrasive liquid-solids slurry flows used in oilfield pumping services (e.g. in cementing and fracturing).

[00124] To reduce erosion, there is typically a specified straight length of pipe upstream and downstream. The tubing inner walls may be coated with material such as polyurethane rubber, ceramics (for superior abrasion resistance). These coatings are application-specific; for example, ceramics may be suitable for abrasion but are susceptible to chemical attack by acids and alkalines.

[00125] For fluid-contacting non-invasive measurement electrodes (including guard electrodes needed in the sensor design) for use with an electrical impedance tomography system, abrasion-resistant and corrosion-resistant metal material (coating) may be used.

[00126] To reduce scaling or other deposit-layer (with some fluids such as gel or cement) on the sensing electrodes, the measurement-section pipe design may incorporate anti-fouling means, such as scale-resistant and abrasive-resistant coating, self flush or acid wash, or periodic vibration etc.

[00127] The calibration approach disclosed intends to remove largely the wall-capacitance and/or contact-impedance effects of the sensing electrodes. It may be able to

remove further the effects on the (complex) permittivity measurement of the deposits on the wall with periodic (dynamic) online calibration from near-wall complex-permittivity measurement, near-wall flow velocity detection (a deposit layer will be stationary and can be detected over time). An (array of) range-gated pulsed Doppler ultrasound sensor(s) may be used to detect the deposit layer, in addition to profiling flow velocity beyond the deposit layer (see Schlumberger US patent number 7,673,525B2 for reference).

[00128] The electrical tomography flow-measurement system may also be used in a feedback-loop to the multiphase fluid input means or a conveyance device such as a conveyor and/or gate valve, such that a desired target solids mass flow rate can be maintained by adjusting the control signal of the conveyance method. For example, for the dry powder, the speed for the screw-feeder or conveyor and/or the gate-valve positioning may be controlled; the rotational speed of a water centrifugal pump may also be controlled to adjust the dry powder uptake-rate enabled by the use a water-driven eductor.

[00129] The conveyor speed and/or the gate-valve positioning may also be controlled to (periodically) create a desired solids-rich flow pattern(s) (e.g. near-pipe-bottom or near-pipe-wall moving solids bed) that may facilitate the tracking of solids complex-permittivity (hence loss factor in the case of a gas-solids flow) from near-wall electrode-pair measurements. This may enable the capture of the variation in the moisture-content in solids and/or in the deposit-layer thickness (together with velocity profiling data), and to use permittivity/ conductivity mixing model(s) (or density-dielectric calibration model, or deposit acoustic-impedance-density model) to correct for such changes to make moisture-independent and/or deposit-corrected solids-fraction measurement.

[00130] In other embodiments, feedback means may be provided, which may be a software based means or a physical device operated by the processor. The feedback means may be adapted to adjust the flow rate of the multiphase fluid/dry powder in addition to that of the water supplied to the eductor, via adjustment of a pressure valve, a variable speed drive (for use with the water pump) or the like. In other scenarios, the feedback means may be adapted to alter

the conditions in which the multiphase fluid is stored. For example, the feedback means may be adapted to alter the humidity or temperature of a multiphase storage bin, such as the guar powder bin shown in Fig. 14. In other words, the feedback means may create favourable storage conditions or favourable flow conditions for the multiphase fluid on the basis of desired parameters to be achieved of the multiphase fluid.

[00131] In one exemplary embodiment of wellsite cementing or fracturing operations, the electrical impedance (capacitance/permittivity and conductance/conductivity) sensor-array system may be used to measure the flow rate of dry solids additives (with moisture-content correction from loss-factor tracking from near-wall sensing). The flow rates of other liquid additives may be measured by using off-the-shelf liquid flowmeters (such as coriolis meters). The mass flow rate of the mixed solids and liquid (slurry flow) may be measured by using an electromagnetic flowmeter with abrasion-resistant and/or chemical-resistant material lining (such as made of rubber composite to withstand erosion, corrosion and also is lightweight), together with a nuclear-free mixture density device based on weighing (such as SCIAM meter used in dredging and mining). It may be possible to use a coriolis flowmeter specially designed with abrasion-resistant and/or chemical-resistant material pipe-liner to measure the mass flow rate, mass density (and potentially the viscosity) of the (mixed liquid/solids) slurry flows.

[00132] It will be appreciated that the example embodiments described in detail above can be modified and varied within the scope of the concepts which they exemplify. Features referred to above or shown in individual embodiments above may be used together in any combination as well as those which have been shown and described specifically. Accordingly, all such modifications are intended to be included within the scope of this disclosure as defined in the following claims.

CLAIMS

1. A tomography system for determining properties of flowing gas solids, liquid-solids, and/or gas-liquid-solids multiphase fluid, comprising:

a duct having a duct wall and an interior space within the duct wall for carrying a flow of a multiphase fluid;

a plurality of sensors which are distributed at positions around the duct wall on at least a planar cross section through the duct, for making a plurality of measurements of electrical or magnetic properties through the multiphase fluid at single or a plurality of operating frequencies in the range of 1 MHz to 400 MHz; and

a processor adapted to receive measurement data from the sensors and configured to compute from the measured properties to derive quantitative values of at least one property selected from permittivity, conductivity, magnetic permeability, complex-conductivity, and complex-permittivity of the multiphase fluid independent of effects external to the fluid flow.

2. A system according to claim 1 wherein determining said quantitative values selected from permittivity, conductivity, permeability, complex-conductivity, and complex-permittivity of the multiphase fluid from the measured electrical properties comprises determining normalized values from measurements of electrical properties representative of at least one of capacitance, conductance, inductance and admittance, and converting the normalized capacitance, conductance, inductance, or admittance to said quantitative values of permittivity, conductivity, permeability, complex-conductivity, or complex-permittivity of the multiphase fluid.

3. A system according to any of the preceding claims, wherein the system is an electrical tomographic system and wherein the sensors are electrodes adapted to measure values representative of capacitance, conductance or admittance between a plurality of pairs of electrodes at positions distributed around the exterior of the duct wall and the processor receiving measurement data from the electrodes is configured to determine a plurality of

quantitative values of permittivity, conductivity, complex-conductivity, or complex-permittivity of the multiphase fluid.

4. A system according to any of the preceding claims wherein the sensors are coils which are adapted to measure values representative of inductance between a plurality of pairs of coils and the processor adapted to receive measurement data from the coils and is configured to determine a plurality of quantitative values of conductivity or magnetic permeability of the multiphase fluid.

5. A system according to any of the preceding claims wherein the processor is configured to compute at least one of a solids fraction and solids velocity of the multiphase mixture from one or more of said plurality of quantitative values.

6. A system according to any of the preceding claims wherein the processor is configured to compute at least one image showing spatial distribution of permittivity, conductivity, magnetic permeability, complex-conductivity, or complex-permittivity of the multiphase fluid within the planar cross-section of the duct, and/or

to compute at least one image showing temporal distribution of permittivity, conductivity, magnetic permeability, complex-conductivity, or complex-permittivity of the multiphase fluid within the planar cross-section of the duct and/or along a longitudinal section of the duct, and/or

to compute at least one image showing solids-fraction distribution and/or solids-velocity distribution of the multiphase fluid within the planar cross-section of the duct and/or along a longitudinal section of the duct.

7. A system according to any of the preceding claims, wherein the sensors are adapted to measure, online, complex permittivities or complex conductivities of at least one liquid-rich and/or at least one solid-rich part of the multiphase fluid flowing within the duct based upon near-wall tomographic sensing, the near-wall sensing including sensing a region between at least two near-by or adjacent sensors, the region containing the at least one solid-rich or liquid-rich part of the multiphase fluid.

8. A system according to any of the preceding claims, wherein the processor is adapted to control feedback means, the feedback means adapted to alter the flow properties of the multiphase fluid within the duct, wherein the processor is adapted to operate the feedback means to provide desired parameters of the multiphase fluid on the basis of the measured permittivity, conductivity, magnetic permeability, complex-conductivity, and/or complex-permittivity.

9. A computer implemented method of measuring properties of a flowing multiphase fluid containing solids, comprising making a plurality of measurements at a single or a plurality of frequencies in the frequency range of 1 MHz to 400 MHz representative of capacitance, resistance, inductance or admittance at one or more cross sections through the fluid and computing permittivity, conductivity, magnetic permeability, complex-conductivity, or complex-permittivity of the multiphase fluid from the measurements made.

10. A method according to claim 9 wherein measurements are made between electrodes or coils mounted outside or around a duct carrying the flowing multiphase fluid and the method includes determining normalised values representative of capacitance, resistance, inductance or admittance at the one or more cross sections through the fluid, where the normalised values are independent of effects external to the flow of the multiphase mixture.

11. A method according to claim 10 further comprising computing permittivity, conductivity, magnetic permeability, complex-conductivity, or complex-permittivity of the multiphase fluid from one of the normalised values.

12. A method according to any of claims 9 to 11 comprising computing at least one of a solids fraction and solids velocity of the multiphase mixture from the computed permittivity, conductivity, magnetic permeability, complex-conductivity, or complex-permittivity of the multiphase fluid.

13. A method according to any of claims 9 to 12 comprising computing one or more images showing spatial distribution of permittivity, conductivity, magnetic permeability,

complex-conductivity, or complex-permittivity within one or more planar and/or longitudinal cross-sections through the multiphase flow, and/or

computing one or more images showing temporal distribution of permittivity, conductivity, magnetic permeability, complex-conductivity, or complex-permittivity within one or more planar and/or longitudinal cross-sections through the multiphase flow, and or

computing one or more images showing solids-fraction distribution and/or solids-velocity distribution within one or more planar cross-sections and/or longitudinal through the multiphase flow.

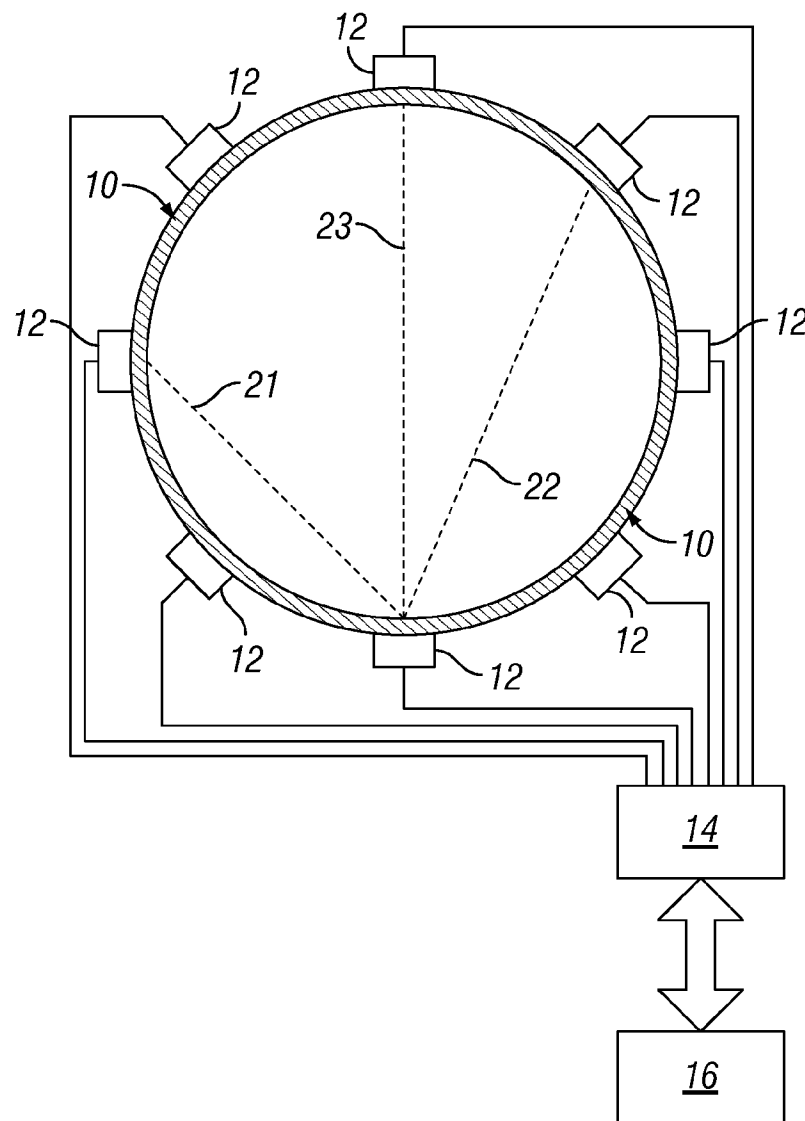
14. An oil-field formation fracturing system comprising solids multiphase fluid input means, an eductor, and the tomography system of any of claims 1 to 8, wherein the solids multiphase fluid input means is connected to the eductor via the duct and supplies the solids multiphase fluid to the duct and eductor, and wherein the eductor is configured to uptake the solids multiphase fluid and mix with a quantity of water and output the solids-water mixture to produce a linear gel.

15. The system of claim 14, further comprising a water flow pipe adapted to supply water to the eductor, and a tank compartment equipped with mixers and agitators adapted to receive the solids-water mixture output from the eductor to produce well-mixed linear gel, further mix the linear gel with proppants in a blending unit, and output a fracturing fluid from the blending unit, wherein

the tomography system is adapted to measure the complex-permittivity or the complex-conductivity or the flow rate of the solids multiphase fluid to be transferred into the eductor, a first flow meter is provided to measure the properties of the water in the water flow pipe, and a second flow meter is provided to measure the properties of the fracturing base fluid (the linear gel) output from the tank compartment, the processor or a second processor adapted to receive the measurement outputs of the first and second flow meters, and wherein a/the feedback means is adapted to alter at least one of the flow properties of the solids multiphase

fluid and the flow of the water so as to optimize the properties of the produced linear gel and/or the proppants-containing fracturing fluid.

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**FIG. 1**

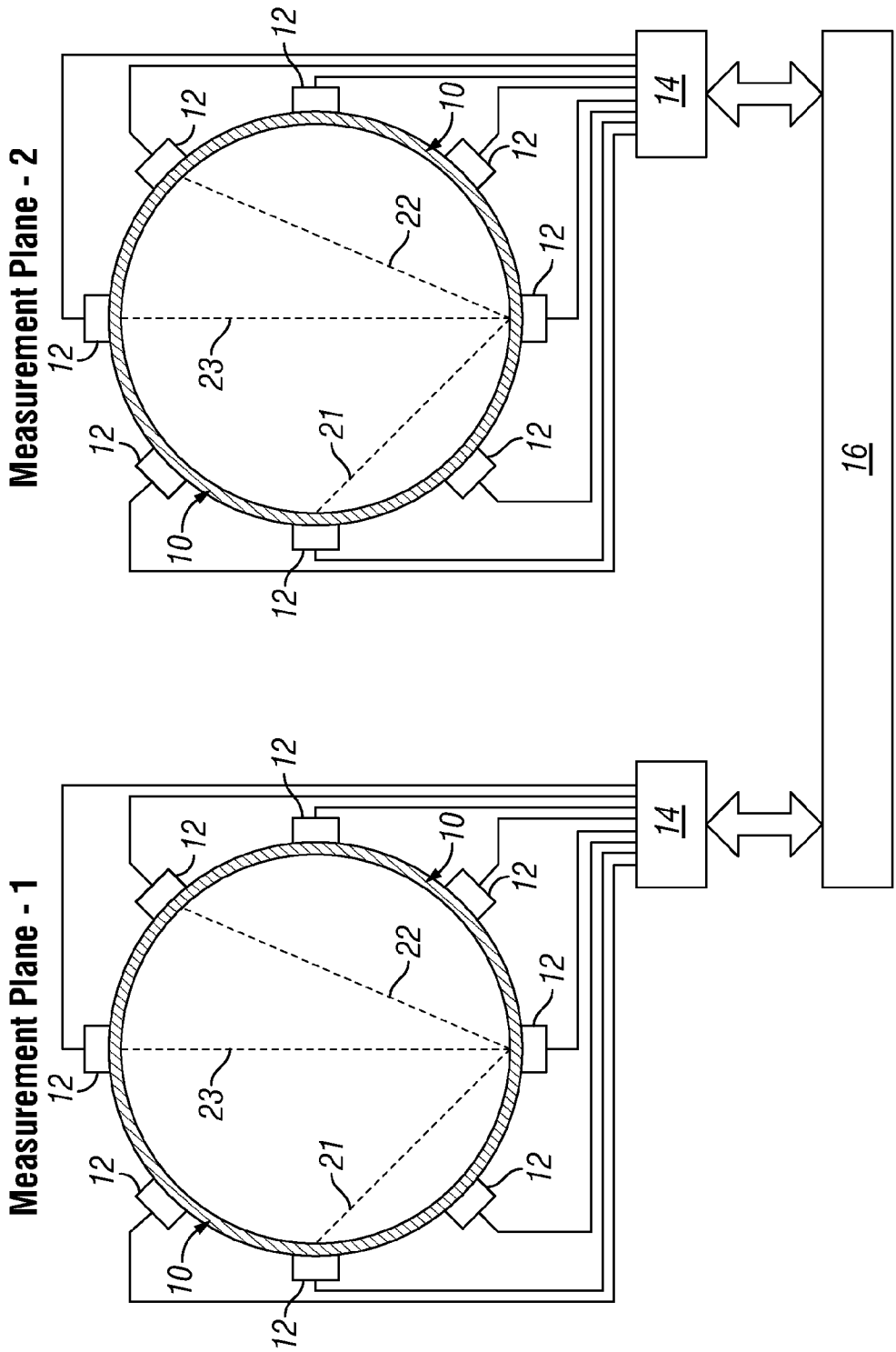


FIG. 1A

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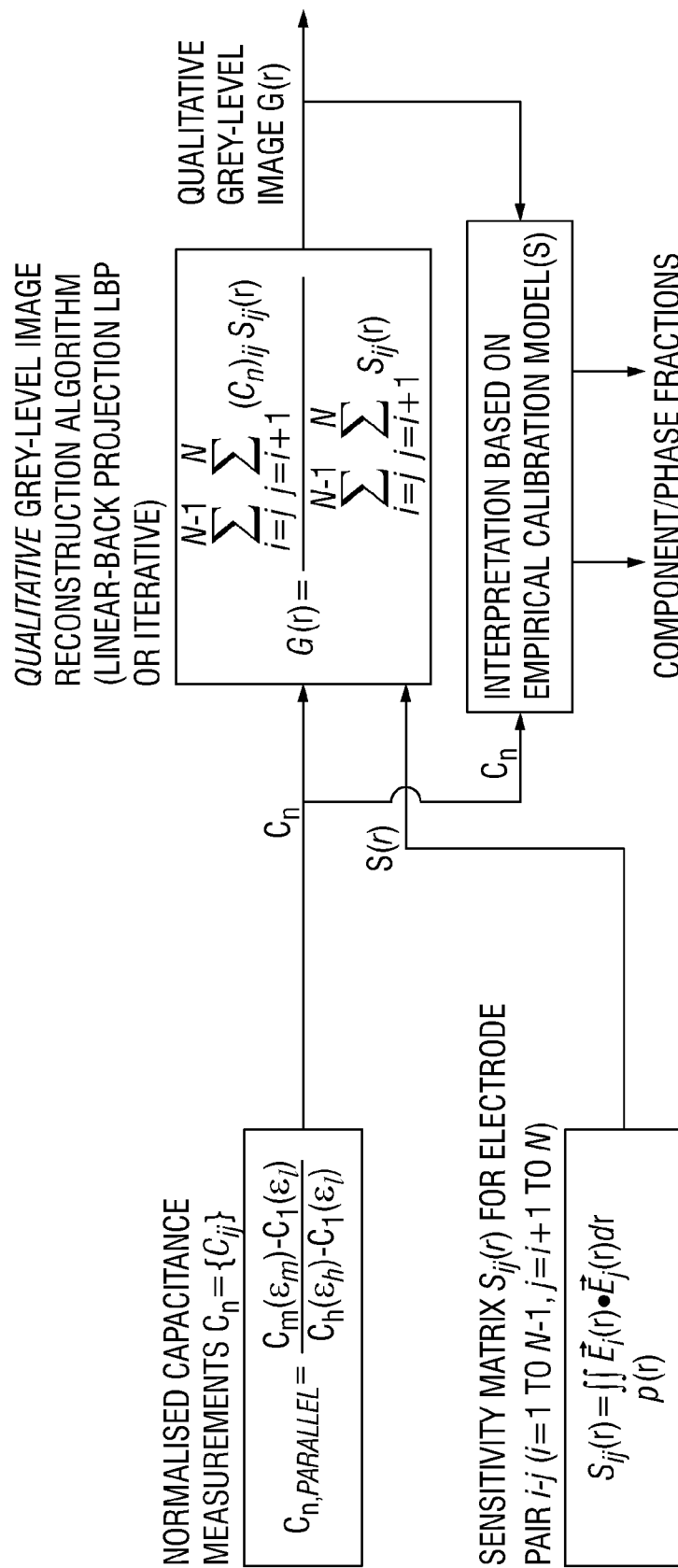


FIG. 2
(Prior Art)

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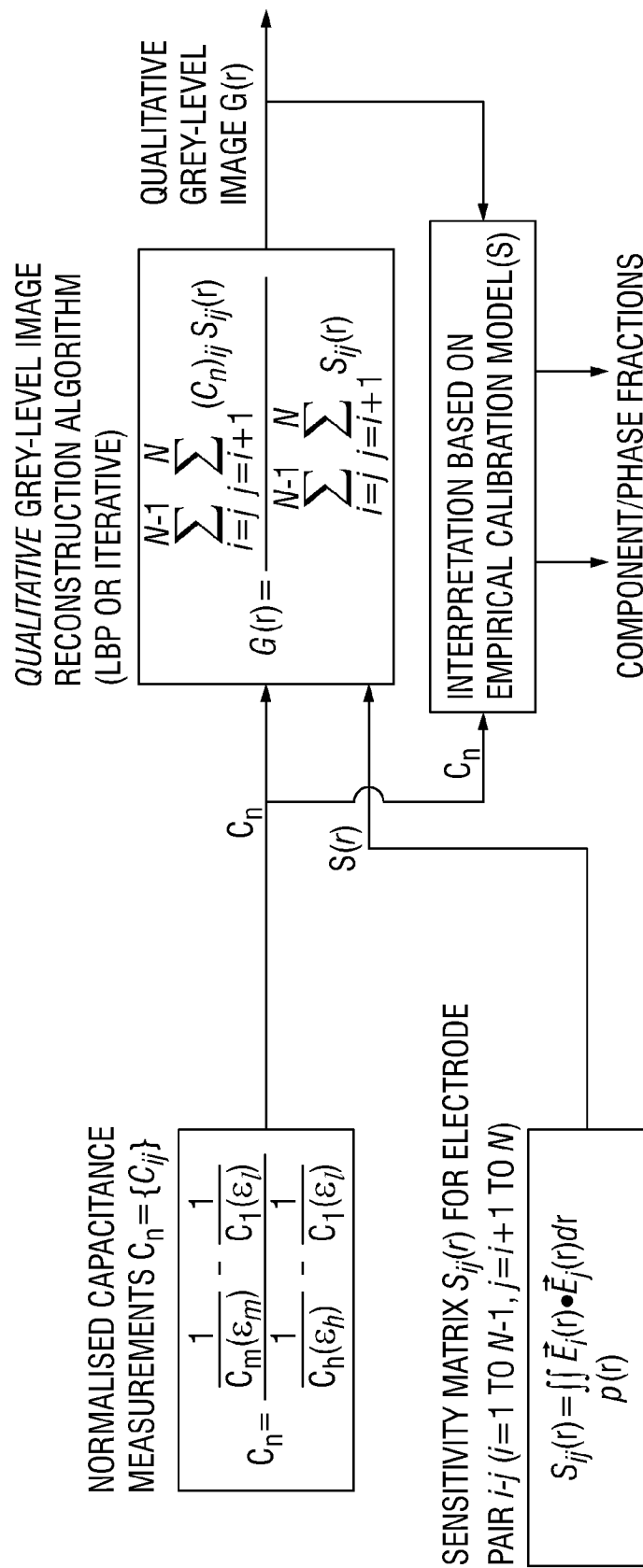


FIG. 3
(Prior Art)

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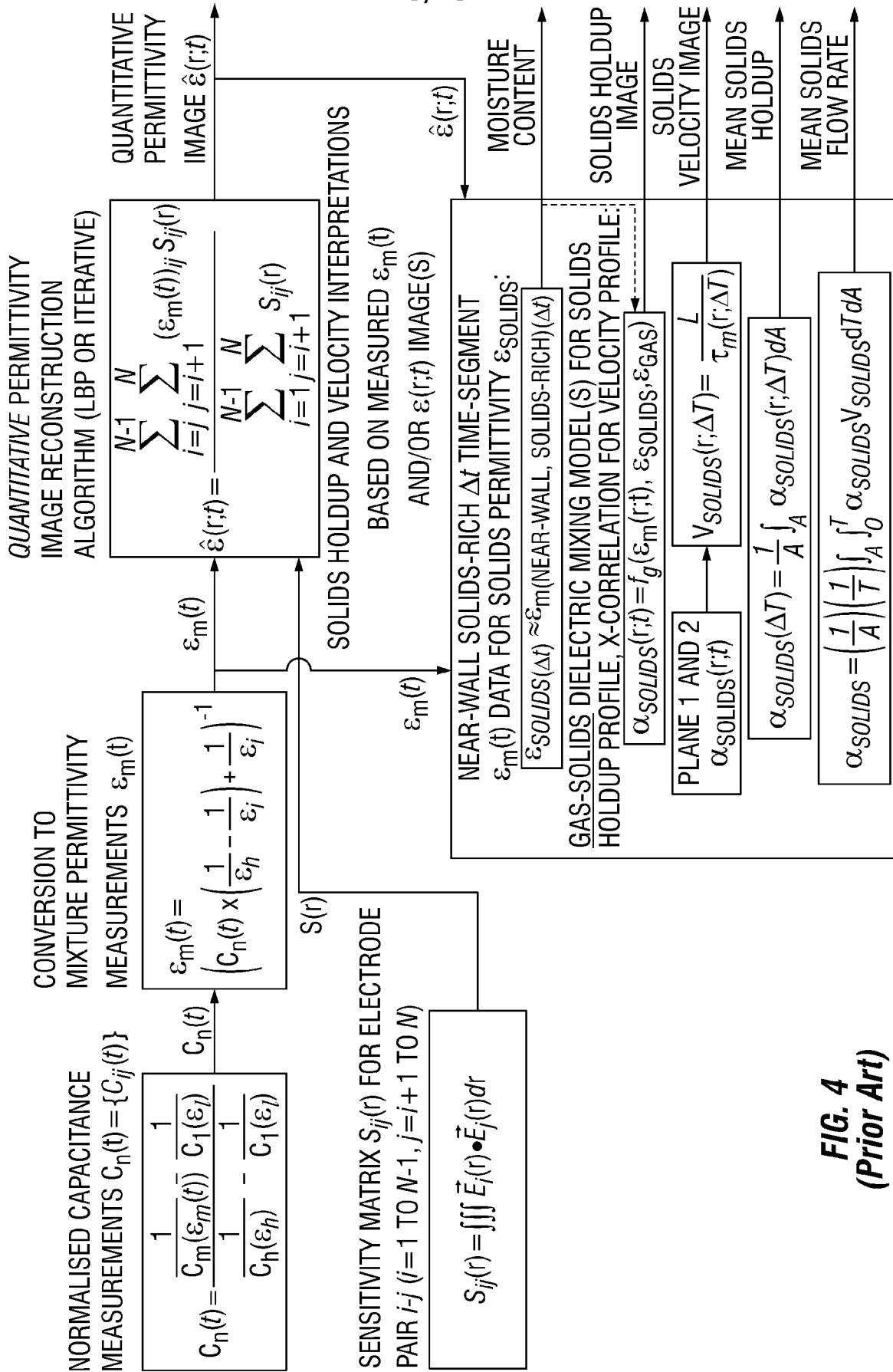


FIG. 4
(Prior Art)

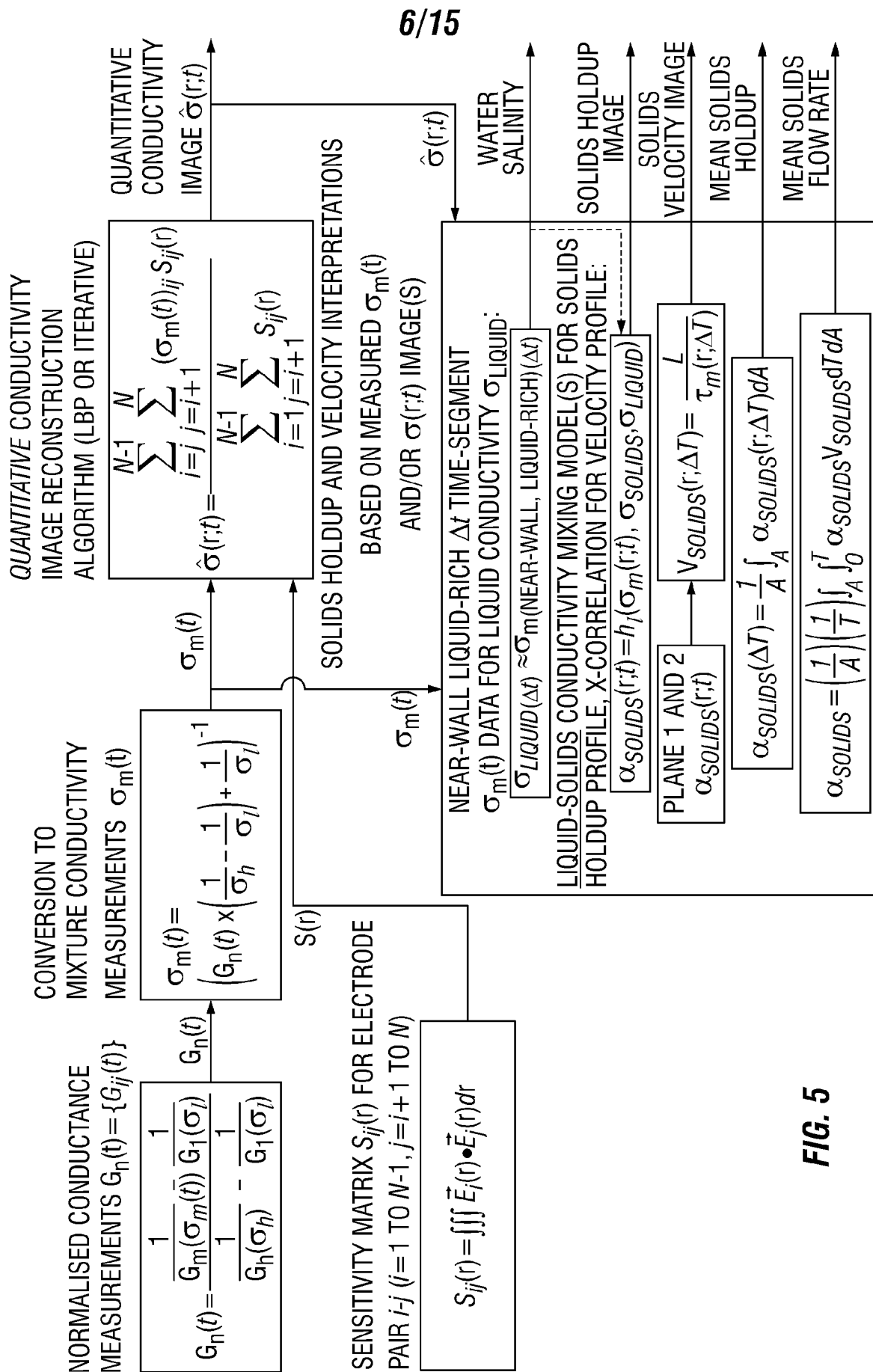


FIG. 5

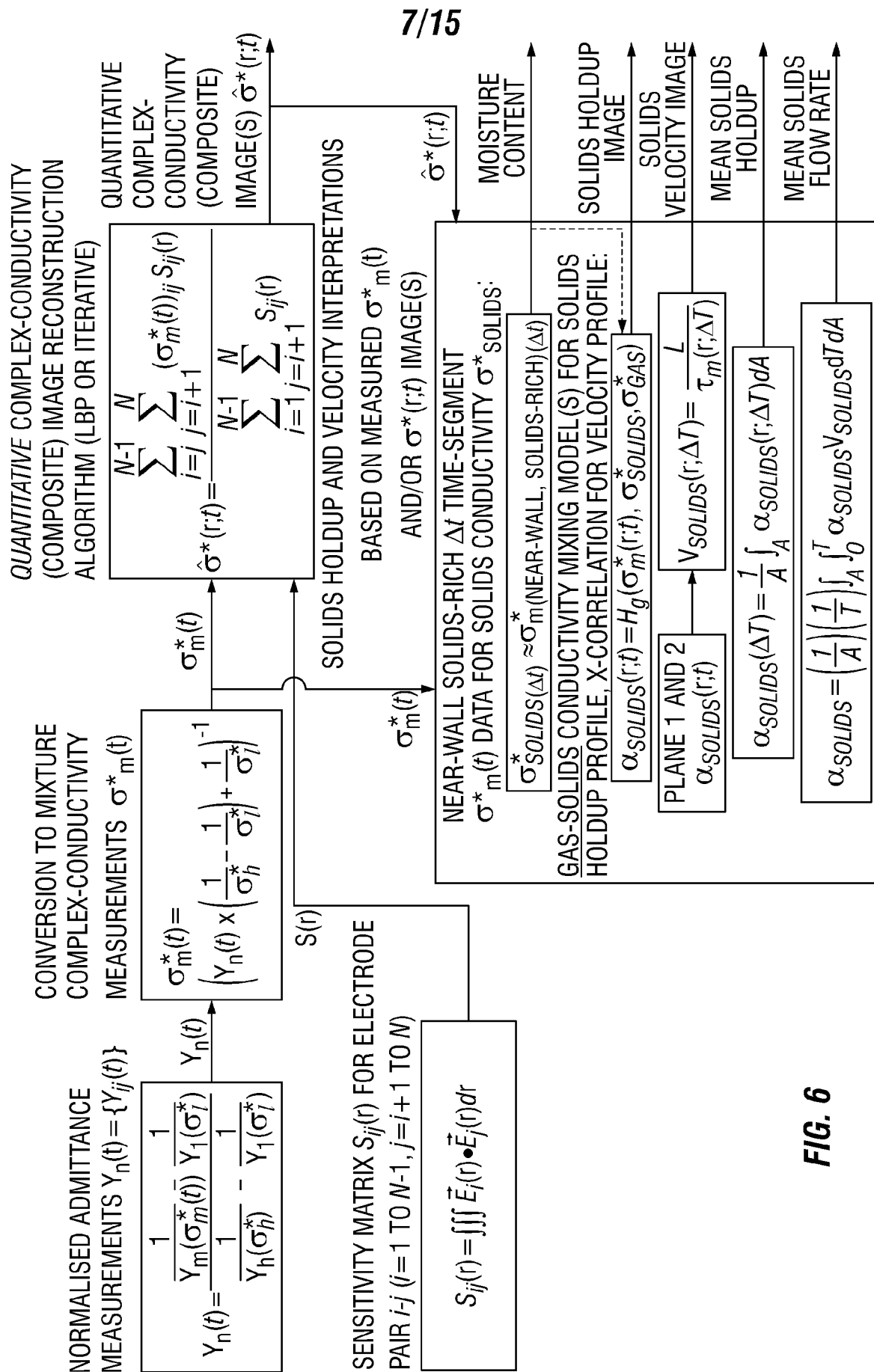


FIG. 6

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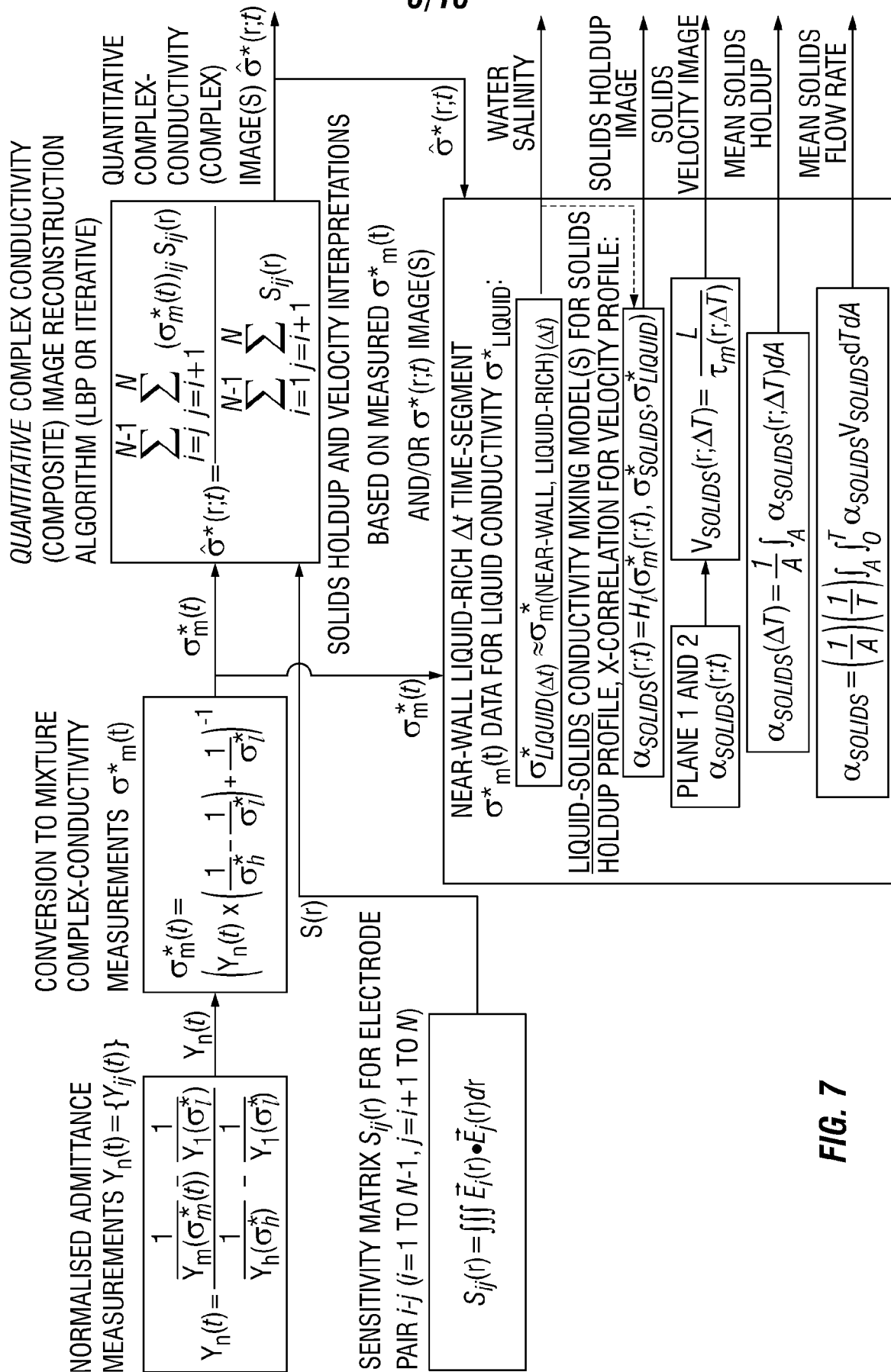


FIG. 7

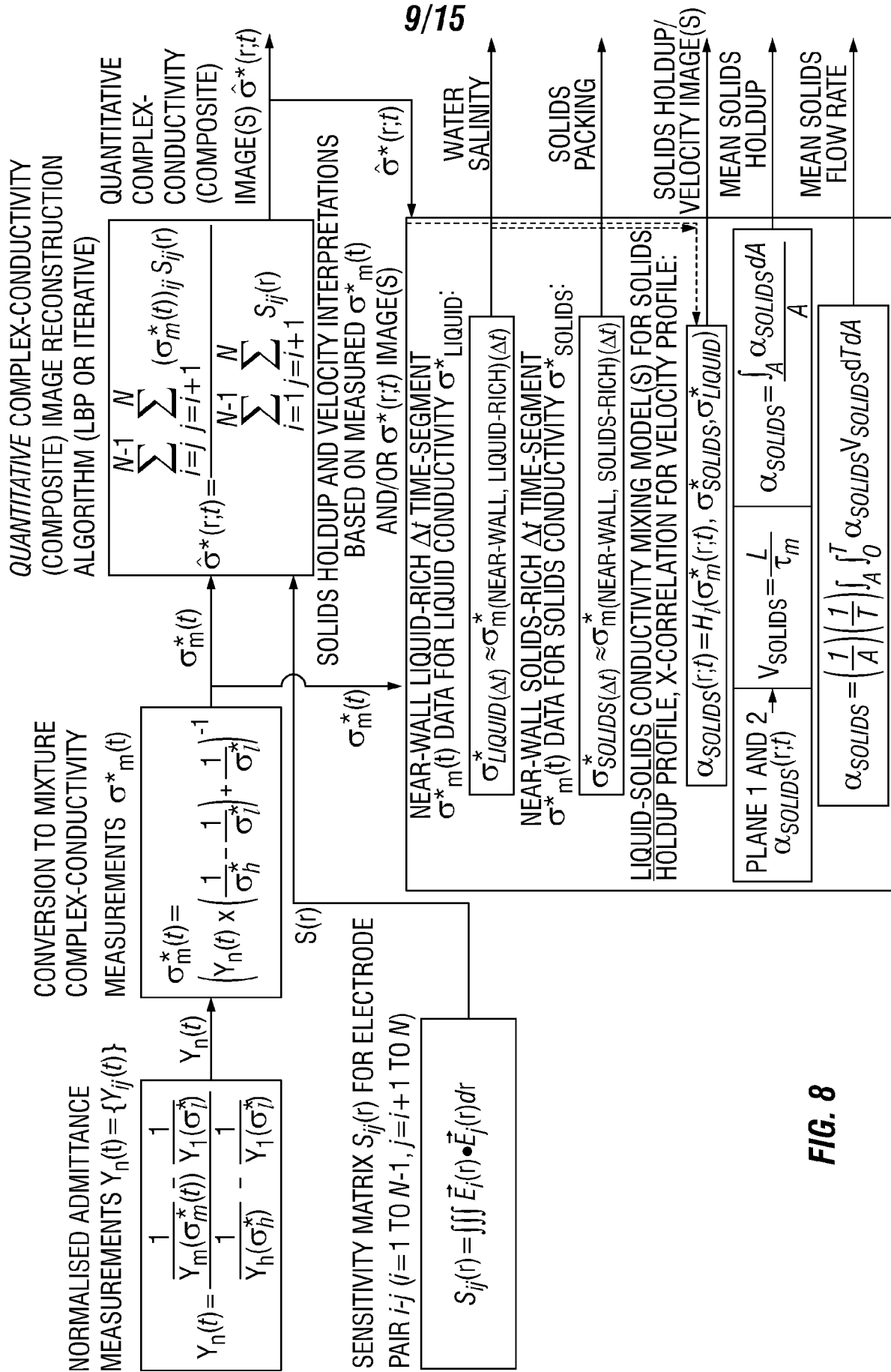


FIG. 8

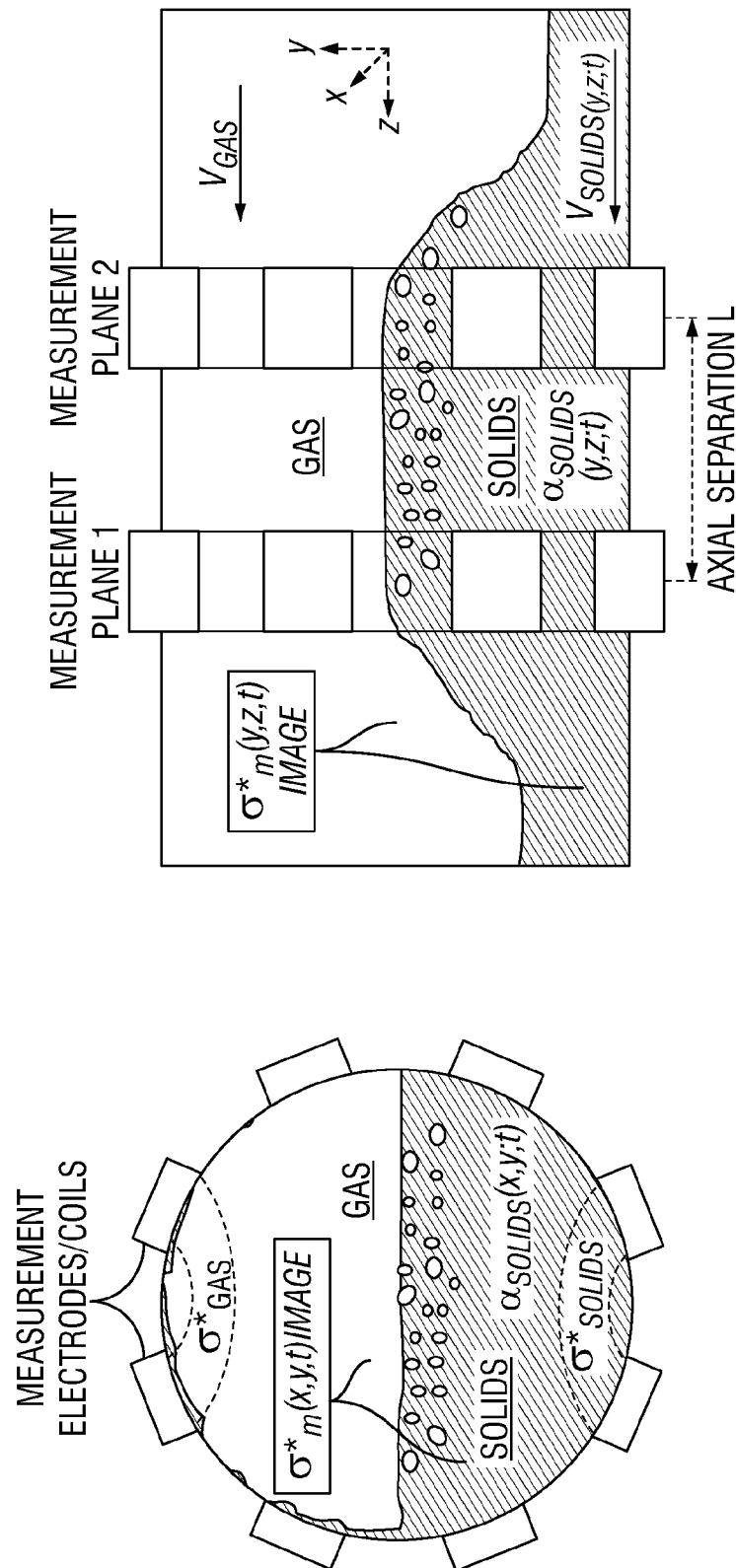


FIG. 9

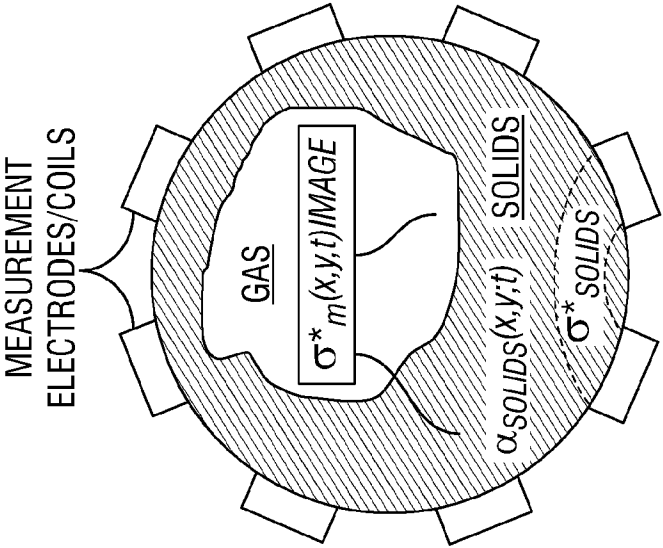
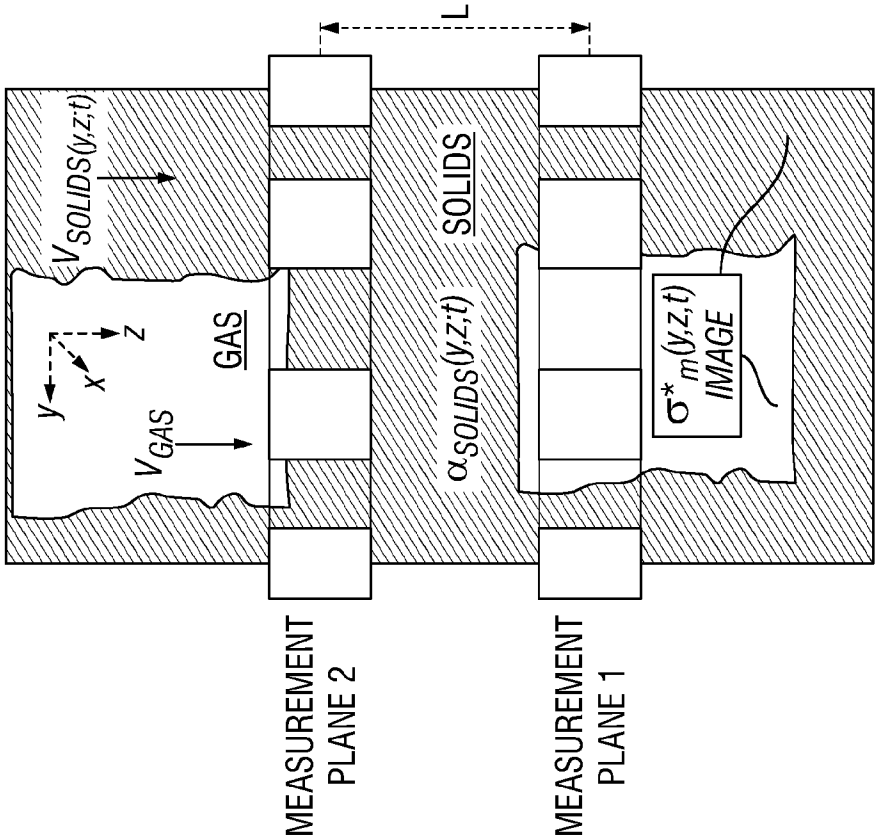


FIG. 10

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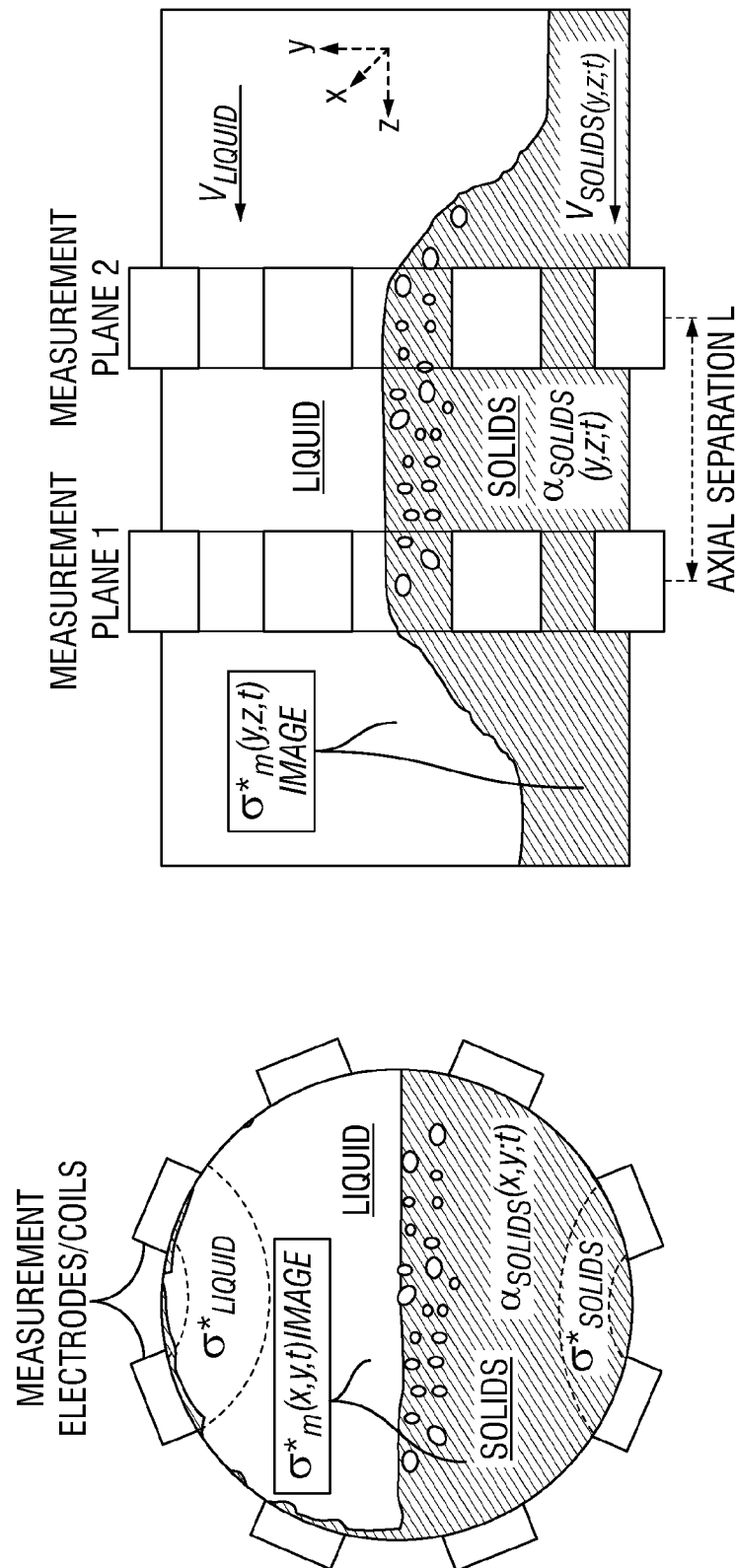


FIG. 11

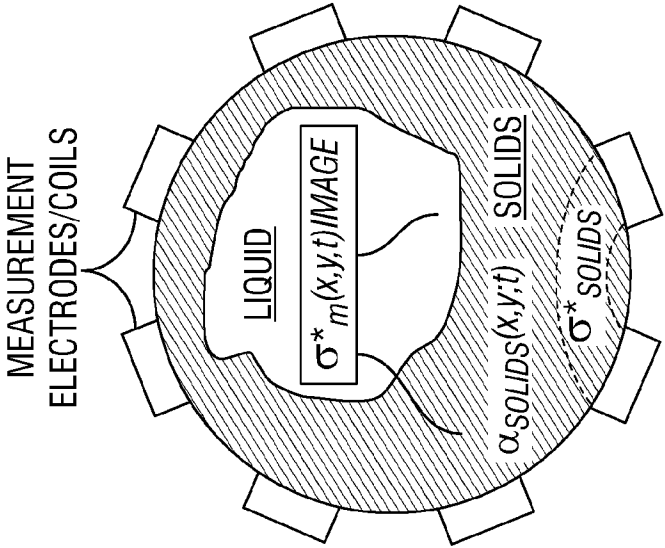
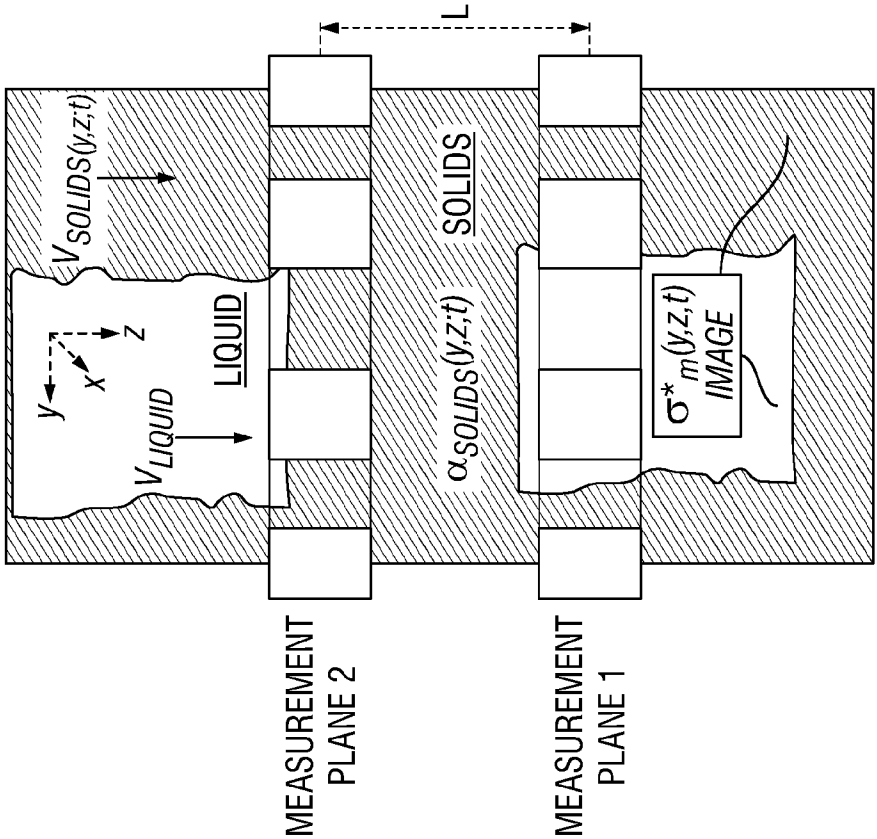


FIG. 12

14/15

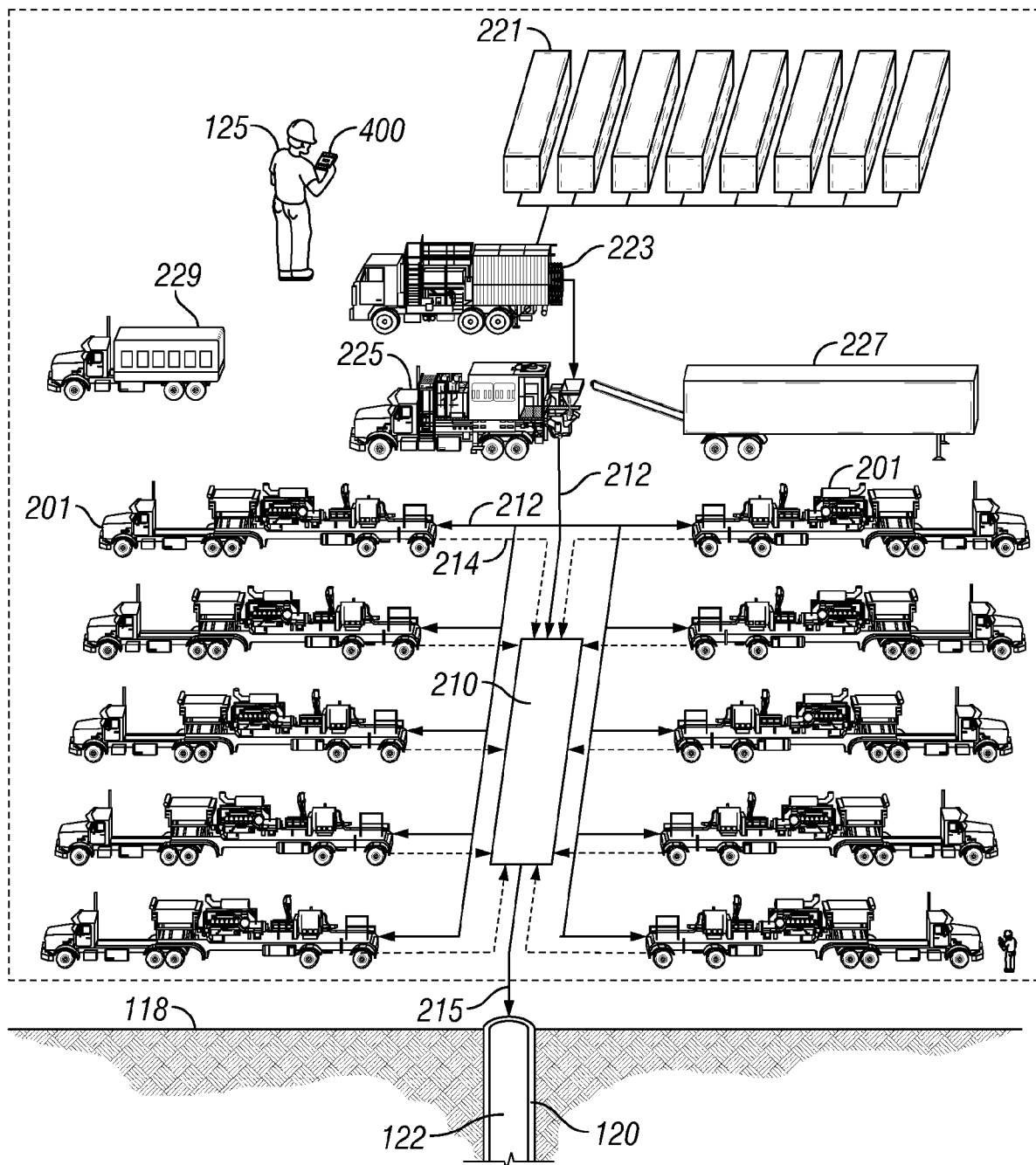


FIG. 13

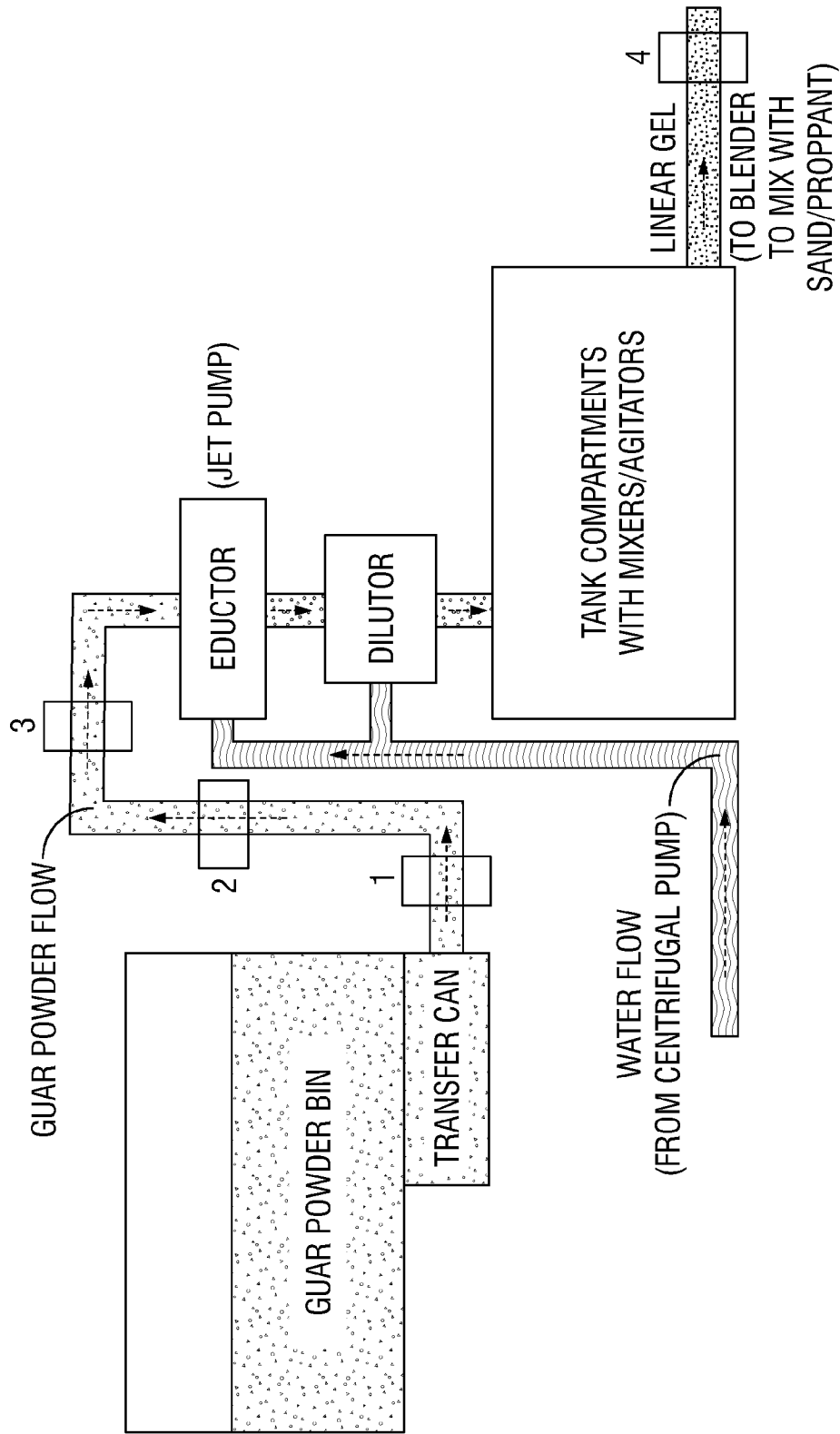


FIG. 14

INTERNATIONAL SEARCH REPORTInternational application No.
PCT/US2015/020131**Box No. II Observations where certain claims were found unsearchable (Continuation of item 2 of first sheet)**

This international search report has not been established in respect of certain claims under Article 17(2)(a) for the following reasons:

1. ☐ Claims Nos.:
because they relate to subject matter not required to be searched by this Authority, namely:
2. ☒ Claims Nos.: 15
because they relate to parts of the international application that do not comply with the prescribed requirements to such an extent that no meaningful international search can be carried out, specifically:
Claim 15 refers to multiple dependent claim 14 which does not comply with PCT Rule 6.4(a).
3. ☒ Claims Nos.: 4-8, 13-14
because they are dependent claims and are not drafted in accordance with the second and third sentences of Rule 6.4(a).

Box No. III Observations where unity of invention is lacking (Continuation of item 3 of first sheet)

This International Searching Authority found multiple inventions in this international application, as follows:

1. ☐ As all required additional search fees were timely paid by the applicant, this international search report covers all searchable claims.
2. ☐ As all searchable claims could be searched without effort justifying an additional fees, this Authority did not invite payment of any additional fees.
3. ☐ As only some of the required additional search fees were timely paid by the applicant, this international search report covers only those claims for which fees were paid, specifically claims Nos.:
4. ☐ No required additional search fees were timely paid by the applicant. Consequently, this international search report is restricted to the invention first mentioned in the claims; it is covered by claims Nos.:

Remark on Protest

- ☐ The additional search fees were accompanied by the applicant's protest and, where applicable, the payment of a protest fee.
- ☐ The additional search fees were accompanied by the applicant's protest but the applicable protest fee was not paid within the time limit specified in the invitation.
- ☐ No protest accompanied the payment of additional search fees.

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US2015/020131**A. CLASSIFICATION OF SUBJECT MATTER****G01R 33/24(2006.01)i, G01R 33/02(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)

G01R 33/24; G01R 27/00; G06F 15/00; G01B 15/06; G01N 23/02; G01N 25/00; G01N 29/024; G01N 29/00; G01R 33/02

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) & keywords: tomography, frequency, pipe, property, sensor

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	US 2013-0144548 A1 (XIE) 06 June 2013 See abstract, paragraphs [0029]–[0030], claims 1–10 and figure 1.	1–3, 9–12
Y	WO 2014-027322 A2 (SCHLUMBERGER TECHNOLOGY B.V.) 20 February 2014 See abstract, paragraphs [0029]–[0041], claims 20–25 and figures 1–4.	1–3, 9–12
A	US 2012-0055239 A1 (SINHA) 08 March 2012 See paragraphs [0031]–[0043], claims 1–12 and figures 1A–1C.	1–3, 9–12
A	US 2008-0163692 A1 (HUANG et al.) 10 July 2008 See abstract, claims 1–10 and figures 1A–5A.	1–3, 9–12
A	US 2007-0133746 A1 (ORTIZ ALEMAN et al.) 14 June 2007 See abstract, claims 1–7 and figures 1–4.	1–3, 9–12



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

"E" earlier application or patent but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search

19 June 2015 (19.06.2015)

Date of mailing of the international search report

19 June 2015 (19.06.2015)

Name and mailing address of the ISA/KR

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INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No.

PCT/US2015/020131

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
US 2013-0144548 A1	06/06/2013	None	
WO 2014-027322 A2	20/02/2014	WO 2014-027322 A3	24/04/2014
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US 2007-0133746 A1	14/06/2007	AU 2003-256141 A1 US 7496450 B2 WO 2005-019779 A1	10/03/2005 24/02/2009 03/03/2005