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(71) **Applicant**: **COVAR APPLIED TECHNOLOGIES, INC.** [US/US]; 1495 Chain Bridge Road, McLean, Virginia 22101 (US).

(72) **Inventors**: **KOEROGHLIAN, Mark M.**; 19 Freestone Place, The Woodlands, Texas 77382 (US). **GILMER, Hendrik**; 11012 Byrd Dr., Fairfax, Virginia 22030 (US). **MILNER, George Martin**; 11 Oakmore, Round Rock, Texas 78664 (US).

(74) **Agents**: **PORTER, Gregory L.** et al.; Andrews Kurth LLP, 600 Travis St., Suite 4200, Houston, Texas 77002 (US).

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(54) Title: DISCRETE CAPACITIVE FLOW STREAM HEIGHT MEASUREMENT FOR PARTIALLY FILLED PIPES

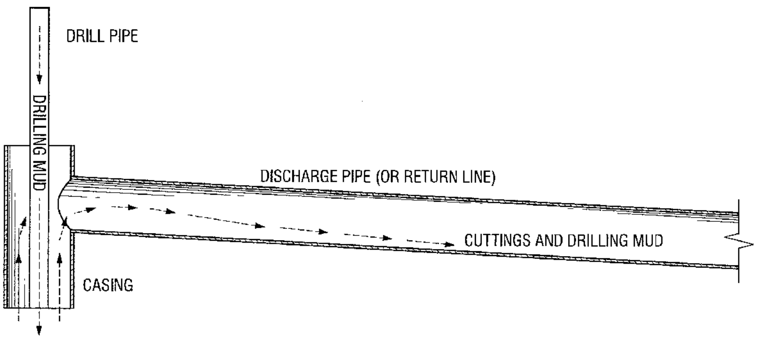

FIG. 1

(57) **Abstract**: The invention relates to a system and method for measuring the flow stream height and velocity and other properties of water, drilling mud, or other liquid flowing through a pipe. The system comprises at least one and preferably a plurality of capacitive pads, connected to a data acquisition system capable of measuring the capacitance of each pad. These capacitive pads may be arranged radially around the inner diameter of a pipe or on a vertical probe inserted into the pipe. The pads that are submerged below the liquid level within the pipe will have a larger capacitance due to their proximity with a high dielectric fluid such as water or drilling mud. Conversely, the pads above the flow stream will have a lower capacitance due to their proximity to air. The fluid level can be inferred by determining the number of pads submerged in the fluid and by analysis of the capacitive values of pads nearest the fluid-air interface.

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DISCRETE CAPACITIVE FLOW STREAM HEIGHT MEASUREMENT FOR PARTIALLY FILLED PIPES

CROSS REFERENCE TO RELATED APPLICATION

This application claims the benefit of U.S. Provisional Application Serial No. 62/145,783 filed April 10, 2015. Applicant incorporates by reference herein Application Serial No. 62/145,783 in its entirety.

FIELD OF THE INVENTION

[0001] The invention relates to systems and methods for sensing the amount and properties of drilling mud or any other liquid or flowing media with a dielectric constant different than air flowing through a pipe or channel.

BACKGROUND AND SUMMARY

[0002] During the drilling process, drilling mud (actually a complex mixture of compounds) is usually pumped down the drill pipe and returns, carrying cuttings, up the annular region between the drill pipe and bore. The mud is typically routed away from the vertical well bore via a shallow angled pipe, e.g. 3 to 10 degrees from horizontal. The well bore could be either open hole or casing; however, at the top of the well, the bore will consist of steel casing. A representative flow path and pipe arrangement at the top of the well is depicted in Figure 1.

[0003] When the mud pumps are shut-off (sometimes referred to as a "pumps off" event), flow rapidly decreases (shown in Figure 2) and a corresponding drop in equivalent circulating density ("ECD") can cause significant decreases in down hole pressures. Theses fluctuations in pressure are difficult to calculate precisely, and thus the well is vulnerable to transient influx (aka "a kick") from the formation. Control during pumps off is also exacerbated by the difficulty in measuring flow accurately during the rapid transient decreases in flow. After flow-out has decreased to zero, influx may be indicated by a very small amount of flow ("trickle-flow"), which many flow sensing methodologies have difficulty measuring.

[0004] The ECD is the effective density exerted by a circulating fluid against the formation that takes into account the pressure drop in the annulus above the point being considered. The ECD is calculated as: $d + P/0.052*D$, where d is the mud weight in pounds per gallon (ppg), P is the pressure drop in the annulus between depth D and surface in pounds per square inch (psi), and D is the true vertical depth (feet). The ECD is an important parameter in avoiding kicks and losses, particularly in wells that have a narrow window between the fracture gradient and pore-pressure gradient.

[0005] Influx at pumps-off events typically manifests itself first as transient flow relative to an expected value near zero or as values rapidly converging to zero. Early influx detection is often dependent on detecting these initial small flow increments (or trickle-flow) at the return line since the corresponding pit volume increases can be significantly delayed, and thus changes in pit volume are usually detected only after significant influx has occurred. Accurate, reliable detection of trickle-flow may significantly improve influx detection at pumps-off.

[0006] A characteristic of the return line flow is often that the pipe is not full, rather, it is more like a trough flow. Mud from the well bore enters the return line and is accelerated by gravity until the force due to gravity is balanced by shear forces at the pipe wall. While the flow stream is accelerating, the fluid height continuously decreases and the average fluid velocity continuously increases until uniform flow conditions exit, at which point the height and velocity remain constant. The distance required for uniform flow to occur varies with flow rate and return line diameter; at high flow rates, it could be as much as 100 feet from the entrance. A typical velocity contour plot is shown in Figure 3 (excerpted from Sandia National Labs report SAND91-2607, 1992), where lines of constant velocity are shown over the fluid cross-section for a pipe slope of 10° and a flow rate of 800 gpm. Steep velocity gradients can be observed near the pipe wall, while the vast majority of the flow cross-section is near the maximum speed. This is the conventional signature of turbulent flow and can exist down to 100 gpm or less. Accurately measuring flow in a partially-filled return line presents an additional challenge because the drilling mud is usually a non-Newtonian fluid.

[0007] The paddle meter (Figure 4) is often used for measuring flow out on drilling rigs, both land-based and off-shore. A paddle is placed in the mud-flow and the deflection of the paddle is measured. Higher flow rates are indicated by a larger angular deflection of the paddle. A calibration function is applied to convert the angular deflection to flow-rate. This calibration function is often non-linear and may be a function of paddle geometry, assumed fluid viscosity, pipe diameter, and other factors. As can be seen in the graph below, there is significant scatter in the paddle meter output as a function of actual flow rate (Figure 5, extracted from Sandia report, 1992). Independent research performed by Sandia National Labs reported ±15% accuracy for paddle meters.

[0008] Another method for obtaining flow rate in open channel flow systems is to measure the mean stream velocity and the flow stream height. If the channel geometry is known, then the flow area can be calculated based on the flow stream height, and if this is multiplied by the mean flow stream velocity, then volumetric flow rate can be calculated. Applying this methodology, the trickle flow rate resolution is governed by the resolution in flow stream height measurement and the resolution of the mean stream velocity measurement.

[0009] While this invention addresses a non-intrusive method to measure flow stream height in partially filled pipe flow, it could be combined with an existing means of measuring flow stream velocity to determine the bulk flow rate. For example, Doppler radar flow stream velocity measurements combined with ultrasonic flow stream height measurement has been used in other industries to determine the bulk stream velocity.

[00010] The method proposed herein utilizes the difference in dielectric properties of drilling mud (as compared to air) to detect the presence of mud by means of capacitance measurement. Most drilling fluids of interest have a dielectric constant between approximately 4 and 20, whereas air has a dielectric constant of 1. The sensor often comprises an array of capacitive pads formed radially around the inner diameter of a pipe with a data acquisition system ("DAQ") which measures the capacitance of each pad. The dielectrically insulated, submerged pads will have a large capacitance due to their proximity with a high dielectric fluid. Conversely, the pads above the flow stream will have a lower capacitance due to their proximity to air. The liquid level can be measured by determining the number of pads submerged in the liquid, and measuring the response of the pads nearest the liquid-air interface. Additionally, the flow stream velocity (at some distance from the sensor pads) may be measured by comparing the temporal responses of capacitive pads in the downstream direction at equal relative heights with respect to the pipe wall.

[00011] The disclosed system and method are related to the drilling industry for example purposes only. Disclosed embodiments may be applicable for determining the type and amount of any flowing media that has a dielectric constant different than air flowing through a pipe, channel, or pipeline. The mining industry utilizes such flow conditions as does the water transportation industry.

BRIEF DESCRIPTION OF THE DRAWINGS

[00012] Figure 1 depicts a mud flow path and pipe arrangement at the top of the well bore.

[00013] Figure 2 depicts a typical flow out characteristic curves when mud pumps are shut off. Time along x-axis is in seconds. Volume flow rate is along y-axis.

[00014] Figure 3 depicts the velocity contours for 800 gpm drilling mud flow in a 10° return line.

[00015] Figure 4 depicts a paddle style mud flow meter.

[00016] Figure 5 depicts a graph of the flow rate calibration of a paddle meter.

[00017] Figure 6 depicts an example schematic for a capacitive sensor.

[00018] Figure 7 depicts the simulated output from a capacitive sensor.

[00019] Figure 8 depicts a graph of capacitive measurement sensitivity, Distance (mm) v. Clock Cycles.

[00020] Figure 9 depicts a graph showing capacitive measurements for a variety of fluid types.

[00021] Figure 10 depicts a sensor cartridge concept with a spanner nut.

[00022] Figure 11 depicts pad spacing on the interior wall of a pipe.

[00023] Figure 12 depicts a discrete capacitive pipe wall configuration with three sensor arrays.

[00024] Figure 13 depicts a discrete capacitive sensor in the vertical probe configuration.

[00025] Figure 14 depicts a basic capacitive pad.

[00026] Figure 15 depicts an interdigital finger to increase capacitance and sensitivity as compared to straight pads.

[00027] Figure 16 depicts capacitive pads array wrapped in circular ring on inside of pipe.

[00028] Figure 17 depicts two capacitive pad arrays wrapped around inside diameter of pipe, offset angularly from each other to increase resolution.

[00029] Figure 18 shows the radial orientation of capacitive pads is somewhat inconsequential as any pad pair can serve as the "bottom" of the pipe. The bottom pad pair can be determined by the sensor system.

[00030] Figure 19 depicts multiple capacitive pads arrays.

[00031] Figure 20 depicts a closer view of multiple capacitive pad arrays.

[00032] Figure 21 depicts a possible change to the angle of the boards relative to flow direction in order to increase the resolution.

[00033] Figure 22 depicts a graph of the flow stream height as a function of radial distance measured in capacitive pads.

[00034] Figure 23 depicts a graph of the change in fluid height per capacitive pad as a function of radial distance (measured in pad width) for several pipe diameters.

[00035] Figure 24 depicts a graph of the change in flow rate (gpm) per pad as a function of flow rate. As the flow rate increases (from trickle flow to ½ full pipe), the sensitivity to change in flow rate decreases.

[00036] Figure 25 depicts multiple examples of Doppler radar field-of-view for different in-pipe fluid levels.

DETAILED DESCRIPTION

[00037] To understand how discrete capacitive sensing can be used to measure flow rate, the general principle is described. The basic equation for a parallel plate capacitor is:

[00038] $C = \varepsilon \frac{A}{d}$

[00039] In this equation, ε is the dielectric constant (or relative permittivity) of the material between the pads, A is the shared area of the capacitive pads, and d is the distance between pads. As can be seen, a capacitor's value can be changed by changing the dielectric between the two plates.

[00040] In most capacitive sensing configurations, there are not parallel pads and the equation is more complex. However, capacitance is still proportional to pad area and the dielectric properties of the material adjacent to the pad. Hence a pad adjacent to water and oil-based fluids has a much higher capacitance than an equivalent pad adjacent to air, due to water and oil-based fluids having a much higher dielectric constant than air.

[00041] Capacitive sensors typically consist of one or multiple pads adjacent to the environment being sensed, and an electronic circuit that measures the capacitance of those pads. An example of such an electronic circuit is shown in Figure 6. In this example, C_1 is the capacitive pad with a nominal capacitance of 50 pico-Farads. The pad is connected to voltage source V_1 through a large series resistor. V_1 transmits a square wave with a 50% duty cycle and an ON time of 1000 msec. A receiver is connected to the pad via a much smaller series resistor. At the receiver, a delayed version of the square wave is seen. This can be seen in Figure 7, the simulated output of the circuit in Figure 6. The delay between the transmitted (green) and received (blue) waveforms is a function of the series resistance R1 and the pad capacitance value, C_1. If C_1 changes due to the presence of water or drilling mud near the pad, the received waveform delay will increase relative to the transmitted waveform.

[00042] Discrete capacitive flow stream height sensors are based on the principle described above. Large numbers of long, narrow capacitive pads are placed at the perimeter of the flow stream, or possibly in the flow stream. To determine flow height, a data acquisition system compares the delay value of each capacitive pad to a threshold to determine whether that pad is above or below the surface of the fluid. Then, an algorithm calculates the fluid level based on the number of submerged pads, the known pad and

pipe geometry, and the relative measured capacitance of the pads nearest the liquid-air interface.

[00043] Based on initial test results, it appears that this method could yield an overall height measurement resolution of less than 2 mm and a trickle flow height resolution of less than 1 mm. This is illustrated in Figure 8 where the sensor capacitive response is plotted against a reference distance from a fluid sample to a capacitive pad.

[00044] Initial results also suggest that it is possible to distinguish between oil-based muds ("OBMs") and water-based muds ("WBMs"). This is shown in Figure 9, where sensor response (in clock cycles) is plotted against effective capacitance for various combinations of capacitive pad areas/shapes, dielectric insulation material thicknesses, and fluids. Given that this technique is very sensitive to different fluid samples and the specific fluid properties, it may also be possible to determine if there is gas entrained in the mud stream based on measurements from the capacitive pads.

[00045] The sensor hardware is compatible with existing mud return line construction. It is robust to the operational environment and substantially insensitive to temperature as well as gas composition in the head-space above the mud flow stream.

[00046] There are multiple potential embodiments for a discrete capacitive sensor. In one embodiment, a single sensor "element" comprised of one or more flexible or rigid circuit boards containing arrays of capacitive pads line a steel pipe wall (depicted in Figures 10 and 16). A multi-sensor version of this 'pipe-wall' configuration is envisioned where the sensor elements are spaced some distance apart to provide redundant sensing. Multiple sensors separated by axial distance has an additional benefit of potentially detecting standing waves in the flow stream. A 3-element sensor version is shown in shown in Figure 12.

[00047] Based on initial experiments, the pad width (w) is 0.125” and the spacing (or pitch, p) is twice the pad width ($p=2w$) as shown in Figure 11. The arc angle (θ) of the pad (including the space between pads) is a function of the pipe radius (R), such that $p=R\theta$ where θ is the included angle of pad-space pair. There are 2π radians in the circumference of a circle. The number of capacitive pad elements (n) within the circumference of the circular cross-section is $2\pi/\theta$. Substituting $2w/R$ for θ yields $n=2\pi R/(2w)$ which simplifies to $\pi R/w$. In reality, there may be fewer than “n” pads for any given pipe diameter because some pads at the top of the pipe may be missing to allow for connections to the electronics. This should not usually pose a problem because the flow rate when the pipe is full or nearly full is not particularly critical and the incremental flow not accounted for by the last few missing pads becomes less significant as the pipe approaches “full”. If it is not negligible, then adjustment to the calculations may be useful. Some embodiments of the disclosed system may utilize an alternate pad geometry optimized to provide a higher signal to noise ratio under certain conditions. Alternate geometries may also be configured to minimize sensor size.

[00048] In an alternate discrete capacitive embodiment, a thin vertical probe containing an array of capacitive pads on both sides may be inserted through the center of the pipe into the flow-stream. This approach has the advantage of a simplified installation. An example of a single-channel ‘vertical probe’ configuration is shown in Figure 13. This embodiment may be used to determine the height of a fluid flowing through a pipe.

[00049] Additionally, a sensor module or processor may be configured to calculate the height of the fluid above a calculated “ground” plane. This will allow the system to control the distance from the capacitive pads to the apparent pipe wall independent of the position of the actual pipe wall.

[00050] **Dynamic Sampling for Increased Height Resolution**

[00051] There are many sampling options for the system. Time Division Multiplexing is one possible approach to measure capacitance from all capacitive pads. Specifically, the data acquisition system will measure the value of one pad at a time, starting at the bottom of the pipe. This sampling method may result in a lower frame rate than might otherwise be desirable. There are several methods of sampling that can potentially increase the frame rate significantly.

[00052] Several dynamic sampling methods are available. The first method is to sample from several pads simultaneously. This method has the potential to increase the sample rate by several orders of magnitude. Ideally, it would be possible to sample from one pad of all N sampling chips simultaneously, thereby increasing frame rate by a factor of N. One should consider the bandwidth of the communication link, and the potential for electro-magnetic interference from simultaneous sampling of pads in close proximity.

[00053] Another dynamic sampling method is to increase sampling of pads close to the fluid level, and decrease the sampling of pads well below or well above the fluid level. This method also has the potential to increase frame-rate significantly because there are a low number of pads at the fluid level relative to those well below or above the fluid level. Feedback from the fluid height algorithm may be useful for this method.

[00054] **Multiple Pad Sampling for Increased Depth Penetration**

[00055] The measurement range of a capacitive pad can often be increased by increasing the area of the pad. The significance of high-range measurements in mud flow sensing is the ability to detect sediment buildup on the bottom of the pipe, and the ability to detect the presence of fluid beyond the sediment buildup. One method useful in capacitive sensing to increase pad size is to simultaneously activate multiple adjacent pads and use them in a similar manner as one large capacitive pad.

[00056] **Sediment Build-up Identification**

[00057] Sediments are known to build up in the mud return lines. A discrete capacitive sensor should be able to detect this sedimentation build-up. As sediments build up above the capacitive pads, they can eventually create a constant dielectric “field” and the capacitance measured in the pads will remain relatively constant. Conversely, the dielectric properties of a flowing mud stream are expected to vary with changes in the fluid dielectric. It may be useful to differentiate these different behaviors and modify the pipe geometry to provide a more accurate flow stream height estimate (or perhaps a flow area estimate). Additionally, the sensor could alert the operator that sediments are detected with the return line.

[00058] **Entrained Gas Detection**

[00059] Gas entrained in the mud flow stream can change the fluid dielectric properties. Because the sensors measure the capacitance of the fluid in close proximity, it is conceivable that the proposed sensor system may be able to detect the change in dielectric properties of the mud (drilling fluid) as gas is introduced into the flow stream

[00060] **Fluid Velocity Measurements**

[00061] Fluid velocity is essential to conversion of fluid height to fluid volume flow rate. One method of measuring fluid velocity is the Doppler radar technique described previously. Another possible method would use the capacitive pads in series in an axial configuration so that the waveforms of capacitive value versus time due to inhomogeneous fluid properties will be delayed by a known distance for the fluid flow. The delay can be estimated through cross correlation techniques and the measured delay can be converted to an estimated fluid flow rate.

[00062] **Doppler Radar in Combination with the Discrete Capacitive Flow Stream Height Sensor**

[00063] Doppler radar flow stream velocity measurements combined with ultrasonic flow stream height measurement may be used to determine the bulk stream velocity. The surface of the fluid measured by a Doppler radar system can be thought of as a circular or elliptical area, where the size of the ellipse is a function of the sensor height, sensor angle, and the directionality of the antenna. Figure 25 shows this concept graphically for several in-pipe fluid levels. As shown in previous sections, different regions of the flow stream have different velocities. Therefore, if Doppler radar illuminates a large surface of the flow stream, there should be multiple velocities at its receiver.

[00064] Most commercial Doppler radar systems digitize the received signal and after processing, only provide the user with a single velocity measurement. In this case, it may be desirable to receive the raw Doppler velocity spectrum at the receiver, and use this for a more accurate velocity calculation.

[00065] One drawback to using the above approach with a single Doppler radar is that as flow height increases, the area illuminated by the sensor decreases, and the velocity profile may be reduced to, e.g. a single velocity measurement at the center of the channel. One potential method to overcome this is by adding one or multiple axially offset sensors to measure surface fluid velocity profile.

[00066] At trickle flow, the field-of-view is wider than the fluid channel and the velocity reading will include some areas with zero velocity. At low to medium fluid levels, the field-of-view will include a large portion of the flow cross section and it may be possible to measure an accurate fluid surface velocity profile.

[00067] Disclosed embodiments relate to a system for measuring the flow stream height of a liquid flowing through a pipe. Embodiments of the system comprise a plurality of capacitive pads, said capacitive pads arranged within a pipe, a data acquisition system connected to said pads wherein said data acquisition system is capable of

measuring the capacitance of each pad, and a processor capable of calculating the flow stream height based on the capacitance of each pad.

[00068] In some embodiments the capacitive pads are protected from abrasion and corrosion using a film or polymer coating. Embodiments may also be configured to optimize the signal to noise ratio by adjusting the pad geometry based on the application.

[00069] Preferred embodiments disclosed include:

[00070] (1) A system for measuring the flow stream height of a liquid flowing through a pipe comprising:

a plurality of capacitive pads, said capacitive pads arranged within a pipe;

a data acquisition system connected to said pads wherein said data acquisition system is capable of measuring the capacitance of each pad; and

a processor capable of calculating the flow stream height based on the capacitance of each pad.

[00071] (2) The system of embodiment 1 wherein the capacitive pads are arranged radially within the interior of a pipe.

[00072] (3) The system of embodiment 1, wherein the capacitive pads are protected from abrasion and corrosion.

[00073] (4) The system of embodiment 1, wherein the capacitive pad geometry is optimized to maximize the signal to noise ratio.

[00074] (5) The system of embodiment 1, wherein the capacitive pad geometry is optimized to maximize the signal to noise ratio while minimizing sensor size.

[00075] (6) The system of embodiment 1, wherein the position of an apparent ground plane is calculated by the processor.

[00076] (7) The system of embodiment 1 wherein multiple capacitive pads are axially displaced along the pipe.

[00077] (8) The system of embodiment 1 wherein multiple capacitive pads are arranged in an array.

[00078] (9) The system of embodiment 8 wherein a plurality of arrays are angularly offset from each other.

[00079] (10) The system of embodiment 1 wherein the capacitive pads are interdigital finger pads.

[00080] (11) The system of embodiment 1 wherein time division multiplexing is used to measure the capacitance of the capacitive pads.

[00081] (12) The system of embodiment 1 wherein a dynamic sampling method is used to measure the capacitance of the capacitive pads.

[00082] (13) The system of embodiment 12 wherein the capacitance of multiple capacitive pads is measured simultaneously.

[00083] (14) The system of embodiment 13 wherein the capacitance of multiple adjacent capacitive pads is measured simultaneously.

[00084] (15) The system of embodiment 12 wherein the capacitance of the capacitive pads proximate to a liquid gas interface is measured more frequently than the capacitance of the capacitive pads further from said interface.

[00085] (16) The system of embodiment 1 wherein the capacitive pads are arranged on a vertical probe.

[00086] (17) A method for measuring the flow stream height of a liquid within a pipe comprising:

measuring the capacitance of a plurality of capacitive pads,

calculating the height of a flow stream based on the measured capacitance of the capacitive pads.

[00087] (18) The method of embodiment 17 further comprising measuring the capacitance of a plurality of capacitive pads axially displaced from one another.

[00088] (19) The method of embodiment 17 further comprising using a previously calculated flow stream height to optimize subsequent measuring of the capacitance from a plurality of capacitive pads.

[00089] (20) The method of embodiment 17 wherein the capacitance of multiple capacitive pads is measured simultaneously.

[00090] (21) The method of embodiment 17 further comprising calculating the presence of a gas entrained in a liquid stream based on the measured capacitance.

[00091] (22) The method of embodiment 21 wherein the liquid is a drilling fluid.

[00092] (23) A method for measuring the velocity of a liquid flow stream comprising:

using a Doppler radar system to illuminate the surface of a liquid flow stream,

receiving a Doppler radar signal, and

calculating the velocity of the flow stream based on the received Doppler radar signal.

[00093] (24) The method of embodiment 23 wherein multiple axially offset sensors are used to measure the velocity of the liquid flow stream.

[00094] (25) The method of embodiment 23 further comprising using an ultrasonic flow stream height measurement to calculate the height or velocity of the flow stream

[00095] (26) A method for calculating the flow stream velocity of a liquid within a pipe comprising:

measuring the capacitance waveforms of a first set of capacitive pads,

measuring the capacitance waveforms of a second set of capacitive pads,

said second set of capacitive pads being axially displaced a known distance from the first set, comparing the capacitance waveforms of the first set of capacitive pads with the capacitance waveforms of the second set of capacitive pads,

[00096] calculating the velocity of the flow stream based on the relationship of the capacitance waveforms of the first set and second set of capacitive pads.

[00097] It will be appreciated that the multiple embodiments and methods discussed herein may be used to individually or to corroborate one another. Additionally, multiple techniques and methods may potentially be used with the same physical apparatus. One or all of these redundant techniques may be used to cross-correlate the collected data. Additionally, while this application relates to the drilling industry for example purposes, the disclosed embodiments may be applied to any industry in which sensing the amount and/or type of flowing media, flowing through a pipe, trough or channel is desired.

CLAIMS

What is claimed is:

1. A system for measuring the flow stream height of a liquid flowing through a pipe comprising:

    a plurality of capacitive pads, said capacitive pads arranged within a pipe;

    a data acquisition system connected to said pads wherein said data acquisition system is capable of measuring the capacitance of each pad; and

    a processor capable of calculating the flow stream height based on the capacitance of each pad.

2. The system of claim 1, wherein the capacitive pad geometry is optimized to maximize the signal to noise ratio.
3. The system of claim 1 wherein multiple capacitive pads are axially displaced along the pipe.
4. The system of claim 1 wherein multiple capacitive pads are arranged in at least one array.
5. The system of claim 4 wherein a plurality of arrays are angularly offset from each other.
6. The system of claim 1 wherein the capacitive pads are interdigital finger pads.
7. The system of claim 1 wherein time division multiplexing is used to measure the capacitance of the capacitive pads.
8. The system of claim 1 wherein a dynamic sampling method is used to measure the capacitance of the capacitive pads.
9. The system of claim 8 wherein the capacitance of multiple capacitive pads is measured simultaneously.

10. The system of claim 8 wherein the capacitance of the capacitive pads proximate to a liquid gas interface is measured more frequently than the capacitance of the capacitive pads further from said interface.

11. The system of claim 1 wherein the capacitive pads are arranged on a vertical probe.

12. A method for measuring the flow stream height of a liquid within a pipe comprising:

    measuring the capacitance of a plurality of capacitive pads,

    calculating the height of a flow stream based on the measured capacitance of the capacitive pads.

13. The method of claim 12 further comprising measuring the capacitance of a plurality of capacitive pads axially displaced from one another.

14. The method of claim 12 further comprising using a previously calculated flow stream height to optimize subsequent measuring of the capacitance from a plurality of capacitive pads.

15. The method of claim 12 wherein the capacitance of multiple capacitive pads is measured simultaneously.

16. The method of claim 12 further comprising calculating the presence of a gas entrained in a liquid stream based on the measured capacitance.

17. A method for measuring the velocity of a liquid flow stream comprising:

    using a Doppler radar system to illuminate the surface of a liquid flow stream,

    receiving a Doppler radar signal, and

    calculating the velocity of the flow stream based on the received Doppler radar signal.

18. The method of claim 17 wherein multiple axially offset sensors are used to measure the velocity of the liquid flow stream.

19. The method of claim 17 further comprising using an ultrasonic flow stream height measurement to calculate the height or velocity of the flow stream

20. A method for calculating the flow stream velocity of a liquid within a pipe comprising:

    measuring the capacitance waveforms of a first set of capacitive pads,

    measuring the capacitance waveforms of a second set of capacitive pads,

        said second set of capacitive pads being axially displaced a known distance from the first set,

    comparing the capacitance waveforms of the first set of capacitive pads with the capacitance waveforms of the second set of capacitive pads,

    calculating the velocity of the flow stream based on the relationship of the capacitance waveforms of the first set and second set of capacitive pads.

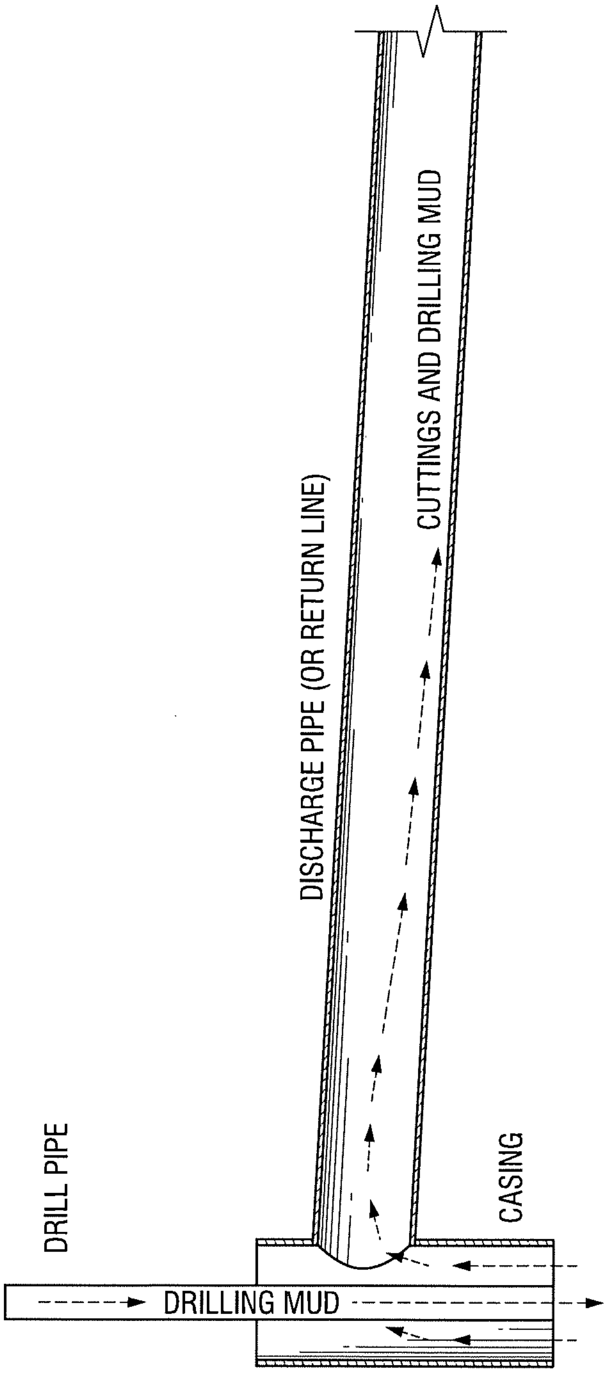
DISCHARGE PIPE (OR RETURN LINE)
CUTTINGS AND DRILLING MUD
DRILL PIPE
CASING
DRILLING MUD

FIG. 1

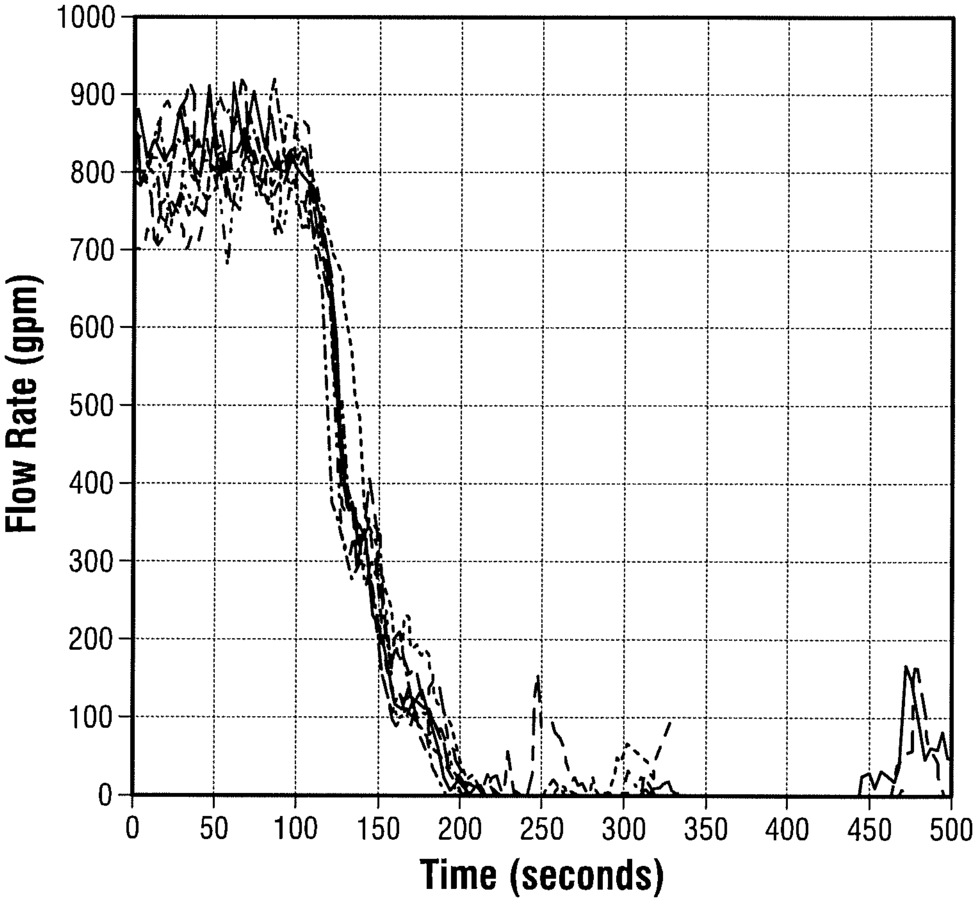
1000
900
800
700
600
500
400
300
200
100
0
Flow Rate (gpm)
0
50
100
150
200
250
300
350
400
450
500
Time (seconds)

FIG. 2

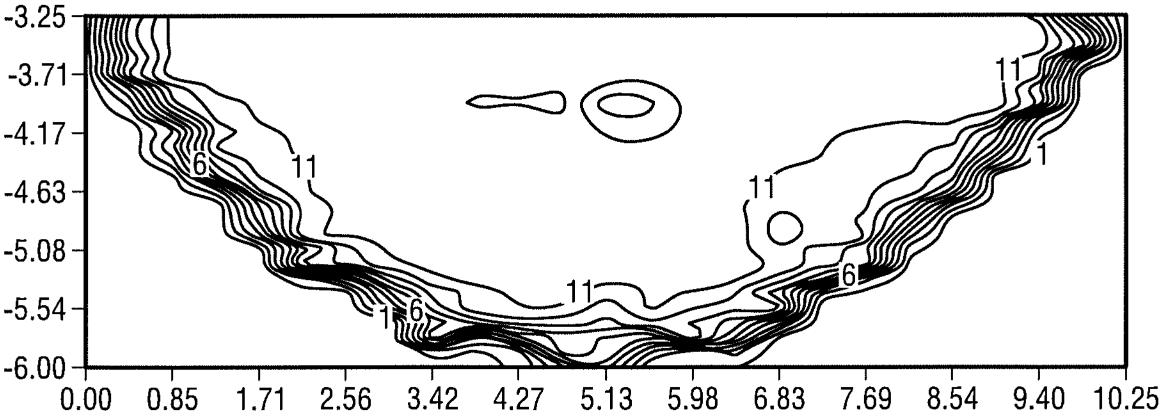
-3.25
-3.71
-4.17
-4.63
-5.08
-5.54
-6.00
0.00
0.85
1.71
2.56
3.42
4.27
5.13
5.98
6.83
7.69
8.54
9.40
10.25
11
11
11
11
11
6
6
6
1
1
1

FIG. 3

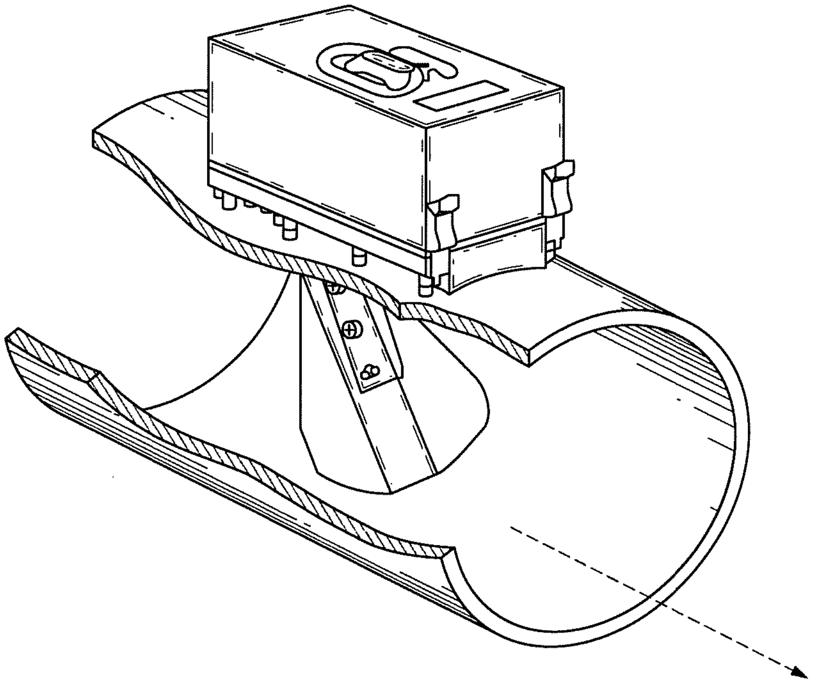

FIG. 4

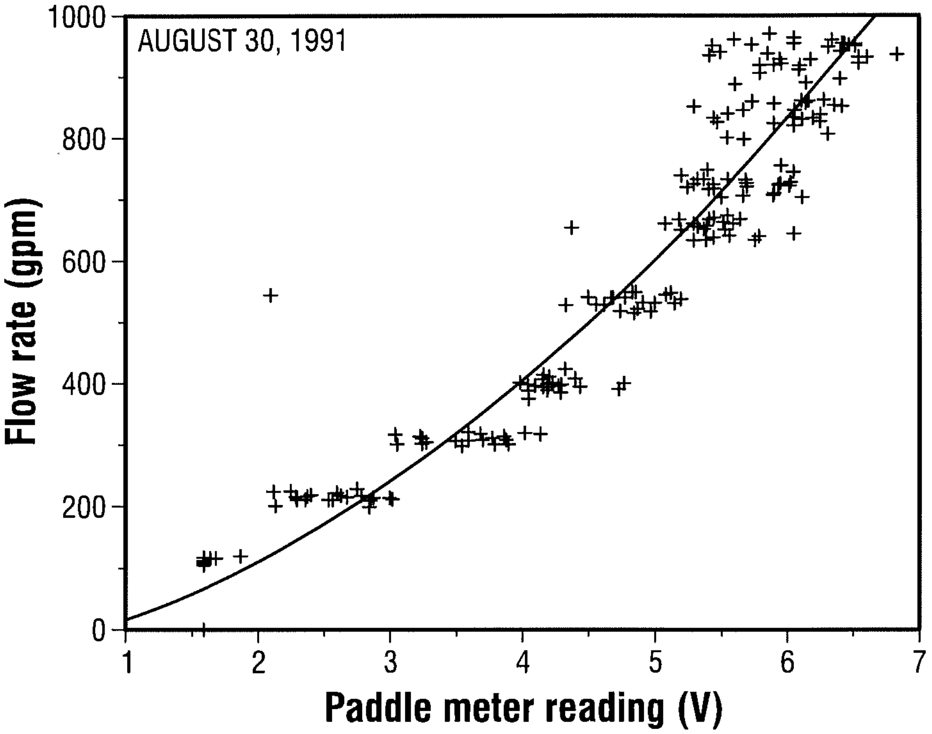
AUGUST 30, 1991
Flow rate (gpm)
1000
800
600
400
200
0
1
2
3
4
5
6
7
Paddle meter reading (V)

FIG. 5

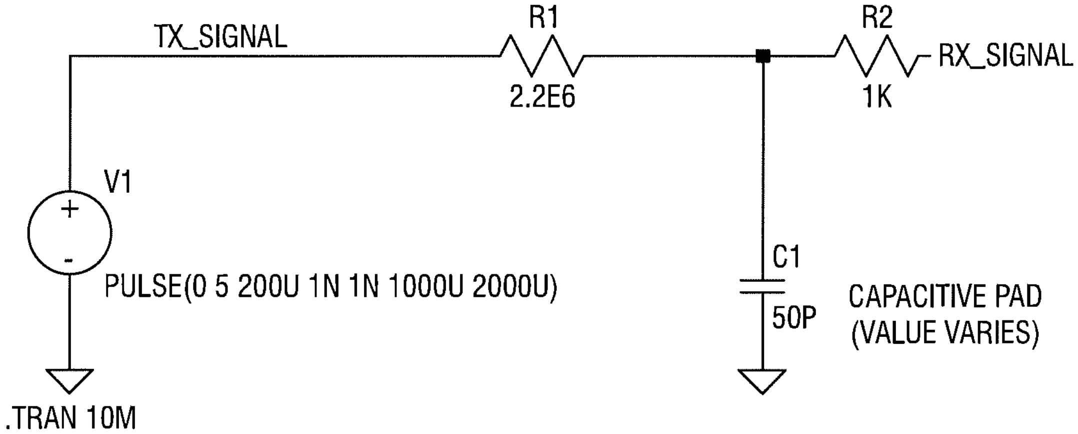
TX_SIGNAL
R1
2.2E6
R2
1K
RX_SIGNAL
V1
+
-
PULSE(0 5 200U 1N 1N 1000U 2000U)
.TRAN 10M
C1
50P
CAPACITIVE PAD
(VALUE VARIES)

FIG. 6

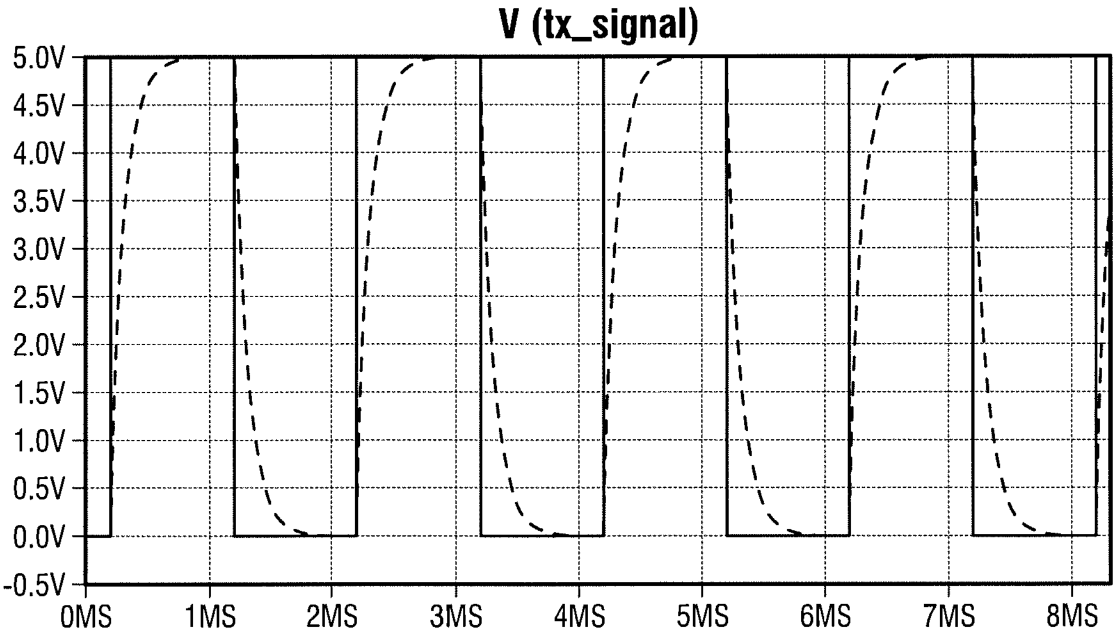
V (tx_signal)
5.0V
4.5V
4.0V
3.5V
3.0V
2.5V
2.0V
1.5V
1.0V
0.5V
0.0V
-0.5V
0MS
1MS
2MS
3MS
4MS
5MS
6MS
7MS
8MS

FIG. 7

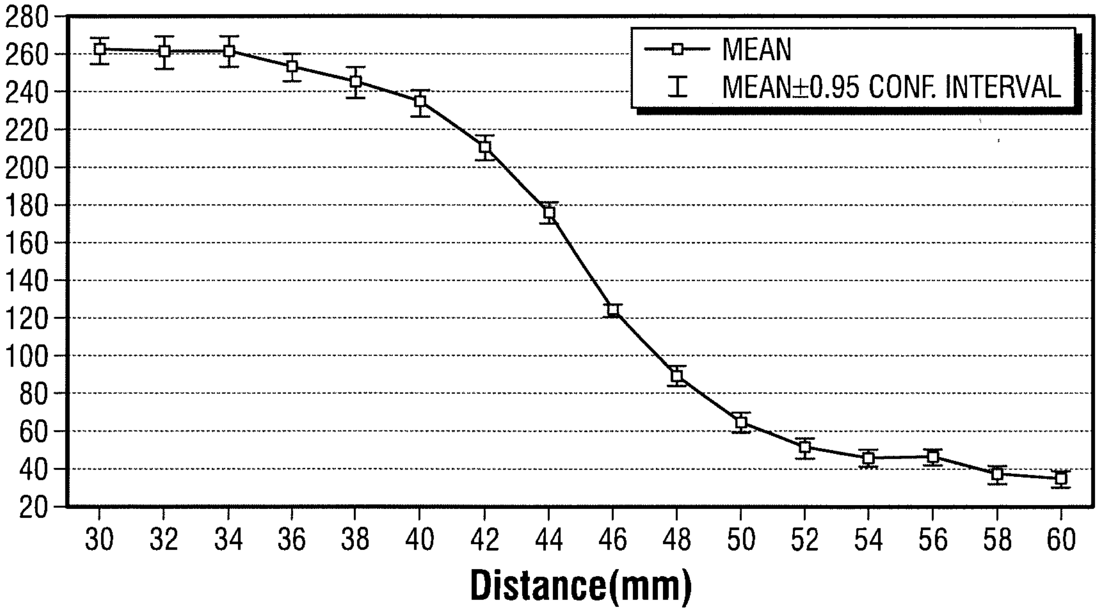
280
260
240
220
200
180
160
140
120
100
80
60
40
20
30
32
34
36
38
40
42
44
46
48
50
52
54
56
58
60
Distance(mm)
MEAN
MEAN±0.95 CONF. INTERVAL

FIG. 8

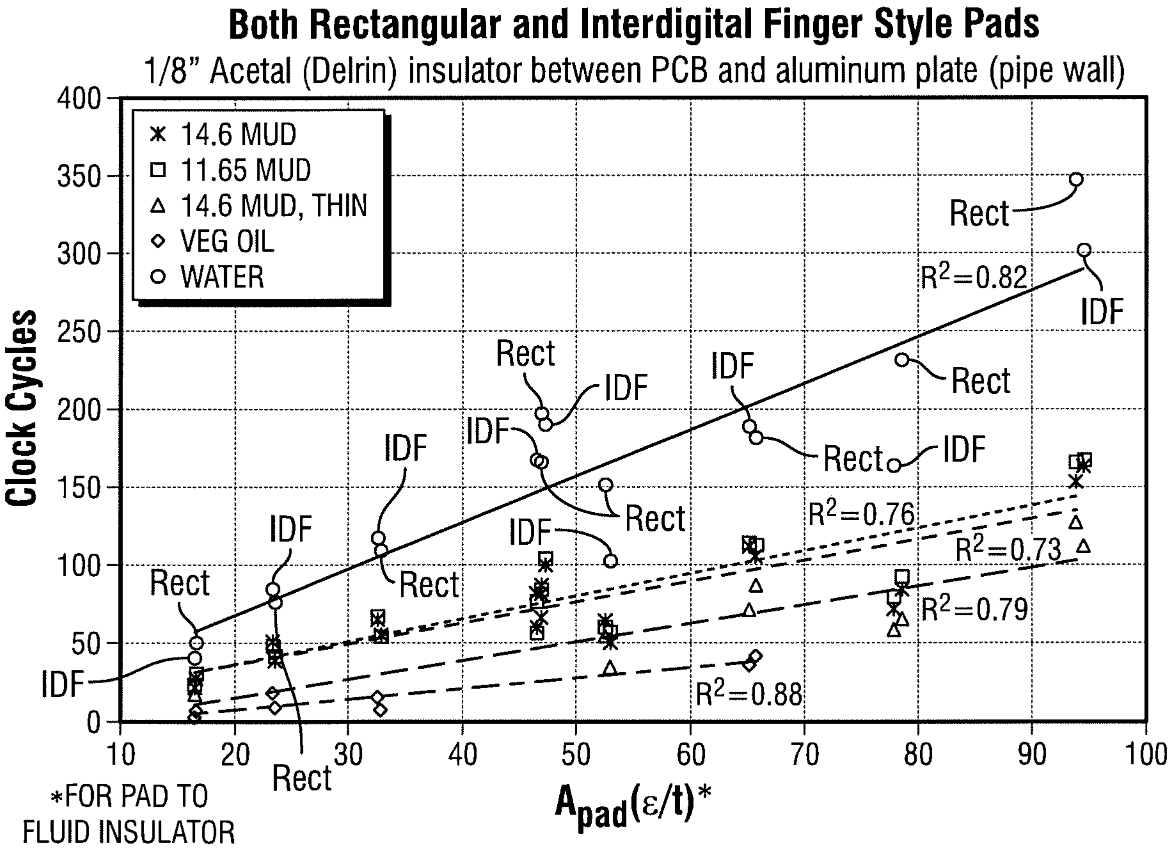
Both Rectangular and Interdigital Finger Style Pads
1/8" Acetal (Delrin) insulator between PCB and aluminum plate (pipe wall)
Clock Cycles
400
350
300
250
200
150
100
50
0
✶ 14.6 MUD
□ 11.65 MUD
△ 14.6 MUD, THIN
◇ VEG OIL
○ WATER
Rect
IDF
R^2=0.82
Rect
IDF
Rect
IDF
IDF
Rect
Rect
IDF
IDF
Rect
IDF
Rect
IDF
Rect
IDF
Rect
Rect
IDF
R^2=0.76
R^2=0.73
R^2=0.79
R^2=0.88
10
20
30
40
50
60
70
80
90
100
Rect
*FOR PAD TO FLUID INSULATOR
A_{pad}(ε/t)*

FIG. 9

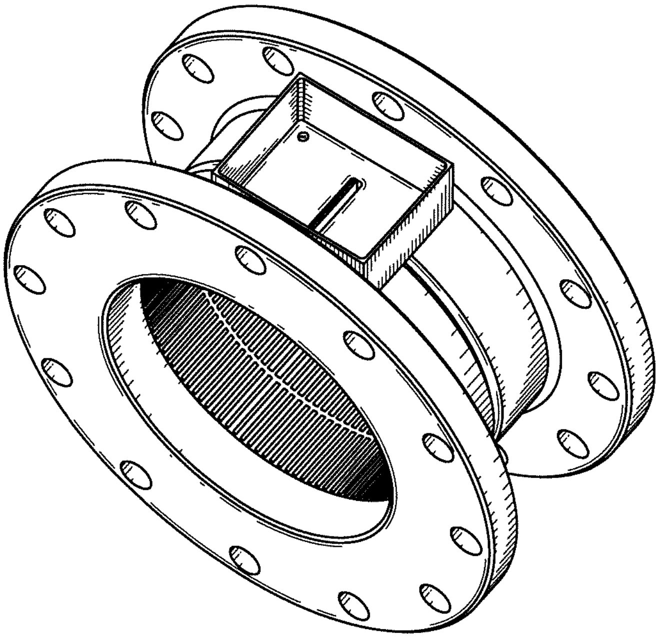

FIG. 10

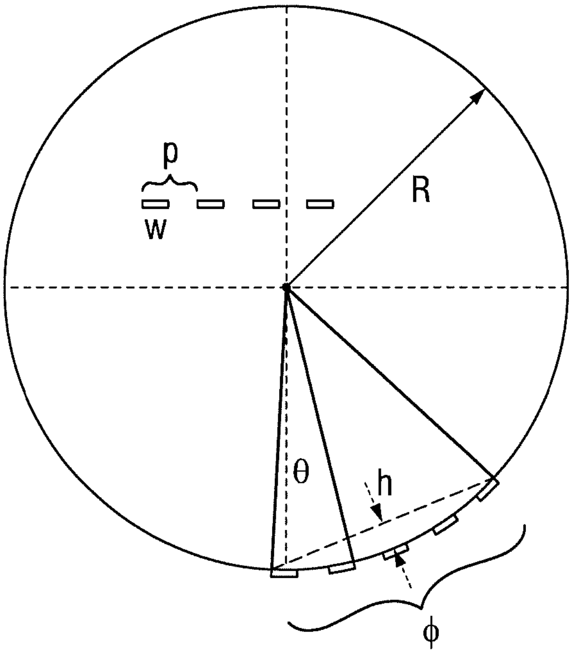

FIG. 11

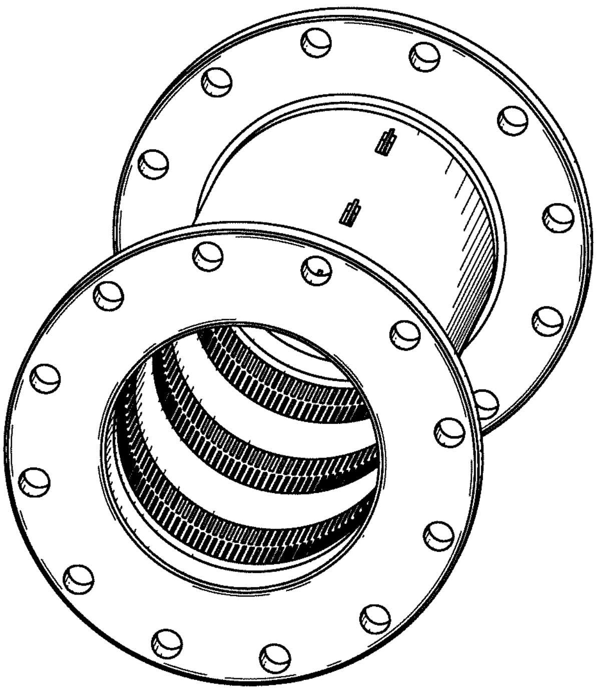

FIG. 12A

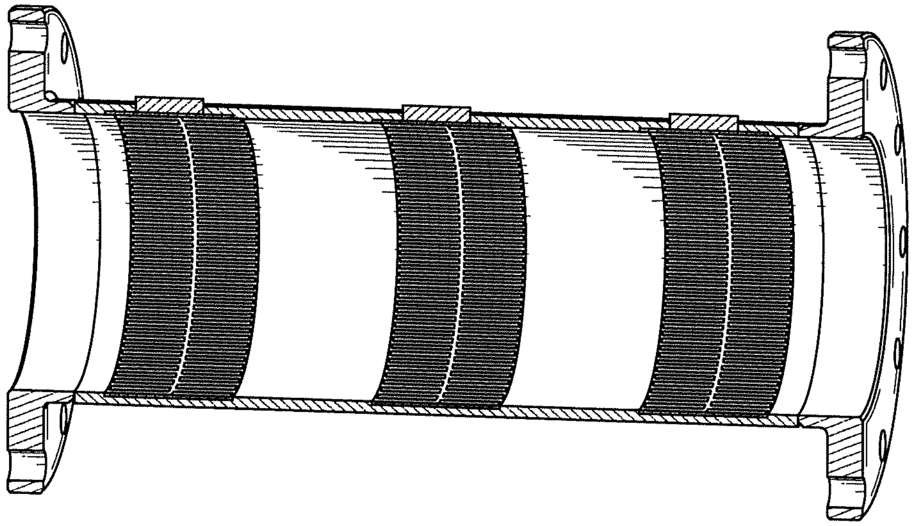

FIG. 12B

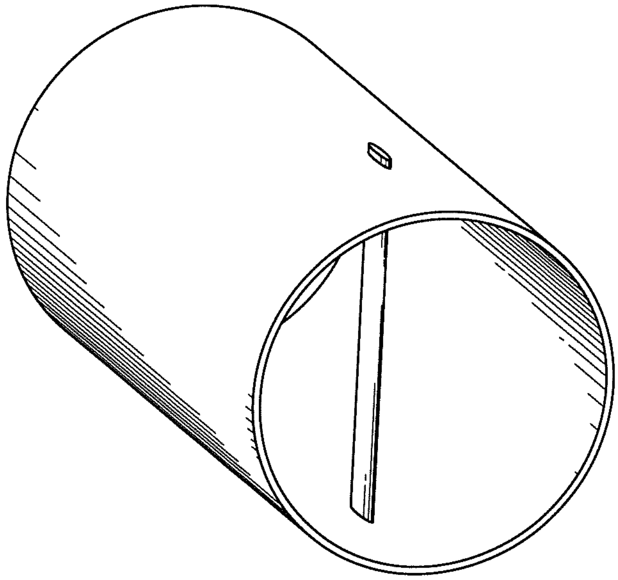

FIG. 13A

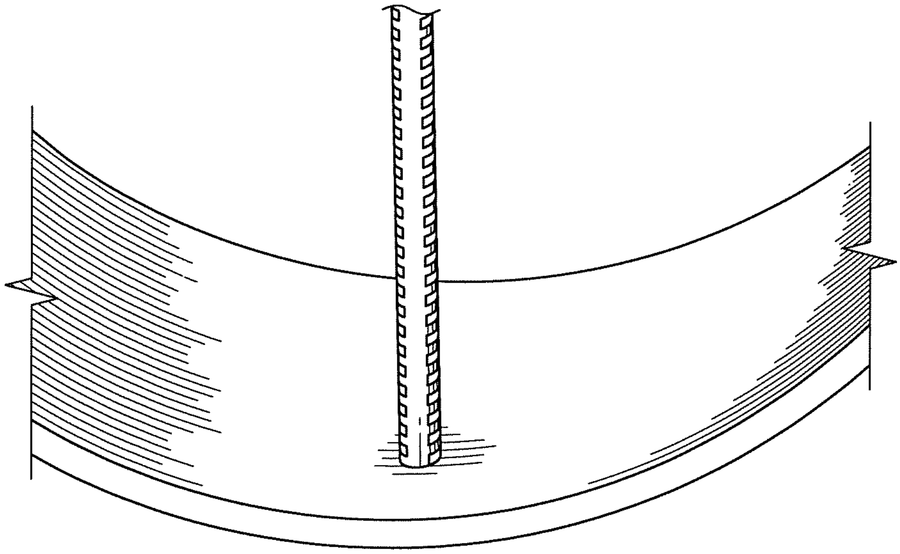

FIG. 13B

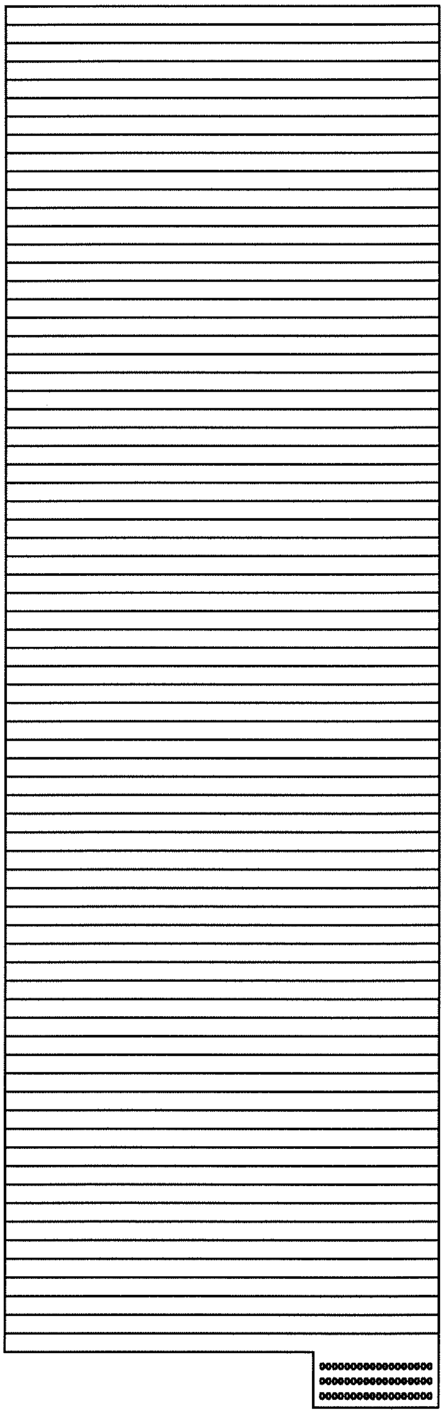

FIG. 14

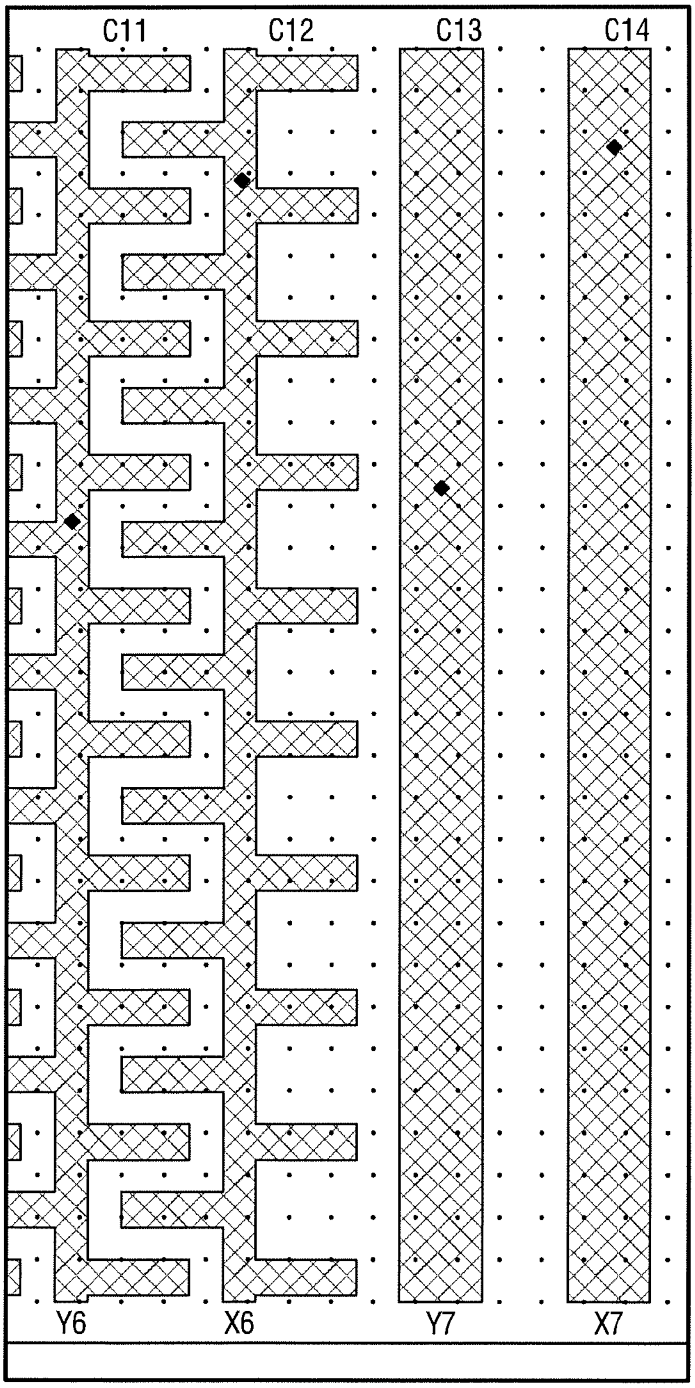

FIG. 15

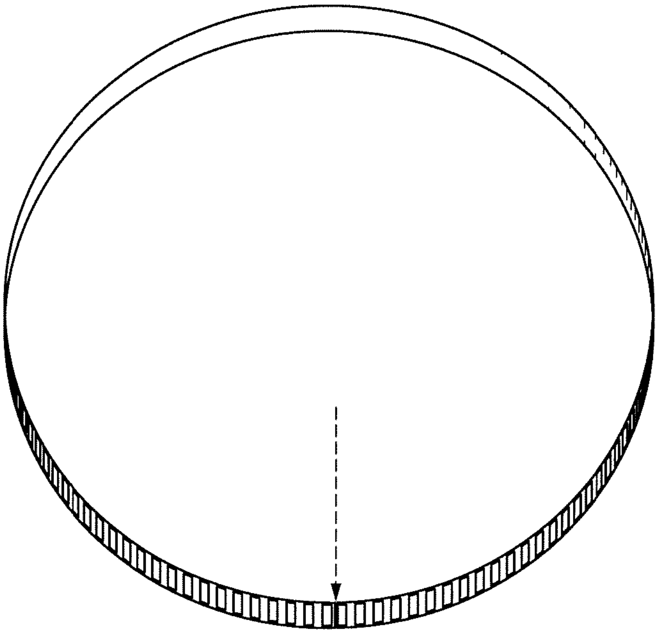

FIG. 16

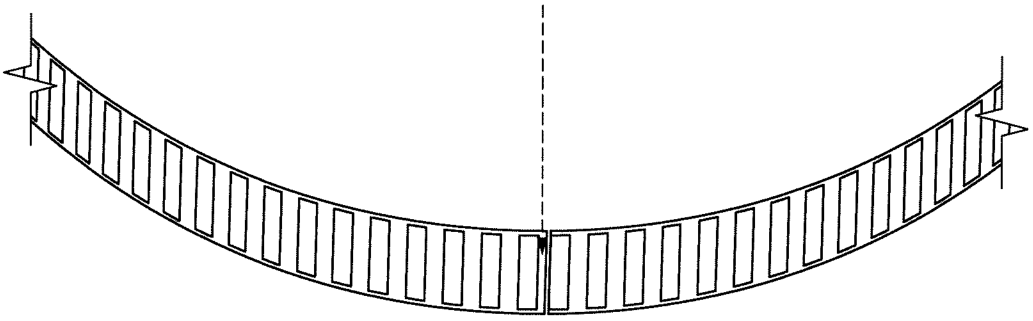

FIG. 17

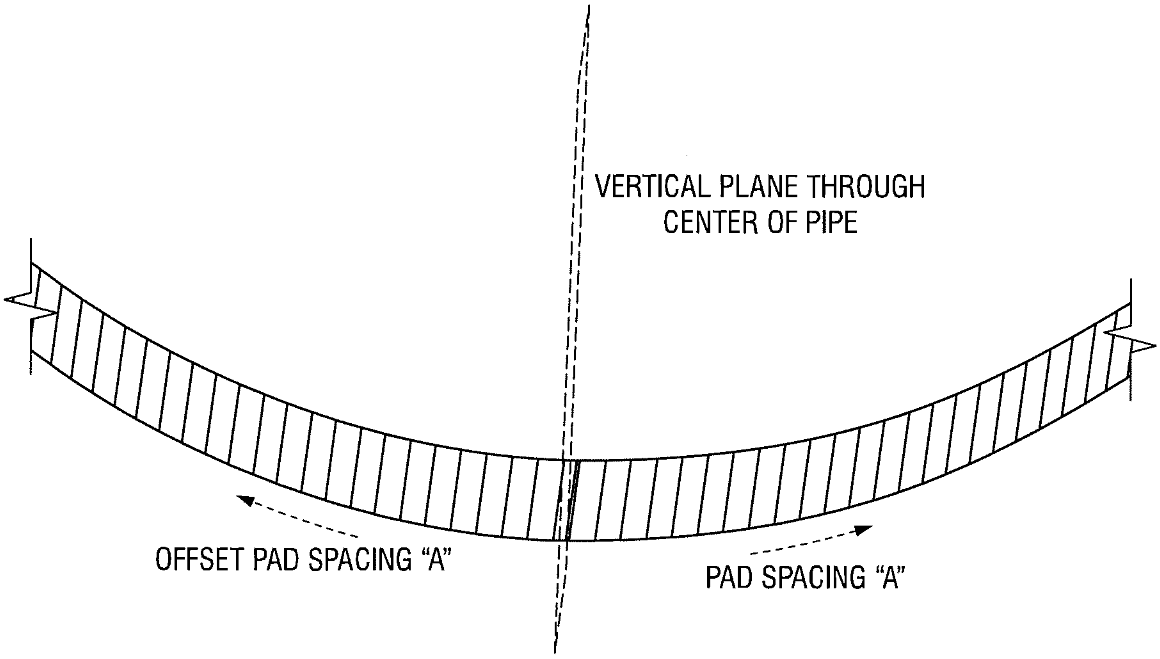
VERTICAL PLANE THROUGH
CENTER OF PIPE
OFFSET PAD SPACING "A"
PAD SPACING "A"

FIG. 18

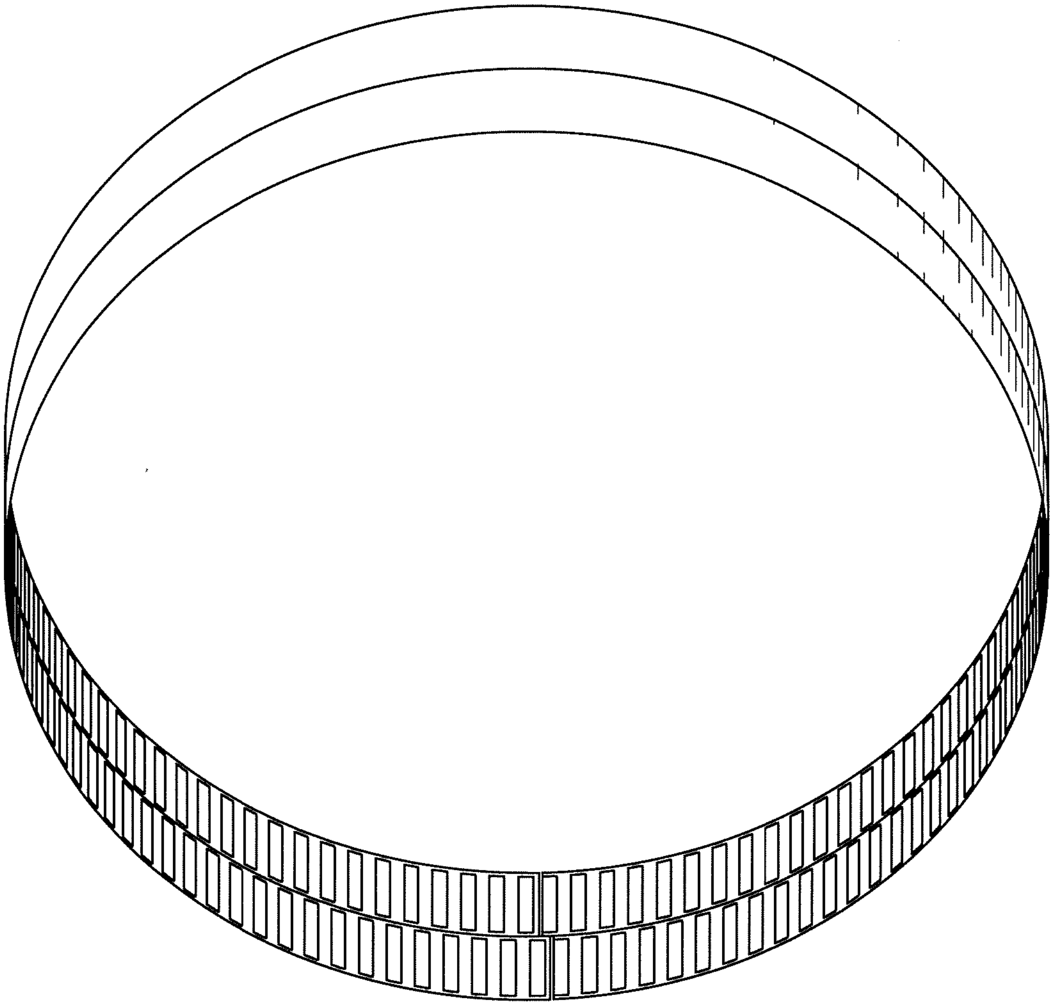

FIG. 19

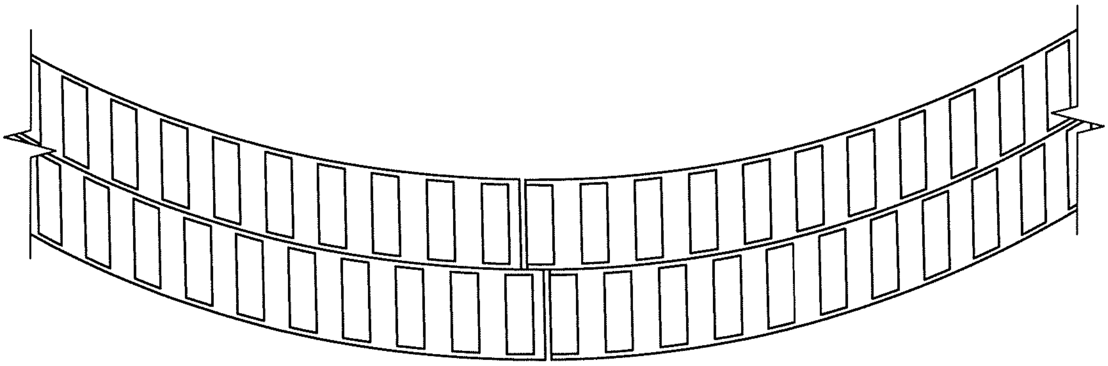

FIG. 20

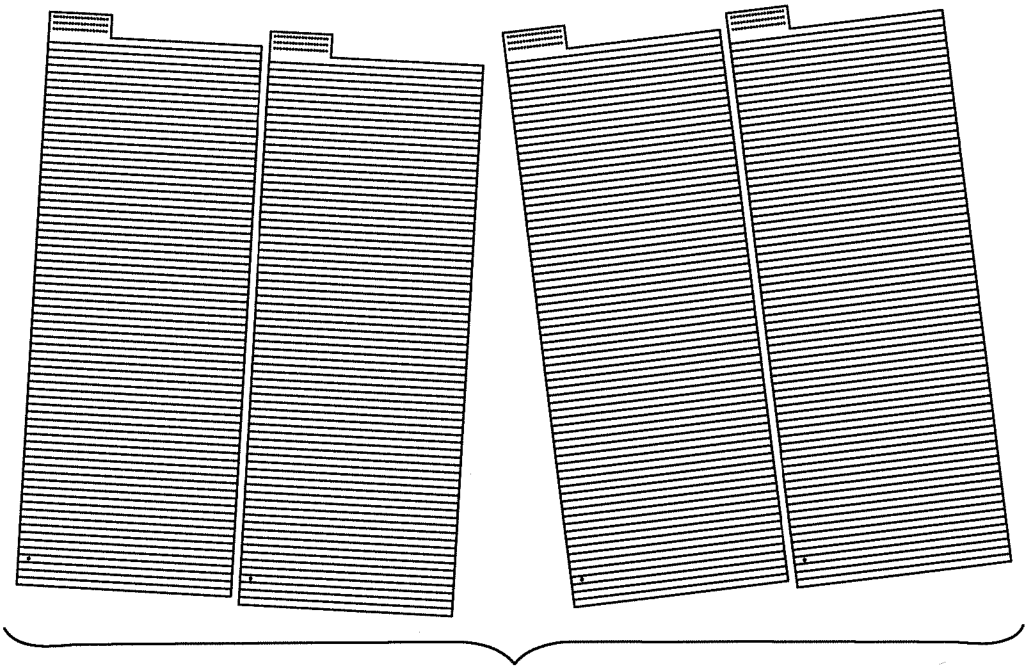

FIG. 21

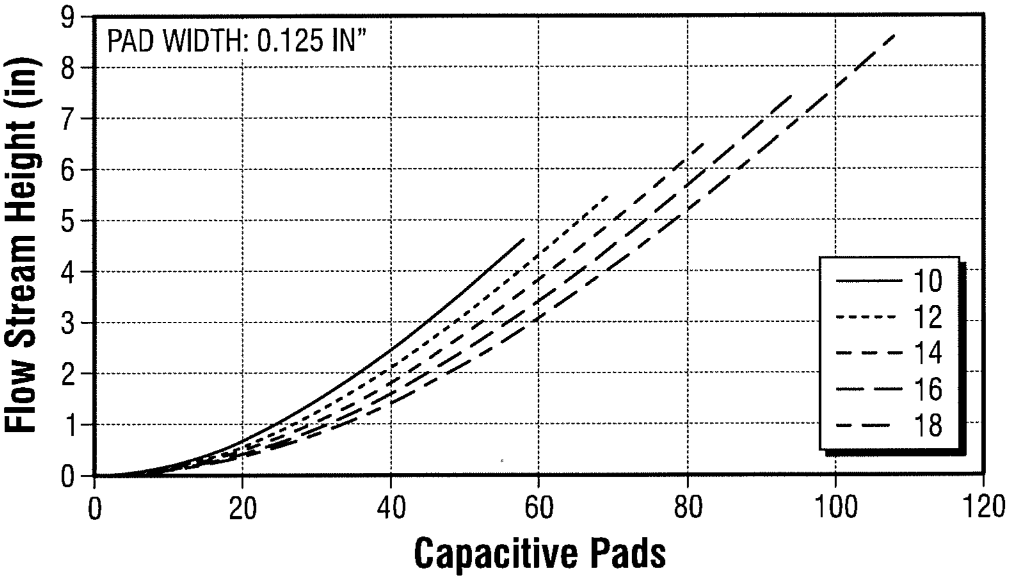
PAD WIDTH: 0.125 IN"
Flow Stream Height (in)
0
1
2
3
4
5
6
7
8
9
0
20
40
60
80
100
120
Capacitive Pads
10
12
14
16
18

FIG. 22

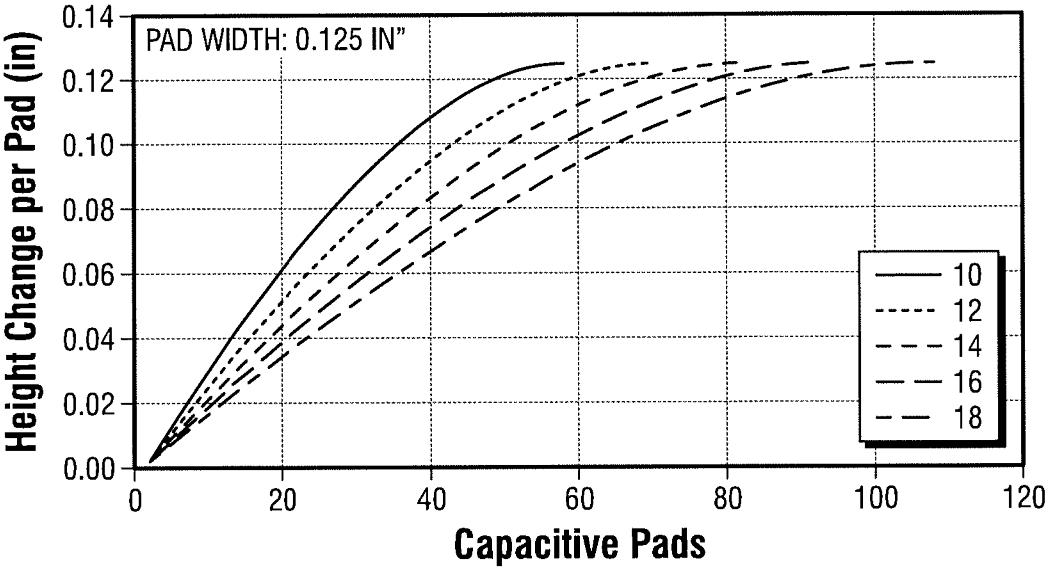
PAD WIDTH: 0.125 IN"
Height Change per Pad (in)
0.14
0.12
0.10
0.08
0.06
0.04
0.02
0.00
0
20
40
60
80
100
120
Capacitive Pads
10
12
14
16
18

FIG. 23

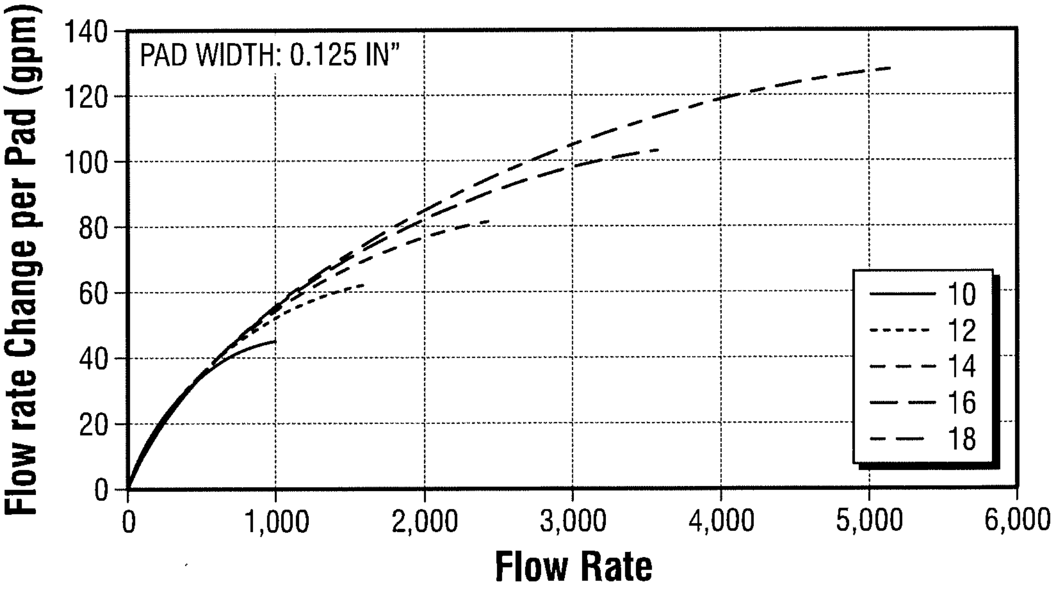
PAD WIDTH: 0.125 IN"
Flow rate Change per Pad (gpm)
140
120
100
80
60
40
20
0
0
1,000
2,000
3,000
4,000
5,000
6,000
Flow Rate
10
12
14
16
18

FIG. 24

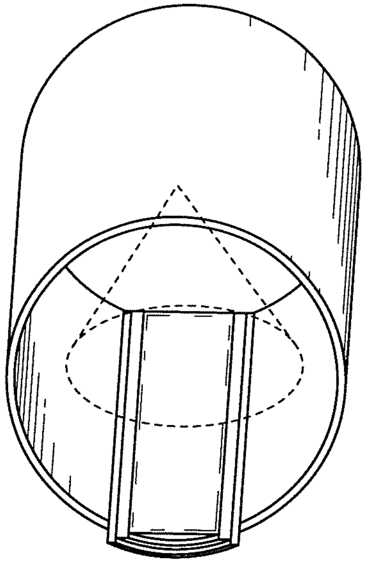

FIG. 25A

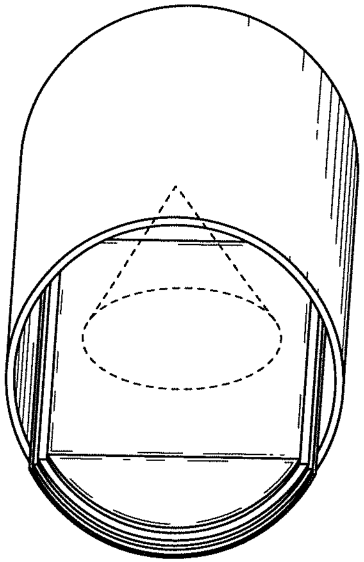

FIG. 25B

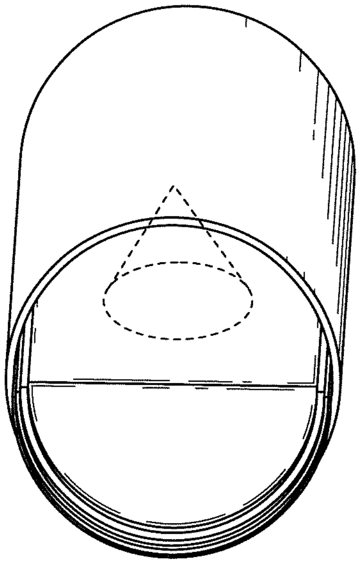

FIG. 25C

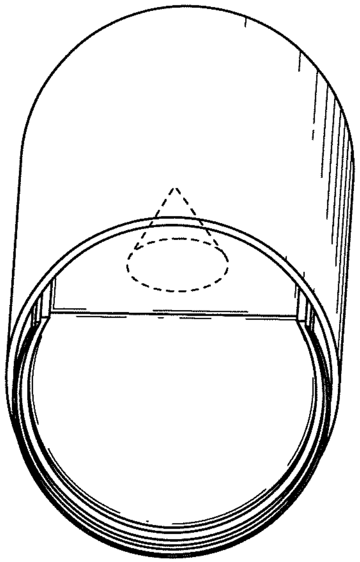

FIG. 25D

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US16/26893

A. CLASSIFICATION OF SUBJECT MATTER
IPC(8) - G01F 23/26; G08B 21/18; G01N 27/22; G01R 27/26; G01D 5/24 (2016.01)
CPC - G01F 23/266, 23/268; G01N 27/221, 27/228; G01R 27/2605
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)
IPC(8): G01F 23/26; G08B 21/18; G01N 27/22; G01R 27/26; G01D 5/24 (2016.01); CPC: G01F 23/266, 23/268; G08B 21/182; G01N 27/221, 27/223, 27/226, 27/227, 27/228; G01R 27/2605, 27/2623, 27/2647, 27/2676; G01D 5/2405

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

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
PatSeer (US, EP, WO, JP, DE, GB, CN, FR, KR, ES, AU, IN, CA, INPADOC Data); Google; Google Scholar; EBSCO; KEYWORDS: flow stream height liquid pipe capacitive pads data acquisition system processor axially array

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X --- Y	US 7,821,411 B1 (WARD, C.) October 26, 2010; figures 2-7; column 2, line 19 to column 5, line 25; claims 1 & 15	1, 3-4, 8-9 and 12-16 --- 2, 5-7 and 10-11
Y	US 2014/0139239 A1 (ZRRO TECHNOLOGIES LTD.) May 22, 2014; paragraphs [0099-0100]	2
Y	US 5,777,532 A (LAKIN, K.) July 07, 1998; figure 1A; column 2, lines 5-12; column 3, lines 35-40; column 4, lines 26-29	5-6 and 11
Y	US 4,003,259 A (HOPE, B.) January 18, 1977; figures 1-3; column 2, line 50 to column 3, line 45; column 4, lines 7-16	7 and 10

☐ 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 23 July 2016 (23.07.2016)	Date of mailing of the international search report 31 AUG 2016
Name and mailing address of the ISA/ Mail Stop PCT, Attn: ISA/US, Commissioner for Patents P.O. Box 1450, Alexandria, Virginia 22313-1450 Facsimile No. 571-273-8300	Authorized officer Shane Thomas PCT Helpdesk: 571-272-4300 PCT OSP: 571-272-7774

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US16/26893

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.:
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:

3. ☐ Claims Nos.:
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:
See extra sheet.

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 additional fees, this Authority did not invite payment of 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.:
1-16

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.

-***-Continued from Box III-***-
This application contains the following inventions or groups of inventions which are not so linked as to form a single general inventive concept under PCT Rule 13.1. In order for all inventions to be examined, the appropriate additional examination fee must be paid.

Group I: Claims 1-16 are directed towards a system for measuring the flow stream height of a liquid.
Group II: Claims 17-19 are directed towards a method for measuring the velocity of a liquid comprising a Doppler radar system.
Group III: Claim 20 is directed towards a method for calculating the flow stream velocity of a liquid comprising a second set of capacitive pads.

The inventions listed as Groups I-III do not relate to a single general inventive concept under PCT Rule 13.1 because, under PCT Rule 13.2, they lack the same or corresponding special technical features for the following reasons:

The special technical feature of Group I includes at least a processor capable of calculating the flow stream height based on the capacitance of each pad, which is not present in Groups II-III.

The special technical features of Group II include at least using a Doppler radar system to illuminate the surface of a liquid flow stream, receiving a Doppler radar signal, and calculating the velocity of the flow stream based on the received Doppler radar signal, which are not present in Groups I and III.

The special technical features of Group III include at least measuring the capacitance waveforms of a second set of capacitive pads, said second set of capacitive pads being axially displaced a known distance from the first set; and comparing the capacitance waveforms of the first set of capacitive pads with the capacitance waveforms of the second set of capacitive pads, which are not present in Groups I-II.

The common technical features shared by Groups I-III are a method of measuring the velocity of a liquid flow stream within a pipe, comprising: measuring the capacitance of a plurality of capacitive pads; and calculating the velocity of the flow stream.

However, these common features are previously disclosed by US 5,861,755 to MOERK et al. (hereinafter "Moerk"). Moerk discloses a method of measuring the velocity of a liquid flow stream within a pipe (determining the velocity of a flow stream; Abstract), comprising: measuring the capacitance of a plurality of capacitive pads (cross-correlating capacitance values across spaced capacitive sensors (pads); Abstract); and calculating the velocity of the flow stream (determining the velocity of the flow stream; Abstract).

Since the common technical features are previously disclosed by the Moerk reference, these common features are not special and so Groups I-III lack unity.