T.C.
TÜRK PATENT VE MARKA KURUMU
Patent Dairesi Başkanlığı

Sayı : E-39616753-110-220205045 31.03.2022
Konu : Patent Yazısı - 2020/21733 Numaralı Başvuru

MEHMET EMRAH ÖZKAYA (ÇANKAYA PATENT MARKA VE DANIŞMANLIK LTD. ŞTİ.)

İlgi: 25/12/2020 tarihli ve 2020/21733 numaralı başvurunuz.

İlgide kayıtlı başvurunuzla ilgili olarak Kurumumuz tarafından düzenlenen tekniğin bilinen durumu konusundaki Araştırma Raporu ve Ekleri ilişikte gönderilmektedir.

6769 sayılı Sınai Mülkiyet Kanununun 98 inci maddesinin birinci fıkrası ve anılan Kanunun Uygulanmasına Dair Yönetmeliğin 102 nci maddesinin birinci fıkrası hükümleri uyarınca bildirim tarihinden itibaren üç ay içinde ücretinin de ödenerek inceleme talebinde bulunulması gerekmektedir. Aksi takdirde başvurunuz geri çekilmiş sayılacaktır.

İşbu yazıya konu talebi, Kurumumuzun Elektronik Başvuru Sistemi (epats.turkpatent.gov.tr) üzerinden, Benim Sayfam panelinde Başvuru Sonrası İşlemler menüsü altında yer alan "İnceleme Talebi" işlemini seçerek gerçekleştirebilirsiniz.

Öte yandan başvurunuzun korunması için gerekli olan yıllık ücretler üçüncü yıldan başlamak üzere her yıl vadesinde ödenir. Vade tarihi, başvuru tarihine tekabül eden ay ve gündür. Yıllık ücretler, vadesinde ödenmediği takdirde ek ücretle birlikte vadeyi takip eden altı ay içinde de ödenebilir. Yıllık ücretlerin bu süre içinde de ödenmemesi halinde başvuru geçersiz sayılır.

Başvuru tarihi veya varsa rüçhan tarihinden itibaren on sekiz aylık sürenin dolması veya bu süre dolmadan erken yayın talebiniz üzerine başvurunuz Bültende yayımlanır.

Saygılarımla.

Serkan ÖZKAN
Kurum Başkanı a.
Sınai Mülkiyet Uzmanı

EK:
1- Ek Listesi (1 Sayfa)

Bu belge, güvenli elektronik imza ile imzalanmıştır.
Belge Doğrulama Adresi : https://belgedogrulama.turkpatent.gov.tr/bg.aspx?Id=AF4382EC-168E-40D7-A24E-3D5F8EAE5066

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Ek-1

EK LİSTESİ

1- Araştırma Raporu Ekleri

2- Araştırma Raporu

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US 20060105467A1

(19) United States

(12) Patent Application Publication (10) Pub. No.: US 2006/0105467 A1

Niksa et al. (43) Pub. Date: May 18, 2006

(54) MEMS-BASED SENSOR FOR LUBRICANT ANALYSIS

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(21) Appl. No.: 10/987,874

(22) Filed: Nov. 12, 2004

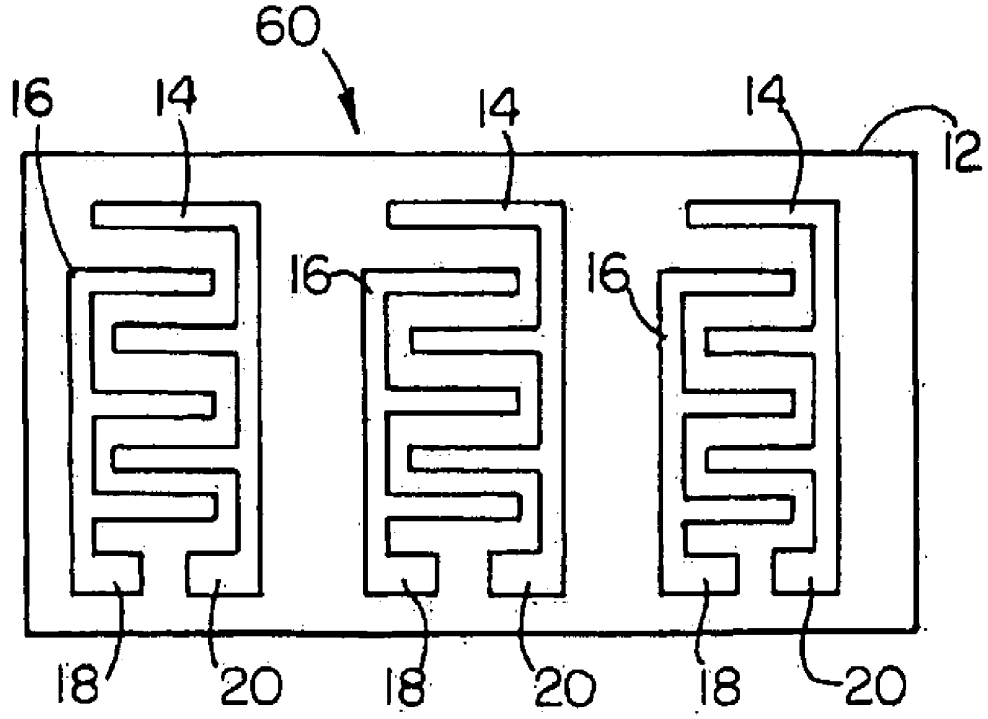
Publication Classification

(51) Int. Cl.
G01N 27/02 (2006.01)

(52) U.S. Cl. 436/150

(57) ABSTRACT

A fluid contamination analyzer employs one or more MEMS-based sensors. The sensors are incorporated into probes or alternatively may be employed in an in-line analyzer residing in the fluid. The sensors, which can be selective to detect a distinct contaminant within the fluid, sense an impedance of the fluid, which is a function of its contamination and communicates the impedance to analysis circuitry.



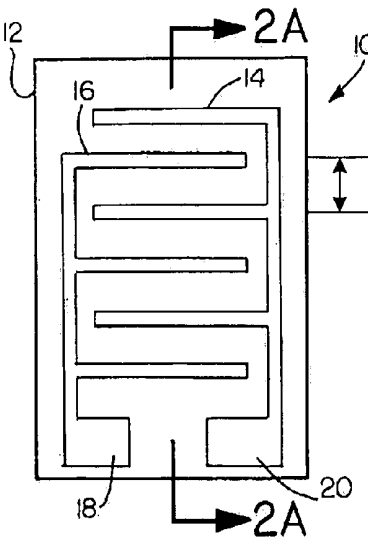


FIG. 1A

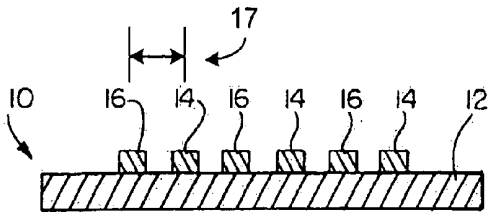


FIG. 2A

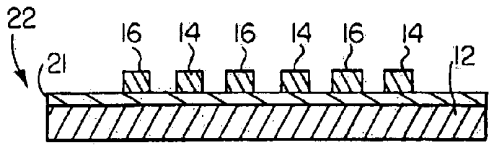


FIG. 2B

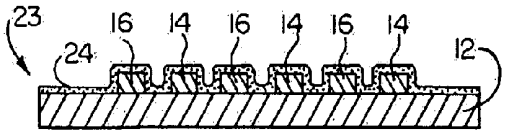


FIG. 2C

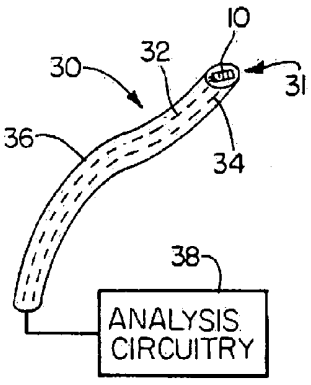


FIG. 3A

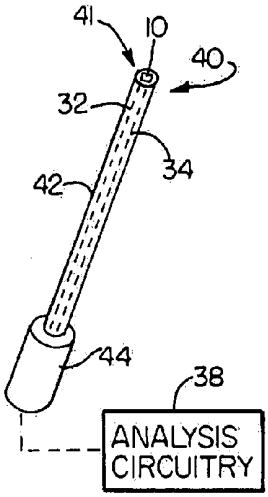


FIG. 3B

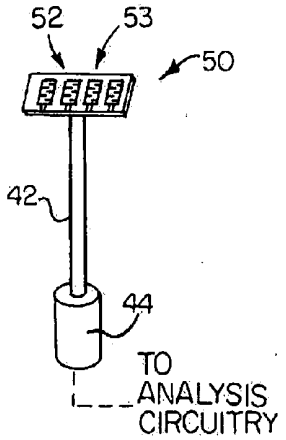


FIG. 3C

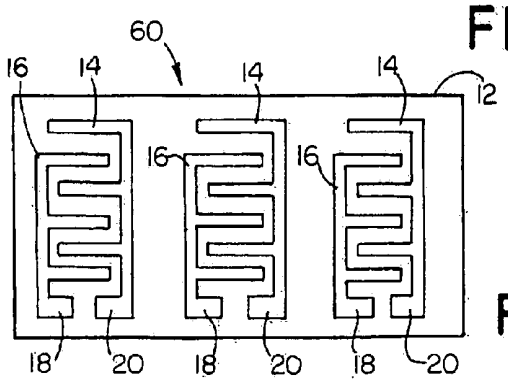


FIG. 4

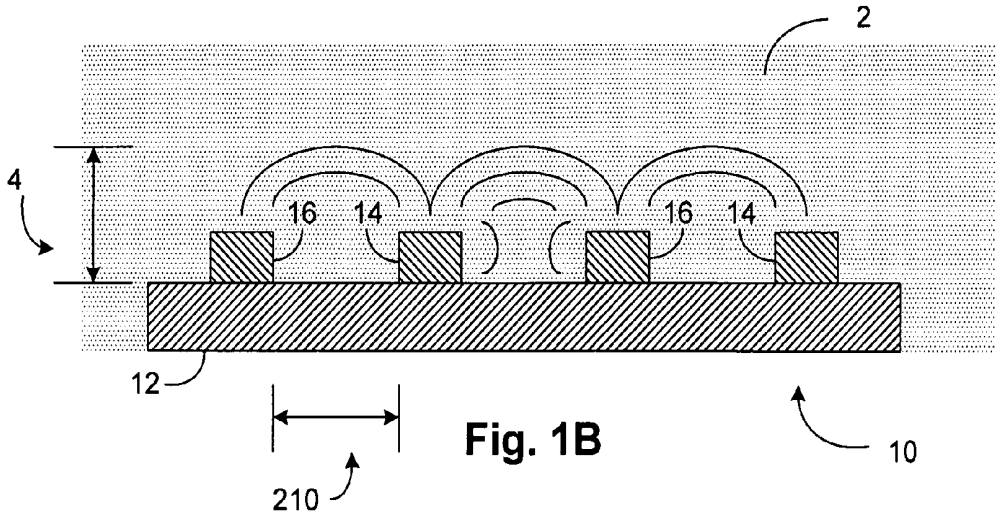

2
4
16
14
16
14
12
210
10

Fig. 1B

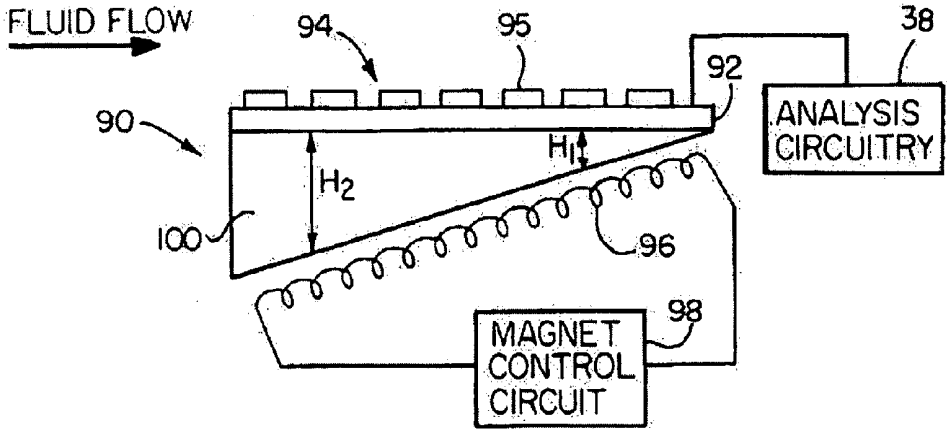

FLUID FLOW
94
95
38
92
ANALYSIS CIRCUITRY
90
H1
H2
100
96
98
MAGNET CONTROL CIRCUIT

Fig. 5

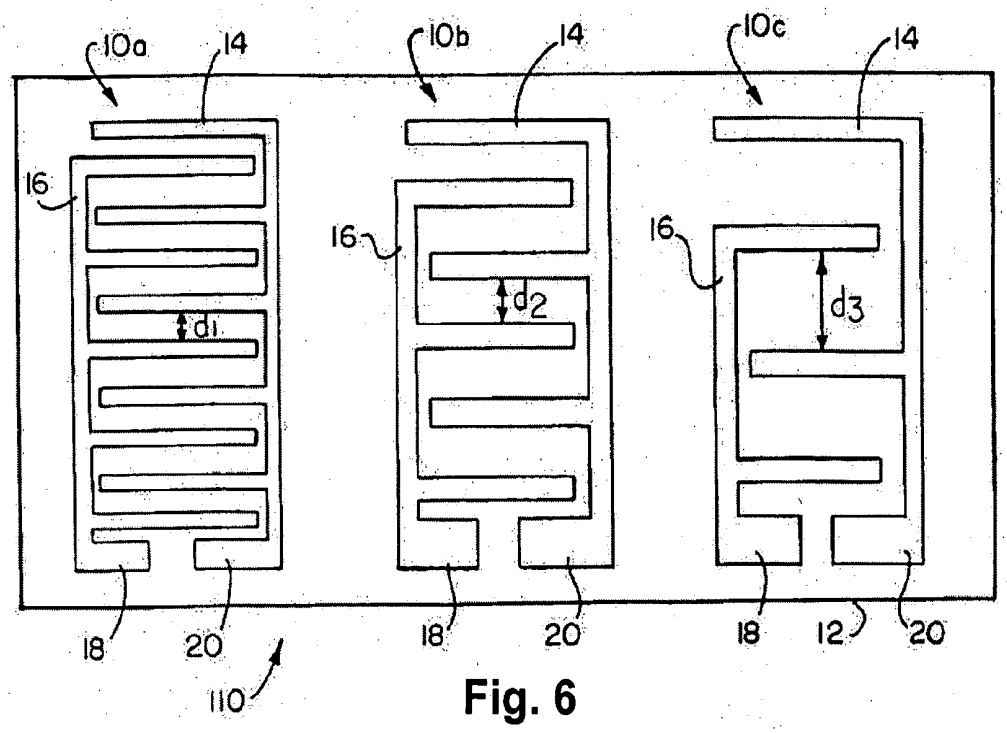


Fig. 6

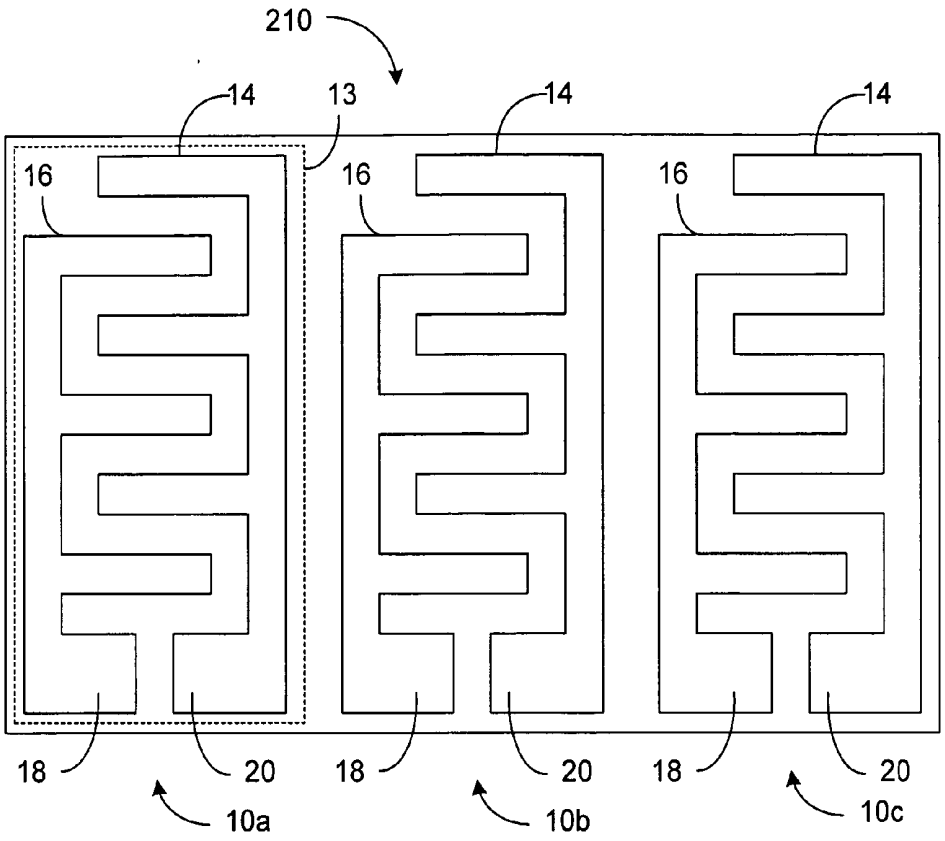

210
14
13
14
14
16
16
16
18
20
18
20
18
20
10a
10b
10c

Fig. 7

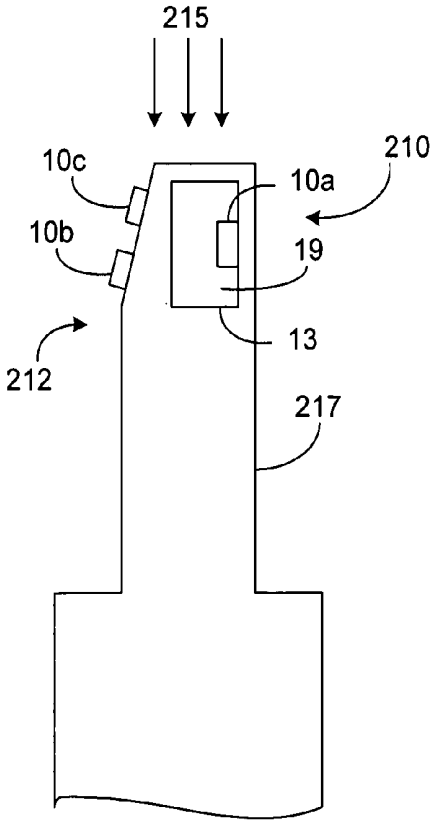

215
210
10c
10a
10b
19
13
212
217

Fig. 8

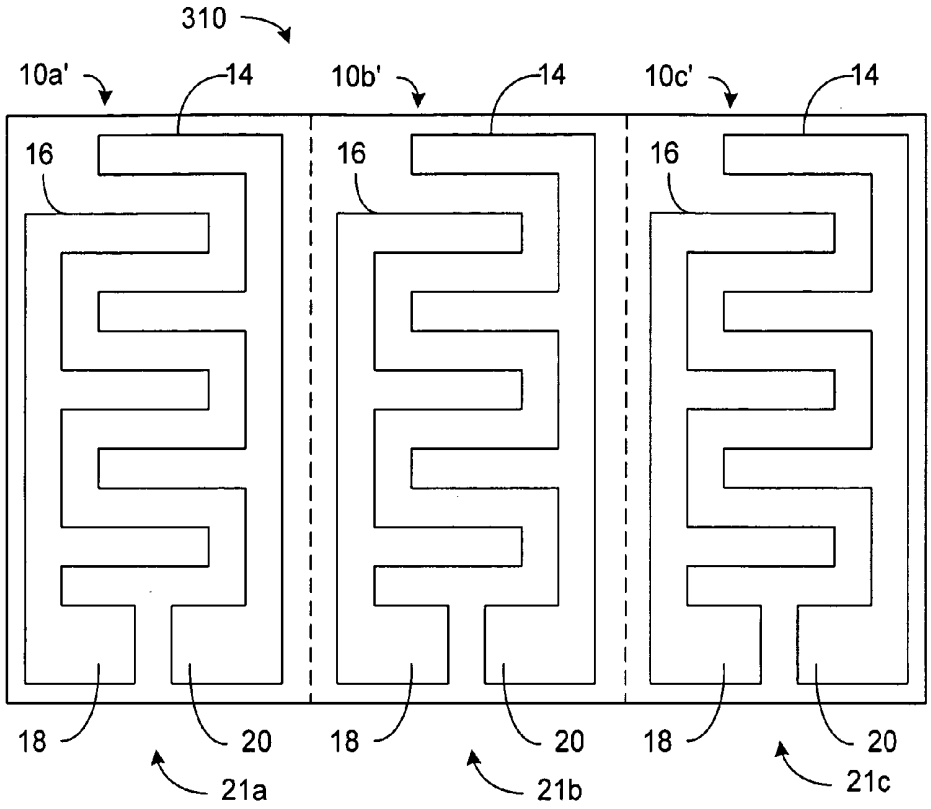

310
10a'
14
10b'
14
10c'
14
16
16
16
18
20
18
20
18
20
21a
21b
21c

Fig. 9A

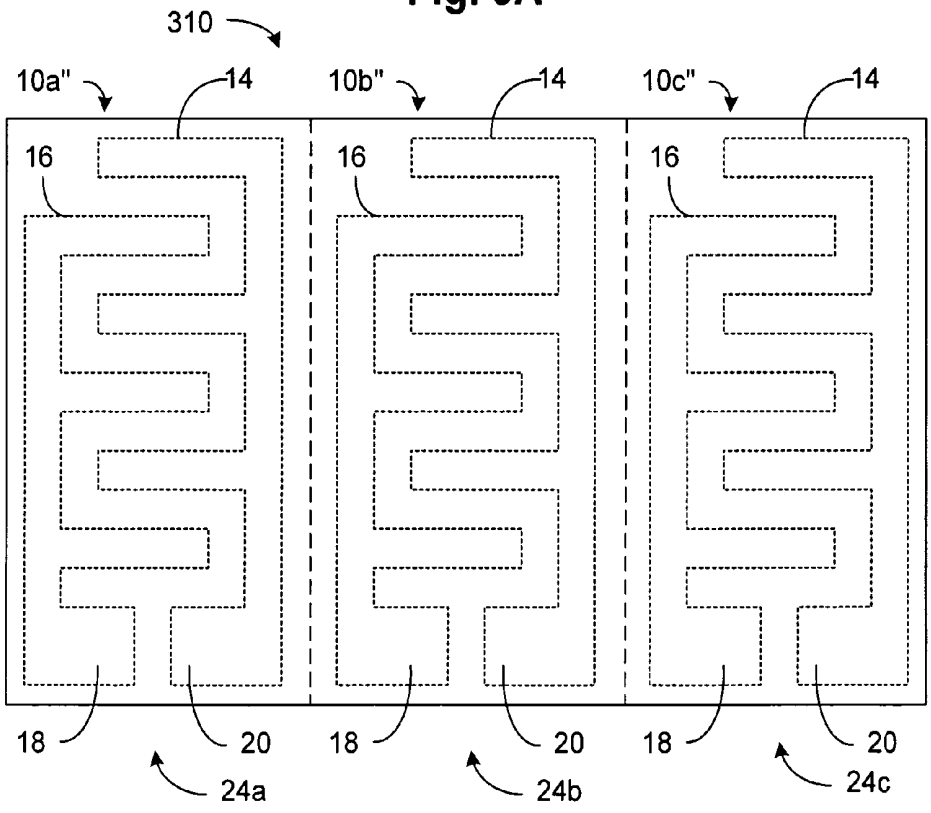

310
10a"
14
10b"
14
10c"
14
16
16
16
18
20
18
20
18
20
24a
24b
24c

Fig. 9B

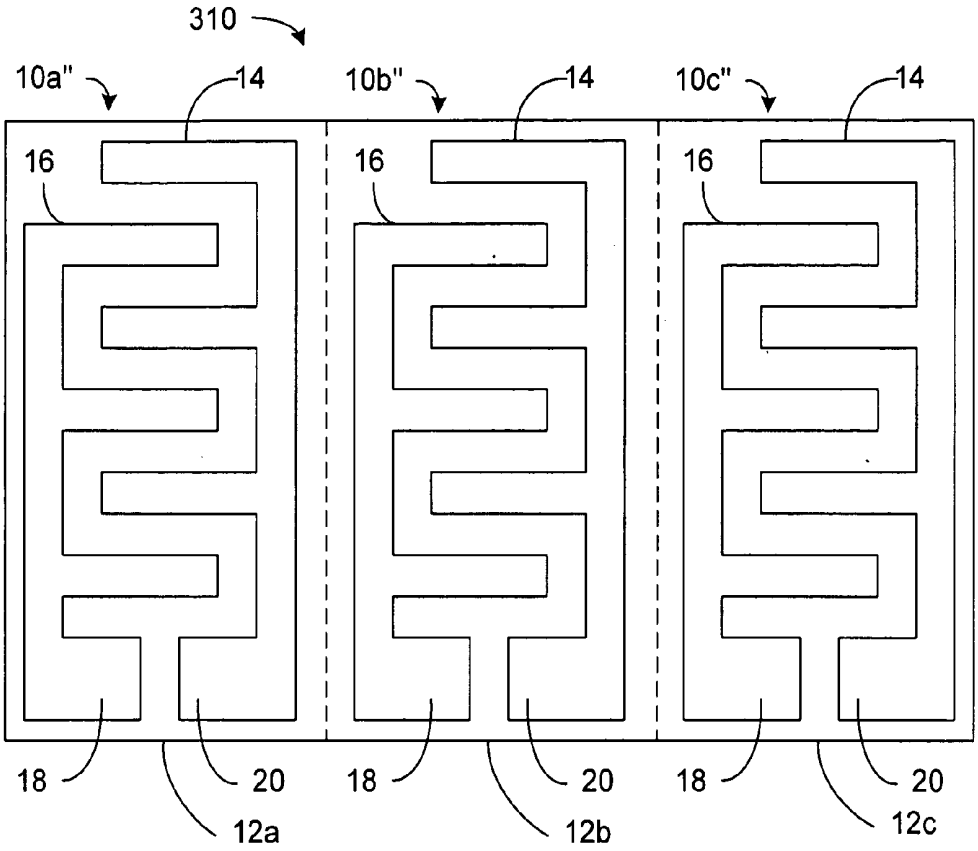


Fig. 9C

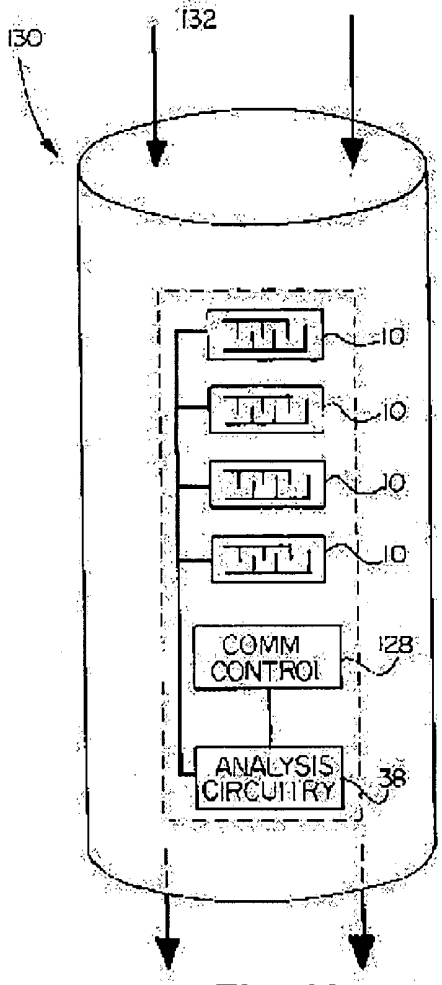

130
132
10
10
10
10
COMM CONTROL
128
ANALYSIS CIRCUITRY
38

Fig. 10

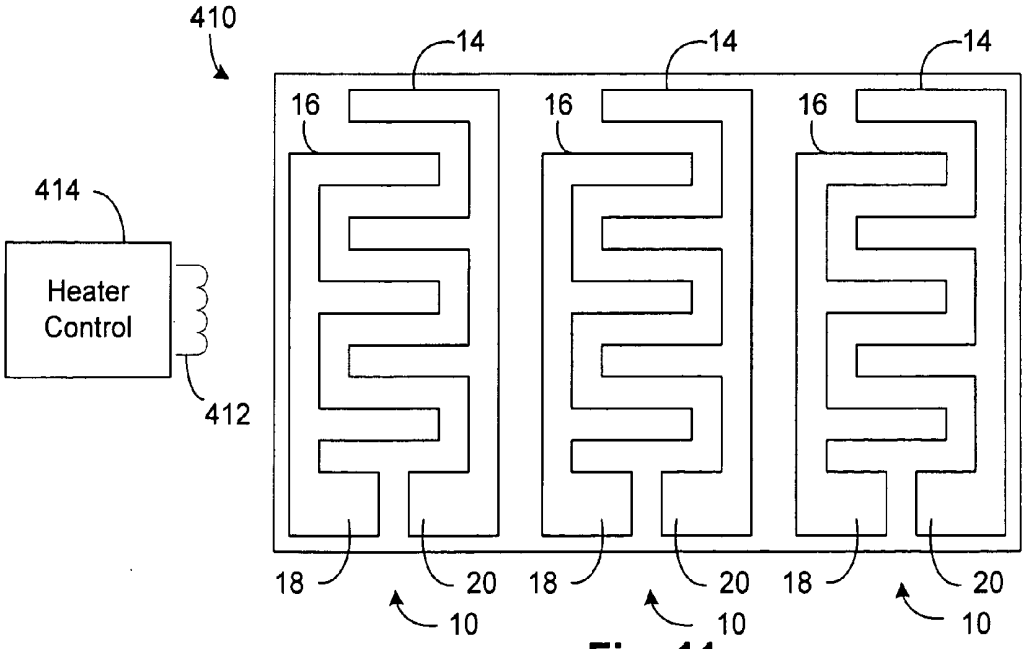

410
14
14
14
16
16
16
414
Heater Control
412
18
20
18
20
18
20
10
10
10

Fig. 11

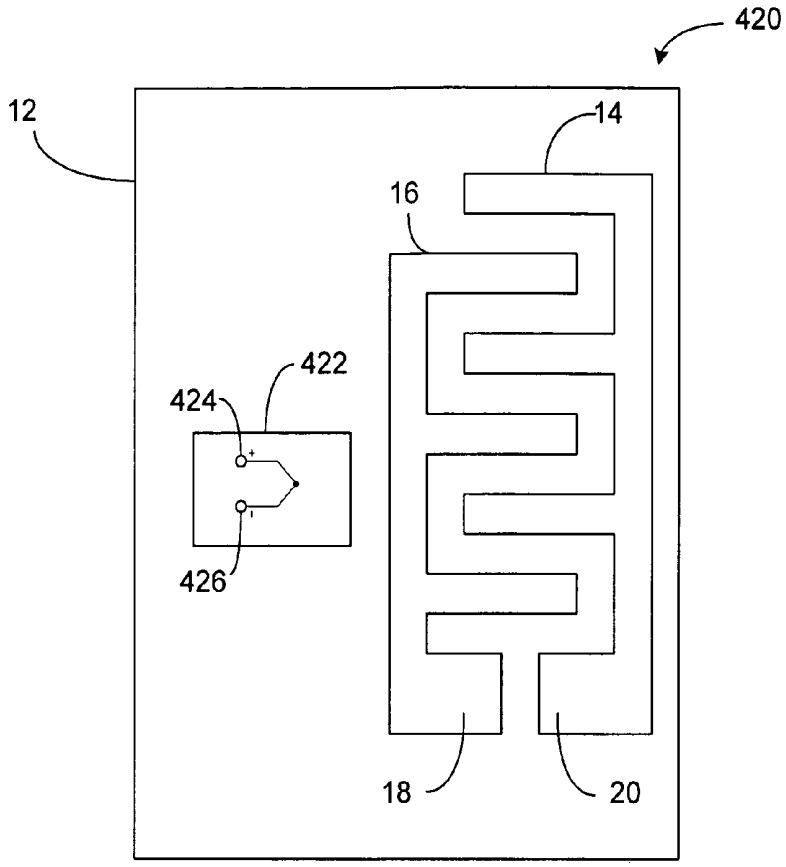


Fig. 12

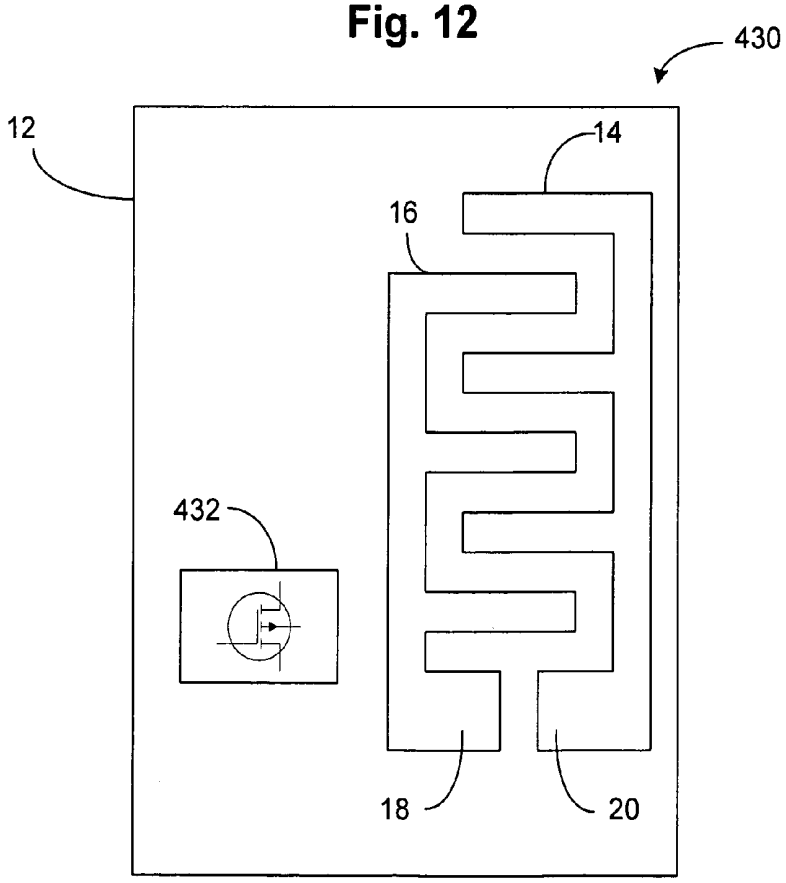


Fig. 13

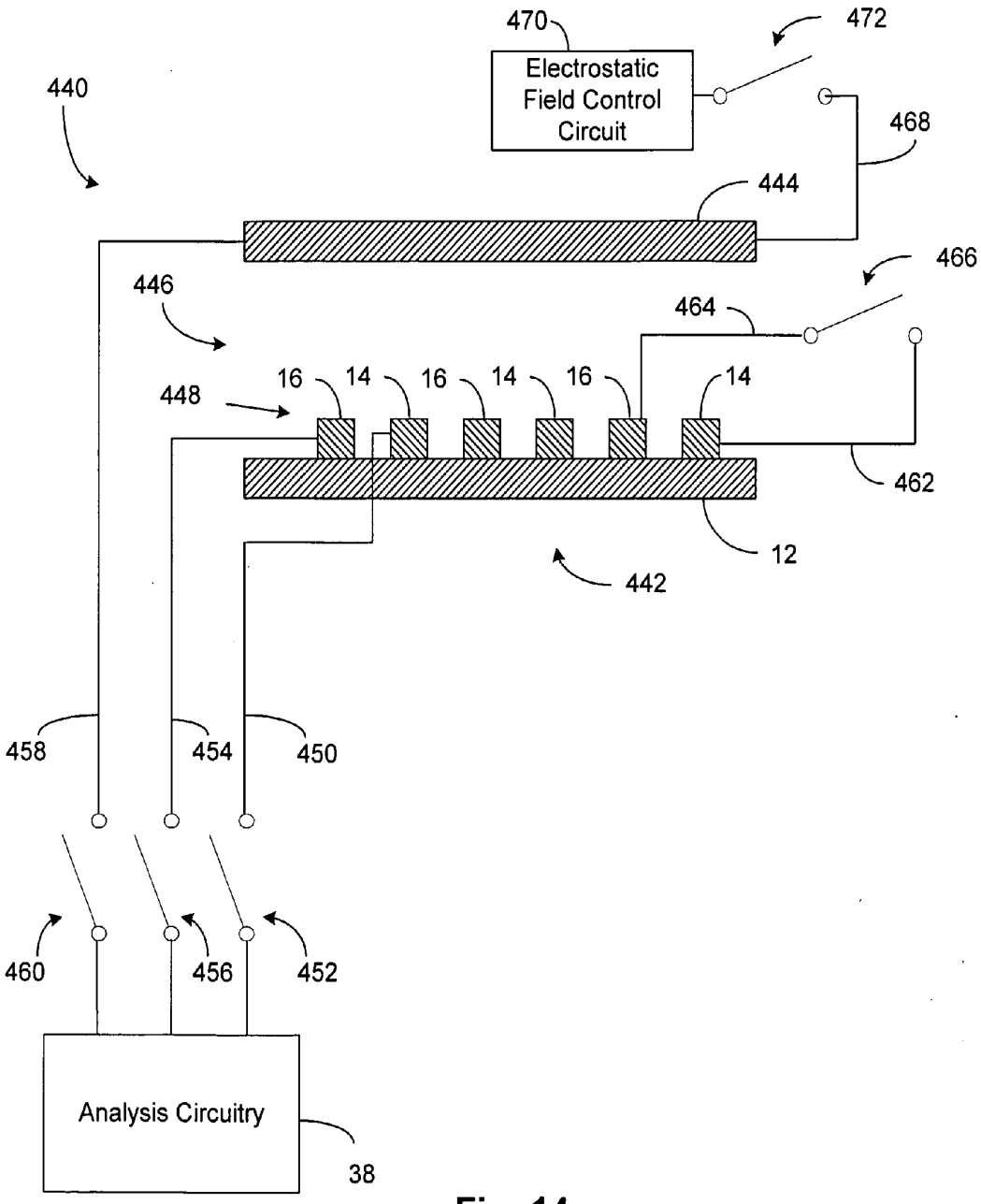

470
472
Electrostatic Field Control Circuit
440
468
444
466
446
464
16
14
16
14
16
14
448
462
12
442
458
454
450
460
456
452
Analysis Circuitry
38

Fig. 14

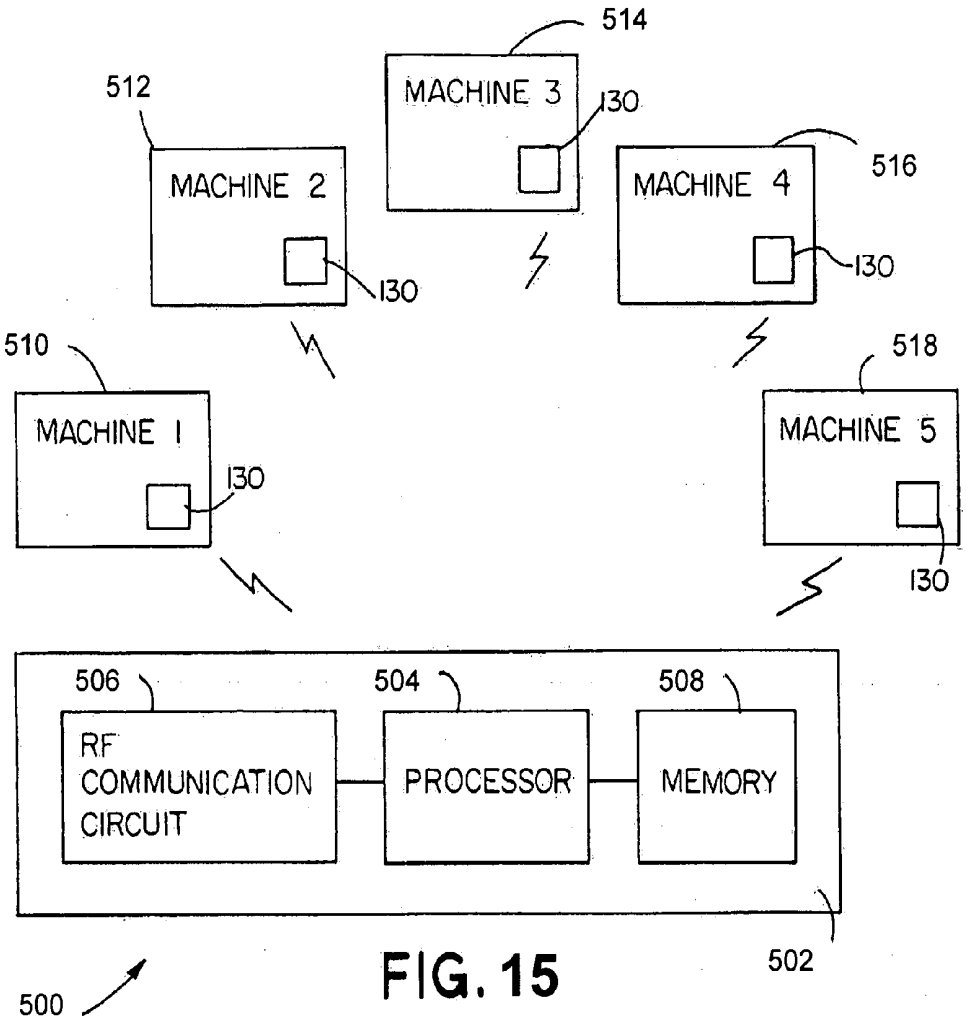

514
MACHINE 3
130
512
MACHINE 2
130
516
MACHINE 4
130
510
MACHINE 1
130
518
MACHINE 5
130
506
RF COMMUNICATION CIRCUIT
504
PROCESSOR
508
MEMORY
502
500

FIG. 15

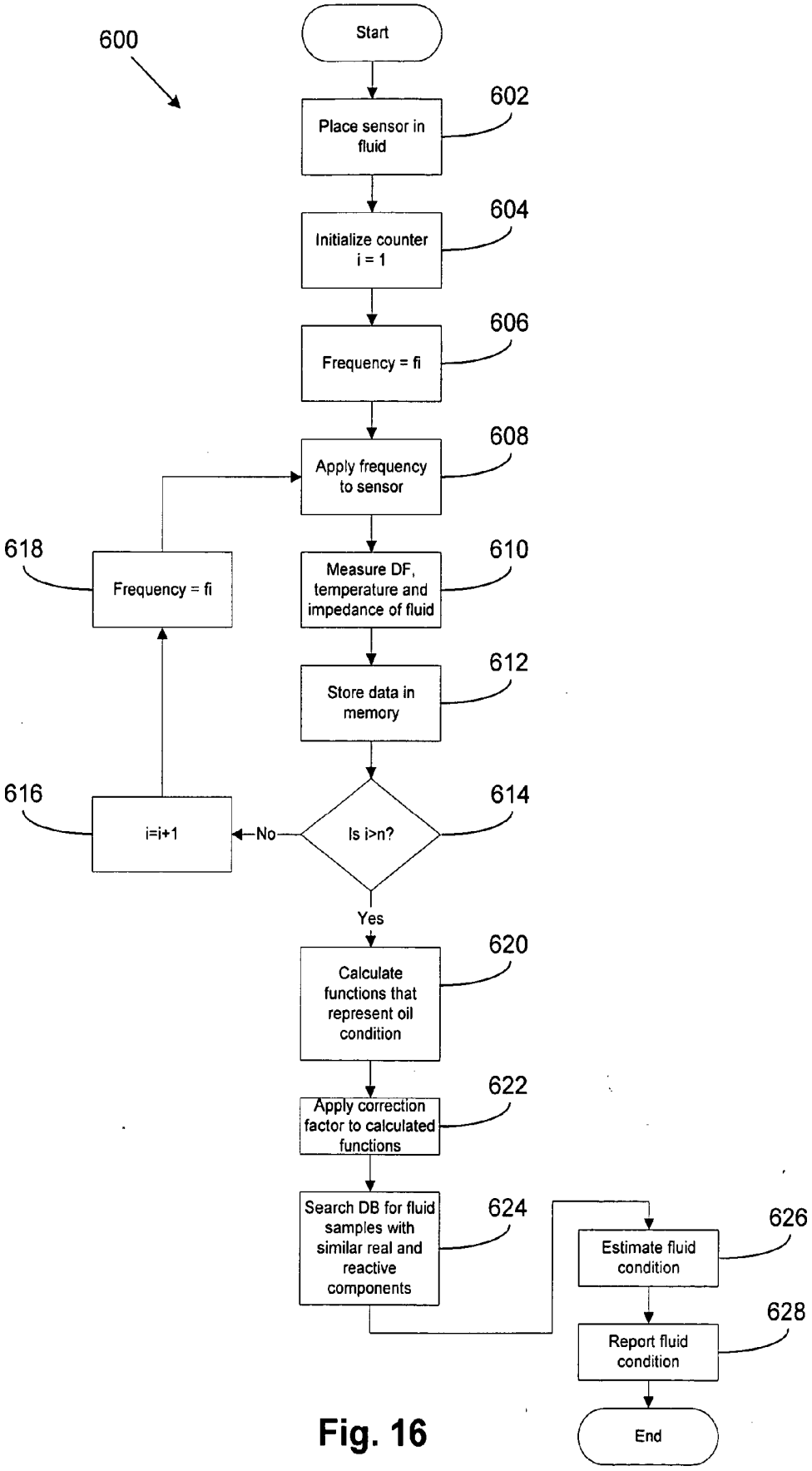

600
Start
Place sensor in fluid
602
Initialize counter i = 1
604
Frequency = fi
606
Apply frequency to sensor
608
Measure DF, temperature and impedance of fluid
610
Store data in memory
612
Is i>n?
614
No
i=i+1
616
Frequency = fi
618
Yes
Calculate functions that represent oil condition
620
Apply correction factor to calculated functions
622
Search DB for fluid samples with similar real and reactive components
624
Estimate fluid condition
626
Report fluid condition
628
End

Fig. 16

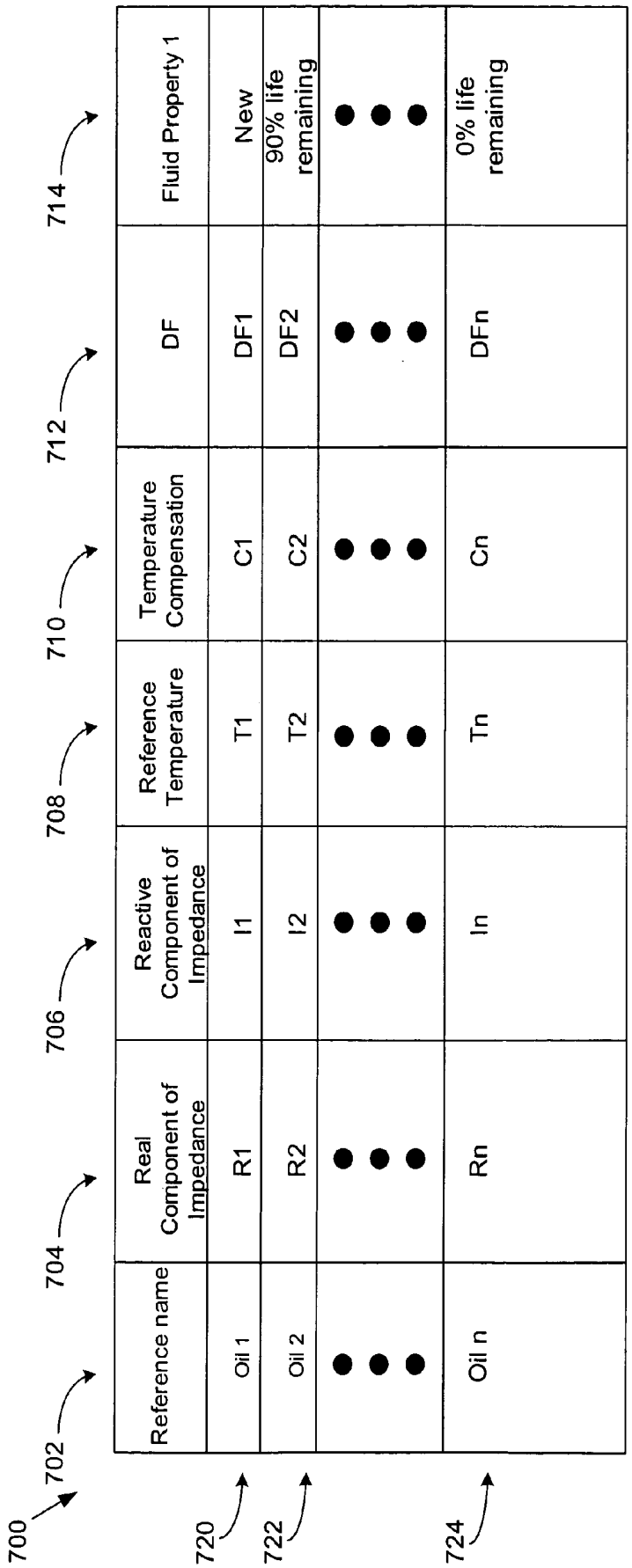

700
702
704
706
708
710
712
714
720
722
724
Reference name
Real Component of Impedance
Reactive Component of Impedance
Reference Temperature
Temperature Compensation
DF
Fluid Property 1
Oil 1
R1
I1
T1
C1
DF1
New
Oil 2
R2
I2
T2
C2
DF2
90% life remaining
Oil n
Rn
In
Tn
Cn
DFn
0% life remaining

FIG. 17

MEMS-BASED SENSOR FOR LUBRICANT ANALYSIS

FIELD OF THE INVENTION

[0001] The present invention relates generally to an apparatus and method for analyzing fluids such as lubricants. More particularly, the invention relates to a miniature sensor using micro-electromechanical (MEMS) device technology for detecting and monitoring conditions of a fluid, such as water content, oxidation and metallic or conductive particle contamination.

BACKGROUND OF THE INVENTION

[0002] The presence of corrosive products, contaminants, metallic particles, oxidation, etc. in fluids, such as lubricants, can cause problems. For example, contaminants in lubricants can lead to damage of machinery in which the lubricant is utilized, causing unnecessary or accelerated wear on the lubricated members.

[0003] Various approaches have been developed to detect conditions involving deterioration and/or contaminants in fluids. One conventional system described in U.S. Pat. No. 4,646,070 utilizes a pair of capacitor electrodes positioned in a fluid. The fluid serves as a dielectric between the electrodes to develop a frequency voltage signal across the capacitor electrodes. Based on such signal, the dielectric, and therefore, the deterioration of the fluid is determined. However, this solution suffers from a drawback in that the sensor is large and bulky and is difficult to move from machine to machine to make fluid contamination measurements.

[0004] U.S. Pat. No. 5,262,732 describes a system, which utilizes an oscillator circuit coupled to a capacitive sensor. The fluid under test is placed in a reservoir containing the capacitive sensor. The oscillator circuit generates a signal having a frequency that increases or decreases depending on the capacitance of the sensor. The system of U.S. Pat. No. 5,262,732 is also rather large and cumbersome and does not lend itself to portability. In the field, it would be difficult to transport the device from machine to machine to analyze the lubricant at the location of the machinery, for example.

[0005] Some prior art sensors have been rather large so that a user could insert the sensor into the fluid and thereby remove a fluid sample from a machine for analysis. This large, sturdy construction also allowed the sensor to be subsequently cleaned for use at another machine without causing damage to the sensor. Unfortunately, in some machines, obtaining a manual fluid sample with a large, unwieldy sensor is inconvenient due to machine construction. Also, in some applications, it is desirable to affix a lubricant analysis sensor to the machine in the lubricant fluid flow path (called an in-line configuration) in order that a user may merely attend the machine and obtain a lubricant contamination reading without having to insert an analyzer apparatus into the fluid flow path. In some cases, prior art sensors are too large and unwieldy and do not conveniently affix to the machine without interfering with proper machine operation.

[0006] As disclosed in U.S. Pat. Nos. 4,047,814 and 5,504,573, magnetic field gradients have been utilized to precipitate conductive or ferromagnetic particulates out of a sample fluid (e.g., a lubricant) such that particulates of varying sizes are withdrawn along a horizontal strip for subsequent analysis. Knowledge of the particulate size distribution is then utilized to determine the status of machinery wear and the potential for failures from wearing parts, etc. Prior to U.S. Pat. Nos. 4,047,814 and 5,504,573, this method relied upon a visual analysis of particulate distribution, which was a strong function of the technician's experience performing the analysis, thereby leading to inconsistent conclusions. In addition, since the horizontal strip was removed for analysis, evaluation of the fluid at the machine site was difficult and, in many cases, impossible.

[0007] U.S. Pat. Nos. 4,047,814 and 5,504,573 provided analysis improvement over the manual analysis by illuminating the particulate distribution with radiation and detecting the radiation via a plurality of photodetectors that traverse the particulate sample. Although such a technique provides for an improvement in subsequent analysis conclusions, this technique does not overcome the requirement that an operator initially procure the sample and send it off-site for analysis. The sample must still be removed for analysis which limits the locations in which such analysis materials may be located and, in some cases, prohibits their use altogether. Further, if one wishes to affix the particulate distribution collection apparatus with its analysis equipment so that the horizontal strip need not be removed from the machine, the radiation source and photodetectors are undesirably large and thereby further limit the scope of their application.

[0008] A miniature sensor for lubricant analysis was disclosed in commonly owned U.S. Pat. No. 6,204,656. The sensor included one or more micro-miniature sensors that provided a substantial reduction in sensor dimensions relative to prior art sensors. The sensors are incorporated into probes for easy lubricant fluid accessibility or in an in-line configuration. The sensors sense a capacitance of the fluid (therefore the impedance), and based on the impedance, determine the condition of the fluid. The sensor disclosed in U.S. Pat. No. 6,204,656, however, determined the impedance of the fluid based on the magnitude of the impedance and contaminant selective materials were not thoroughly discussed.

[0009] In view of the aforementioned shortcomings associated with existing systems for analyzing conditions of a fluid such as a lubricant, there is a strong need in the art for a fluid screening device which provides detailed information regarding the particular types of contamination, degree of oxidation or other deterioration, etc. Moreover, there is a strong need in the art for such a screening device which is miniature and thereby provides for ease of lubricant contamination status procurement for machine predictive maintenance programs.

SUMMARY OF THE INVENTION

[0010] According to one aspect of the invention, a fluid contamination analyzer includes at least one sensor. The at least one sensor includes: a substrate; a plurality of electrodes formed over the substrate; and a contaminant selective layer disposed adjacent at least one of (i) the electrodes and (ii) the substrate, said layer being selective to attract a predetermined contaminant within the fluid; wherein when a fluid contacts the sensor an impedance of the fluid may be determined using the electrodes of the sensor, thereby providing an indication of fluid contamination.

[0011] Another aspect of the invention relates to an in-line fluid contamination analyzer, including: an array of MEMS-based sensors located within a fluid, wherein each sensor includes a substrate, a plurality of electrodes formed over the substrate, and a contaminant-selective layer disposed adjacent the electrodes, said array including: a first MEMS-based sensor having a first contaminant-selective layer which is selective to attract a first class of contaminant within the fluid; a second MEMS-based sensor having a second contaminant-selective layer which is selective to attract a second class of contaminant within the fluid; and a third MEMS-based sensor having a third contaminant-selective layer which is selective to attract a third class of contaminant within the fluid; wherein each sensor is operative to determine an impedance of the fluid contacting each sensor, thereby providing an indication of fluid contamination.

[0012] Yet another aspect of the invention relates to a fluid contamination analyzer, including: a first reference MEMS-based sensor disposed within a reference housing, said reference housing containing a substantially contaminant-free volume of the fluid being analyzed; and a plurality of sample MEMS-based sensors disposed adjacent the reference housing within a fluid.

[0013] Another aspect of the invention relates to a fluid contamination analyzer, including at least one MEMS-based sensor, said at least one sensor including: a substrate; a plurality of conductors formed over the substrate; and a local heater disposed adjacent the at least one MEMS-based sensor, said local heater providing a temperature gradient through which the fluid is run; wherein the conductors form electrodes of the sensor and when a fluid contacts the sensor an impedance of the fluid may be determined as a function of temperature, thereby providing an indication of fluid contamination.

[0014] Yet another aspect of the invention relates to a method of analyzing the quality of a fluid, including the steps of: immersing a sensor into the fluid, wherein the fluid acts as a dielectric for the sensor; obtaining a complex impedance of the fluid; measuring a temperature of the fluid in contact with the sensor; applying a correction factor to the complex impedance based on the measured temperature of the fluid; and estimating the quality of the fluid based on a comparison of known fluids producing substantially the same Dissipation Factor and complex impedance values.

[0015] Another aspect of the invention relates to a method of analyzing the quality of a fluid, including the steps of: immersing a sensor into the fluid, wherein the fluid acts as a dielectric for the sensor; measuring an impedance of the fluid over a temperature gradient; and estimating the quality of the fluid based on a change in slope of the measured impedance over the temperature gradient.

[0016] Yet another aspect of the invention relates to a method of analyzing the quality of a fluid in which a sensor has been immersed, wherein the fluid acts as a dielectric on the sensor, including the steps of: using a contaminant selective layer on the sensor to selectively attract contaminants within the fluid near a surface of the sensor; measuring an impedance of the fluid near the surface of the sensor; and correlating the quality of the fluid to the measured impedance of the fluid.

[0017] Another aspect of the invention relates to a method of analyzing the quality of a sample fluid, wherein the fluid acts as a dielectric on the sensor, comprising the steps of: immersing a sample sensor in the sample fluid; immersing a reference sensor in a substantially contaminant-free reference fluid, wherein the reference fluid and the sample fluid are the same type of fluid; measuring an impedance of the fluid near the surface of the sample sensor and the reference sensor; and correlating the quality of the sample fluid to the measured impedance of the sample fluid and the reference fluid.

[0018] Other aspects, features, and advantages of the invention will become apparent from the following detailed description. It should be understood, however, that the detailed description and specific examples, while indicating several embodiments of the present invention, are given by way of illustration only and various modifications may naturally be performed without deviating from the present invention.

BRIEF DESCRIPTION OF THE DRAWINGS

[0019] **FIG. 1A** is a top view of a MEMS-based sensor according to an embodiment of the invention.

[0020] **FIG. 1B** is a cross section diagram illustrating the field of view of the MEMS-based sensor of **FIG. 1A**

[0021] **FIG. 2A** is a cross section diagram illustrating the MEMS-based sensor of **FIG. 1A** taken along arrows **2A-2A**.

[0022] **FIG. 2B** is a cross section diagram illustrating an alternative MEMS-based sensor according to the invention.

[0023] **FIG. 2C** is a cross section diagram illustrating another alternative MEMS-based sensor according to the invention.

[0024] **FIG. 3A** is a diagram illustrating use of the MEMS-based sensor of **FIG. 1A** in an elongate probe.

[0025] **FIG. 3B** is a diagram illustrating use of the MEMS-based sensor in a rigid, elongate probe having a handle.

[0026] **FIG. 3C** is a diagram illustrating a MEMS-based sensor array at one end of a probe.

[0027] **FIG. 4** is a top view illustrating an array of MEMS-based sensors as disclosed in **FIG. 1A**.

[0028] **FIG. 5** is a side view of a system according to one aspect of the invention having an array of MEMS-based sensors placed within a magnetic field intensity gradient.

[0029] **FIG. 6** is a top view of an alternative embodiment of the invention, wherein an array of MEMS-based sensors have variations in electrode spacings.

[0030] **FIG. 7** is a top schematic view of an alternative embodiment of the invention, wherein an array of MEMS-based sensors includes a reference sensor.

[0031] **FIG. 8** is a sectional view illustrating an array of MEMS-based sensors including a reference sensor, wherein the MEMS based sensors are mounted on a probe.

[0032] **FIG. 9A** is a top view of an alternative embodiment of the invention, wherein an array of MEMS-based sensors include a selective layer to detect particular contaminants, wherein the selective layer is formed between the electrodes and the substrate.

[0033] **FIG. 9B** is a top view of an alternative embodiment of the invention, wherein an array of MEMS-based sensors are selective to detect particular contaminants, wherein the selective layer is formed over the electrodes and the substrate.

[0034] **FIG. 9C** is a top view of an alternative embodiment of the invention, wherein an array of MEMS-based sensors are selective to detect particular contaminants, wherein each substrate is formed of a different selective material.

[0035] **FIG. 10** is a perspective view of an in-line fluid analyzer having an array of MEMS-based sensors in a lubricant fluid flow path having both circuitry for analyzing the impedance and communicating the results to other circuitry.

[0036] **FIG. 11** is a top view of an alternative embodiment of the invention, wherein a local heater is employed to generate a temperature gradient.

[0037] **FIG. 12** is a top view of an alternative embodiment of the invention, wherein the MEMS based sensor includes a temperature sensor.

[0038] **FIG. 13** is a top view of an alternative embodiment of the invention, wherein the MEMS based sensor includes a non-volatile memory device.

[0039] **FIG. 14** is a side view of an alternative embodiment of the invention, wherein the sensor includes a MEMS based sensor and a plate electrode.

[0040] **FIG. 15** is a block, system level diagram illustrating an environmental view of the invention, wherein a plurality of machines contain MEMS-based sensors for sensing fluid contamination and circuitry for communicating the results to a central data analysis and storage site.

[0041] **FIG. 16** is a flow diagram illustrating an exemplary method of estimating the quality of a fluid in accordance with an embodiment of the present invention.

[0042] **FIG. 17** is an exemplary database structure used to store fluid sample data in accordance with an embodiment of the present invention

DETAILED DESCRIPTION OF THE INVENTION

[0043] The present invention will now be described with reference to the drawings wherein like reference numerals are used to refer to like elements throughout. As will become more apparent based on the following description, a fluid contamination analyzer for monitoring contaminants in lubricating fluids utilizes micro-electromechanical (MEMS)-based sensors, thereby substantially reducing the sensor dimensions while providing a similar electrical response. This results in a greater variety of machine fluid analysis applications for the sensor. The MEMS-based sensor fabrication techniques also allow for a substantial reduction in sensor costs and provide high sensor manufacturability. Such fabrication techniques also allow for a substantial number of sensor variations with a sensor array for collecting a variety of types of data relating to fluid contamination.

[0044] Throughout the disclosure, reference will be made to impedance and impedance measurements. Impedance can be represented and analyzed in many forms, and each are contemplated to fall within the scope of the present invention. For example, impedance may be characterized as capacitance, complex capacitance, resistance and reactance, capacitance and dissipation factor, impedance and phase angle, admittance, susceptance and conductance. Each of these characterizations have their own terminologies. For example, for capacitance the terms capacitance, dissipation factor, Tan delta, Q factor or loss factor may be utilized.

[0045] Additionally, the invention will be described with respect to an in-line sensor. However, the sensor can be applied in other configurations and/or applications, and the description with respect to an in-line sensor is not intended to be limiting in any way. Other configurations include, for example, placement of the sensor in a sump (e.g., not in a direct path of fluid flow) or external from the fluid flow (e.g., a separate test unit not part of the machine).

[0046] **FIG. 1A** is a top view of a MEMS-based sensor **10** formed using MEMS device fabrication techniques. The sensor **10** includes a substrate **12**, preferably made of glass or quartz, upon which a conductive layer is formed and etched to create a pair of interdigitated conductors **14** and **16**, respectively. The first conductor **14** forms a first electrode **14** while the second conductor **16** forms a second electrode **16**. The electrodes are interdigitated to provide uniformity in impedance measurement. Alternatively, the electrodes may take on any suitable configuration and still fall within the scope of the invention. The electrodes **14**, **16** can be less than 1 micron wide, the limiting factor being the ability to manufacture the thin electrodes and the conductivity of the material. There is no particular constraint on the upper limit of the electrode width. In one embodiment, the electrodes have a width between about 1 micron and about 50 microns.

[0047] In another embodiment, the substrate **12** can be made of ceramic or a semiconductor material, such as silicon, silicon nitride, silicon carbide, germanium and the like. As is discussed more fully below, the substrate material may be chosen to provide an optimized selectivity with respect to one or more contaminants being detected.

[0048] In yet another embodiment, the interdigitated electrodes **14**, **16** are formed of tungsten, platinum, gold, chrome, aluminum, polysilicon, titanium, nickel, copper, silver, and the like. Electrodes **14** and **16** are electrically isolated from one another and may be coupled to either discrete instrumentation or circuits integrated with the substrate **12** or other integrated circuits via bond pads **18** and **20**, respectively. Since the sensor **10** is fabricated using conventional MEMS-based and/or semiconductor processing techniques, fine line width geometries may be constructed thereby allowing the sensor dimensions to be **1** mm by **1** mm or smaller. MEMS-based techniques allow the sensor to be reduced in size while maintaining a relatively large feedback signal and, therefore, achieving good precision of the measured data.

[0049] During operation, the sensor analyzes a thin film of material, e.g., a fluid, directly adjacent to the sensor surface. In other words, an electric field of the sensor **10** extends up into the fluid at least a distance equal to about the line spacing **17** (i.e., the distance of separation between adjacent electrodes) of the electrodes **14**, **16** and generally a distance significantly further. For example, and with further reference

to **FIG. 1B**, if the line spacing **17** were 10 microns, then the sensor **10** could analyze or "look into" the fluid **2** a distance **4** of at least 10 microns above the surface of the sensor **10**. Similarly, if the line spacing were 100 microns, then the sensor **10** could analyze the fluid at least 100 microns above the surface of the sensor **10**. The line spacing **17** of the electrodes **14**, **16** can be less than 1 micron or up to about 250 microns, for example. In one embodiment, the line spacing of the electrodes **14**, **16** is 1 micron wide and equally spaced (e.g., the line spacing **17** is 1 micron), and in another embodiment the line spacing is about 2 microns and equally spaced. As will be appreciated, the line spacing **17** may be larger or smaller as desired.

[**0050**] The sensor **10** operates in the following manner. When the sensor **10** comes into contact with a fluid sample, the fluid acts as a dielectric between the electrodes **14**, **16** thereby impacting the impedance of the sensor. By way of example, the sensor can be approximated by a parallel plate capacitor having a capacitance characterized by $C=\epsilon A/d$, wherein A is the electrode surface area and d represents the electrode spacing. The measured capacitance provides an indication of the properties of the dielectric (the fluid). Accordingly, the sensor **10** senses the capacitance (and therefore the impedance) of the fluid at its leads (bond pads **18** and **20**) and provides this value at the bond pads **18** and **20** for analysis by analysis circuitry (not shown). The analysis circuitry takes the impedance value and determines the level of fluid contamination based upon a comparison with 1) a known clean fluid sample; 2) an expected or reference value; or 3) by trending, e.g., looking at a change over time of a capacitance, a phase angle, resistance, dielectric, etc. Various methods exist for analyzing fluid contamination. At least one method contemplated by the present invention includes using the sensed fluid impedance as a component within an oscillator circuit, thereby impacting the circuit's oscillating frequency which may be used to determine the level of fluid contamination. This method is disclosed in detail in co-owned U.S. Pat. No. 6,028,433 entitled "Portable Fluid Screening Device and Method," which is hereby incorporated by reference in its entirety.

[**0051**] It is to be appreciated that impedance is generally measured. Therefore, the term sensor "impedance" will be used in the remainder of this disclosure. It should be noted that although the capacitance of the fluid is analyzed through the impedance, the impedance sensor **10** extends to other fluid impedance variations and therefore, for example, contemplates inductive type sensors within the scope of the present invention.

[**0052**] Turning now to **FIG. 2A**, a cross sectional view of the sensor **10** taken along lines **2A-2A** of **FIG. 1A** is illustrated. The sensor **10** has the electrodes **14** and **16** located along a horizontal plane on the substrate **12**. When a lubricant fluid sample contacts the sensor **10**, it rests between and/or above the electrodes **14** and **16**, thereby affecting the dielectric constant therebetween. Accordingly, the presence of contaminants within the fluid results in different impedance readings of the sensor at its leads (bond pads **18** and **20**). These differences are analyzed via analysis circuitry (not shown) to determine, within an acceptable accuracy bandwidth, the level of fluid contamination, which may then be used, for example, either as an indication for timely fluid replacement or an indication of machine wear for preventative maintenance and/or quality control purposes.

[**0053**] Although the electrodes **14** and **16** are illustrated in **FIG. 2A** as residing entirely within a single horizontal plane, it should be understood that the substrate **12** may undertake a variety of contours and the electrodes **14** and **16** may follow that contour to be customized for various applications as may be desired. Each of these sensor variations are contemplated by the present invention. In an alternate embodiment, illustrated in **FIG. 2B**, the sensor **22** includes insulating layer **21**, such as silicon nitride, between the substrate **12** and the electrodes **14** and **16**. As is described more fully below, the insulating layer **22** serves a variety of purposes, including, but not limited to, electrically insulating the electrodes **14** and **16** from an electrically conductive substrate **12**, providing a sensor that can operate at higher operating temperatures, and enhancing selectivity of the sensor with respect to detecting a particular contaminant within the fluid under test.

[**0054**] **FIG. 2C** is a cross-sectional view of an alternative embodiment of a sensor **23** similar to the sensor **10** of **FIG. 1A**. Sensor **23** includes the substrate **12** having the electrodes **14** and **16** formed thereon. Subsequently, an insulating layer **24**, such as silicon dioxide layer, is formed over the electrodes **14** and **16** which helps protect the sensor **23** from experiencing "shorts" across the electrodes **14** and **16** caused, for example, by substantially sized conductive particulates in a fluid under test. The insulated sensor **23** provides improved performance in detection of non-particulate forms of contamination, for example, water content in the fluid or fluid oxidation. Additionally, and as will be described in more detail below, the insulation layer **24** can be selected to enhance the selectivity of the sensor with respect to detecting a particular contaminant within the fluid under test or to prevent accumulation of soils or contaminants on the sensor surface.

[**0055**] As stated above, the sensors **10**, **22** and **23** of **FIGS. 2A, 2B** and **2C** substantially reduce the dimensions of a fluid sensor from approximately 2 in.×2 in. to approximately 1 mm×1 mm, thereby providing substantial improvements in procuring fluid samples for analysis. For example, a probe utilizing a sensor having such dimensions may easily be inserted into a machine containing a fluid for analysis without either substantially impacting the machine's operation or requiring any disassembly of the machine. **FIG. 3A** illustrates a probe assembly **30** incorporating the sensor at one end **31**. The bond pads **18** and **20** (not shown) of the sensor **10** are coupled to lines **32** and **34** along a flexible probe body **36**, thereby transmitting the fluid impedance sensed by the sensor **10** to an analysis circuit **38**. The flexible, elongate probe body **36** allows a user to manipulate the probe into numerous shapes to access difficult-to-reach fluid samples within operating machinery. Further, since the sensor **10** is compact in size, the sensor **10** does not negatively impact the size of the probe **30** at the end **31**, thereby facilitating the testing of fluid samples in difficult-to-reach locations without adversely impacting a machine's operation or requiring a disassembly of the machine.

[**0056**] In **FIG. 3A**, the analysis circuitry **38** is illustrated as being separate from the probe. Alternatively, the analysis

circuitry may reside at the end **31** of the probe **30** as a circuit integrated with the sensor **10**. This alternative embodiment advantageously provides for fluid contamination level determinations to be made local to the measurement site itself, thereby improving analysis accuracy by eliminating errors due to electrical line losses and noise.

[**0057**] **FIG. 3B**, much like **FIG. 3A**, is a diagram illustrating an alternative probe assembly **40** having a sensor **10** at one end **41**. The sensor **10** is connected to lines **32** and **34** via bond pads **18** and **20** (not shown), which extend through a substantially rigid channel member **42** to a handle **44**. The handle **44** provides for ease of use and connects the lines **32** and **34** to the analysis circuitry **38**. Alternatively, handle **44** may contain a communications circuit therein to provide wireless transmission of the fluid impedance data to the analysis circuitry **38** through an RF data link, for example. Such wireless capability provides even greater flexibility by allowing a user to be unimpeded by any wire length, etc., which is useful and safe in a factory setting utilizing heavy machinery having moving parts. Although the rigid channel member **42** is not as ductile as the elongate body **36** of **FIG. 2A**, the channel member **42** provides for firm, precise positional control of the sensor location, while the handle **44** allows a user to easily manipulate the probe assembly **40** while avoiding hazards present by moving parts within the machinery.

[**0058**] Another advantage provided by the dimensional feature of the sensor **10** is that an array of such sensors may be incorporated together within a single probe assembly without substantially impacting the probe size. **FIG. 3C** illustrates such a probe assembly **50** wherein an array **52** of sensors reside at one end **53** of the probe assembly **50**. It is to be appreciated that **FIG. 3C** greatly exaggerates the dimensions of the array **52** with respect to the other members in order to illustrate the array **52** of sensors **10**. In actual practice, the sensor array **52** can reside at the end **53** of the probe assembly **50** and not be substantially larger than the channel member **42**, for example. In one embodiment, the sensor array **52** may be utilized to provide improved analysis accuracy by providing impedance measurement redundancy. For example, since a fluid contamination concentration is not always uniform (such as when a substantially large particulate is identified, which skews the aggregate contamination determination), the sensor array **52** allows for multiple fluid impedance readings to be collected and subsequent data processing techniques used to interpret the data to accurately determine the fluid contamination level. For example, multiple readings may be averaged together or if one reading is substantially different from the others, it may be ignored. Alternatively, various statistical operations may be performed on the collected data to yield a more accurate determination of fluid contamination. When utilizing an array **52** as illustrated in **FIG. 3C**, each sensor **10** at the probe end **53** may be individually hard-wired to analysis circuitry **38** via the channel member **42** and handle **44**. Alternatively, a time multiplexer circuit (or other type multiplexing methodology) may be utilized at the end **53** of the probe assembly **50** to reduce the need for multiple lines **32** and **34** in the channel member **42** to thereby keep the probe assembly **50** compact.

[**0059**] The sensor array **52** of **FIG. 3C** may comprise various configurations. In one embodiment, multiple sensors **10** may be formed on a single substrate **12**, such as the array **60** illustrated in **FIG. 4**. In one embodiment, multiplexing circuitry may be integrated onto the substrate **12** to collect the multiple measured fluid impedances and multiplex them (via either time multiplexing or other multiplexing technique) for transmission via lines **32** and **34** to the analysis circuitry **38**. Further still, the analysis circuitry **38** may also be integrated onto the substrate **12** such that data acquisition and fluid contamination determination may be made at the end **53** of the probe assembly **50**, thereby reducing fluid determination errors due to line loss, noise, etc. Alternatively, multiple discrete sensors **10** having separate substrates **12** may reside on another support structure and be affixed to the end **53** of the probe assembly **50**.

[**0060**] The sensor arrays **52** and **60** of **FIGS. 3C and 4** may comprise various array configurations as may be desired. For example, as illustrated, the sensor array **52** may be configured in a longitudinal row or be stacked vertically. In addition, the sensor array **52** may extend into two dimensions to form a square shaped sensor or any type of pattern depending upon the desired application. In yet another alternative embodiment, the sensor array may extend into three dimensions by stacking the sensors above one another such that sufficient space is provided for fluid contact to the-various sensors. Any configuration of sensors **10** to form one dimensional, two dimensional or three dimensional arrays are contemplated by the present invention.

[**0061**] **FIG. 5** is a system level diagram which illustrates a fluid contamination analyzer system **90** having a substrate **92** upon which a sensor array **94** resides, wherein each sensor **95** is constructed and behaves as the sensors **10**, **22** and **23** of **FIGS. 2A, 2B** and 2C, respectively. Each sensor **95** is coupled (not shown) to the analysis circuitry **38** either directly or via a multiplexer circuit that may reside on the substrate **92**. A magnetic field source **96**, preferably an electromagnet coil or a movable permanent magnet, is coupled to a magnetic control circuit **98** to selectively activate the magnetic field source **96**, such that the magnetic field may be turned on and off as desired. The magnetic field source **96** is preferably oriented to provide a magnetic field intensity gradient along a length of the sensor array **94**. Preferably, the orientation is determined by a spacer wedge **100**, as illustrated, however, other mechanisms such as brackets, etc. may also be utilized and are contemplated by the present invention.

[**0062**] The sensor array **94** of **FIG. 5** operates in the following manner. A lubricant fluid for analysis is brought into contact with the sensor array **94**. This may be accomplished by either placing the fluid contamination analyzer system **90** on a probe and inserting the sensor array **94** into the fluid or preferably affixing the system **90** to a machine in the fluid flow path to thereby provide an in-line fluid analyzer. In another embodiment, the fluid may be removed from the machine and brought into contact with the sensor array **94**. The magnetic control circuit **98** activates the coil **96**, thereby generating a magnetic field. The sensor array **94**, due to its positional orientation with respect to the coil **96**, experiences a magnetic field intensity gradient along its length such that at one end a large magnetic field intensity (H_1) is experienced at the substrate **92**, while at another end a substantially smaller magnetic field intensity (H_2) is experienced at the substrate **92**. Due to the magnetic field intensity gradient, ferromagnetic particles (contaminants) of

differing sizes in the fluid are distilled from the fluid flow path onto the sensor array **94**, such that a particulate distribution is generated across the sensor array **94**. Therefore, each sensor **95** in the sensor array **94** will have a unique impedance due to the size and quantity of the particulates at that location. This impedance information is then used by the associated analysis circuitry **38** and processors to determine how much contamination exists at differing particulate sizes, which may be utilized to determine wear modes, wear trends, etc. After the impedance data has been collected, the magnetic control circuit **98** deactivates the coil **96** or moves the permanent magnet away, thereby turning the magnetic field off. Without any magnetic field acting on the particles, the force of fluid flow substantially removes particles from the sensor array **94**.

[**0063**] Various modifications and alternative embodiments may be employed with the sensor array **94**. In one alternative embodiment, a magnetic field intensity gradient may be achieved by utilizing a plurality of independent magnetic field sources fixed at varying distances from the substrate **92** or wherein each source has a unique magnetic field intensity such that their aggregation provides a magnetic field intensity gradient. Any type of magnetic field source or configuration of sources that would provide a variable magnetic field intensity across the sensor array **94** is contemplated in the present invention. Furthermore, although a coil is the preferred magnetic field source **96**, any other type of magnetic source falls within the scope of the present invention.

[**0064**] Another embodiment is illustrated in **FIG. 6**. **FIG. 6** is a top view of a sensor array **110** wherein a substrate **12** contains a plurality of sensors **10** formed thereon. Each sensor **10** is much like the sensor of **FIG. 1A** (or alternatively sensors **22** or **23** of **FIGS. 2B and 2C**), having a substrate **12**, conductors (electrodes) **14** and **16** and bond pads **18** and **20**. The sensor array **110** differs from the sensor array **60** of **FIG. 4** in that at least one of the sensors varies from the others with respect to the spacing between the interdigitated electrodes. For example, as illustrated in **FIG. 6**, sensor **10***a* has a somewhat close conductor spacing (d_1) for fine-sized particulates, sensor **10***b* has a larger electrode spacing (d_2) for medium-sized particulates and sensor **10***c* has a relatively larger electrode spacing (d_3) to accommodate large-sized particulates (wherein $d_1<d_2<d_3$). Such a variable electrode spacing sensor array **110** further accommodates particulate contamination distribution determinations by helping to delineate the size of the particulates due to the difference in spacing of the electrodes **14** and **16**. Therefore to carry out this feature, the sensor **10***c* is preferably located within the array **110** near the largest magnetic field intensity which has sufficient strength to distill large-sized contaminants from the fluid, while sensor **10***a* preferably is located within the array **110** near the weakest magnetic field intensity which has sufficient strength to distill small-sized contaminants from the fluid.

[**0065**] With reference now to **FIG. 7**, a sensor array **210** includes a substrate **12** and a plurality of sensors **10***a*, **10***b*, **10***c* formed thereon. Each sensor includes a substrate **12**, a pair of electrodes **14** and **16** and associated bond pads **18** and **20**. In one embodiment, a first sensor **10***a* serves as a reference sensor, while the other sensors **10***b*, **10***c* are sample sensors for detecting one or more fluid contaminants, including, but not limited to, particles, water, acid, and the like.

[**0066**] In one embodiment, illustrated in **FIG. 8**, a sensor assembly **212** includes the sensor array **210** and a sensor housing **217**. As shown, the reference sensor **10***a* is exposed or otherwise subjected to a known reference fluid **19**, within the reference housing **13**, having a composition and purity, which remains relatively fixed. For example, in a machine which employs a lubrication or cooling oil (flowing in a direction along arrows **215**), the reference sensor **10***a* may be contained or otherwise housed in a reference housing **13**, which is disposed adjacent the sample sensors **10***b*, **10***c*. In one embodiment, the reference housing **13** is comprised of a thermally conductive material, such that the temperature of the reference fluid **19** within the reference housing **13** is at approximately the same temperature as the fluid circulating throughout the machine.

[**0067**] Preferably, the reference sensor **10***a* is immersed in or otherwise exposed to "clean" oil, i.e., oil which is not circulated throughout the machine and is not readily exposed to contamination. In this embodiment, the reference sensor is exposed to a reference oil having the same composition as the oil circulated throughout the machine. In addition, the reference oil and associated reference sensor **10***a* are subjected to all of the same conditions as the circulated oil and associated sample sensors **10***b*, **10***c*, except for the contaminants which develop in the circulated oil over time. As such, the capacitance readings from sample sensors **10***b*, **10***c* can be compared to the capacitance reading from reference sensor **10***a* in order to determine changes (e.g., the development and or presence of contaminants) in the circulated sample oil, and thereby providing enhanced accuracy. It is to be appreciated that the sensor assembly **212** of **FIG. 8** may be used in conjunction with a probe, such as those illustrated in **FIGS. 3A-3C**, as well as in an in-line configuration (as illustrated in **FIG.13**). It is to be appreciated that the reference housing **13** may be removable in order for the reference fluid **19** contained therein to be changed periodically.

[**0068**] With reference to **FIG. 9A** and continued reference to **FIGS. 1-4**, in another alternative embodiment, a sensor array **310** includes a substrate **12** and a plurality of sensors **10***a*', **10***b*', **10***c*' formed thereon. Preferably, each sensor **10***a*', **10***b*', **10***c*' is sensitive to or otherwise selective of a particular fluid contaminant. More particularly, each sensor **10***a*', **10***b*', **10***c*' can include a different contaminant-selective layer. For example, the contaminant-selective layer can include an insulating or intermediate layer **21***a*, **21***b*, **21***c*, disposed between the electrodes **14**, **16** and the substrate **12**, as shown in **FIG. 2B**. Each intermediate layer **21***a*, **21***b*, **21***c* is chosen in order to provide a surface to which a fluid containing a contaminant of interest would preferentially adhere, thereby providing a stronger impedance measurement of the presence of the particular contaminant of interest within the fluid.

[**0069**] For example, an intermediate layer comprised of glass would be particularly sensitive to water within the fluid, while an intermediate layer comprised of silicon nitride would be particularly sensitive to soot and oxidation within the fluid. The sensitivity of a particular contaminant selective layer with respect to a particular contaminant can be determined empirically. The contaminant selective layer can be formed from silicon nitride, silicon dioxide, cerium dioxide, glass, quartz, aluminum oxide, aluminum nitride, boron nitride, titanium nitride, gallium nitride, diamond,

diamond like carbon and silicon carbide. Hydrophilic materials provide more sensitivity to water, while hydrophobic materials provide less sensitivity to water.

[0070] According to one embodiment, the contaminant selective layer is formed from organic coatings, such as parylene, epoxy, polyimide, polycarbonate, polyester, polyphenylene sulfide, and the like.

[0071] According to another embodiment, the contaminant selective layer is formed from a low-K material or stack of materials to form a low-K dielectric stack. As used herein, a "low-K material" or a "low-K dielectric material" refers to a material, or stack of materials, having a relative permittivity in one embodiment of about 5 or less, and in another embodiment of about 3 or less. Relative permittivity is the ratio of the absolute permittivity (ϵ) found by measuring capacitance of the material to the permittivity of free space (ϵ_o), that is $K=\epsilon/\epsilon_o$.

[0072] Examples of low-K dielectric materials include nanopourous silica, hydrogensilsesquioxanes, teflon-AF (Polytetrafluoethylene), Silicon Oxyflouride and the like. It is noted that above-identified low-K materials are not an exhaustive list of low-K materials and other low-K materials may be available.

[0073] In an alternative embodiment of **FIG. 9B**, one or more of the sensors **10***a*", **10***b*", **10***c*" in the sensor array **210**, **310** may be covered with an insulating film or layer, as illustrated in **FIG. 2C**, to provide non-particulate contamination information, such as the water content of the fluid and/or fluid oxidation for analysis. Again, each insulating film **24***a*, **24***b*, **24***c* is chosen in order to provide a surface to which a fluid containing a contaminant of interest would preferentially adhere, thereby providing a stronger capacitive measurement of the presence of the particular contaminant of interest within the fluid. For example, an insulating film comprised of glass would be particularly sensitive to water within the fluid, while an insulating film comprised of silicon nitride would be particularly sensitive to soot and oxidation within the fluid.

[0074] In yet another alternative embodiment shown in **FIG. 9C**, each sensor is formed on a substrate **12***a*, **12***b*, **12***c*, of different material, which is selective of or otherwise sensitive to a particular contaminant being detected. In this embodiment, each sensor substrate **12***a*, **12***b*, **12***c*, may be mounted to a common base structure such that the sensors are disposed in proximity to one another. For example, a substrate comprised of glass would be particularly sensitive to water within the fluid, while a substrate comprised of silicon nitride would be particularly sensitive to soot and oxidation within the fluid.

[0075] **FIG. 10** is a perspective view of the sensor system **130** in an in-line configuration in which the sensors **10** themselves are in a fluid flow path **132** of a machine. As discussed supra, the sensor **10** senses the fluid impedance and transmits this data to the analysis circuit **38**, which analyzes and/or processes the data to arrive at a fluid contamination determination. This result may then be communicated either visually to a user who is taking a fluid contamination reading via a display (not shown) or may alternatively communicate the result to a central data collection station (not shown) via the communications control circuit **128** which is operable to transmit data, preferably via an RF signal, to the data collection station.

[0076] With reference now to **FIG. 11**, a sensor system **410** in accordance with an alternative embodiment is illustrated. The system includes one or more sensors **10** disposed adjacent a local heater **412**, which is controlled by a heater control **414**. A local heater, as used herein, refers to a heater that is within about 5 to about 1000 microns from the sensor. The actual location of the heater with respect to the sensor is not critical, and the heater need only cause a change in temperature of the fluid so a temperature slope can be determined. The sensor system **410** performs impedance measurements on a fluid sample as the fluid is run through a temperature gradient. In one embodiment, the sensor system **410** is integrated into a probe assembly, such as is illustrated in **FIGS. 3A-3C**. Alternatively, the probe system **410** is embodied in an in-line configuration, such as is illustrated in **FIG. 10**. Because the rate at which the sensed impedance changes with temperature (temperature slope) is altered by contamination of the fluid, the change in slope can be used as an indication of fluid condition. It is to be appreciated that this embodiment of the invention may be employed in conjunction with a single sensor system as well as a multi-sensor array.

[0077] Referring now to **FIG. 12**, an alternative embodiment of the sensor **420** is illustrated. The sensor **420** is similar to the sensor **10**, **22**, **23** shown in **FIGS. 2A-2C**, and includes electrodes **14**,**16** located along a horizontal plane on the substrate **12**. When a lubricant fluid sample contacts the sensor **10**, it rests between and above the electrodes **14** and **16**, thereby affecting the dielectric constant therebetween. Accordingly, the presence of contaminants within the fluid results in different impedance readings of the sensor at its leads (bond pads **18** and **20**). Bond pads **18**, **20** provide a connection point for coupling to discrete instrumentation or circuits integrated with the substrate. Additionally, the sensor **420** includes a temperature sensor **422**, such as, for example, a thermocouple, a thermistor, or a Resistance Temperature Detector (RTD). Terminals **424**, **426** provide a connection means for connecting the temperature sensor **422** to a monitoring device, such as the analysis circuitry **38** (**FIG. 3A**), for example. As will be appreciated, the number of terminals required for the temperature sensor **422** depends on the type of temperature sensor implemented, e.g., two terminals for a thermocouple, three terminals for a 3-wire RTD, etc. Alternatively, the temperature data from the temperature sensor **422** and fluid data from the sensor may be transmitted to the analysis circuitry **38** wirelessly or through a data communications link. The temperature sensor **422** provides a temperature measurement of the fluid that is in contact with the sensor **420**. The temperature measurement can be used by the analysis circuitry to improve the accuracy of the analysis of the fluid, e.g., by compensating the impedance measurement of the fluid based on the temperature of the fluid.

[0078] For example, correction factors can be applied to the data obtained by the sensor **420** based on the temperature of the fluid. It may be known that the sensor **420** produces a first set of data for a fluid in a first temperature range, and a second set of data, which is different from the first set of data, in a second temperature range. In each case the fluid is identical (except for temperature), yet different test data is obtained. To compensate for this difference, a correction factor can be applied to the measured data based on the measured temperature of the fluid. It should be appreciated that the correction factor can be applied by the analysis

circuitry **38** or by the temperature sensor **422** itself. Alternatively, temperature data obtained from the temperature sensor **422** can be used for monitoring the fluid temperature, thereby eliminating the need for a separate temperature sensor.

[**0079**] With reference now to **FIG. 13**, another embodiment of the sensor is illustrated. The sensor **430** again is similar to the sensor of **FIGS. 2A-2C**, and includes electrodes **14**,**16** located along a horizontal plane on the substrate **12**. Bond pads **18**, **20** provide a connection point for coupling to discrete instrumentation or circuits integrated with the substrate, as described previously. Additionally, the sensor **430** includes a non-volatile memory module **432**, such as an EEPROM. The non-volatile memory module **432** is operatively coupled to the sensor to receive data, such as sensor data, temperature data, etc. Additionally, the non-volatile memory module is operatively coupled to a memory controller (not shown). Memory controllers are well known and therefore will not be discussed in detail. Briefly, the memory controller coordinates the data routed to the non-volatile memory module **432** and the data retrieved from the non-volatile memory module. Additionally, the memory controller instructs the non-volatile memory module to store and/or to retrieve data to/from non-volatile memory.

[**0080**] The non-volatile memory module **432** can store and/or retrieve data pertaining to the sensor, e.g., calibration data, date of manufacture, serial number, sensor type etc., customer data, e.g., customer name, location, etc., or application data, e.g., location of the sensor, last maintenance date of the sensor, selected reference fluid (e.g., reference oil), operating time, minimum and maximum operating temperature, minimum and maximum fluid measurements (e.g., impedance, temperature), etc. As will be appreciated, numerous other types of data can be stored in the non-volatile memory module **432** as required. Additionally, the temperature sensor **422** of the sensor **420** and the non-volatile memory module **432** of the sensor **430** can be combined in a single sensor, thereby providing both memory storage/retrieval functions and temperature monitoring functions on a single sensor.

[**0081**] With reference to **FIG. 14**, another embodiment of the sensor is illustrated. The sensor **440** includes a MEMS based sensor **442** as described in any one of the previously discussed embodiments. The MEMS based sensor **442** includes electrodes **14**,**16** located along a horizontal plane on the substrate **12**. Bond pads (not shown) provide a connection point for coupling to discrete instrumentation or circuits integrated with the substrate. Above the MEMS sensor **442** is a plate electrode **444**, which can be formed from any one of several materials, including, for example, tungsten, platinum, gold, chrome, aluminum, polysilicon, titanium, nickel, copper, silver and the like. The plate electrode **444** is generally rectangular in shape, although it should be appreciated that other shapes can be implemented without departing from the scope of the invention. The plate electrode **444** has a footprint that is about equal to a footprint of the MEMS based sensor **442**. Additionally, the plate electrode **444** is generally parallel to the MEMS based sensor **442**. The plate electrode can be less than 1 micron to about 10,000 microns thick, and the spacing **446** between the plate electrode and a top surface **448** of the electrodes **14**, **16** can range from 50 to about 3000 microns. In one embodiment, the spacing **446** is about 1000 microns.

[**0082**] A first connector **450** couples the first electrode **14** to analysis circuitry **38** via a first switch **452**. A second connector **454** couples the second electrode **16** to the analysis circuitry **38** via a second switch **456**. A third connector **458** couples the plate electrode **444** to the analysis circuitry **38** via a third switch **460**. A fourth connector **462** and a fifth connector **464** couple the first electrode **14** to the second electrode **16** via a fourth switch **466**. Finally, a fifth connector **468** couples the plate electrode **444** to an electrostatic field control circuit **470** via a fifth switch **472**.

[**0083**] As will be appreciated, the above described switches can be MEMS based switches or any other suitable switch used in low power signal systems. Additionally, connections for operating the switches are not shown. Such connections, however, would be obvious to one skilled in the art and therefore are omitted for sake of brevity. The switches can be located remote from the sensor **440**, e.g., in or near the analysis circuitry **38**, or integrated on the sensor **440**, e.g., on the substrate **12** of the MEMS based switch **442**. Based on the switch settings, the sensor **440** can operate in anyone of several modes.

[**0084**] In a first mode, the first switch **452** and the second switch **456** are closed, while the third switch **460** and the fourth switch **466** are open. In this mode of operation, the sensor **440** behaves as the sensors previously described herein, i.e., the sensor analyzes the fluid between and above the electrodes **14**, **16** within its field of view. The sensor **440** is immersed in a fluid and a measurement is made by the analysis circuitry **38** via the first and second connectors **450**, **454**. The fluid surrounding the electrodes **14**, **16** of the sensor **440** acts as a dielectric between the electrodes **14**, **16** thereby impacting the impedance of the sensor. The analysis circuitry **38** determines the level of fluid contamination based upon either a comparison with a known clean fluid sample or with an expected or reference value.

[**0085**] In a second mode, the first switch **452** and the third switch **460** are closed, and the second switch **456** and the fourth switch **466** are open. In this configuration the sensor **440** measures the impedance of the bulk fluid between the first electrode **14** and the plate electrode **444**. The first electrode **14** and the plate electrode **444** form the respective plates of a parallel plate capacitor, and the fluid between the plates forms the dielectric material. The analysis circuitry **38** determines the level of fluid contamination based upon either a comparison with a known clean fluid sample or with an expected or reference value.

[**0086**] In a third mode, the second switch **456** and the third switch **460** are closed, and the first switch **452** and the fourth switch **466** are open. In this configuration the sensor **440** measures the impedance of the bulk fluid between the second electrode **16** and the plate electrode **444**. The second electrode **16** and the plate electrode **444** form the respective plates of a parallel plate capacitor, and the fluid between the plates forms the dielectric material. The analysis circuitry **38** determines the level of fluid contamination based upon either a comparison with a known clean fluid sample or with an expected or reference value.

[**0087**] In a fourth mode, the first switch **452**, the third switch **460** and the fourth switch **466** are closed, and the second switch **456** is open. In this configuration the sensor **440** measures the impedance of the bulk fluid between the combination of the first electrode **14** and the second elec-

trode **16** and the plate electrode **444**. The first electrode **14** and the second electrode **16** form a first plate of a parallel plate capacitor, and the plate electrode **444** forms the second plate of a parallel plate capacitor. The fluid between the two plates forms the dielectric material. The analysis circuitry **38** determines the level of fluid contamination based upon either a comparison with a known clean fluid sample or with an expected or reference value. It is noted that the same configuration can be obtained by opening the first switch **452** and closing the second, third and fourth switches **456**, **460**, **466**.

[**0088**] In a fifth mode, the first switch **452**, the second switch **456** and the fifth switch **472** are closed and the third switch **460** and the fourth switch **466** are open. The sensor **440** operates in the following manner. After a magnetic field source (not shown) is deactivated, particulates are preferably washed away due to fluid flow. There are frequently, however, particulates that contain a residual static charge large enough to remain stuck to one of the electrodes **14** and **16** despite the fluid flow over the electrodes. The electrostatic field control circuit **470** then applies a voltage to the plate electrode **444** such that an electrostatic field is generated that is sufficiently large such that particulates are dislodged and washed away by the fluid flow. In this manner, fluid contamination accuracy is improved by eliminating the chance of residual particulates from previous fluid sample measurements interfering with subsequent fluid measurements by washing performed periodically via the electrostatic control circuit **470** and the plate electrode **444**.

[**0089**] **FIG. 15** is a system level diagram, which illustrates a dynamic fluid contamination analysis system **500**. System **500** includes a central data collection, processing and storage unit **502**, which contains a processor **504**, an RF communications circuit **506** and a memory **508**. The central data collection unit **502** may also include an I/O port, an input peripheral device and a display for interacting with a user. The system **500** includes a plurality of machines **510**, **512**, **514**, **516** and **518** which operate in a factory setting and utilize fluids of lubricant and cooling purposes. Each machine contains a sensor system **130** (as illustrated in **FIG. 10**, for example) that performs in an in-line configuration. Periodically, as dictated by the processor **504** and RF communications circuit **506**, the sensor systems **130** are instructed to measure the fluid impedance of the fluid in their respective machines. Each sensor system **130** then communicates its present fluid impedance to the processor **504** via its communications control circuit **128**. The processor **504** then makes a fluid contamination determination, stores it in the memory **508** for trending purposes and indicates the determination to monitoring personnel if the fluid contamination level exceeds a predetermined threshold. In this manner, the fluid contamination analysis system **500** monitors a plurality of machines without requiring a user to go from machine to machine taking fluid samples and interfering with the machine operation. In addition, since the sensor arrays of the present invention are small, they may serve in in-line configurations without interfering with machine operation.

[**0090**] With reference to **FIG. 16**, a flow diagram of an example technique, or process **600** of determining the quality of a fluid in accordance with the present invention is illustrated. The process **600** can be thought of as depicting steps in a method. The flow diagram includes a number of process blocks arranged in a particular order. As should be appreciated, many alternatives and equivalents to the illustrated process **600** may exist and such alternatives and equivalents are intended to fall within the scope of the claims appended hereto. Alternatives may involve carrying out additional steps or actions not specifically recited and/or shown, carrying out steps or actions in a different order from that recited and/or shown, and/or omitting recited and/or shown steps. Alternatives also include carrying out steps or actions concurrently or with partial concurrence.

[**0091**] As will be described more fully below, the method includes immersing a sensor into a fluid and measuring the impedance of the sensor and fluid. Based on the measured impedance, the quality of the fluid is estimated.

[**0092**] The method will be described in conjunction with the analysis circuitry **38** previously discussed herein. In the exemplary embodiment, the analysis circuitry is the computer **500** (**FIG. 15**) executing program instructions that carry out the steps of the method. It should be appreciated that the particular vehicle used to implement the method is not germane to the invention, and other forms of the analysis circuitry are contemplated. For example, the analysis circuitry could be configured as a group of discrete components interconnected together to form a logical circuit.

[**0093**] The sensor of the present invention can be modeled as a resistor having a resistance R connected in parallel with a capacitor having a capacitance C. Thus, the sensor includes both real and reactive components.

[**0094**] Another factor for consideration is the dissipation factor (DF). DF represents one form of heat-producing losses within a capacitor. DF and "loss tangent" are largely equivalent terms describing capacitor dielectric losses. DF refers specifically to losses encountered at low frequencies. At high frequencies, capacitor dielectric losses are described in terms of loss tangent (tan δ). The higher the loss tangent, the greater the capacitor's equivalent series resistance (ESR) to signal power.

[**0095**] For small and moderate capacitor values, losses within the capacitor occur primarily in the dielectric, the medium for the energy transfer and storage. The dielectric loss angle, δ, is the difference between (theta) and 90°. The name "loss tangent" simply indicates that tan δ goes to zero as the losses go to zero. Note that the dielectric's DF is also the tangent of the dielectric loss angle. These terms are used interchangeably in the art.

[**0096**] The actual values of R and C for the sensor model as well as the DF are dependent on the sensor itself as well as on the fluid the sensor is measuring. A clean or new fluid will produce values of R, C and DF that are distinct from values of R, C and DF produced by a contaminated or used fluid. Based on the measured values of R, C, and DF, the analysis circuitry can estimate the remaining life of the fluid, the particular type of contamination in the fluid, e.g., water, metal, soot, oxidation, additive depletion, etc., and the relative amounts of the particular type of contamination in the fluid.

[**0097**] Beginning at step **602**, a sensor in accordance with the present invention is immersed in a fluid, such as oil from an internal combustion engine, for example. At step **604**, the processor **504** initializes a counter, and at step **606** the processor selects an initial frequency f**1**. The selected fre-

quency f1 can range between 0.1 Hz and 10 MHz, and preferably is at an optimum frequency for the application. According to one embodiment, f1 is between about 100 Hz and 20 KHz. The processor **504** applies the selected frequency to the bond pads **16**,**18** of the sensor at step **608**, and the temperature and impedance of the sensor/fluid are measured by the processor.

[**0098**] Moving to step **612**, the processor **504** stores the measured temperature and impedance in memory **508** for use in later steps. At step **614**, the processor checks the counter to determine if another iteration is required. If the counter is less than or equal to n, then at step **616** the processor **504** increments the counter, and at step **618** the processor selects a second test where electrical conditions may be changed in frequency, voltage, time duration or not changed as required by the test protocol for the application. For example, the frequency f2 can be higher, lower or equal to the frequency f1. Preferably, the frequency f2 is about 10 times the frequency f1 of the previous iteration. After selecting the second frequency, the processor **504** moves back to step **608**, and the process is repeated for n tests as required by the protocol for that application.

[**0099**] Moving back to step **614**, if the processor **504** determines the counter is greater than n, then at step **620** the processor retrieves the measured data from memory **508**. At step **620**, the processor calculates functions that best represent the oil conditions of concern, e.g., the impedance at each frequency. Threshold values for the functions will be determined with used fluids with known levels of contamination and/or depletion. Processor **504** will generate a report of the test point, date/time, multiple test functional values for the test point, threshold functional values and temperature, for example.

[**0100**] For example, and as was noted previously, the sensor can be modeled as a resistor connected in parallel to a capacitor. The impedance can be measured by applying a sine wave signal of a given frequency and amplitude to the sensor and comparing the input signal to the output signal with respect to amplitude and phase shift (phase angle). From this information, and using the parallel R-C (resistor-capacitor) model of the sensor, the impedance is resolved into real and reactive components.

[**0101**] Moving to step **622**, once the impedance is resolved into its real and reactive components, a correction factor is applied to the complex impedance. The correction factor is based on the measured temperature of the sample fluid during the impedance measurement relative to the measured temperature of a reference fluid during its impedance measurement. The correction factor can be a simple fraction, an equation describing the change in impedance as temperature varies, or a lookup table containing the impedance of a stable fluid at various temperatures. According to one embodiment, temperature compensation factors are generated for a particular reference fluid type after all measurements of the reference fluid have been made at various temperatures.

[**0102**] As was discussed previously, impedance measurements of certain fluids can be affected by the temperature of the fluid. Impedances may increase, decrease or remain unchanged throughout a temperature range. Due to the operating characteristics of a particular machine, it may not be feasible to obtain an impedance measurement of a sample fluid at the same or similar temperature as an impedance measurement of a reference fluid. In such situations, a correction of the measured impedance of the sample fluid provides increased accuracy of the impedance measurement and, thus, increased accuracy in the estimate of the condition of the fluid. The correction factor for a given fluid can be stored in memory, such as a database, which is discussed in more detail below.

[**0103**] Now that a corrected value of the complex impedance has been calculated, the processor at step **624** retrieves reference fluid data from memory (e.g., data stored in a reference database on a storage medium, such as a hard drive of a computer). Referring briefly to **FIG. 17**, an exemplary database structure **700** that can be used to construct the reference database is illustrated. The database structure **700** includes a reference name entry **702**, which is a listing of fluid names that may be used in a particular machine or process, e.g., 80 weight gear lube, Brand X 10W-40 motor oil, etc. A real component of impedance entry **704** stores the real component of impedance for the particular reference fluid, and a reactive component impedance entry **706** stores the reactive component of impedance for the particular reference fluid. A reference temperature entry **708** stores the temperature of the reference fluid during its impedance measurement, and a temperature compensation entry **710** stores the correction factor for the particular fluid. Additionally, a DF entry **712** stores the dissipation factor for the fluid and, finally, a fluid property entry **714** provides information relating to the characteristics of the particular fluid. For example, the condition of the reference fluid (e.g., new, used, etc.), the type of contaminants in the fluid (e.g., soot, water, fuel, etc.) and/or the amount of contaminant in the fluid (e.g., 1% fuel) is entered in the fluid property entry **714**.

[**0104**] As will be appreciated, multiple columns for fluid property can be included in the database structure **700** depending on the requirements of the system. For example, a first fluid property entry can be dedicated to the age or remaining life of the fluid, a second fluid property entry can be dedicated to the type of contaminant in the fluid, and a third fluid property entry can be dedicated to the amount of the contaminant in the fluid. Additionally, the impedance may be expressed in other terms as described previously, e.g., terms other than real/reactive components and DF.

[**0105**] Each reference fluid is entered into the reference database along with its respective properties as in the above described entries. For example, a first fluid name entry **702** may be Brand X 10W-30 motor oil, and is entered in a first row **720** of the database. Corresponding fluid properties, real component of impedance, reactive component of impedance, reference temperature, correction factor, and DF also are stored in the first row under their respective columns. A second fluid name may be the same fluid, e.g., Brand X 10W-30 motor oil, and is entered in a second row **722** of the reference database, along with its corresponding fluid properties, real component of impedance, reactive components of impedance, reference temperature, correction factor and DF. As should be apparent, the second entry will have a different fluid property, and thus different values for the real component of impedance, the reactive component of impedance, or the DF. The reference temperature entry **708** may or may not be the same, depending on the temperature of the second reference fluid during its impedance measurement. The temperature compensation entry **710** is the same for refer-

ence fluids of the same type. Further entries can be made for the same type of fluid and/or for different types of fluid, as needed. In one embodiment, the reference database includes a single type of reference fluid, and numerous entries for the reference fluid at various levels of contamination and/or various type of contaminants.

[0106] In operation, the processor searches and retrieves from the database **700** fluid name entries **702** that match the fluid sample being tested. From the list of matching fluid names, the processor searches the real component of impedance **704**, the reactive component of impedance **706**, and the DF **712** for values that match or are within a specified range of the calculated real component of impedance, the calculated reactive component of impedance and the calculated DF for the sample fluid. At step **626**, the processor **504** estimates the sample fluid to have the same fluid properties as a reference fluid of the same type with the same or similar DF, real component of impedance and reactive component of impedance. At step **628**, the status of the fluid is reported to a user via an screen, e.g., a computer monitor, or via a status indicator, for example.

[0107] The various features of the present invention may be utilized in a variety of applications, configurations and packages. For example, the aspects of each embodiment can be mixed and matched to create alternative embodiments. Each variation is contemplated as falling within the scope of the present invention. Additionally, the sensors may be potted or secured in a DIP (dual in-line package) for easy insertion and replacement. Furthermore, the number of iterations at various frequencies may be increased as required.

[0108] Although the invention has been shown and described with respect to certain preferred embodiments, it is obvious that equivalents and modifications will occur to others skilled in the art upon the reading and understanding of the specification. The present invention includes all such equivalents and modifications, and is limited only by the scope of the following claims.

What is claimed is:

1. A fluid contamination analyzer, comprising:

at least one sensor, wherein the at least one sensor includes:

a substrate;

a plurality of electrodes formed over the substrate; and

a contaminant selective layer disposed adjacent at least one of (i) the electrodes or (ii) the substrate, said layer being selective to attract a predetermined contaminant within the fluid;

wherein when a fluid contacts the sensor an impedance of the fluid may be determined using the electrodes of the sensor, thereby providing an indication of fluid contamination.

2. The fluid contamination analyzer according to claim 1, wherein the contaminant selective layer comprises an intermediate layer disposed between the electrodes and the substrate.

3. The fluid contamination analyzer according to claim 2, wherein the contaminant selective layer is a low-K dielectric material.

4. The fluid contamination analyzer according to claim 3, wherein the low-K dielectric material is chosen from the group consisting of nanopourous silica, hydrogensilsesquioxanes, teflon-AF (Polytetrafluoethylene) and Silicon Oxyflouride.

5. The fluid contamination analyzer according to claim 1, wherein the contaminant selective layer comprises a top layer disposed over the electrodes.

6. The fluid contamination analyzer according to claim 5, wherein the contaminant selective layer is a low-K dielectric material.

7. The fluid contamination analyzer according to claim 6, wherein the low-K dielectric material is chosen from the group consisting of nanopourous silica, hydrogensilsesquioxanes, teflon-AF (Polytetrafluoethylene) and Silicon Oxyflouride.

8. The fluid contamination analyzer according to claim 1, wherein the contaminant selective layer is selected from the group consisting of silicon nitride, silicon dioxide, cerium dioxide, glass, quartz, aluminum oxide, aluminum nitride, boron nitride, titanium nitride, gallium nitride, diamond, diamond like carbon, silicon carbide, parylene, epoxy, polyimide, polycarbonate, polyester, and polyphenylene sulfide.

9. The fluid contamination analyzer according to claim 1, wherein the electrodes are formed from the group consisting of tungsten, platinum, gold, chrome, aluminum, polysilicon, titanium, nickel, copper and silver.

10. The fluid contamination analyzer according to claim 1, wherein the plurality of electrodes are interdigitated.

11. The fluid contamination analyzer according to claim 10, wherein a spacing between adjacent electrodes is between about 1 micron to about 250 microns.

12. The fluid contamination analyzer according to claim 10, wherein a spacing between adjacent electrodes is less than 1 micron.

13. The fluid contamination analyzer according to claim 1, further comprising a temperature sensor for measuring a temperature of the fluid in contact with the sensor.

14. The fluid contamination analyzer according to claim 13, wherein the temperature of the fluid is used to compensate the impedance measurement of the fluid.

15. The fluid contamination analyzer according to claim 13, wherein the temperature sensor is selected from the group consisting of a thermocouple, a thermistor and a resistance temperature detector (RTD).

16. The fluid contamination analyzer according to claim 13, wherein data is communicated to a remote monitoring device through a communications link.

17. The fluid contamination analyzer according to claim 16, wherein the communications link is a wireless communications link.

18. The fluid contamination analyzer according to claim 1, further comprising a non-volatile memory module for storing data.

19. The fluid contamination analyzer of according to claim 18, wherein the data stored in the non-volatile memory module is at least one of a customer name, a serial number of the sensor, a manufacture date of the sensor, a calibration factor of the sensor, a temperature of the fluid, a sensor type, a location of sensor, a maintenance date of sensor, a selected reference oil, or an impedance of the fluid.

20. The fluid contamination analyzer according to claim 18, wherein the non-volatile memory module is an electrically erasable programmable read only memory module (EEPROM).

21. The fluid contamination analyzer according to claim 1, further comprising a temperature sensor for measuring a temperature of the fluid in contact with the sensor and a non-volatile memory module for storing data.

22. The fluid contamination analyzer according to claim 1, further comprising a plate electrode disposed over the at least one MEMS based sensor, wherein when a fluid is disposed between the plate electrode and the at least one MEMS based sensor an impedance of the fluid is determined using the plate electrode and at least one electrode of the at least one MEMS based sensor or the plurality of electrodes of the MEMS based sensor, thereby providing an indication of fluid contamination.

23. The fluid contamination analyzer according to claim 22, further comprising an electrostatic field control circuit electrically coupled to the plate electrode, wherein the electrostatic field control circuit develops an electrostatic field between the plate electrode and the plurality of electrodes, thereby dislodging with an electrostatic force any particulates that may have become stuck within the sensor due to static charge on the particulates.

24. The fluid contamination analyzer according to claim 22, further comprising:

a plurality of switches, including

a first switch operatively coupled to a first electrode of the plurality of electrodes;

a second switch operatively coupled to a second electrode of the plurality of electrodes;

a third switch operatively coupled to the plate electrode; and

a fourth switch operatively coupled to the first electrode and the second electrode.

25. The fluid contamination analyzer according to claim 24, wherein the plurality of switches selectively configure the fluid contamination analyzer to measure an impedance between the plate electrode and at least one electrode of the at least one MEMS based sensor.

26. The fluid contamination analyzer according to claim 24, wherein the plurality of switches selectively configure the fluid contamination analyzer to measure an impedance of the fluid between and adjacent to the electrodes of the MEMS based sensor.

27. The fluid contamination analyzer according to claim 24, wherein the plurality of switches are MEMS switches.

28. The fluid contamination analyzer according to claim 24, wherein the plurality of switches are formed on the substrate of the MEMS based sensor.

29. The fluid contamination analyzer according to claim 22, wherein the plate electrode and the plurality of electrodes are formed from the group consisting of tungsten, platinum, gold, chrome, aluminum, polysilicon, titanium, nickel, copper and silver.

30. The fluid contamination analyzer according to claim 22, wherein the plate electrode is about 1 micron to about 10,000 microns thick.

31. The fluid contamination analyzer according to claim 22, wherein the plate electrode is substantially parallel to a top surface of the at least one MEMS based sensor.

32. The fluid contamination analyzer according to claim 1, wherein the substrate is the contaminant selective layer.

33. The fluid contamination analyzer of claim 1, wherein the sensor is a MEMS based sensor.

34. The fluid contamination analyzer of claim 1, wherein the substrate is at least one of a glass substrate or a quartz substrate.

35. The fluid contamination analyzer of claim 1, wherein the plurality of electrodes have a width between about 1 micron to about 50 microns.

36. The fluid contamination analyzer of claim 1, further comprising a selectively activatable electromagnet in proximity to the at least one sensor, wherein the magnet may be activated and deactivated in response to control signals and provides a magnet gradient across the at least one sensor, wherein the magnet gradient provides a contaminant distribution across the at least one sensor.

37. The fluid contamination analyzer according to claim 1, wherein the contaminated selective layer is an insulator.

38. An in-line fluid contamination analyzer, comprising:

an array of MEMS-based sensors located within a fluid, wherein each sensor includes a substrate, a plurality of electrodes formed over the substrate, and a contaminant-selective layer disposed adjacent the electrodes, said array including:

a first MEMS-based sensor having a first contaminant-selective layer which is selective to attract a first contaminant within the fluid;

a second MEMS-based sensor having a second contaminant-selective layer which is selective to attract a second contaminant within the fluid; and

a third MEMS-based sensor having a third contaminant-selective layer which is selective to attract a third contaminant within the fluid;

wherein each sensor is operative to determine an impedance of the fluid contacting each sensor, thereby providing an indication of fluid contamination.

39. The fluid contamination analyzer according to claim 38, wherein the contaminant selective layer comprises an intermediate layer disposed between the electrodes and the substrate.

40. The fluid contamination analyzer according to claim 39, wherein the contaminant selective layer is a low-K dielectric material.

41. The fluid contamination analyzer according to claim 40, wherein the low-K dielectric material is chosen from the group consisting of nanopourous silica, hydrogensilsesquioxanes, teflon-AF (Polytetrafluoethylene) and Silicon Oxyflouride.

42. The fluid contamination analyzer according to claim 38, wherein the contaminant selective layer comprises a top layer disposed over the electrodes.

43. The fluid contamination analyzer according to claim 42, wherein the contaminant selective layer is a low-K dielectric material.

44. The fluid contamination analyzer according to claim 43, wherein the low-K dielectric material is chosen from the group consisting of nanopourous silica, hydrogensilsesquioxanes, teflon-AF (Polytetrafluoethylene) and Silicon Oxyflouride.

45. The fluid contamination analyzer according to claim 38, wherein the contaminant selective layer is selected from

the group consisting of silicon nitride, silicon dioxide, cerium dioxide, glass, quartz, aluminum oxide, aluminum nitride, boron nitride, titanium nitride, gallium nitride, diamond, diamond like carbon, silicon carbide, parylene, epoxy, polyimide, polycarbonate, polyester, and polyphenylene sulfide.

46. The fluid contamination analyzer according to claim 38, wherein the electrodes are formed from the group consisting of tungsten, platinum, gold, chrome, aluminum, polysilicon, titanium, nickel and silver.

47. The fluid contamination analyzer according to claim 38, wherein the plurality of electrodes are interdigitated.

48. The fluid contamination analyzer according to claim 47, wherein a spacing between adjacent electrodes is between about 1 micron to about 250 microns.

49. The fluid contamination analyzer according to claim 47, wherein a spacing between adjacent electrodes is less than 1 micron.

50. The fluid contamination analyzer according to claim 38 further comprising a temperature sensor for measuring a temperature of the fluid in contact with the sensor.

51. The fluid contamination analyzer according to claim 50, wherein the temperature of the fluid is used to compensate the impedance measurement of the fluid.

52. The fluid contamination analyzer according to claim 50, wherein the temperature sensor is selected from the group consisting of a thermocouple, a thermistor and a resistance temperature detector (RTD).

53. The fluid contamination analyzer according to claim 50, wherein temperature data and/or sensor data is communicated to a remote monitoring device through a communications link.

54. The fluid contamination analyzer according to claim 53, wherein the communications link is a wireless communications link.

55. The fluid contamination analyzer according to claim 38, further comprising a non-volatile memory module for storing data.

56. The fluid contamination analyzer of according to claim 55, where the data stored to the non-volatile memory module is at least one of a customer name, a serial number of the sensor, a manufacture date of the sensor, a calibration factor of the sensor, a temperature of the fluid, a sensor type, a location of sensor, a maintenance date of the sensor, a selected reference oil, or an impedance of the fluid.

57. The fluid contamination analyzer according to claim 55, wherein the non-volatile memory module is an electrically erasable programmable read only memory module (EEPROM).

58. The fluid contamination analyzer according to claim 38, further comprising a temperature sensor for measuring a temperature of the fluid in contact with the sensor and a non-volatile memory module for storing data.

59. The fluid contamination analyzer according to claim 38, further comprising a plate electrode disposed over at least one MEMS based sensor, wherein when a fluid is disposed between the plate electrode and the at least one MEMS based sensor an impedance of the fluid is determined using the plate electrode and at least one electrode of the at least one MEMS based sensor or the plurality of electrodes of the MEMS based sensor, thereby providing an indication of fluid contamination.

60. The fluid contamination analyzer according to claim 59, further comprising:

a plurality of switches, including

a first switch operatively coupled to a first electrode of the plurality of electrodes;

a second switch operatively coupled to a second electrode of the plurality of electrodes;

a third switch operatively coupled to the plate electrode; and

a fourth switch operatively coupled to the first electrode and the second electrode.

61. The fluid contamination analyzer according to claim 60, wherein the plurality of switches selectively configure the fluid contamination analyzer to measure an impedance between the plate electrode and at least one electrode of the at least one MEMS based sensor.

62. The fluid contamination analyzer according to claim 60, wherein the plurality of switches selectively configure the fluid contamination analyzer to measure an impedance of the fluid between and adjacent to the electrodes of the MEMS based sensor.

63. The fluid contamination analyzer according to claim 60, wherein the plurality of switches are MEMS switches.

64. The fluid contamination analyzer according to claim 60, wherein the plurality of switches are formed on the substrate of the MEMS based sensor.

65. The fluid contamination analyzer according to claim 59, wherein the plate electrode and the plurality of electrodes are formed from the group consisting of tungsten, platinum, gold, chrome, aluminum, polysilicon, titanium, nickel, copper and silver.

66. The fluid contamination analyzer according to claim 59, wherein the plate electrode is about 1 micron to about 10,000 microns thick.

67. The fluid contamination analyzer according to claim 59, wherein the plate electrode is substantially parallel to a top surface of the at least one MEMS based sensor.

68. The fluid contamination analyzer of claim 38, wherein the substrate is at least one of a glass substrate or a quartz substrate.

69. The fluid contamination analyzer of claim 38, wherein the plurality of electrodes have a width between about 1 micron to about 50 microns.

70. The fluid contamination analyzer of claim 38, further comprising a selectively activatable electromagnet in proximity to the array of MEMS-based sensors, wherein the magnet may be activated and deactivated in response to control signals and provides a magnet gradient across the array of MEMS-based sensors, wherein the magnet gradient provides a contaminant distribution across the array of MEMS based sensors.

71. A fluid contamination analyzer, comprising:

a reference MEMS-based sensor disposed within a reference housing, said reference housing containing a substantially contaminant-free volume of the fluid being analyzed; and

a plurality of sample MEMS-based sensors disposed adjacent the reference housing within a fluid.

72. The fluid contamination analyzer according to claim 71, wherein the reference sensor and the sample sensor further comprise:

a substrate;

a plurality of electrodes formed over the substrate; and

a contaminant selective layer disposed adjacent at least one of (i) the electrodes or (ii) the substrate, said layer being selective to attract a predetermined contaminant within the fluid;

wherein when a fluid contacts the sensor an impedance of the fluid may be determined using the electrodes of the sensor, thereby providing an indication of fluid contamination.

73. The fluid contamination analyzer according to claim 72, wherein the contaminant selective layer comprises an intermediate layer disposed between the electrodes and the substrate.

74. The fluid contamination analyzer according to claim 73, wherein the contaminant selective layer is a low-K dielectric material.

75. The fluid contamination analyzer according to claim 74, wherein the low-K dielectric material is chosen from the group consisting of nanopourous silica, hydrogensilsesquioxanes, teflon-AF (Polytetrafluoethylene) and Silicon Oxyflouride.

76. The fluid contamination analyzer according to claim 72, wherein the contaminant selective layer comprises a top layer disposed over the electrodes.

77. The fluid contamination analyzer according to claim 76, wherein the contaminant selective layer is a low-K dielectric material.

78. The fluid contamination analyzer according to claim 77, wherein the low-K dielectric material is chosen from the group consisting of nanopourous silica, hydrogensilsesquioxanes, teflon-AF (Polytetrafluoethylene) and Silicon Oxyflouride.

79. The fluid contamination analyzer according to claim 72, wherein the contaminant selective layer is selected from the group consisting of silicon nitride, silicon dioxide, cerium dioxide, glass, quartz, aluminum oxide, aluminum nitride, boron nitride, titanium nitride, gallium nitride, diamond, diamond like carbon, silicon carbide, parylene, epoxy, polyimide, polycarbonate, polyester, and polyphenylene sulfide.

80. The fluid contamination analyzer according to claim 72, wherein the electrodes are formed from the group consisting of tungsten, platinum, gold, chrome, aluminum, polysilicon, titanium, nickel, copper and silver.

81. The fluid contamination analyzer according to claim 72, wherein the plurality of electrodes are interdigitated.

82. The fluid contamination analyzer according to claim 81, wherein a spacing between adjacent electrodes is between about 1 micron to about 250 microns.

83. The fluid contamination analyzer according to claim 81, wherein a spacing between adjacent electrodes is less than 1 micron.

84. The fluid contamination analyzer according to claim 71, further comprising at least one temperature sensor for measuring a temperature of the fluid in contact with the reference sensor and/or sample sensors.

85. The fluid contamination analyzer according to claim 84, wherein the temperature of the fluid is used to compensate the impedance measurement of the fluid.

86. The fluid contamination analyzer according to claim 84, wherein the temperature sensor is selected from the group consisting of a thermocouple, a thermistor and a resistance temperature detector (RTD).

87. The fluid contamination analyzer according to claim 84, wherein temperature data and/or sensor data is communicated to a remote monitoring device through a communications link.

88. The fluid contamination analyzer according to claim 87, wherein the communications link is a wireless communications link.

89. The fluid contamination analyzer according to claim 71, further comprising a non-volatile memory module for storing data.

90. The fluid contamination analyzer of according to claim 89, wherein the data stored in the non-volatile memory module is at least one of a customer name, a serial number of the sensor, a manufacture date of the sensor, a calibration factor of the sensor, a temperature of the fluid, a sensor type, a location of sensor, a maintenance date of the sensor, a selected reference oil, or an impedance of the fluid.

91. The fluid contamination analyzer according to claim 89, wherein the non-volatile memory module is an electrically erasable programmable read only memory module (EEPROM).

92. The fluid contamination analyzer according to claim 71, further comprising a temperature sensor for measuring a temperature of the fluid in contact with the sensor and a non-volatile memory module for storing data.

93. The fluid contamination analyzer according to claim 71, further comprising a plate electrode disposed over the reference sensor and/or at least one sample sensor of the plurality of sample sensors, wherein when a fluid is disposed between the plate electrode and the MEMS based sensors an impedance of the fluid is determined using the plate electrode and at least one electrode of the MEMS based sensors or a plurality of electrodes of the MEMS based sensor, thereby providing an indication of fluid contamination.

94. The fluid contamination analyzer according to claim 93, further comprising:

a plurality of switches, including

a first switch operatively coupled to a first electrode of the plurality of electrodes;

a second switch operatively coupled to a second electrode of the plurality of electrodes;

a third switch operatively coupled to the plate electrode; and

a fourth switch operatively coupled to the first electrode and the second electrode.

95. The fluid contamination analyzer according to claim 94, wherein the plurality of switches selectively configure the fluid contamination analyzer to measure an impedance between the plate electrode and at least one electrode of the at least one MEMS based sensor.

96. The fluid contamination analyzer according to claim 94, wherein the plurality of switches selectively configure the fluid contamination analyzer to measure an impedance of the fluid between and adjacent to the electrodes of the MEMS based sensor.

97. The fluid contamination analyzer according to claim 94, wherein the plurality of switches are MEMS switches.

98. The fluid contamination analyzer according to claim 94, wherein the plurality of switches are formed on the substrate of the MEMS based sensor.

99. The fluid contamination analyzer according to claim 94, wherein the plate electrode and the plurality of electrodes are formed from the group consisting of tungsten, platinum, gold, chrome, aluminum, polysilicon, titanium, nickel, copper and silver.

100. The fluid contamination analyzer according to claim 93, wherein the plate electrode is about 1 micron to about 10,000 microns thick.

101. The fluid contamination analyzer according to claim 93, wherein the plate electrode is substantially parallel to a top surface of the at least one MEMS based sensor.

102. The fluid contamination analyzer of claim 72, wherein the substrate is at least one of a glass substrate or a quartz substrate.

103. The fluid contamination analyzer of claim 72, wherein the plurality of electrodes have a width between about 1 micron to about 50 microns.

104. The fluid contamination analyzer of claim 71, further comprising a selectively activatable electromagnet in proximity to the sample sensors, wherein the magnet may be activated and deactivated in response to control signals and provides a magnet gradient across the sample sensors, wherein the magnet gradient provides a contaminant distribution across the sample sensors.

105. A fluid contamination analyzer, comprising:

at least one MEMS-based sensor, said at least one sensor including:

a substrate;

a plurality of conductors formed over the substrate; and

a local heater disposed adjacent the at least one MEMS-based sensor, said local heater providing a temperature gradient through which the fluid is run;

wherein the conductors form electrodes of the sensor and when a fluid contacts the sensor an impedance of the fluid may be determined as a function of temperature, thereby providing an indication of fluid contamination.

106. The fluid contamination analyzer according to claim 105, wherein the sensors further comprise a contaminant selective layer disposed adjacent at least one of (i) the electrodes or (ii) the substrate, said layer being selective to attract a predetermined contaminant within the fluid.

107. The fluid contamination analyzer according to claim 106, wherein the contaminant selective layer comprises an intermediate layer disposed between the electrodes and the substrate.

108. The fluid contamination analyzer according to claim 107, wherein the contaminant selective layer is a low-K dielectric material.

109. The fluid contamination analyzer according to claim 108, wherein the low-K dielectric material is chosen from the group consisting of nanopourous silica, hydrogensilsesquioxanes, teflon-AF (Polytetrafluoethylene) and Silicon Oxyflouride.

110. The fluid contamination analyzer according to claim 106, wherein the contaminant selective layer comprises a top layer disposed over the electrodes.

111. The fluid contamination analyzer according to claim 110, wherein the contaminant selective layer is a low-K dielectric material.

112. The fluid contamination analyzer according to claim 111, wherein the low-K dielectric material is chosen from the group consisting of nanopourous silica, hydrogensilsesquioxanes, teflon-AF (Polytetrafluoethylene) and Silicon Oxyflouride.

113. The fluid contamination analyzer according to claim 106, wherein the contaminant selective layer is selected from the group consisting of silicon nitride, silicon dioxide, cerium dioxide, glass, quartz, aluminum oxide, aluminum nitride, boron nitride, titanium nitride, gallium nitride, diamond, diamond like carbon, silicon carbide, parylene, epoxy, polyimide, polycarbonate, polyester, and polyphenylene sulfide.

114. The fluid contamination analyzer according to claim 106, wherein the electrodes are formed from the group consisting of tungsten, platinum, gold, chrome, aluminum, polysilicon, titanium, nickel, copper and silver.

115. The fluid contamination analyzer according to claim 106, wherein the plurality of electrodes are interdigitated.

116. The fluid contamination analyzer according to claim 115, wherein a spacing between adjacent electrodes is between about 1 micron to about 250 microns.

117. The fluid contamination analyzer according to claim 115, wherein a spacing between adjacent electrodes is less than 1 micron.

118. The fluid contamination analyzer according to claim 106, further comprising a temperature sensor for measuring a temperature of the fluid in contact with the sensor.

119. The fluid contamination analyzer according to claim 118, wherein the temperature of the fluid is used to compensate the impedance measurement of the fluid.

120. The fluid contamination analyzer according to claim 118, wherein the temperature sensor is selected from the group consisting of a thermocouple, a thermistor and a resistance temperature detector (RTD).

121. The fluid contamination analyzer according to claim 118, wherein temperature data and/or sensor data is communicated to a remote monitoring device through a communications link.

122. The fluid contamination analyzer according to claim 121, wherein the communications link is a wireless communications link.

123. The fluid contamination analyzer according to claim 106, further comprising a non-volatile memory module for storing data.

124. The fluid contamination analyzer of according to claim 123, wherein the data stored in the non-volatile memory module is at least one of a customer name, a serial number of the sensor, a manufacture date of the sensor, a calibration factor of the sensor, a temperature of the fluid, a sensor type, a location of sensor, a maintenance of the sensor, a selected reference oil, or an impedance of the fluid.

125. The fluid contamination analyzer according to claim 123, wherein the non-volatile memory module is an electrically erasable programmable read only memory module (EEPROM).

126. The fluid contamination analyzer according to claim 106, further comprising a temperature sensor for measuring a temperature of the fluid in contact with the sensor and a non-volatile memory module for storing data.

127. The fluid contamination analyzer according to claim 106, further comprising a plate electrode disposed over the at least one MEMS based sensor, wherein when a fluid is disposed between the plate electrode and the at least one MEMS based sensor an impedance of the fluid is determined using the plate electrode and at least one electrode of the at

least one MEMS based sensor or the plurality of electrodes of the MEMS based sensor, thereby providing an indication of fluid contamination.

128. The fluid contamination analyzer according to claim 127, further comprising an electrostatic field control circuit electrically coupled to the plate electrode, wherein the electrostatic field control circuit develops an electrostatic field between the plate electrode and the plurality of electrodes, thereby dislodging with an electrostatic force any particulates that may have become stuck within the sensor due to static charge on the particulates.

129. The fluid contamination analyzer according to claim 127, further comprising:

a plurality of switches, including

a first switch operatively coupled to a first electrode of the plurality of electrodes;

a second switch operatively coupled to a second electrode of the plurality of electrodes;

a third switch operatively coupled to the plate electrode; and

a fourth switch operatively coupled to the first electrode and the second electrode.

130. The fluid contamination analyzer according to claim 129, wherein the plurality of switches selectively configure the fluid contamination analyzer to measure an impedance between the plate electrode and at least one electrode of the at least one MEMS based sensor.

131. The fluid contamination analyzer according to claim 129, wherein the plurality of switches selectively configure the fluid contamination analyzer to measure an impedance of the fluid between and adjacent to the electrodes of the MEMS based sensor.

132. The fluid contamination analyzer according to claim 129, wherein the plurality of switches are MEMS switches.

133. The fluid contamination analyzer according to claim 129, wherein the plurality of switches are formed on the substrate of the MEMS based sensor.

134. The fluid contamination analyzer according to claim 128, wherein the plate electrode and the plurality of electrodes are formed from the group consisting of tungsten, platinum, gold, chrome, aluminum, polysilicon, titanium, nickel, copper and silver.

135. The fluid contamination analyzer according to claim 128, wherein the plate electrode is about 1 microns to about 10,000 microns thick.

136. The fluid contamination analyzer according to claim 128, wherein the plate electrode is substantially parallel to a top surface of the at least one MEMS based sensor.

137. The fluid contamination analyzer according to claim 106, wherein the substrate is the contaminant selective layer.

138. The fluid contamination analyzer of claim 105, wherein the substrate is at least one of a glass substrate or a quartz substrate.

139. The fluid contamination analyzer of claim 105, wherein the plurality of electrodes have a width between about 1 micron to about 50 microns.

140. A method of analyzing the quality of a fluid, comprising the steps of:

immersing a sensor into the fluid, wherein the fluid acts as a dielectric for the sensor;

obtaining a complex impedance of the fluid;

measuring a temperature of the fluid in contact with the sensor;

applying a correction factor to the complex impedance based on the measured temperature of the fluid;

estimating the quality of the fluid based on a comparison of known fluids producing substantially the same complex impedance values.

141. The method of claim 140, further comprising the step of obtaining a dissipation factor (DF) of the fluid; and

further estimating the quality of the fluid based on a comparison of known fluids producing substantially the same DF.

142. The method of claim 140, wherein the step of obtaining the complex impedance of the fluid includes the steps of:

measuring an impedance of the fluid at a first oscillation frequency; and

measuring the impedance of the fluid at a second oscillation frequency.

143. The method of claim 142, wherein the step of measuring an impedance at a first and second oscillation frequency includes the step of using oscillation frequencies between the range of about 0.1 Hz to about 10 MHz.

144. The method of claim 142, wherein the step of measuring an impedance at a first and second oscillation frequency includes the step of using a second oscillation frequency that is about 10 times the first oscillation frequency.

145. The method of claim 142, wherein the step of measuring an impedance at a first and second oscillation frequency includes the step of using a first oscillation frequency between about 100 Hz to about 20 KHz.

146. The method of claim 140, wherein the step of measuring the impedance includes measuring the impedance of the fluid adjacent and above a plurality of electrodes of a MEMS based sensor.

147. The method of claim 146, wherein the step of measuring the impedance of the fluid above the plurality of electrodes includes the step of measuring the impedance of the fluid within a depth that is substantially equal to a separation between adjacent electrodes.

148. The method of claim 140, wherein the step of measuring the impedance includes measuring the impedance of the fluid between a plate electrode and at least one electrode of a MEMS based sensor.

149. The method of claim 140, further comprising the step of applying a contaminant selective layer to the sensor, wherein the contaminant selective layer increases a selectivity of the sensor to at least one type of contaminant.

150. A method of analyzing the quality of a fluid, comprising the steps of:

immersing a sensor into the fluid, wherein the fluid acts as a dielectric for the sensor;

measuring an impedance of the fluid over a temperature gradient; and

estimating the quality of the fluid based on a change in slope of the measured impedance over the temperature gradient.

151. The method of claim 150, wherein the step of measuring the impedance over a temperature gradient includes applying a heat source to the fluid to alter the temperature of the fluid.

152. The method of claim 150 wherein the step of measuring an impedance includes the step of measuring at least one of capacitance, resistance, reactance, dissipation factor, phase angle, admittance, susceptance or conductance.

153. A method of analyzing the quality of a fluid in which a sensor has been immersed, wherein the fluid acts as a dielectric on the sensor, comprising the steps of:

using a contaminant selective layer on the sensor to selectively attract contaminants within the fluid near a surface of the sensor;

measuring an impedance of the fluid near the surface of the sensor; and

correlating the quality of the fluid to the measured impedance of the fluid.

154. The method of claim 153, further comprising the step of using an array of MEMS-based sensors immersed within the fluid, wherein at least one sensor of the array of sensors includes a contaminant selective layer different from a contaminant selective layer of other sensors of the array of sensors.

155. The method of claim 153, wherein the step of measuring an impedance includes the step of measuring at least one of capacitance, resistance, reactance, dissipation factor, phase angle, admittance, susceptance or conductance.

156. A method of analyzing the quality of a sample fluid, wherein the fluid acts as a dielectric on the sensor, comprising the steps of:

immersing a sample sensor in the sample fluid;

immersing a reference sensor in a substantially contaminant-free reference fluid, wherein the reference fluid and the sample fluid are the same type of fluid;

measuring an impedance of the fluid near the surface of the sample sensor and the reference sensor; and

correlating the quality of the sample fluid to the measured impedance of the sample fluid and the reference fluid.

157. The method of claim 156, wherein the step of measuring an impedance includes the step of measuring at least one of capacitance, resistance, reactance, dissipation factor, phase angle, admittance, susceptance or conductance.

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US006459995B1

(12) **United States Patent**
Collister

(10) **Patent No.: US 6,459,995 B1**
(45) **Date of Patent: Oct. 1, 2002**

(54) **ELECTRICAL MEASUREMENT OF OIL QUALITY**

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(73) Assignee: **Lubrigard Limited**, Exeter (DE)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days.

(21) Appl. No.: **09/423,478**

(22) PCT Filed: **May 7, 1998**

(86) PCT No.: **PCT/GB98/01321**

§ 371 (c)(1),
(2), (4) Date: **May 4, 2000**

(87) PCT Pub. No.: **WO98/50790**

PCT Pub. Date: **Nov. 12, 1998**

(30) **Foreign Application Priority Data**

May 7, 1997 (GB) 9709290

(51) **Int. Cl.**[7] **G01N 31/00**

(52) **U.S. Cl.** ..... **702/23**; 702/24; 702/25; 702/104; 73/304 C; 73/64.41; 73/54.01

(58) **Field of Search** ..... 702/23, 24, 25, 702/104; 73/304 C, 54.01, 54.02, 54.05, 61.44, 61.61, 61.43; 324/665, 670, 678, 689, 655, 668, 663, 682, 683, 675, 76.79, 662, 664, 671; 340/620, 439, 450.3, 618, 631

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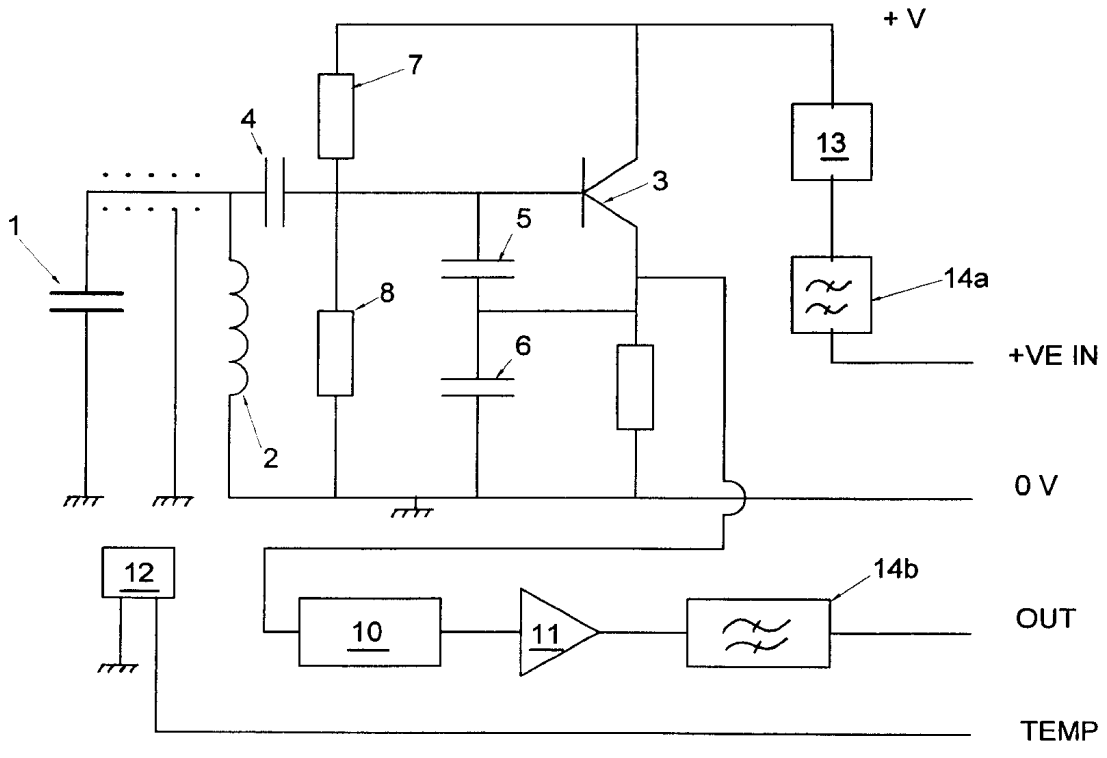
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Assistant Examiner—Hien Vo
(74) *Attorney, Agent, or Firm*—Marshall, Gerstein & Borun.

(57) **ABSTRACT**

Method and apparatus for measuring oil quality based on the permittivity of the oil comprising a capacitive or radiative sensor for exposure to the oil, and an oscillator circuit including the sensor, wherein the oscillator circuit comprises a LC or crystal oscillator which provides an output signal, the amplitude of which is dependent upon the lossiness of the Tan δ of the oil, and a measuring device that responds to the amplitude of the output signal as a measure of oil quality.

18 Claims, 12 Drawing Sheets



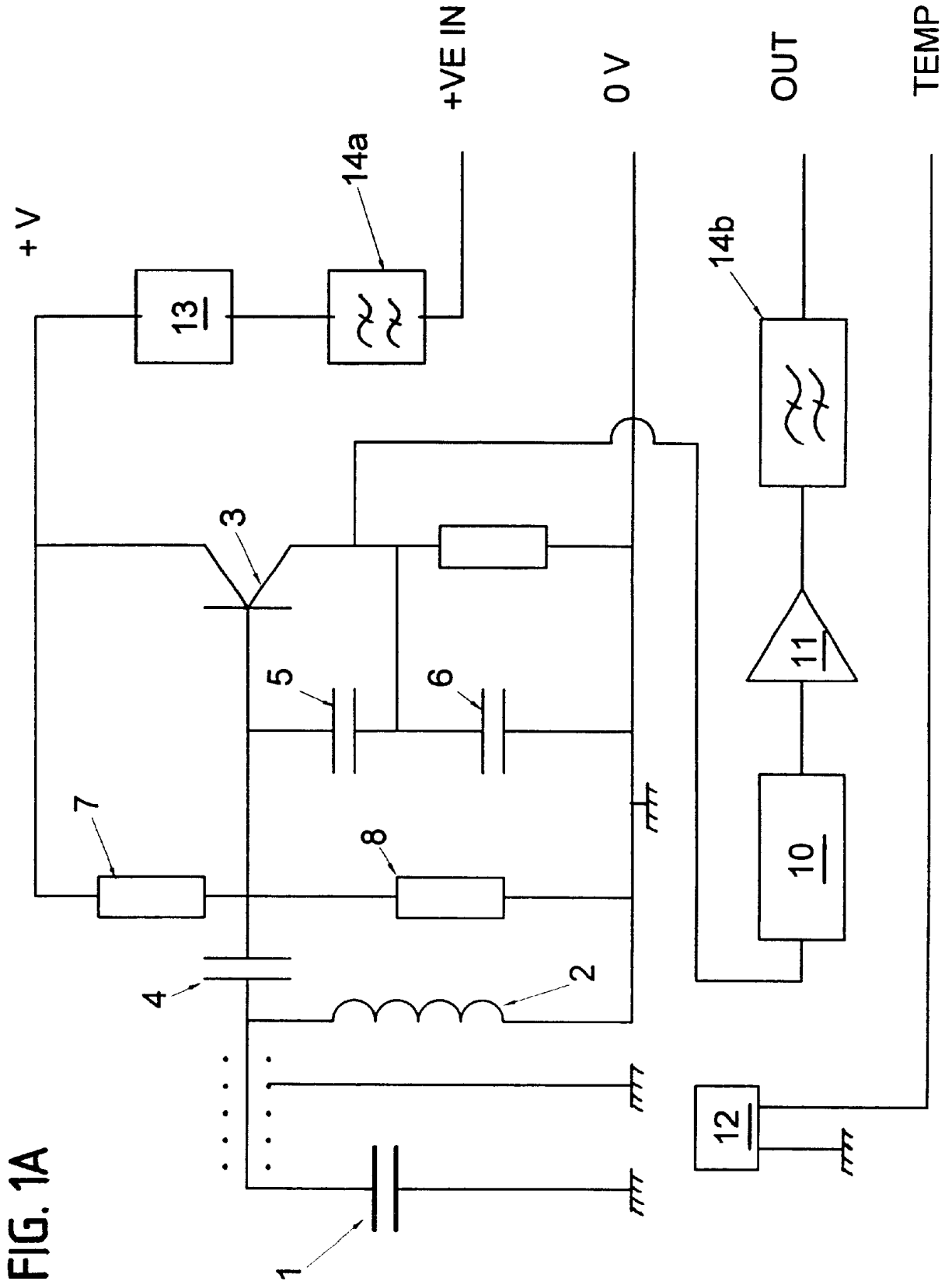


FIG. 1A

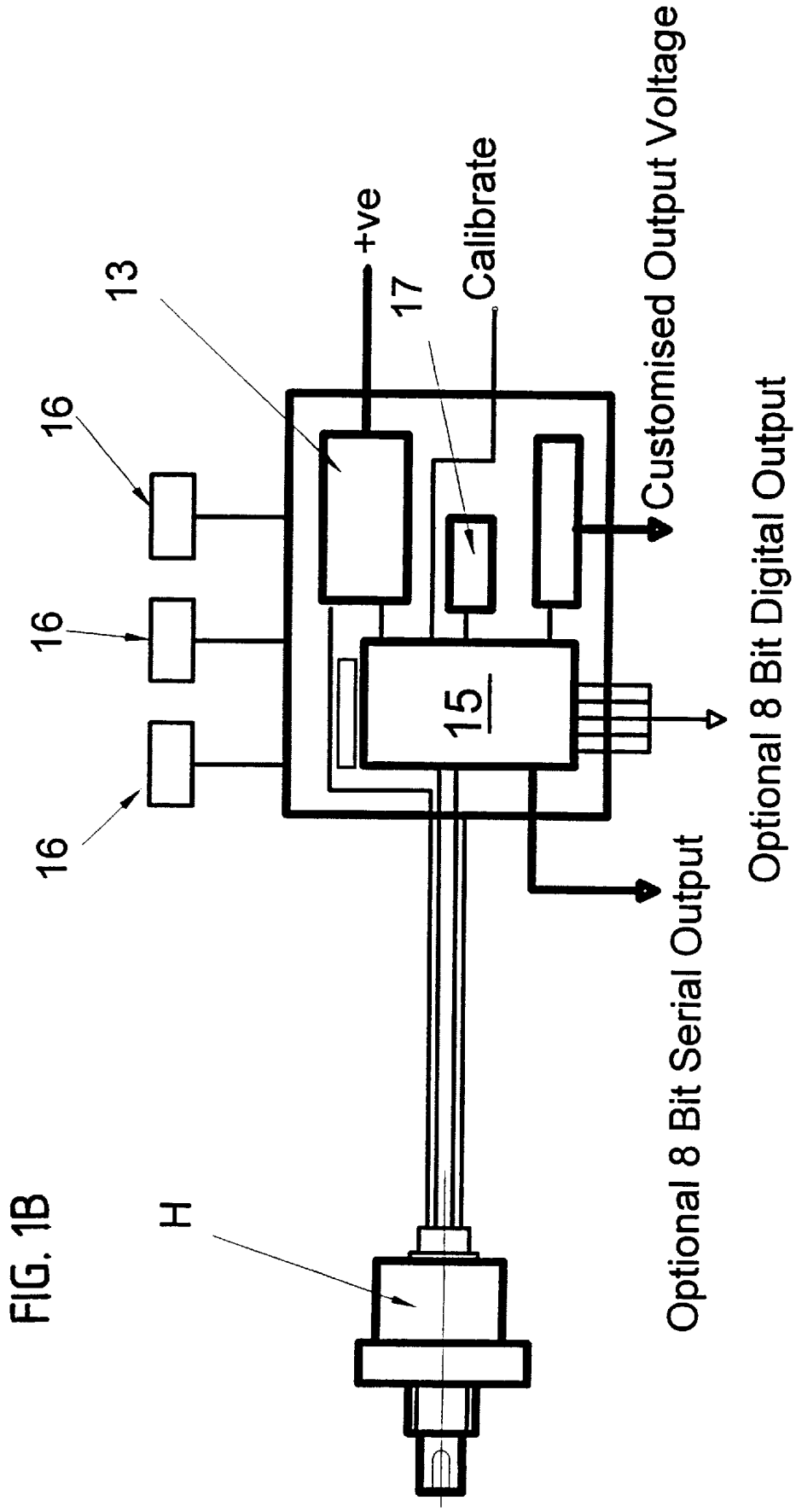

13
+ve
17
Calibrate
Customised Output Voltage
16
16
16
15
Optional 8 Bit Digital Output
Optional 8 Bit Serial Output
H

FIG. 1B

FIG. 2

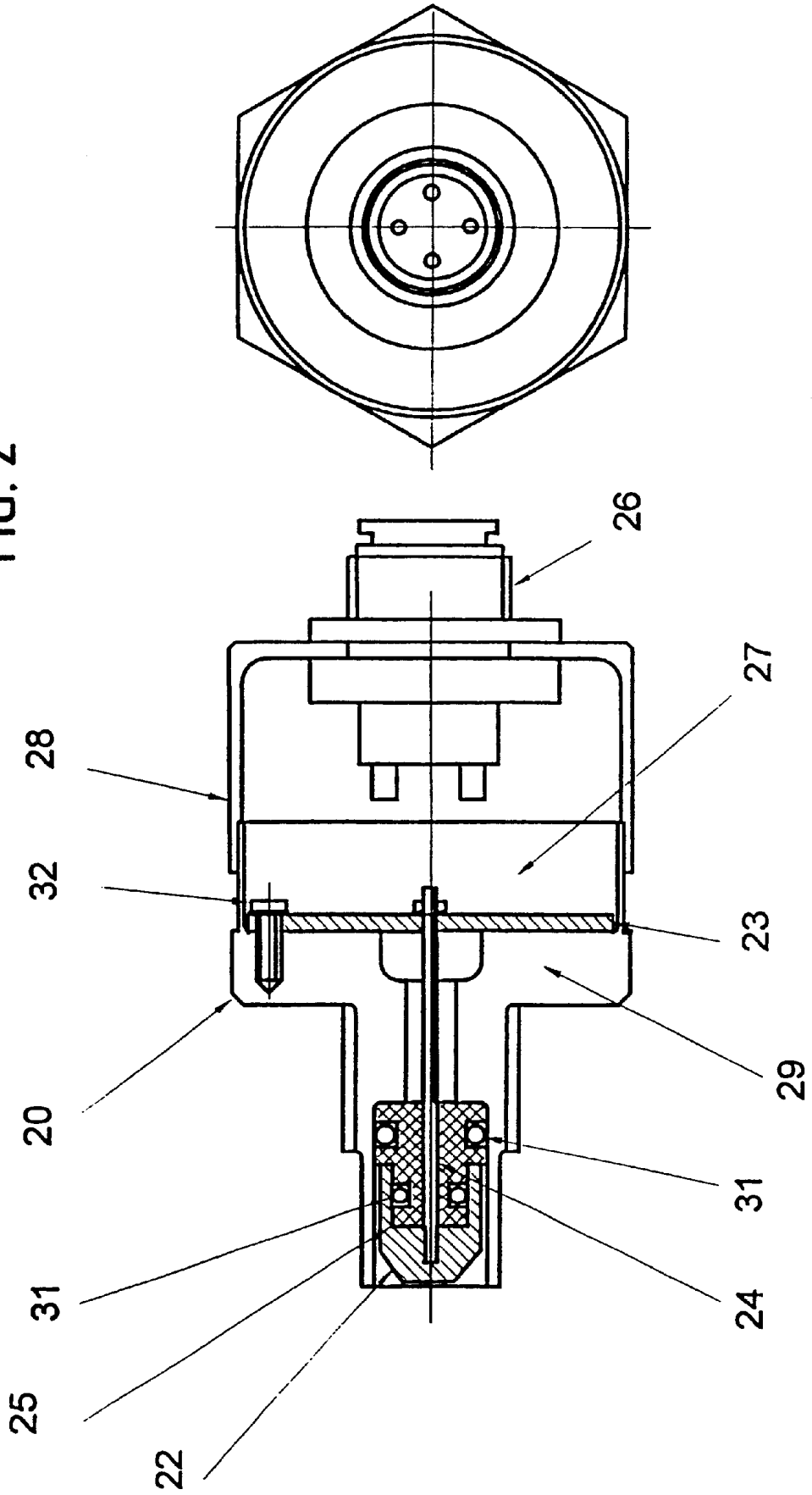


FIG. 3

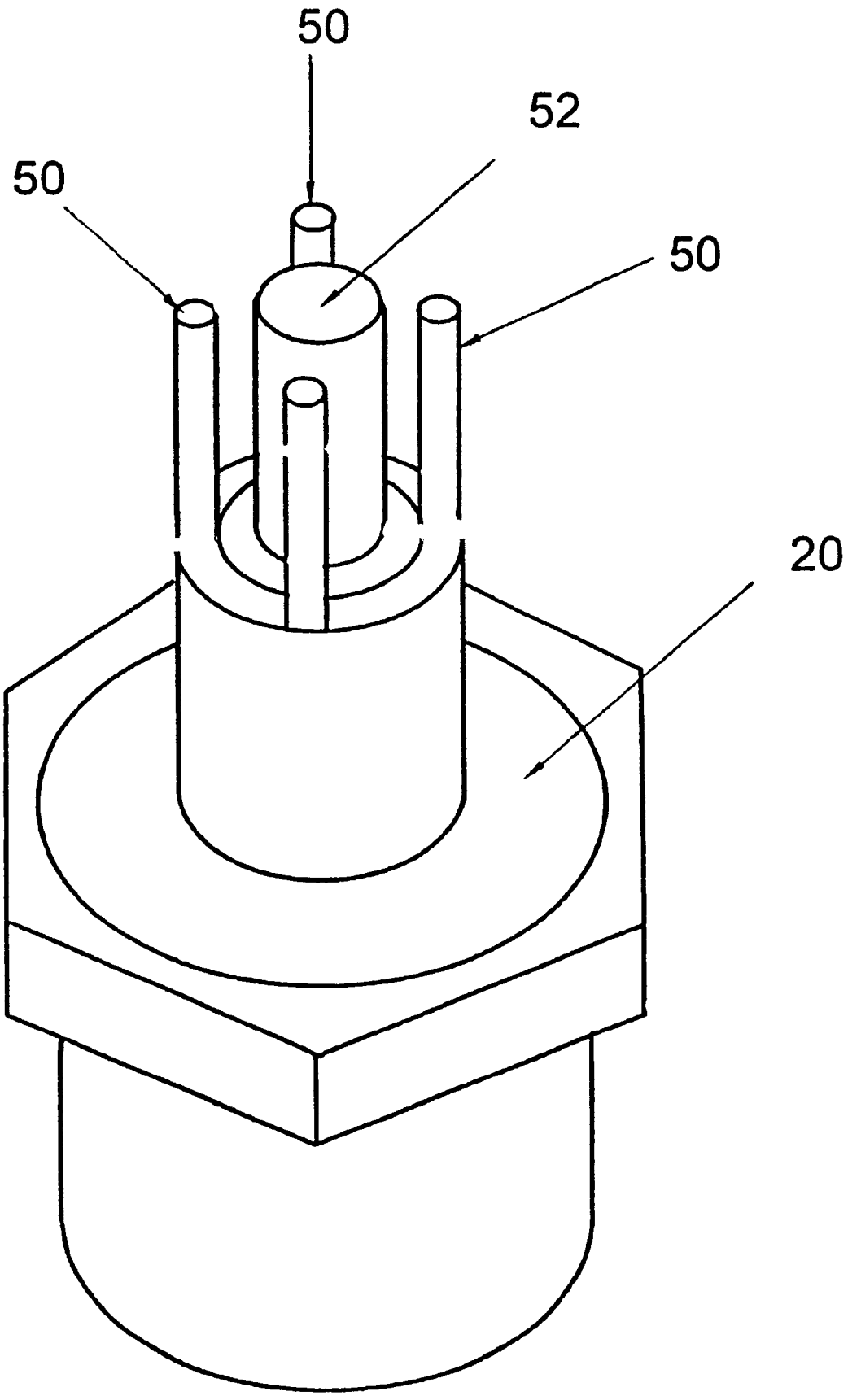


FIG. 4A

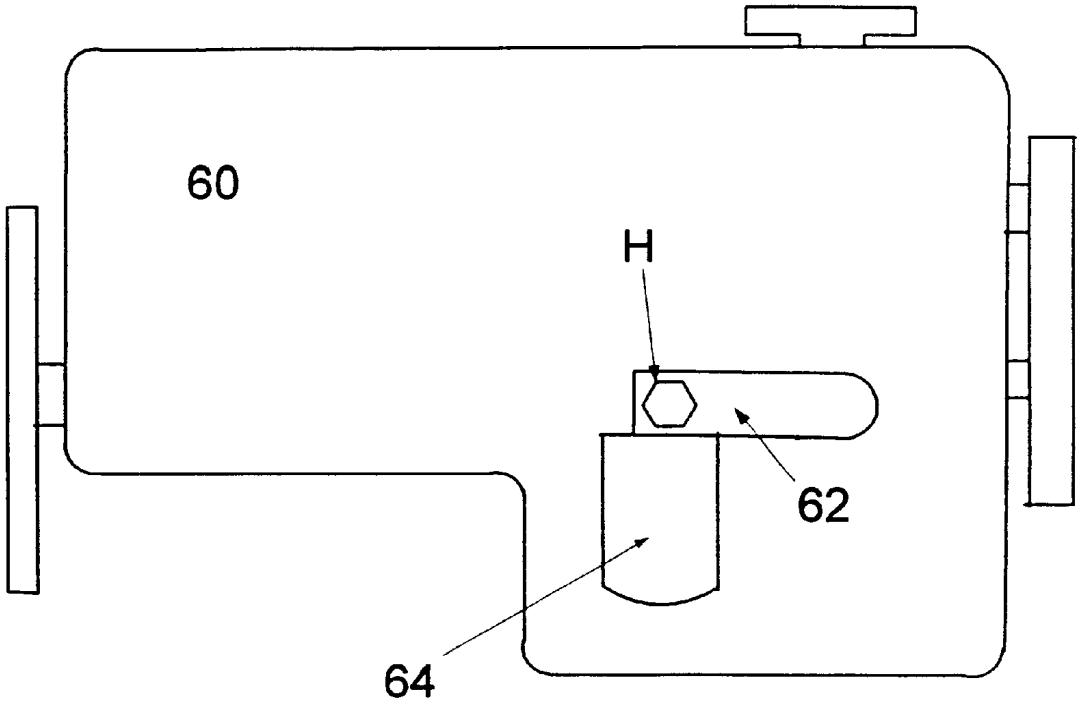


FIG. 4B

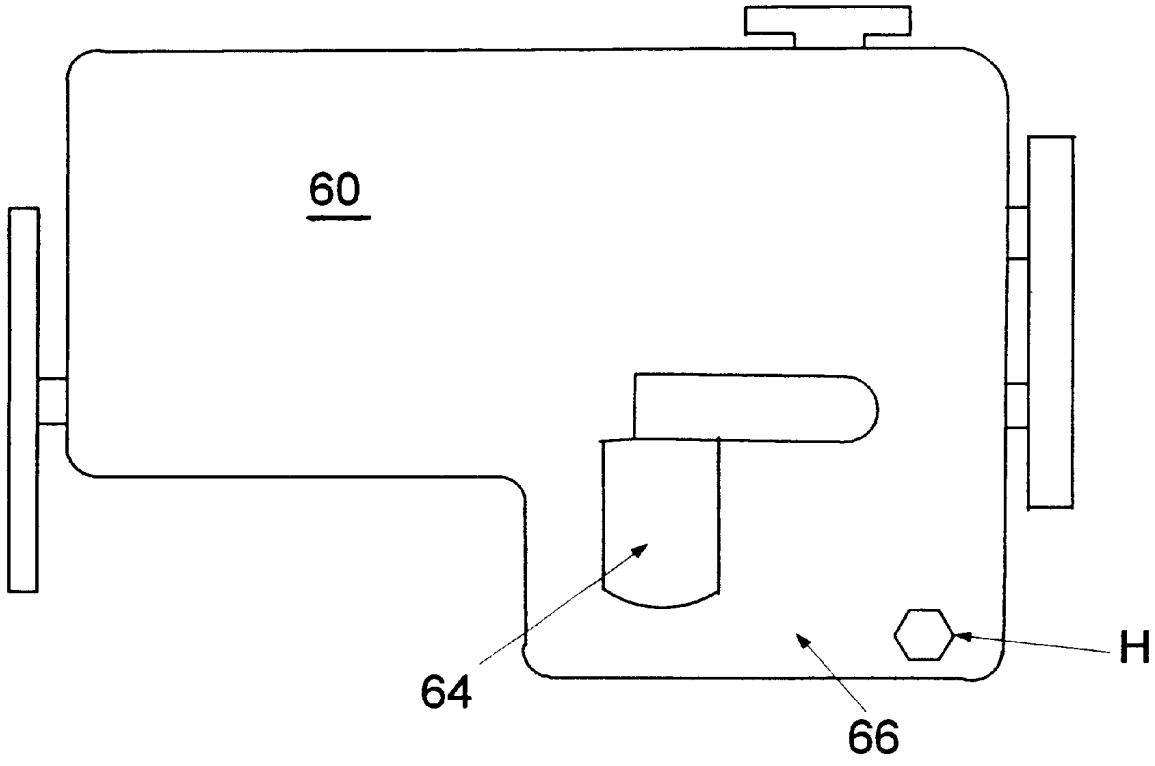
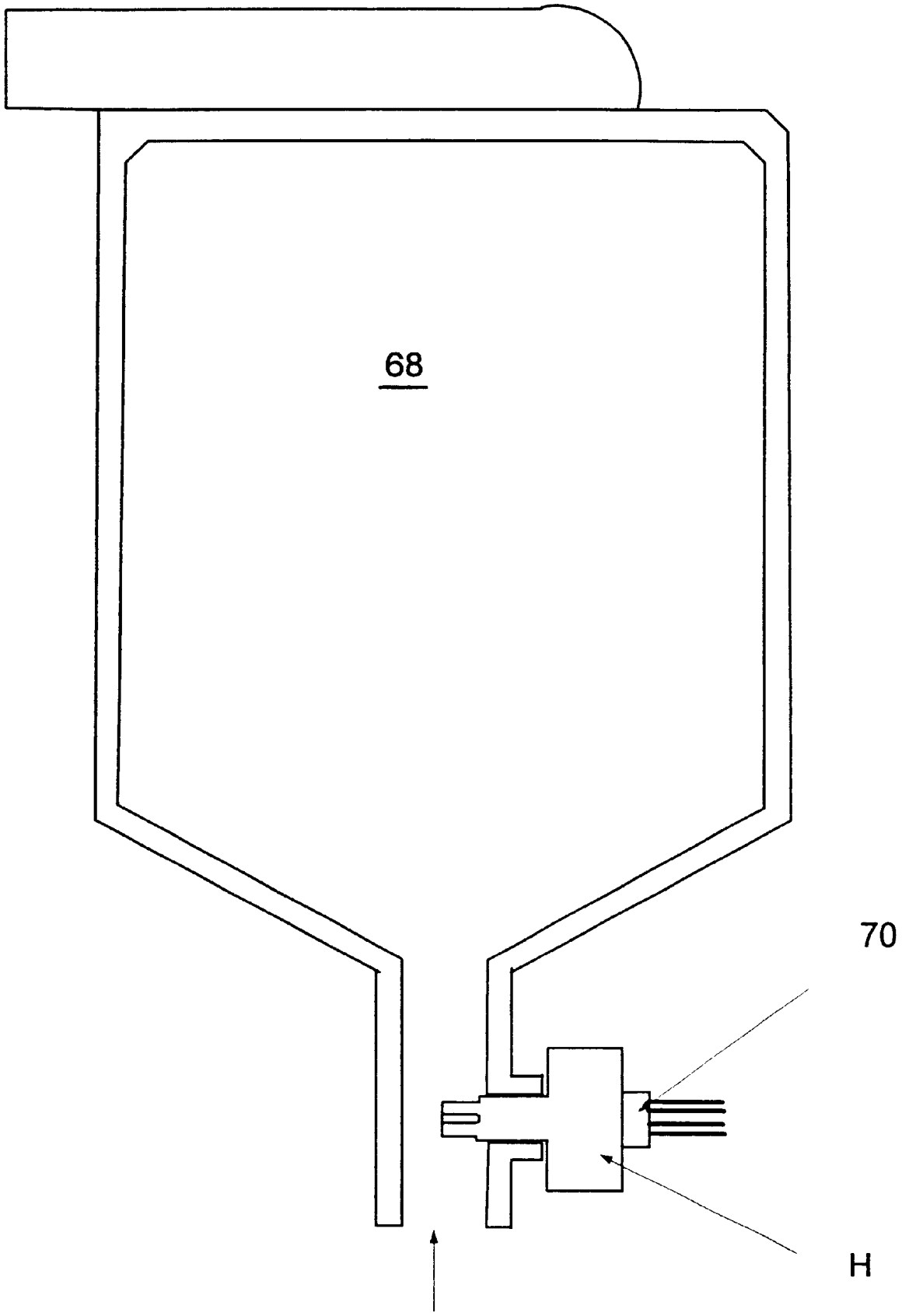


FIG. 5



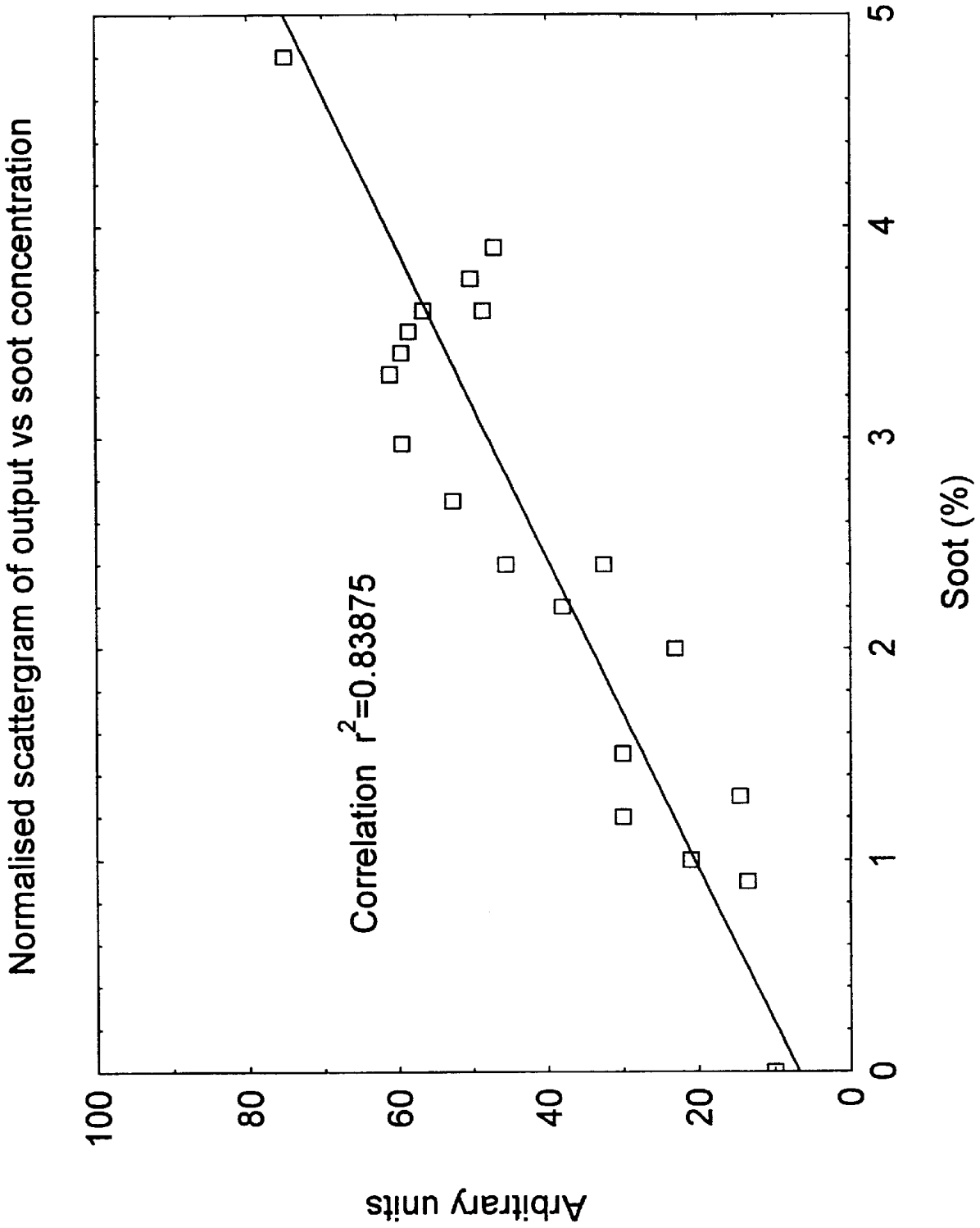

Normalised scattergram of output vs soot concentration
Correlation r^2=0.83875
Arbitrary units
Soot (%)
0
20
40
60
80
100
0
1
2
3
4
5

FIG. 6

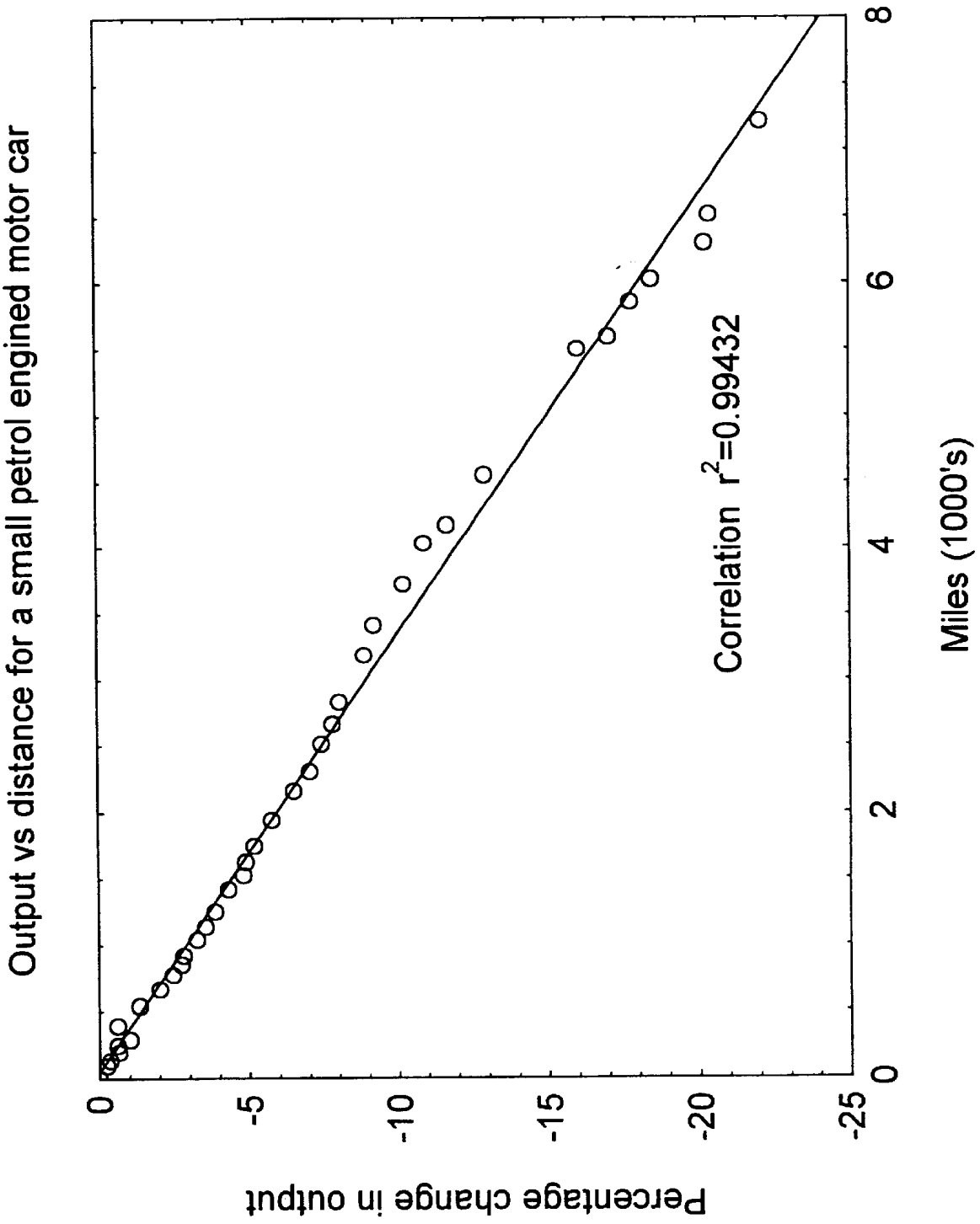

Output vs distance for a small petrol engined motor car
Correlation r^2=0.99432
Percentage change in output
0
-5
-10
-15
-20
-25
0
2
4
6
8
Miles (1000's)

FIG. 7

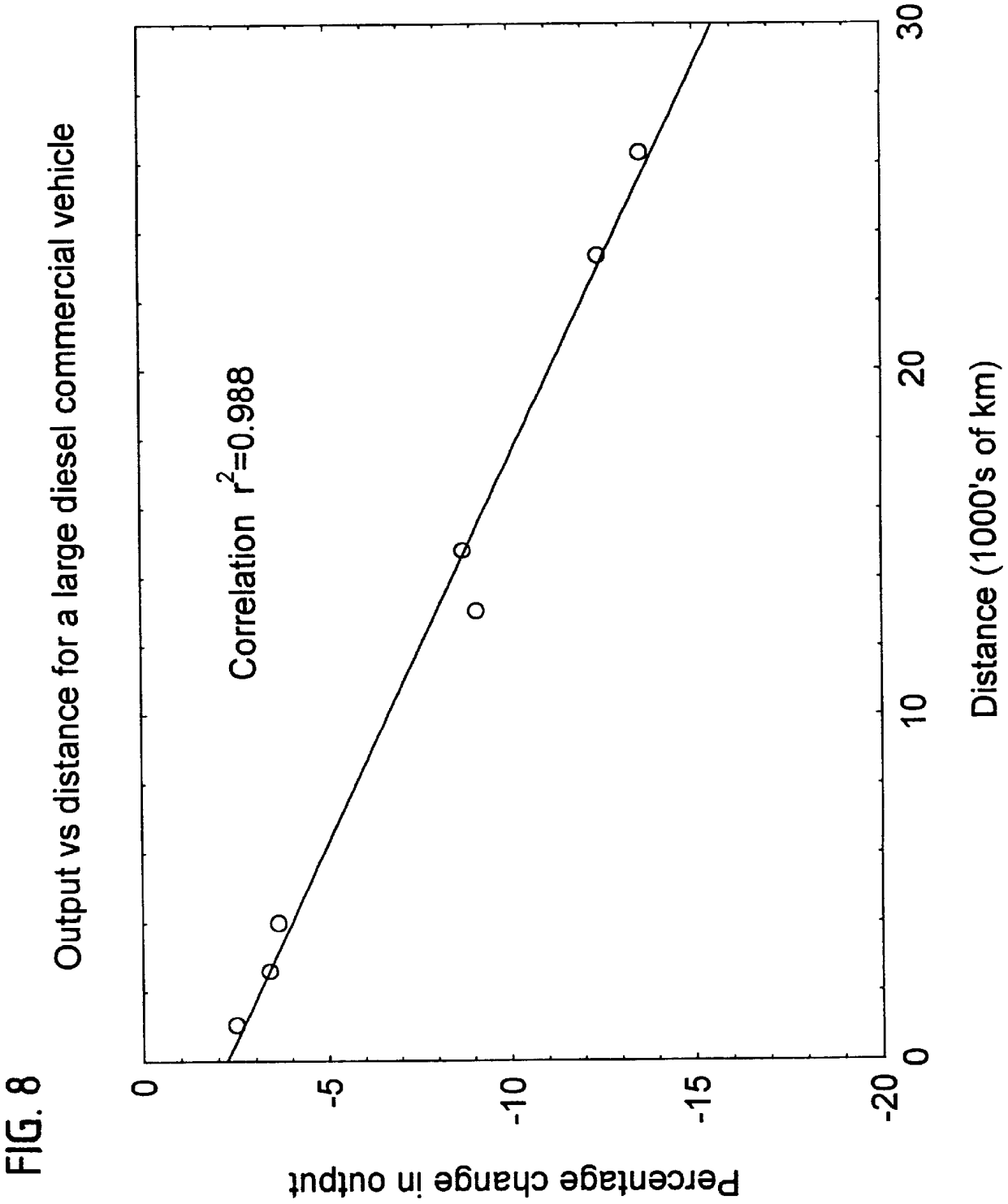

Output vs distance for a large diesel commercial vehicle
Correlation r^2=0.988
Percentage change in output
0
-5
-10
-15
-20
0
10
20
30
Distance (1000's of km)

FIG. 8

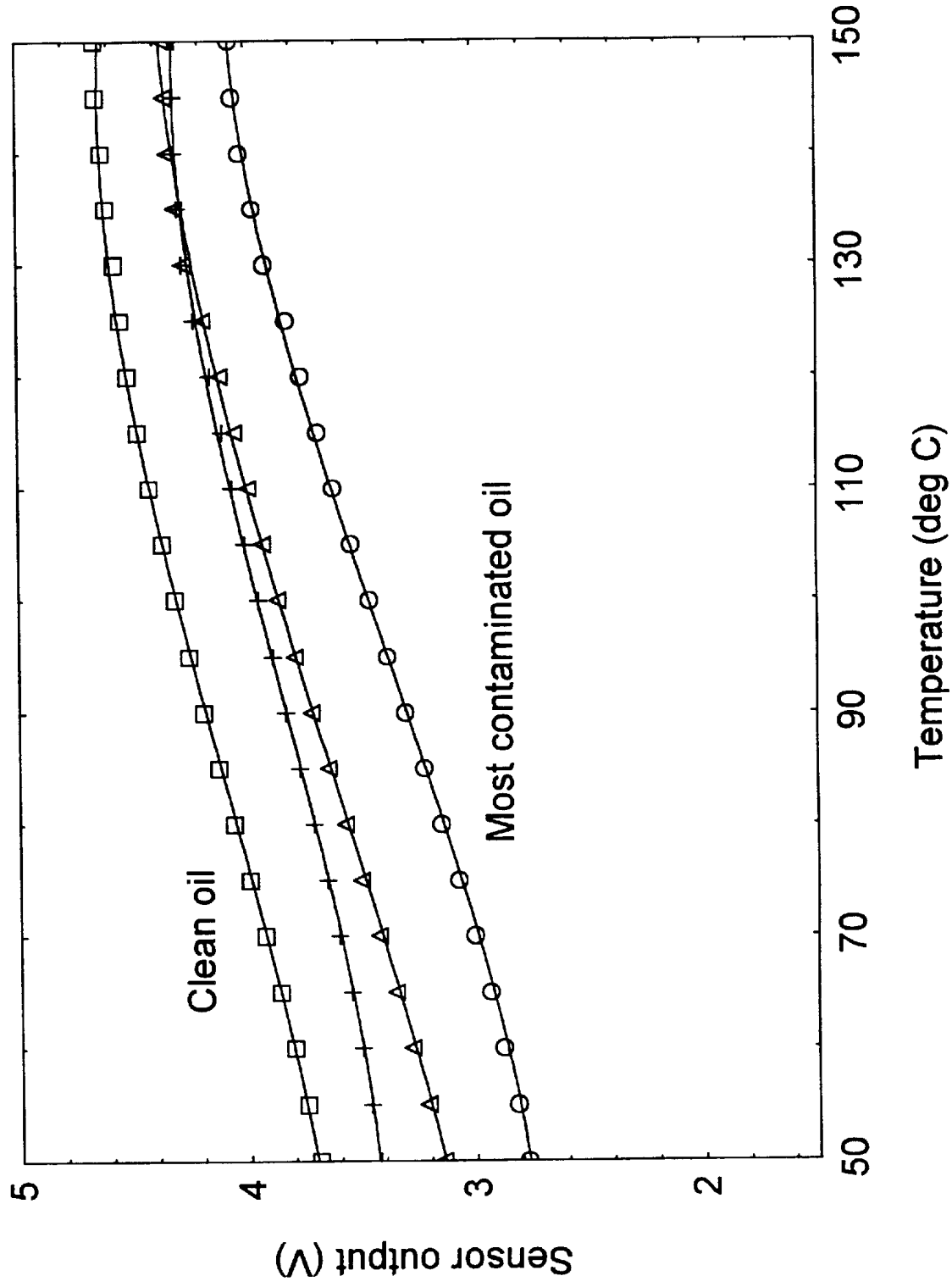

Sensor output (V)
5
4
3
2
Temperature (deg C)
50
70
90
110
130
150
Clean oil
Most contaminated oil

FIG. 9

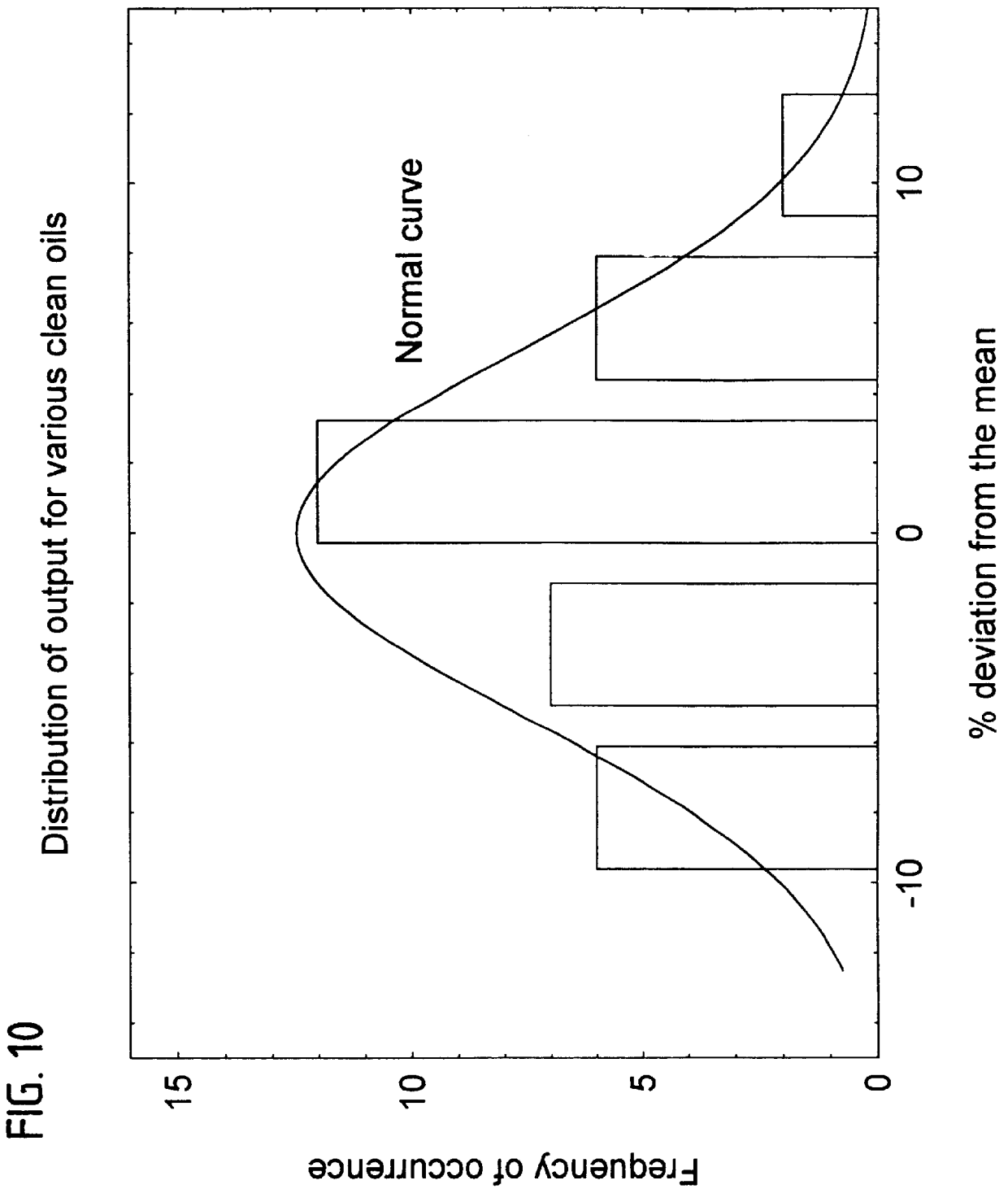
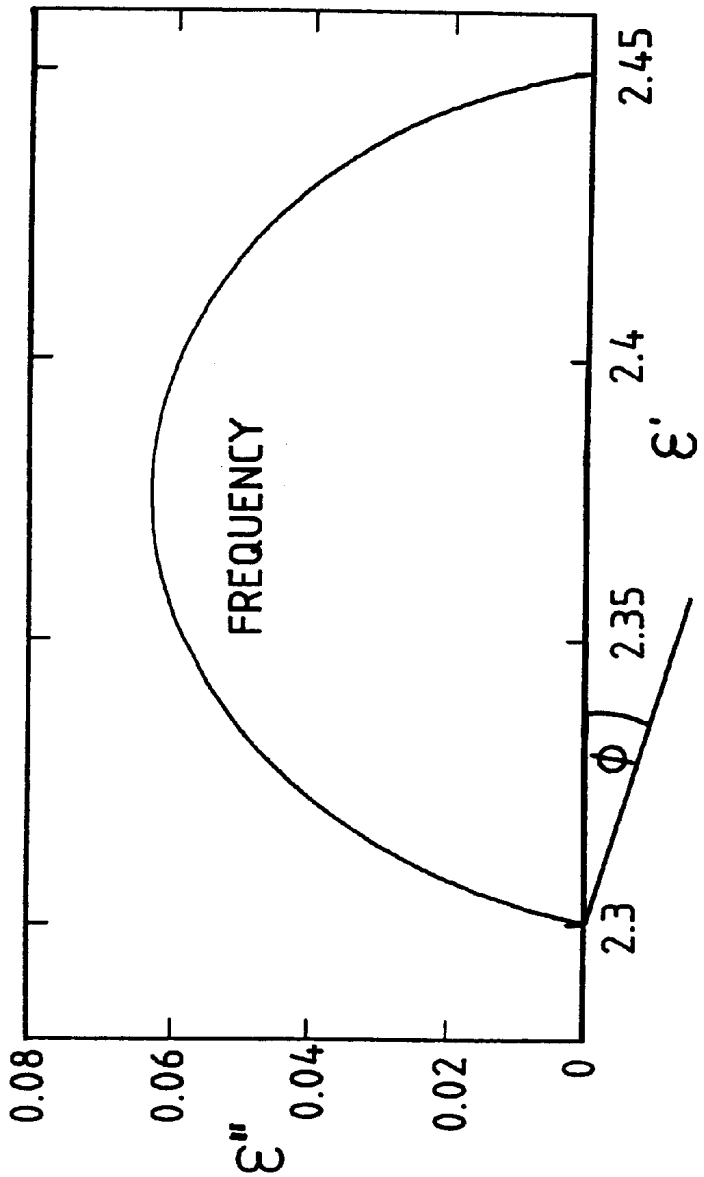

Distribution of output for various clean oils
Normal curve
Frequency of occurrence
0
5
10
15
-10
0
10
% deviation from the mean

FIG. 10

FIG. 11



A typical complex plane plot for a liquid dielectric

Angle of depression (high frequency limit) $\phi=(1-\alpha).\frac{\pi}{2}$ $\phi=9$ deg

$\alpha=0.9$ $\beta=0.95$

ELECTRICAL MEASUREMENT OF OIL QUALITY

This invention relates to a method and apparatus for electrical measurement of oil quality, applicable to diesel fuel, or hydraulic, gearbox, transformer or engine oil, and preferably lubricating oil; and especially a method and apparatus for use in an engine, machine or filter.

BACKGROUND

It has been known for many years that the complex permittivity (or dielectric coefficient) of an engine lubricating oil changes with use, that is to say, both the real pan and the imaginary part change in response to changes in dissolved and suspended components of the oil. Such components are, for example, soot particles, water, acid combustion products, glycols, and ferrous and non ferrous metallic particles . In addition, oils often contain additives such as viscosity improvers and anti-oxidants which tend to break down with continued engine use, especially in the presence of water and metallic particles, which also accelerate the process of oxidation and general degradation.

It is also known that the reliability and longevity of an engine is crucially dependent upon the quality of its lubricating oil, and that an apparatus designed to detect some point at which the quality is deemed to be unacceptable would be desirable. In particular, when used in conjunction with a secondary bypass engine filter designed to remove particulate material down to 1 micron, such a device would be useful. Since such a filter may pass say 1% of the output from the oil pump, the differential pressure across the input and output of the filter is very low. making it difficult to measure. Consequently it is also difficult to know whether the filter element has become blocked. If this were to happen, however, the effect of the bypass filter in removing debris would be lost, and the concentration of contaminants would rise rapidly. Such a rise, or rate of change, could be detected by an oil quality monitor, enabling the filter or filter element to be replaced. If the oil quality monitor were to indicate poor quality, a sample may then be taken from the engine or machine, and sent to a suitable laboratory or facility for advanced spectrographic or chemical analysis, which may then reveal the presence of excessive soot, water, glycol, oxidation products, or metallic particles.

Also, degradation of most oils, such as due to oxidation or electrical breakdown, tends to result in the generation of products whose molecules are generally more polar than the oil from which they came. The base oil often comprises large hydrocarbon molecules which are generally only weakly polar, so the presence of most contaminants will result in an increase in one or both parts of the oil's complex permittivity. An oil quality monitor which measures permittivity is therefore suitable for measuring changes in, for example, transformer oil, or the oil in gearboxes and transmissions which may be subjected to the high temperatures and agitation which are conducive to oxidation.

Transmission units and other hydraulic systems such as rams may also become contaminated with water as a result of working in wet or damp environments. Water will cause an increase in both parts of the oil's complex permittivity, and may therefore be detected by apparatus according to the invention.

Advanced oil analysis as carried out by an accredited laboratory subjects oil samples to a battery of tests, one of which is often a basic measurement of dielectric properties, often carried out by hand. An oil quality monitor according to the invention may be incorporated into an automated production line. The invention may be adapted so that a sensing head is provided at the end of a slender flexible rod suitable for insertion into the dipstick orifice of, an engine or machine to allow in situ measurement of oil quality in an engine or machine not otherwise fitted with an oil quality measuring device.

DESCRIPTION OF PRIOR ART

In U.S. Pat. No. 3,182,255, Hopkins et al. describe a device in which a bridge circuit is used to measure the AC impedance of one arm of the bridge, which contains a capacitive element whose capacitance changes with the dielectric strength (sic) of a drop of lubricating oil.

This device requires the physical removal of an oil sample from the vehicle, and makes no distinction as to whether the measured parameter is the real or the imaginary part of the permittivity. It can be shown that the impedance of a capacitor containing a dielectric depends, to first order, upon the real part, and to second order, upon the imaginary part, so that, even if no change occurs in the real part, there will nevertheless be a change in the modulus, or magnitude, of the permittivity, if there is a change in the lossiness of the dielectric, such as may occur through the presence of carbon particles. It is this magnitude which is usually referred to loosely as "dielectric constant". In another patent, U.S. Pat. No. 4,064,455, Hopkins et al. describe the use of an identical bridge circuit, but this time in conjunction with data storage and computational facilities.

In EP 0291363, Warenghem et al. describe a parallel plate capacitor, the capacitance of which varies with the concentration of carbon particles. In this document, capacitance is not defined as complex and is taken to refer to the modulus, or magnitude. No indication is given as to the means by which capacitance is actually measured.

In U.S. Pat. No. 4,733,556, Meitzler et al. describe a parallel plate capacitive sensor designed to fit between the engine block and the filter, where changes in the magnitude of capacitance are used to generate changes in the frequency of an associated oscillator. It is this change in frequency which is measured and subsequently compared, not with soot content of the oil, but with its viscosity. Although it is known that the complex permittivity of polar liquids will change with viscosity, it is also known that the viscosity will tend to increase with increasing soot concentration. This increase in viscosity is a macroscopic effect in the sense that a soot particle is many orders of magnitude larger than a molecule, and it is felt that measurement of dielectric constant is not a reliable indicator of viscosity in sooty oils.

In U.S. Pat. No. 4,345,202, Nagy et al. describe the use of microwaves in the range 8 to 12 GHz to measure soot content in engine oil, whereby nulls in the standing waves on a coaxial transmission line are located by means of a plurality of detectors arranged along the transmission line which is itself immersed in the sump of the engine

In U.S. Pat. No. 5,134,381, Schmitz et al. describe the use of a concentric capacitive sensor along whose axis passes, a fuel/alcohol mixture. Measurement of the capacitance of the sensor then provides the means whereby the alcohol content of the fuel may be determined, given a priori knowledge of the water content also. It appears that the capacitive sensor is excited by an external oscillator with the intention of measuring the impedance of the sensor and possibly also an associated phase shift.

Many other known devices are concerned with the measurement of the relative permittivity of fluids or fluid-like

materials other than engine oil, many of which are distinctly multiphase. For example, in U.S. Pat. No. 2,121,920 a means for measuring the mass and moisture content of tobacco is described in which a parallel plate capacitive test cell is placed in series with an inductance. The resulting RLC circuit is tested for resonance by manually sweeping it with an oscillator, and measuring the magnitude and frequency of the response.

In U.S. Pat. No. 5,272,444, Cox describes a method for measuring the water content and salinity (water cut) of a petroleum stream via measurement of temperature, resistivity and dielectric constant, but gives no details as to the mechanical arrangement of the sensor. It is clear however that the sensor is excited by an oscillator running at one of two fixed frequencies viz. 15 MHz and 30 MHz.

In U.S. Pat. No. 4,932,243, Suh et al. describe an online means for measuring the moisture content of a material, for example polymer pellets, using a capacitive sensor comprising three conductive concentric cylinders through which the material passes axially. The capacitance and dielectric loss are determined using "well known techniques" which are not detailed.

In U.S. Pat. No. 4,288,741, Dechene et a). describe a method for measuring both displacement and conduction currents in a two phase fluid of which one is assumed to be conductive, to determine the relative fractions of the phase. This is achieved by driving a capacitive sensor via an oscillator of fixed frequency with the intention of separating the relatively large conduction current from the relatively small capacitive current due to the AC excitation voltage.

In U.S. Pat. No. 4,181,881, Preikschat describes an apparatus also intended to measure the so-called dielectric coefficient and conductivity of various materials. This appears to be a batch testing method, and precise details of the capacitive sensor are not provided, other than to describe it as an earthed rectangular box with an active centre electrode. The capacitive sensor is excited by means of a stable crystal oscillator, the bridge circuitry being designed to measure the phase and amplitude of the voltage across the sensor.

In U.S. Pat. No. 3,979,581, Reulend describes a method of measuring the mass of tobacco by exciting a capacitive sensor with a signal from a swept external oscillator. In this arrangement a discriminator measures the frequency while a demodulator and differentiator locate the frequency and amplitude at which amplitude resonance occurs. Precise details of the capacitive sensor are not provided, but it appears to be a parallel plate capacitor of indeterminate size, possibly of the same order of magnitude as a cigarette.

In GB 2249636, McBrearty describes an inline dielectric sensor using a form of interdigitating capacitor to measure the dielectric coefficient and loss factor of molten polymers. This is accomplished by exciting the sensor with a sine wave generator. In the document, it is stated that a current to voltage converter and a lock-in amplifier are used to measure the amplitude and phase of the resultant alternating current.

WO 96/28742 describes an apparatus intended specifically for on-line monitoring of engine lubricating oils in diesel engines, and discusses the necessity or desirability of carrying out continuous monitoring of the oil. In this apparatus, the fundamental principal is that of measuring the dielectric coefficient of the oil, but in order to extract the greatest amount of information from the sample, the apparatus uses an arrangement of electromagnets to concentrate ferrous particles in the vicinity of a flat interdigitating capacitive sensor. Although the interdigitating capacitor is an interesting and useful configuration, the given formula relating capacitance to the dimensions of the capacitor refers to a parallel plate configuration, and so appears to be inaccurate in that context. The capacitor forms part of an oscillator circuit whose frequency varies with the dielectric coefficient of the oil. Since no inductor is present in the block diagram or in the text, it is assumed that the circuit is found to be self resonant as a result of parasitic inductances or the self inductance of the capacitive sensor. The inventors state that "the sensor element is charged by an oscillator circuit . . . using a monostable multivibrator to generate an output signal at a frequency corresponding to the sensor element capacitance". This can be taken to mean that the oscillator frequency is determined directly by the sensor capacitance, or that the frequency of the oscillator is adjusted until it coincides with the self resonant frequency of the sensor. In any event, the measurand is the frequency, so the parameter actually being measured is the magnitude of the dielectric coefficient (sometimes referred to as "dielectric constant").

It is known that a few devices have attempted to correlate oil quality with dielectric coefficient by measuring the capacitance of a capacitor with the oil as a dielectric. This has been achieved by measuring either the change in AC impedance or by measuring the change in frequency when connected in an LC resonant circuit. However, in these cases what is actually being measured is the magnitude of the capacitance, which changes slightly with the lossiness Tan δ of the dielectric, but also changes with dielectric constant. Such devices therefore have the disadvantages of being sensitive to oil base type, and only being sensitive to the second order as regards the loss term Tan δ.

SUMMARY OF THE INVENTION

The present invention provides apparatus for measuring oil quality based on the permittivity (dielectric coefficient) of the oil comprising a capacitive sensor for exposure to the oil, and an oscillator circuit including the sensor, characterised in that the oscillator circuit comprises an LC or crystal oscillator and provides an output signal, the amplitude of which is dependent upon the lossiness Tan δ of the oil, and measuring means that responds to the amplitude of said output signal as a measure of oil quality.

In particular, the amplitude can be inversely proportional to the Tan δ value. Tan δ is the ratio e ϵ''/ϵ' where ϵ'' is the imaginary part of the complex relative permittivity and ϵ' is the real part. The oil can be diesel fuel or another light mineral oil. The oil is preferably lubricating oil.

Thus, the output of the oscillator varies in response to changes in the lossiness of the dielectric medium (the oil), which in turn are determined principally by changes in the oil's soot content, acidity, and polar oxidation products. It is this change in the amplitude of the oscillator output which provides a measure of the oil quality.

The present invention is applicable to diesel fuel and oil in engines, or oil in hydraulic transmissions or machines, or oil in electrical machines where contaminants may be introduced into the oil by electrical breakdown or ingress of moisture.

The present invention also relates to an engine or machine including said electrical measuring apparatus. In particular, the sensor may be fitted to the oil supply tunnel or sump of the engine or machine. Alternatively, the sensor may be fitted to an oil filter, such as an oil bypass filter, attached to the engine.

The present invention also relates to an oil bypass filter for attachment to an engine, the oil bypass filter including said electrical measurement apparatus.

The present invention also relates to a method of measuring oil quality based on the permittivity of the oil using an oscillator circuit including a capacitive sensor, characterised in that the sensor is an LC or crystal oscillator which provides an output signal, the amplitude of which is dependent upon the lossiness Tan δ of the oil, and is used to give a measure of oil quality.

The sensor is preferably incorporated in a sensor head which is generally concentric or radially symmetric. It is preferably perforated or slotted to allow the free passage of oil over the electrically active surfaces of the sensor. Typically, the sensor head is about 10 mm in diameter, being small enough to fit into a hole such as might be provided in an engine for an oil pressure switch, such as a ⅛" NPT (National Pipe Thread) or ¼" BSP (British Standard Pipe) orifice. The associated oscillator electronics are located in the space behind the sensor head, which can take the form of a hollow hexagonal nut approximately 30 mm A/F by 20 mm deep. Since the electronic circuitry is at approximately the same temperature as the oil, it comprises components which will operate in elevated temperatures, for example, up to 150° C., and, optionally, which will also provide compensation to allow for temperature dependent changes in the dielectric medium.

It is known that changes in temperature affect electronic components such as transistors, inductors and capacitors, so that the output of the circuit, independently of the oil dielectric, is a function of temperature. The electrical properties of the oil itself are also affected by temperature. The most visible effect is the change in density, which is effectively linear over the range of interest, that is, from about 30° C. to 150° C. It follows that the concentration of contaminants, being inversely proportional to volume, will fall with increasing temperature. Simultaneously, however, the viscosity of the oil also falls with temperature, allowing greater freedom of motion for the constituent molecules, and it can be shown theoretically that the greater the average dipole moment of the liquid, the greater will be its dependence on temperature. In order to operate accurately over a wide range of temperatures, some form of compensation is necessary. Incorporated into the electronics is a small temperature sensor whose output, after suitable buffering, is passed out of the sensor head to a display unit.

The display unit incorporates a microprocessor which accepts as input the output voltage from the oscillator and the output from the temperature sensor. By means of a suitable lookup table or algorithm, this allows the appropriate adjustments to be made in order to render the final indication independent of temperature over the range say 30° C. to 150° C.

Generally, the curve showing oscillator output versus temperature is a bivariate function of permittivity and temperature, so full compensation requires a two dimensional lookup table or algorithm. However, it is found in practice that with the correct choice of operating frequency the slope of the curve is only weakly dependent on the concentration of contaminants, allowing the use of a simpler one dimensional table. FIG. **9** shows a number of typical curves where the change in oscillator output is plotted against temperature. The upper curve is for a clean engine oil, while the lower curves are for progressively more contaminated engine oil.

Oils are generally a complex mixture of hydrocarbons and proprietary additives, such that the output of the oscillator differs slightly according to the precise formulation. Although it has been found in practice, that the output differs by only a few percent to within one standard deviation over a wide range of different oils from different manufacturers (as shown in FIG. **10**), calibration means is included to eliminate even this small source of error. When the vehicle or machine is serviced or supplied with fresh oil, the microprocessor may accept an input from a recessed switch or coded transmitter when the correct operating temperature has been reached, such that that particular value is held in memory, and therefore becomes the baseline against which all subsequent readings will be compared.

In the event of the main power supply being cut, such as removal of the vehicle or machine's battery, the contents of the memory are retained in, for example, an electrically erasable programmable read only memory (EEPROM). This same EEPROM may also hold several hundred sets of readings sampled over the lifetime of the oil, typically 300 to 500 hours. The data may then be downloaded into a computer for subsequent examination and analysis, or it may be suitably encoded and transmitted to a remote location by radio for example. In addition to the measured value of the oil's quality, the rate of change of the device's output is an important indicator of engine health. If the slope of output versus time should unexpectedly increase, this would tend to indicate a sudden increase in contaminants, requiring immediate remedial attention before damage should occur. In order to improve the reliability of the data, the microprocessor accepts for example 10 measurements at short intervals, such that the final value displayed or stored is the arithmetic mean of the measured values.

The final, visible part of the microprocessor's output may take the form of a warning light or buzzer, or for test and diagnostic purposes may take the form of an alphanumeric display.

In the preferred sensor, the body of the sensor is at ground potential, while an integral automotive style connector provides one pin for the output signal, one pin for the temperature output, and a further pin for DC power input, which may be 12V or 24V.

In one embodiment, the apparatus is used in conjunction with a secondary filter. In this way, oil drain intervals may be extended with consequent cost savings, and the reliability of the engine is enhanced by the use of oil of consistently high quality. Additionally, analysis of the oil can provide an indication of faults in the engine allowing early rectification and the planned scheduling of preventive maintenance to avoid expensive downtime.

The preferred apparatus according to the present invention is, advantageously, of very low cost, for example, comparable with that of an inexpensive automotive pressure sensor, and of small size, and requiring little or no modification to the engine or machine. It is preferably intended to be fitted permanently to the engine or secondary filter, and to monitor the quality of the oil. continuously throughout the life of the engine or machine. It is preferably insensitive to changes in temperature, within a range of, say, 30° C. to 150° C., or in the case of hydraulic oils, from 20° C. to 100° C. It is insensitive to changes in base oil type from one manufacturer to another. In a preferred embodiment, the apparatus is powered directly by the engine or vehicle 12V or 24V electrical supply, and provides a single output consisting of an analogue voltage which varies in response to changes in the electrical properties of the oil. This signal may be used to drive a dashboard display which indicates the current state of the oil to the operator, and which may include a visible or, audible warning to indicate a filter change, oil change, or sample to be sent for analysis.

In a further embodiment, the output may be passed to the vehicle's on-board computer, where the data may be sampled periodically and stored in memory for real time analysis or for subsequent downloading and examination.

In a further embodiment the sensor comprises an oscillator running at, say, 200 to 300 MHz and mounted on a printed circuit board (PCB) approximately 8 mm wide by 20 mm long. This small size is achieved through the use of surface mount components. The active sensing head is attached directly to the PCB and surrounded by a perforated metallic cover which provides mechanical protection, electrical screening and a return path for radiated electromagnetic energy. A small temperature sensitive element such as a thermistor is also fitted, and its output carried along a flexible hollow tube such as the outer part of a Bowden cable. The oscillator is supplied with power from a separate regulated supply, which is also fed down the hollow tube. Careful choice of the bias point of the oscillator will ensure that, as the oscillator voltage varies with Tan δ, so also does the current, which then reflects any change in Tan δ due to contamination of the oil. Temperature compensation is applied in the manner already referred to by measuring the output from the temperature sensor, and then applying a correction in the display unit. In a further embodiment, the output from the temperature sensor is digitised and carried on the power supply lead. An active sensor of this size may advantageously be used for attachment to the end of a vehicle's dipstick (normally used for checking oil levels), or it may form part of a separate instrument for use by garages and testing stations to carry out a quick check on oil quality for stationary vehicles or machines. The sensor may be used for measuring the quality of oil in an engine, hydraulic machine, gearbox, or any other apparatus using non polar mineral oils.

A preferred embodiment of the present invention will now be described, by way of example and with reference to the accompany drawings in which:

FIG. **1**(*a*) shows the circuit diagram of a sensor head according to the invention,

FIG. **1**(*b*) shows the sensor head of FIG. **1**(*a*) connected to measuring and display means,

FIG. **2** shows a cross sectional view of the sensor head of FIG. **1**(*b*),

FIG. **3** shows the sensor head according to a second embodiment where the outer cylinder is replaced by an arrangement of conducting pins,

FIG. **4**(*a*) shows the sensor attached to an engine block,

FIG. **4**(*b*) shows the sensor alternatively attached to an engine sump,

FIG. **5** shows the sensor attached to a secondary bypass filter of an engine,

FIG. **6** shows a graph which plots the device output against soot concentration for a variety of oils from engines of different type,

FIG. **7** shows a graph which plots the change in output against distance for a typical small petrol driven automobile,

FIG. **8** shows a graph similar to FIG. **7** for a large diesel engined commercial vehicle,

FIG. **9** shows a number of curves of sensor output against temperature for engine oils of different levels of contamination,

FIG. **10** shows the variation in sensor output for different brands of engine oil, and

FIG. **11** shows a typical plot of the real and imaginary part of permittivity for all frequencies.

PHYSICAL BASIS OF THE INVENTION

Mineral lubricating oil is an essentially non-polar liquid dielectric with very high resistivity that is to say, the passage of non alternating conduction current through it is negligible, even when loaded with conductive particles such as soot. It may be characterised by its permittivity, which is in general complex, consisting of a real and an imaginary part, that is

$$\epsilon=\epsilon'-j\epsilon''$$

or equivalently,

$$\epsilon=\epsilon'(1-j\ \mathrm{Tan}\ \delta)$$

where $j=\sqrt{(-1)}$ and $\mathrm{Tan}\ \delta=\epsilon''/\epsilon'$. The phase angle δ is a measure of the lossiness, or dissipation factor, of the dielectric, and will determine the maximum amplitude attainable by a tuned circuit of which it forms a part.

In any capacitor, the capacitance is always proportional to δ, so capacitance is in general complex, and may be written as

$$C=C_0(1-j\ \mathrm{Tan}\ \delta)$$

where C_0 is the value of the capacitance with an otherwise lossless dielectric. It can be seen that the magnitude, Or modulus, of the capacitance is therefore

$$|C|=C_0\sqrt{(1+\mathrm{Tan}^2\delta)}$$

When the sensing element is a simple capacitor such as described, the idea of a lossy dielectric is intuitively clear, and the mathematical analysis is straightforward. However, the sensing element may also take the form of a short antenna radiating into the lossy dielectric medium, where the characteristics of the medium influence the loading on the antenna In this case the analysis, in which the near field components of the antenna are important, is more complicated, but the effect on the oscillator is the same, that is, the voltage and current will change with changes in the value of Tan δ of the medium. These changes may be measured and interpreted as changes in the quality of the oil. In an unused lubricating oil at a typical operating frequency, Tan δ is typically around 0.01, increasing to perhaps 0.1 for a heavily contaminated sample, while ε' is typically 2.25 to 2.45. For small concentrations of soot up to a few percent, Tan δ is approximately proportional to soot concentration, while the corresponding change in ε' is only a few percent at most. This means that Tan δ is the most suitable parameter for indicating oil quality, being insensitive to variations in the composition of clean oils, and having the greatest rate of change during use and subsequent contamination.

Apart from soot in engine oil, a further important contaminant is represented by oxidation products, which may also be present in hydraulic oils. Oxidation tends to occur in particular when the oil is hot, and is accelerated by the presence of catalytic agents such as copper, iron or water. These products consist generally of alcohols, aldehydes, and ketones, which will break down further into acids and esters in varying concentrations. Since these molecules tend to possess strong dipole moments, the oil becomes a more or less dilute solution of polar materials in a non polar solvent. Each polar molecule is associated with a particular relaxation time, or distribution of relaxation times, which are themselves dependent on temperature. As the, temperature increases, the viscosity falls, allowing greater dipole mobility and hence shorter relaxation times.

When ϵ'' is plotted against ϵ' for all frequencies, that is from DC to several GHz, the resultant curve has the general shape shown in FIG. **11**. An empirical model which usually fits the data is a modified form of the Cole Davidson equation:

$$(\epsilon-\epsilon_\infty)/(\epsilon_0-\epsilon_\infty)=(1+(j\omega\tau)^\alpha)^{-\beta},0<\alpha<1$$

where α and β are both positive real numbers, and reflect the distributions of relaxation times τ of the many species present. When $\beta=1$ the curve forms an arc of a circle. The effect of α is to depress the centre of this circle below the imaginary axis, while the effect of β is to skew the curve from a generally circular form. β is usually quite close to 1. Examination of this expression shows that some care is required in selecting the operating frequency. Differentiation of the above expression shows that a low value of frequency ω will give rise to a rapid rate of change in Tan δ, with frequency, making it unduly sensitive to the stability of the oscillator. At the peak value of Tan δ the rate of change of Tan δ with frequency is zero but this is true only for a particular oil at a particular temperature, making the device useless for all but a very limited range of conditions. At the higher frequencies, the rate of change is smaller, but so also is Tan δ, so a tradeoff is necessary between sensitivity on the one hand and accuracy over a range of oils, temperatures and contaminants on the other. The small size of the device tends to dictate the use of higher frequencies, but these must not be so high as to require the use of unnecessarily costly components and construction techniques.

It can be shown that for small Tan δ the frequency is given approximately by

$$\omega=\omega_0(1-\tfrac{1}{4}\ \mathrm{Tan}^{\,2}\delta),$$

so a small change in Tan δ gives rise to a corresponding small change in ω:

$$\Delta\omega=-\tfrac{1}{2}\omega_0\ \mathrm{Tan}\ \delta.\Delta(\mathrm{Tan}\ \delta)$$

The relative change in frequency due to a change in Tan δ is therefore given by

$$\Delta\omega/\omega=-\tfrac{1}{2}\ \mathrm{Tan}\ \delta.\Delta(\mathrm{Tan}\ \delta)$$

from which it can be seen that a small value of Tan δ (which is usually the case) will give rise to only a small change in frequency.

Determination of Tan δ

The Tan δ term is sensed in any of a variety of ways, of which one is the measurement of the potential difference across a tuned circuit for example as shown in FIG. **1**. It is well known that the impedance of a parallel LC or RLC circuit increases as the exciting frequency approaches the resonant frequency (for small Tan δ phase resonance and amplitude resonance are very nearly the same, the former being defined as the point at which the reactance, or imaginary part of the impedance, is zero, while the latter is the point at which the amplitude is a maximum), and that the potential, or voltage across the circuit increases in the same proportion. This apparent amplification is often referred to as the "Q" of the circuit, which is generally the ratio of reactance to resistance in an RLC circuit, but which in the context of a lossy dielectric is simply 1/Tan δ.

If we assume for simplicity that the inductor in a tuned circuit possess no resistance, then the impedances of the inductor and capacitor are respectively.

$$Z_L=j\omega L$$

$$1/Z_C=j\omega C_0(1-j\ \mathrm{Tan}\ \delta)$$

where ω is the angular frequency of the current in the circuit. It can be shown that phase resonance occurs when the two impedances are equal, that is, when

$$\omega_0^2=1/(LC_0)$$

At this frequency the magnitude of the impedance is given by

$$|Z|=\sqrt{(L/C_0)}.1/\mathrm{Tan}\ \delta$$

and it follows that the voltage across the circuit is inversely proportional to Tan δ, all other losses being ignored. For small changes in Tan δ it can be shown that the percentage change in voltage is proportional to the percentage change in Tan δ, that is

$$\Delta V/V=-\Delta(\mathrm{Tan}\ \delta)/\mathrm{Tan}\ \delta$$

so that, owing to the negative sign in the above expression, an increase in Tan δ implies a corresponding decrease in voltage V. Note that by contrast with the corresponding analysis given above for the change in frequency with Tan δ, the relative change in voltage is large for small values of Tan δ. This provides good justification for the choice of amplitude, (rather than frequency), as the preferred measurand.

Given that the voltage across the tuned circuit changes, it follows that the current in the tuned circuit and associated, oscillator also changes. Since this change in current is a reflection of the change in oscillator voltage, it may then advantageously be used to indicate Tan δ, and hence oil quality, as before. This arrangement allows the use of just two wires from the sensor, that is, one wire to supply power (from which the current is measured) and a second wire to provide the output from the temperature sensor. These two outputs may advantageously be duplexed, allowing the use of just one wire, with the sensor body providing the ground connection.

DESCRIPTION OF THE PREFERRED CIRCUIT

Referring to FIG **1**(*a*), the sensing element/capacitor **1** of the sensor head H, has a capacitance between 1 pF and 50 pF, and is connected in parallel across inductor **2** (of High Q) via a short coaxial conductor **9**. The AC voltage across the inductor **2** passes to the base of transistor **3** via series/coupling capacitor **4** which is provided to block the passage of DC current through the inductor **2**. The transistor **3** is provided feedback elements such that the circuit is configured as, for example, a Colpitts oscillator. In this case, the series capacitor **4** and the feedback capacitors **5** and **6** appear across the sensing capacitor **1** to increase its value, so that the resonant frequency, which may be between 10 MHz and 300 MHz, is determined not only by the sensing capacitor but also to a lesser extent by capacitors **4**, **5** and **6**. The values of the bias resistors **7** and **8** are chosen to have only a small effect on the overall "Q" of the circuit. The output from the oscillator, which may be taken from the emitter of the transistor **3** to ensure a low impedance output, passes to a detector circuit **10** whose DC output is proportional to the amplitude of the signal at the base of the transistor, and is filtered to remove the high frequency component. The DC signal then passes to a low output impedance amplifier **11** which provides a small amount of gain and, more importantly, suitable buffering between the detector and the output lead.

In a further embodiment (not shown) the output from the sensor is simply the current drawn by the oscillator circuit, and is measured in the display means, which contains a stabilised constant voltage source. In a related embodiment the output from the temperature sensor is duplexed onto the power supply lead.

Optionally incorporated in the feedback loops of the amplifier are temperature sensitive elements such as diodes or thermistors which are used to maintain a more or less constant output for a given oil sample irrespective of temperature. In a preferred embodiment the sensor contains a temperature sensor **12** whose output passes directly to the display board and is read and interpreted in such a way as to apply temperature compensation by means of software. As shown in FIG **1***a*, the supplied voltage +V for the circuit is derived from a voltage regulator **13** which may also incorporate a temperature dependent element. The power input to the device, which may be 12V or 24V, is protected by surge suppressors against voltage spikes of up to 120 V such as may reasonably be expected on an automotive voltage supply. Both the power input terminal IN and the signal output terminal OUT incorporate EMC protection of EMC/RF filters **14***a*, **14***b* such that high frequency energy is not radiated by the device, nor is it affected by high frequency radiation from some external source.

FIG. **1***b* shows the sensor head H connected to a microprocessor **15** and display board **16**, where the input to the microprocessor consists of a voltage TEMP dependent on temperature and the output voltage OUT from the sensor. The microprocessor includes a memory **17** and means for storage of data and calibration values, and also a lookup table for temperature compensation.

The Capacitive Sensor

The sensor, which is shown in cross section in FIG. **2**, is in the form of a coaxial capacitor, typically 10 mm in diameter, and generously perforated with perforations or slots **30** in the outer cylinder **33** to allow the free passage of oil in the annular space between the cylinders **22**, **33**. In an alternative embodiment (not shown), the inner cylinder **22** can also have perforations. The flow of oil is at least approximately at right angles to the axis of the sensor. The outer cylinder **33**, which is part of the metallic body **20** of the sensor H is at ground potential, and the size of the annular gap to the inner cylinder **22** is chosen so that the capacitance, including fringing effects, is approximately 1 pF to 50 pF. The inner, cylinder **22** extends backwards as a thin shaft or screw **24** into the body **20** of the sensor H, where it connects electrically with the printed circuit board (PCB) **23**. The space between the PCB **23** and the sensing head is designed to prevent the ingress of oil from the engine into the PCB compartment, and incorporates elastomeric compression seals or "O" rings **31** and/or a bush **25** of insulating material such as PTFE (Polytetrafluoroethylene) or PEEK (Polyetheretherketone). External electrical connections are made by for example spade connectors or moulded automotive connectors **26**.

The PCB **23** is held in place by retaining screws **32**. The outer cylinder **33** is provided with a protective perforated screen or gauze. In an alternative embodiment, a protective gauze is not provided.

Since the wavelength at the. frequency of operation is generally much greater than the dimensions of the sensor, it is found that the effect of the perforations or slots is small, such that a high void ratio is possible.

In the annular region of a concentric capacitor, the electric field is essentially uniform, and is confined to the volume between the electrodes. Any change in the dielectric medium will be reflected by a corresponding change in the complex capacitance. If the outer earthed part of the capacitor is removed completely, the inner element will still radiate into the dielectric medium, and the impedance of this element, now behaving like an electrically short antenna, is dependent on its dimensions, the frequency of operation, and the electrical characteristics of the medium. It is therefore not essential for the sensing element to be in the form of a capacitor in which the field is totally contained, and it may simply take the form of a short stub. In constructing a derivative of the sensor for use in a test laboratory, it may be desirable for the sensing element to be as open as possible for ease of cleaning, but consistent with the need to keep radiated energy to a minimum and to allow the sensor to be insensitive to changes in the geometry and material of the vessel in which it is immersed. This requirement may be met by the provision of one or more grounded pins or elements in the vicinity of the active or live sensing element.

In a second embodiment, the sensing head differs in that the outer cylinder is replaced by an arrangement of vertical pins such that the alternating electromagnetic field around the central conductor links with the pins. FIG. **3** shows a view of this sensor with four grounded pins **50** in place of the coaxial outer conductor. It can be seen that the central conductor **52** is, in effect, a short antenna radiating into the dielectric medium. In a third embodiment, the sensing head (not shown) differs in that there is no grounded outer portion at all, this being provided by the engine block itself, or by the hardware (such as a sump, for example) into which the sensor is screwed. In this third embodiment the performance of the device would be dependent upon the precise geometry of the said hardware, and the frequency of operation is determined principally by the secondary coupling and feedback capacitors **4**, **5** and **6**.

In a further embodiment a metallic perforated screen or gauze is included to provide electromagnetic screening (and hence insensitivity to the sensor's immediate surroundings) and protection against mechanical damage.

The compartment **27** which contains the electronics is preferably cylindrical, being formed within a preferably hexagonal bar like a hexagonal nut to allow easy fitment to the engine or machine. It may be typically 30 mm across flats (A/F) and 18 mm deep, and may be fabricated for example from brass. As a protection against the ingress of dust and moisture, and as a protection against shock and vibration, the compartment **27** may be filled with a suitable potting compound such as silicone rubber or epoxy resin. As additional protection and to provide screening against internally or externally generated RF energy, a metallic conductive cap **28** is provided.

FIG. **4***a* shows one possible application of the preferred apparatus, in which the sensor H is attached directly to the pressurised oil supply port **62** of the engine **60**. This oil supply port is usually near the primary oil filter **64**, and an engine **60** usually has at least one tapped hole leading to the supply, frequently for the provision of an oil pressure switch or sender. The oil quality sensor can make advantageous use of one of these openings, given that an adaptor for the oil pressure switch or sender is provided such that both devices can operate simultaneously.

In an alternative application, a T-piece may be provided in the oil supply to, for example, an oil cooler or turbocharger, such that the sensor is exposed to the flow of oil.

FIG. **4***b* shows another possible application of the apparatus, in which it is attached to a sump **66** of the engine

60. In addition to the usual drain plug, large diesel engines are usually fitted with at least one other sump plug, such as may be used for a sump heater, for example. The apparatus fits into the sump in place of one of these other sump plugs.

These plugs are usually found on the side of the sump, so that an oil quality sensor H would lie essentially horizontally within the oil. Since there will always be constant motion of the oil due to the action of the oil pump, there will be no danger of oil stagnating within the sensor, which is generously provided with perforations or slots.

FIG. **5** shows an application of the apparatus in which it is attached directly to the inlet side of an oil bypass filter **68**. The purpose of such a secondary filter is to remove particulate material down to 1 micron. In older or sooty engines in particular, such bypass filters tend to become clogged rapidly, and, since there is no other effective means of detecting this state,the oil quality sensor may therefore form part of the whole package, that is, bypass filter **68**, oil quality sensor H, and associated fittings **70** and hardware (not shown).

FIG. **6** shows a scatter diagram of device output signal amplitude plotted against soot concentration. Several samples were taken from a wide variety of different sources, that is to say, there was a wide range of engine types, all using oils of different viscosities from different manufacturers. Although the sample size is relatively small, it can be seen that the correlation between soot content and sensor output amplitude is good, with a correlation coefficient of 91%. Soot concentration was obtained from a laboratory specialising in oil analysis, using standard techniques, for example reflectometry or gravimetric methods. It is seen from FIG. **6** that output amplitude is sensitive to soot content. It is also seen from FIG. **7** and FIG. **8** that output amplitude changes with distance (and hence with use) for both petrol and diesel engined vehicles.

What is claimed is:

1. Apparatus for measuring oil quality based on the permittivity (dielectrical coefficient) of the oil comprising a capacitive sensor for exposure to the oil, and an oscillator circuit including the sensor, characterised in that the oscillator circuit comprises one of a LC or crystal oscillator and provides an output signal, an amplitude of which is dependent upon a lossiness Tan δ of the oil, and a measuring device that responds to the amplitude of said output signal as a measure of oil quality.

2. Apparatus as claimed in claim **1**, in which the oscillator circuit is such that it draws a current which changes with the lossiness Tan δ of the oil and gives a measure of oil quality.

3. Apparatus as claimed in claim **1**, in which the amplitude is substantially inversely proportional to Tan δ.

4. Apparatus as claimed in claim **1**, in which the sensor is incorporated in a sensor head adapted for fitting to one of an engine, machine filter or probe so as to be exposed to said oil.

5. Apparatus as claimed in claim **4**, in which the oscillator circuit is incorporated in the sensor head.

6. Apparatus as claimed in claim **4**, in which a temperature sensor is incorporated in the sensor head and produces a temperature output signal which is passed to the measuring means so as to allow temperature compensation in the output signal.

7. Apparatus as claimed in claim **6**, in which the measuring means incorporates a processor and memory that incorporates a look-up table of temperature compensation values that are accessed by the processor according to the output signal and temperature output signal received by the processor.

8. Apparatus as claimed in claim **4**, in which the sensor is mounted at the end of a long hollow flexible probe suitable for insertion into an orifice for testing oil.

9. Apparatus as claimed in claim **1**, in which the measuring device includes a calibrator which is operable to cause a baseline value of the output signal to be saved in memory for reference in determining oil quality from subsequent values of the output signal.

10. Apparatus as claimed in claim **9**, in which the memory is such as to retain stored values when power is disconnected.

11. Apparatus as claimed in claim **10**, in which multiple sequential values based on the output signal are stored in the memory for subsequent downloading.

12. Apparatus as claimed in claim **1**, in which the measuring device includes a display that displays an indication of oil quality.

13. Apparatus as claimed in claim **1**, in which the output signal is suitable for interfacing with a data bus.

14. Apparatus as claimed in claim **1**, in which the sensor comprises one or more capacitor plates pierced with openings to facilitate ingress of oil.

15. Apparatus as claimed in claim **14**, comprising a pair of concentric capacitor plates.

16. Apparatus as claimed in claim **1**, in which the sensor is intended to radiate into the oil dielectric medium like a short antenna or dielectric probe.

17. An oil bypass filter for attachment to an engine incorporating apparatus as claimed in claim **1**.

18. A method of measuring oil quality based on the permittivity of the oil using an oscillator circuit including a capacitive sensor, characterised in that the sensor is one of a LC or crystal oscillator circuit and provides and output signal, an amplitude of which is dependent upon a lossiness Tan δ of the oil, and it is used to give a measure of oil quality.

* * * * *

US005260665A

United States Patent [19]

Goldberg et al.

[11] Patent Number: 5,260,665

[45] Date of Patent: Nov. 9, 1993

[54] IN-LINE FLUID MONITOR SYSTEM AND METHOD

[75] Inventors: **Jack Goldberg**, San Diego; **Kurt E. Zublin**, Poway; **Marl J. Bell**, Valley Center, all of Calif.

[73] Assignee: **IVAC Corporation**, San Diego, Calif.

[21] Appl. No.: **693,357**

[22] Filed: **Apr. 30, 1991**

[51] **Int. Cl.**[5] **G01F 1/68**

[52] **U.S. Cl.** **324/636**; 73/861.95; 73/204.23; 604/65

[58] **Field of Search** ..... 324/636, 639; 73/19.1, 73/19.05, 61 R, 204.23; 604/50, 65; 128/653.1; 333/230, 246

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Primary Examiner—Kenneth A. Wieder
Assistant Examiner—Maurak Regan
Attorney, Agent, or Firm—Fulwider, Patton, Lee & Utecht

[57] **ABSTRACT**

A non-invasive, in-line fluid monitor includes a segment of fluid line disposed such that it and the fluid within become a part of the dielectric loading on an energized electromagnetic sensor device. Perturbations of the dielectric loading on the sensor device are monitored to determine certain fluid properties, such as pressure, composition, and the presence of air. The fluid line segment disposed through the electromagnetic sensor may be compliant and thus changes size in response to fluid pressure, altering the volume of the fluid line segment tin the cavity and altering the dielectric loading on the cavity. In one embodiment, a resonant cavity is used to encompass the segment of fluid line and a processor is used to compare changes in the resonant characteristics of the cavity to predetermined data to determine the properties of the fluid. In an alternative embodiment, a transmission device such as a delay line is utilized as the sensor element, and in another embodiment, a microstrip resonator is utilized as the sensor element. In yet another embodiment incorporating a means of determining the volumetric fluid flow rate, the size of air bubbles in the fluid is assessed.

18 Claims, 7 Drawing Sheets

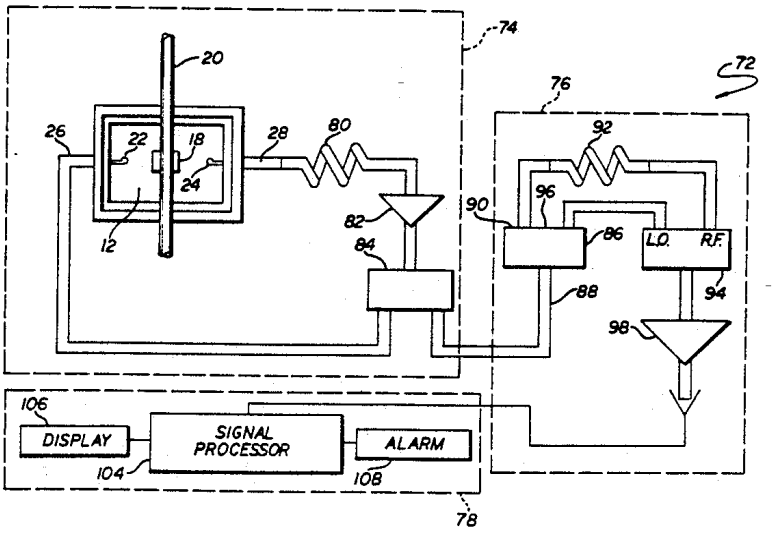


FIG. 1

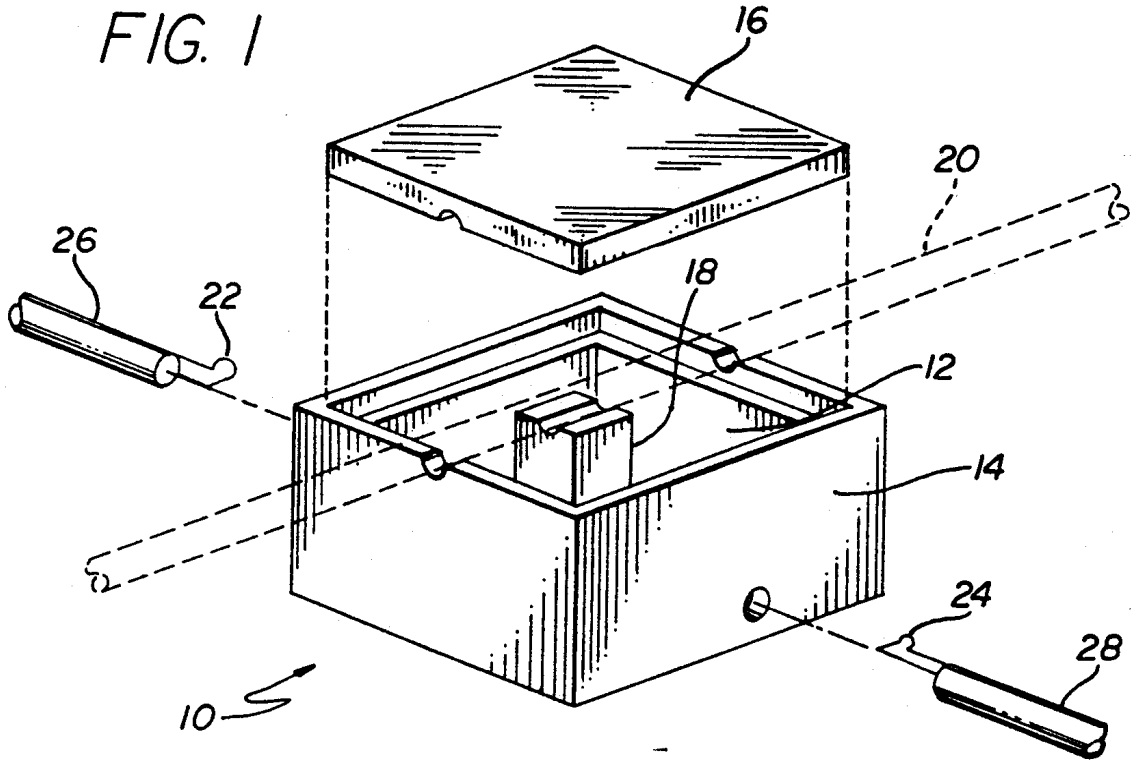


FIG. 2

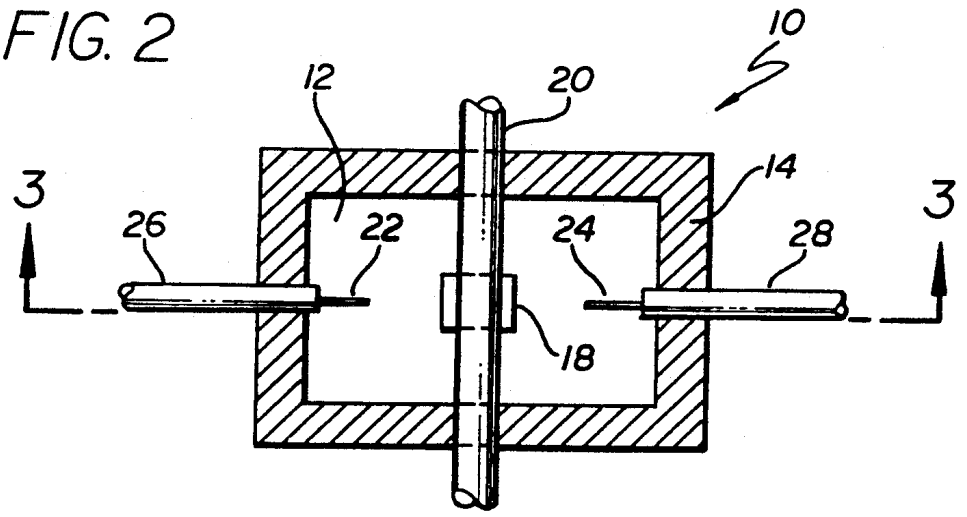


FIG. 3

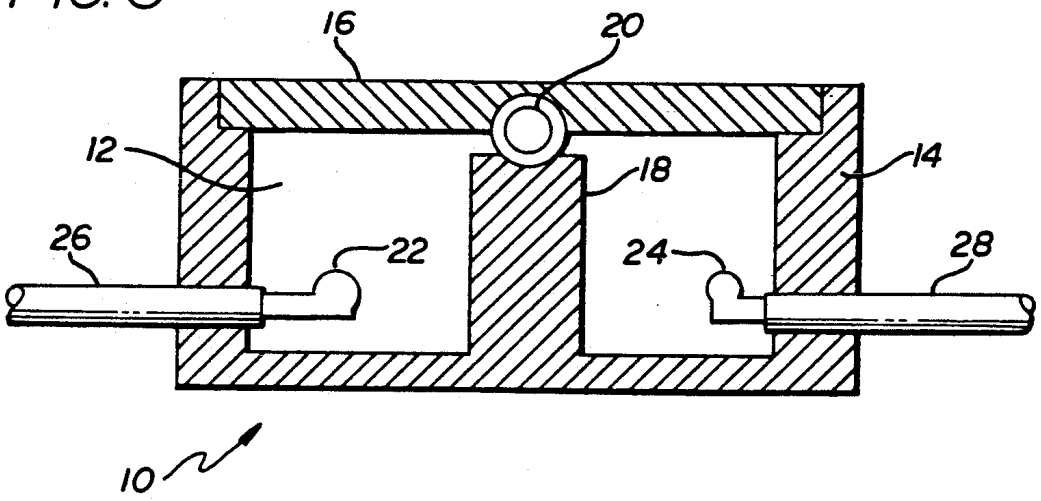
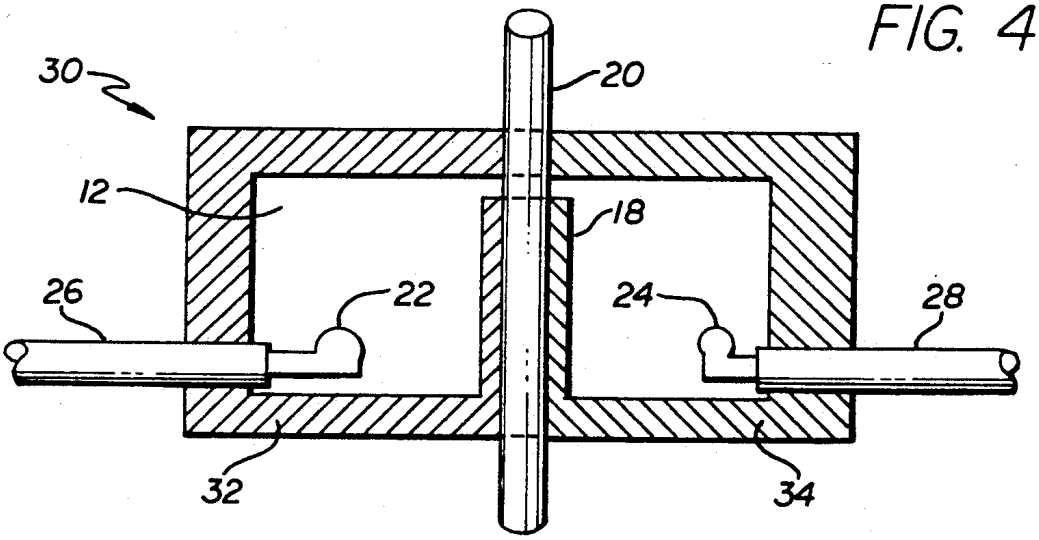


FIG. 4



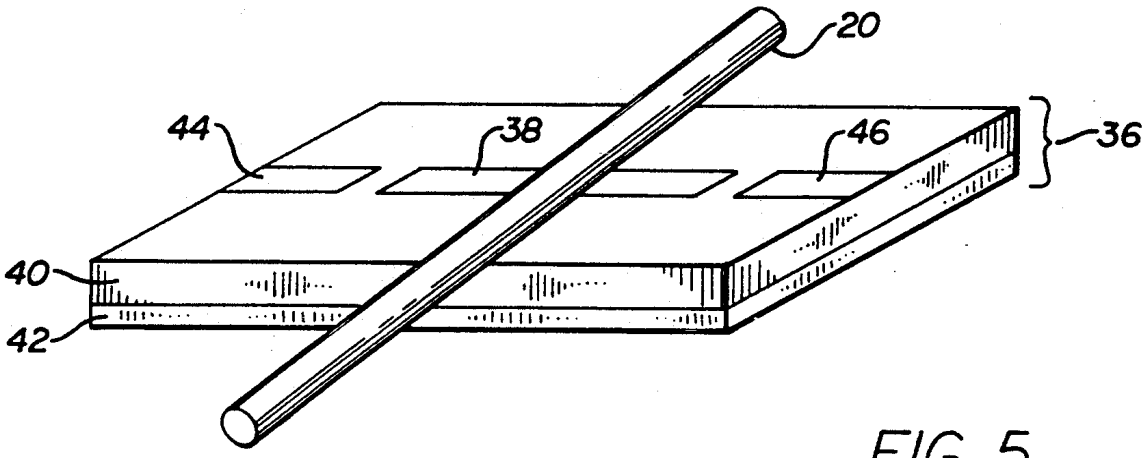
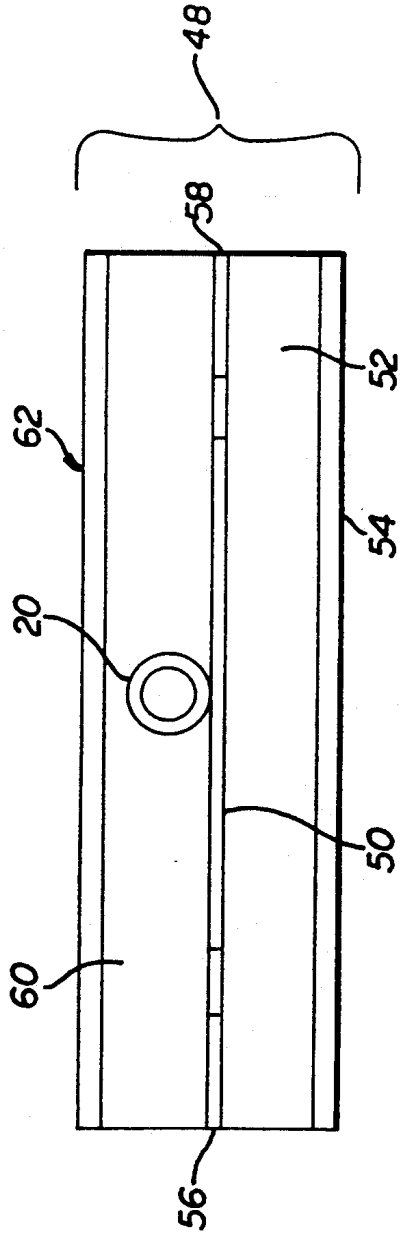


FIG. 5

FIG. 6



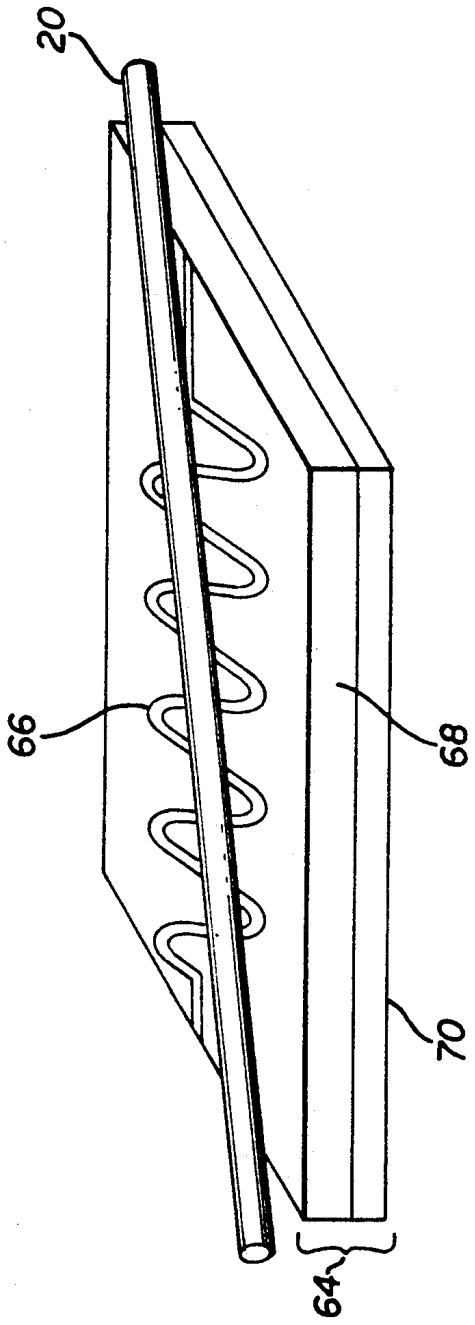


FIG. 7

FIG. 8

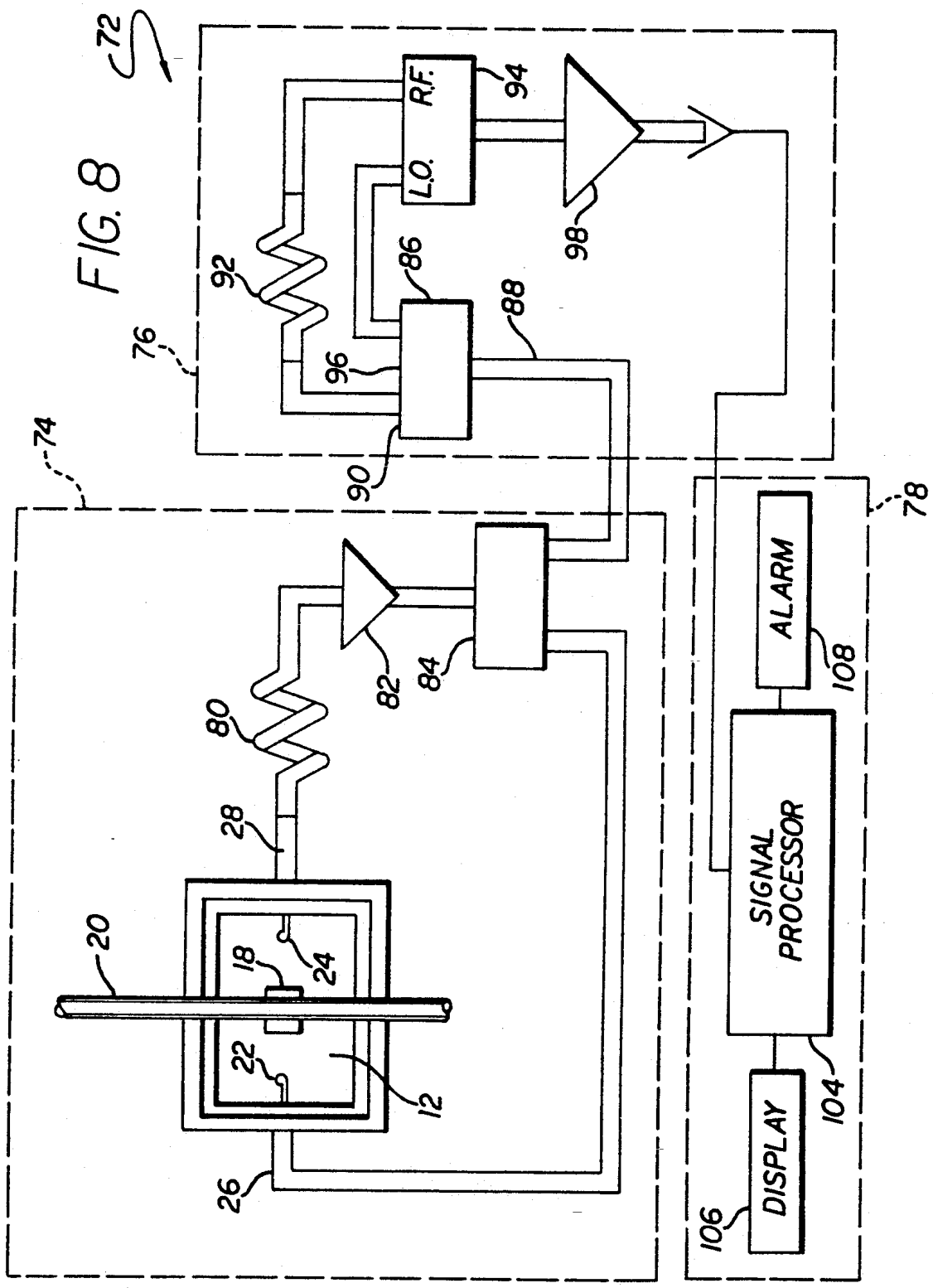
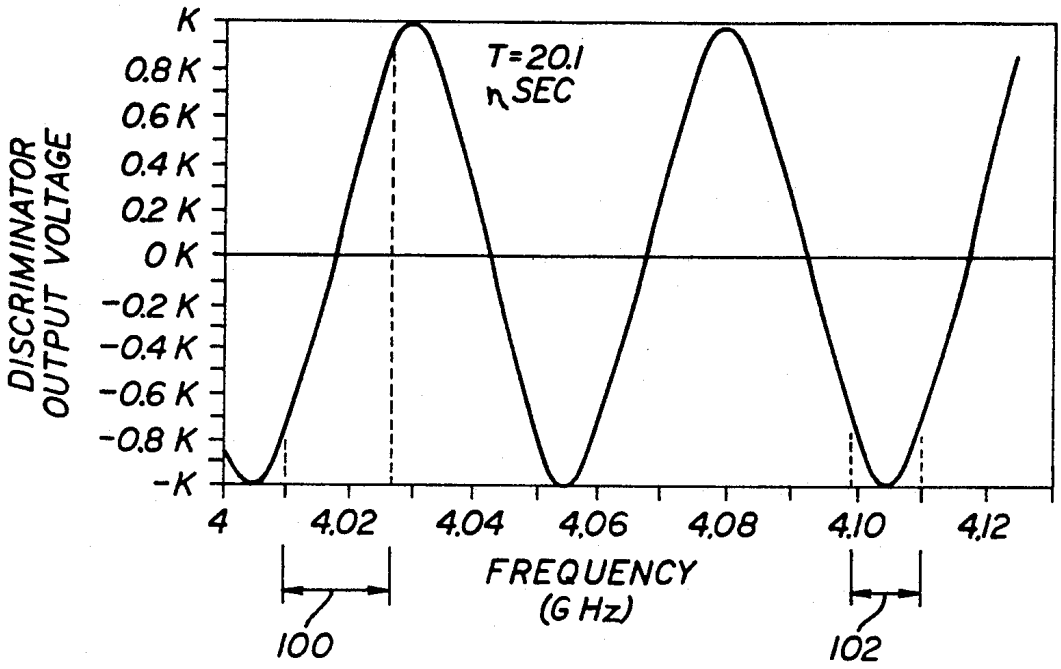

72
R.F.
L.O.
94
98
92
86
88
76
96
90
74
78
82
84
ALARM
108
80
28
SIGNAL PROCESSOR
20
18
24
22
12
104
26
DISPLAY
106

FIG. 9


K
0.8 K
0.6 K
0.4 K
0.2 K
0 K
-0.2 K
-0.4 K
-0.6 K
-0.8 K
-K
DISCRIMINATOR OUTPUT VOLTAGE
T=20.1 n SEC
4
4.02
4.04
4.06
4.08
4.10
4.12
FREQUENCY (G Hz)
100
102

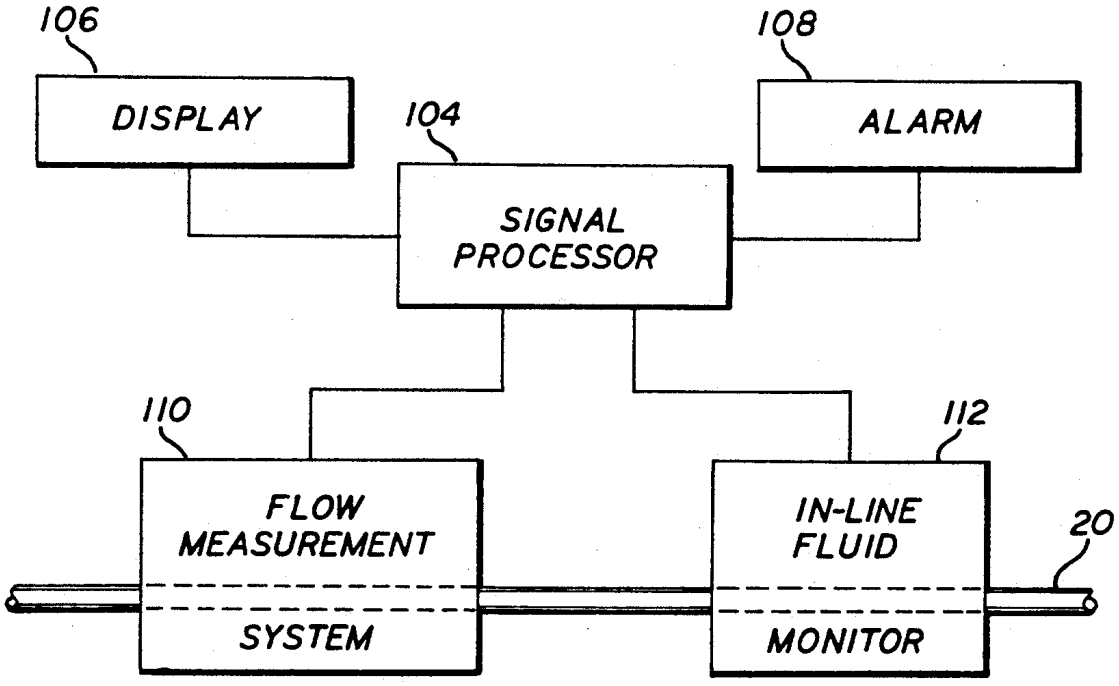
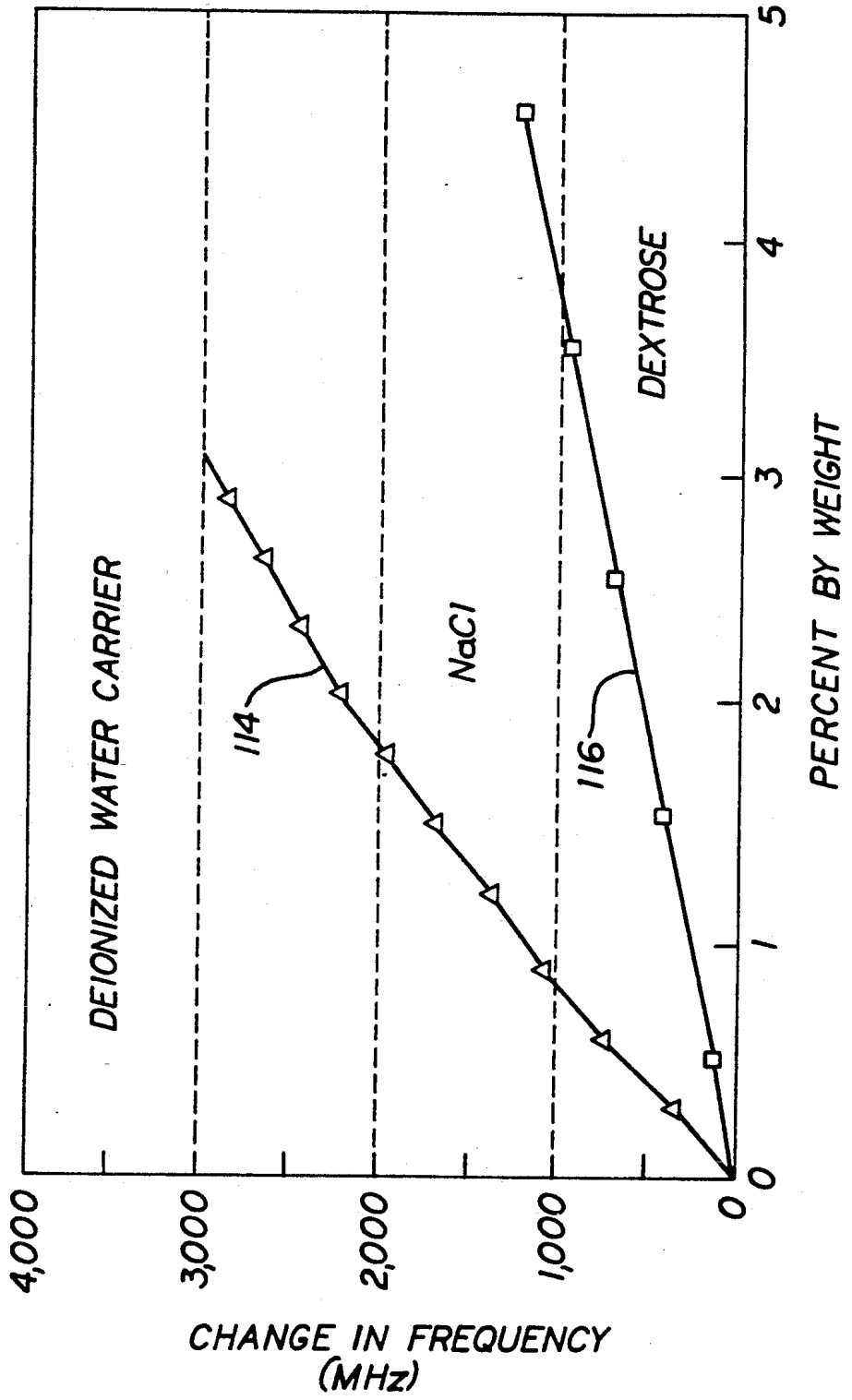

106
DISPLAY
104
SIGNAL PROCESSOR
108
ALARM
110
FLOW MEASUREMENT SYSTEM
112
IN-LINE FLUID MONITOR
20

FIG. 10

FIG. 11


DEIONIZED WATER CARRIER
NaCl
DEXTROSE
114
116
4,000
3,000
2,000
1,000
0
0
1
2
3
4
5
CHANGE IN FREQUENCY (MHz)
PERCENT BY WEIGHT

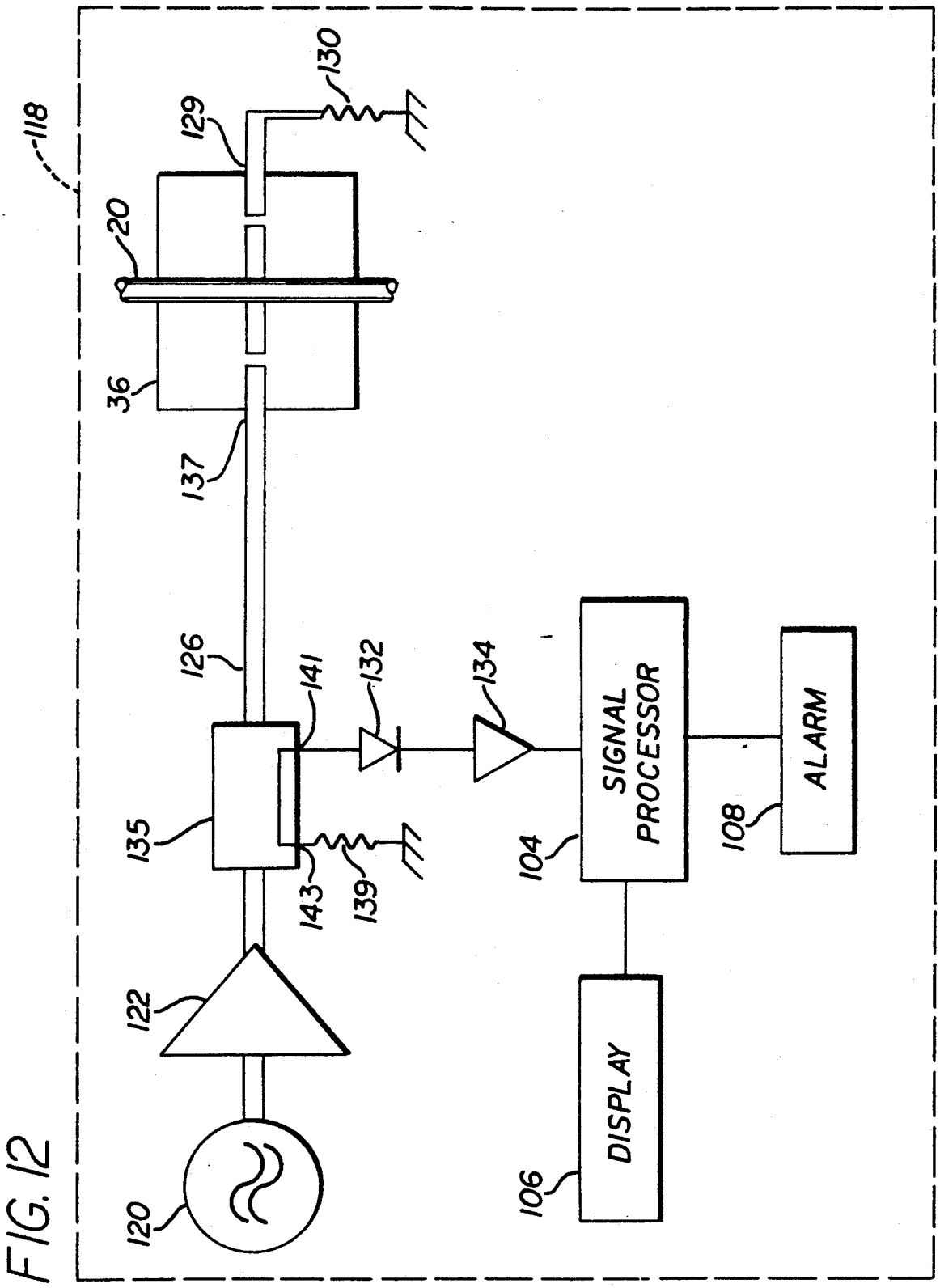

118
130
129
20
36
137
126
141
132
134
SIGNAL PROCESSOR
ALARM
135
104
108
143
139
122
DISPLAY
120
106

FIG. 12

IN-LINE FLUID MONITOR SYSTEM AND METHOD

BACKGROUND

The invention relates generally to monitoring fluid in a line without direct fluid contact, and more particularly, relates to non-intrusively monitoring for changes in fluid properties, including the presence of air or other gas, and for fluid pressure.

In numerous medical and industrial applications, continuous in-line monitoring of a fluid is often necessary to ensure consistency of a process or to ensure safety. For example, the pressure of fluid in a line may be critical to a process. Additionally, the presence of air or other gas within a fluid or the presence of contaminants within a fluid may need to be monitored. Examples of non-medical applications for fluid monitoring can be found in the chemical process industry, where inexpensive and/or disposable fluid conduits may be required, where fluids may be present at high pressure, or where fluids which are highly caustic or highly toxic may be involved.

In the medical area, safety and cost are of great concern. Reliable and inexpensive in-line fluid monitoring without direct fluid contact is especially important in the medical area where sterilization and disposability of the fluid line are requirements. In fluid delivery systems with a positive pressure pumping mechanism, a flow path occlusion can be detected by monitoring the fluid pressure. When flow path disposability is required, fluid pressure is generally measured either by means of a disposable transducer or by means of a non-disposable transducer coupled with a disposable membrane or other compliant region arranged such that the transducer itself is not in direct contact with the fluid. Typically, a disposable transducer or specially designed transducer membrane is more expensive than a disposable fluid line alone. In regard to considerations of cost, it would be desirable to provide a pressure transducer which may be reused and disposable fluid lines which work with that transducer.

Air-in-line detection systems are used to prevent the inadvertent infusion of air into a patient's bloodstream. While small bubbles of air may have no adverse effect on a patient, large air bubbles can cause death. Methods for the in-line detection of air typically involve ultrasound or light transmission through the fluid line being monitored. The transmission characteristics of sound or light may be utilized as an indication of the presence of a gas bubble in liquid in the fluid line. Simple recognizable perturbations of the signals from such sensors may be utilized to trigger an alarm and/or halt the infusion. Such systems require that the fluid and the associated conduit be substantially transparent to the energy being transmitted. However, due to their inability to reliably distinguish between air bubbles of varying sizes, ultrasonic or optical air-in-line detectors sometimes behave erratically, falsely indicating the presence or absence of air bubbles. Typically, such sensors cannot determine the exact size of air bubbles and are configured merely to indicate the presence of air bubbles which are greater than a predetermined size.

Other apparatus capable of detecting impurities such as air within a fluid include electrochemical systems and laser doppler systems. Electrochemical systems can be extremely sensitive to specific compositional variations in a fluid, but incorporate components, such as membranes, which must be in direct contact with the fluid, thus increasing their costs in applications requiring disposability. Laser systems are at present very expensive, and still other systems cannot operate over the wide range of flow rates and fluid types required in many applications.

Hence those concerned with fluid line monitoring have recognized that it would be beneficial to provide an in-line fluid monitoring system and method which does not involve direct fluid contact with a sensor but which exhibits higher sensitivity to variations in fluid composition, including the presence of air or other gas, and which can provide an indication of the size of a gas bubble. In medical systems, there is a need for an apparatus and method which reliably and accurately detect and quantify the presence of air or other impurities in the line but at the same time are relatively inexpensive and can function with an inexpensive disposable fluid line. Additionally, in medical systems, there is a need for an apparatus and a method which can reliably and accurately measure the pressure within an inexpensive disposable fluid line. The present invention fulfills these needs.

SUMMARY OF THE INVENTION

The present invention provides for in-line fluid monitoring without direct fluid contact. Detection of fluid properties, including the presence of air or other gas and the indication of changes in fluid composition, as well as the determination of fluid pressure are provided. The fluid monitor in accordance with the invention includes the use of a segment of fluid line disposed such that it becomes a part of the dielectric loading of an electromagnetic sensing device. The dielectric loading is monitored to determine the fluid properties such as the composition and pressure of the fluid in the fluid line segment. In one embodiment, a resonant electromagnetic sensing device is incorporated into an oscillation circuit and the frequency of oscillation is monitored. Changes in that frequency are used to determine fluid pressure and composition, including the presence of air or other gas in the fluid.

In one embodiment, a resonant electromagnetic cavity, such as a microwave cavity, is used to encompass a compliant segment of the fluid line. Because the fluid line is compliant, the volume of fluid within the cavity varies in accordance with fluid pressure. The compliant segment and fluid therein are used to form a part of the dielectric loading of the cavity and this dielectric loading is monitored to determine the pressure and composition of the fluid. In circumstances where pressure measurement is not required, the fluid line segment is preferably non-compliant. Circuitry is provided which forms an oscillator whose resonant element is the cavity itself and thus changes in the dielectric loading of the cavity produce variations in the oscillating frequency. Perturbations of the oscillating frequency are monitored and indicate changes in fluid pressure and composition. In one embodiment, the electric field in the cavity is focused on the segment of fluid line encompassed by the cavity so that the fluid line accounts for the major portion of dielectric loading of the cavity.

A processor is used to compare changes in the oscillating frequency to predetermined parameters to determine the changes in the composition and pressure of the fluid in the segment of the fluid line. A look-up table may be provided in the processor so that certain changes in the oscillating frequency may be correlated

with fluid composition and pressure and such changes indicated to the user. For example, an inhomogeneity such as a small air bubble presents a markedly different dielectric load than surrounding liquid and thus its presence in the sensor cavity is accompanied by a large shift in the oscillating frequency.

In one embodiment, volumetric flow data of the fluid in the fluid line is furnished. By knowing the volumetric flow rate, the size of the air bubbles in the fluid line can be assessed.

Other aspects and advantages of the invention will become apparent from the following detailed description and the accompanying drawings, illustrating by way of example the features of the invention.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** shows an exploded, perspective three-dimensional view of a two-port resonant cavity having a fluid line traversing it in accordance with the principles of the invention and having an electric field in a focused region parallel to the fluid line;

FIG. **2** is an assembled, top sectional view of the resonant cavity of FIG. **1** with the cover removed;

FIG. **3** is an assembled, side sectional view of the resonant cavity of FIG. **1** taken along lines **3**—**3** of FIG. **2**;

FIG. **4** is a cross-sectional view of a resonant cavity having a fluid line traversing it such that an electric field in a focused region is parallel to the fluid line;

FIG. **5** is a diagram of a microstrip resonator with a fluid line segment disposed such that it forms a part of its dielectric load;

FIG. **6** is a cross-sectional view of a modified stripline resonator with a fluid line segment disposed such that it forms a part of its dielectric load;

FIG. **7** is a diagram of a fluid line segment disposed so that it forms a part of the dielectric loading of a microstrip delay line;

FIG. **8** is a block/schematic diagram of an in-line fluid monitor system in accordance with the principles of the invention;

FIG. **9** is a chart of the output voltage of a discriminator versus frequency;

FIG. **10** is a block diagram of an in-line fluid system which includes volumetric flow data of the fluid in a fluid line and an in-line fluid monitor coupled to the same fluid line and a common processor to determine the size of gas bubbles;

FIG. **11** is a sample graph illustrating the change in oscillating frequency due to changes in concentration of fluid constituents; and

FIG. **12** presents another embodiment of an in-line fluid monitor system utilizing a dielectric resonator oscillator as the signal source.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

Referring now to the drawings with more particularly, wherein like reference numerals designate like or corresponding elements among the several views, there is shown in FIGS. **1** through **3** a resonant cavity device **10** having a cavity **12** formed by five walls **14** which in this embodiment are formed of an electrically conductive metal such as copper or brass. A cover **16** is fitted onto four of the walls **14** to form a sixth wall thereby making cavity **12** a closed cavity.

The cavity device **10** includes a focusing post **18** placed within the cavity **12** for focusing energy imparted to the cavity into a segment of fluid line **20** which is mounted such that it proceeds through the cavity device **10** and is proximate to the focusing post **18**. As shown more clearly in FIG. **1**, the cover **16**, two of the sides **14** and the focusing post **18** have been formed with indentations so that the fluid line **20** can be supported while it proceeds through the cavity device **10**. These indentations effectively form a channel through the cavity device **10** in which the fluid line segment is disposed. In the case where fluid pressure is measured, the fluid line is compliant and its expansion or contraction must not be hindered due to physical contact with either the focusing post **18** or the cavity cover **16**. Also shown in FIGS. **1** though **3** is the use of two probes **22** and **24** which are used to feed energy to and from the cavity **12**. In this embodiment, the probes are coupling loops supported in the cavity **12** by respective cables **26** and **28** or supported by other means.

An alternative resonant cavity embodiment incorporates a cavity constructed of plastic with metallized inner surfaces. Another alternative resonant cavity embodiment incorporates a plastic-filled cavity with metallized outer surfaces and a metallic focusing post electrically connected to the metallized outer surface. In these cases, provision must be made to accommodate the fluid-filled line to be disposed therein as well as the two probes.

The cavity device **10** forms a resonant cavity **12** energized by a transmitter probe **22**. The receiver probe **24** couples energy from the cavity for processing as will be described in more detail below. Such a cavity will resonate at a frequency dependent upon the cavity size, configuration and the dielectric properties of the "medium" in the cavity **12**. In addition, other resonant characteristics such as bandwidth and Q as well as the impedance of the cavity can be affected by dielectric loading. The captured segment of fluid line and fluid therein form a part of the cavity medium and changes occurring in that fluid line and fluid will affect the dielectric properties of the medium. Thus, changes in the fluid composition and changes in the volume of segment **20** of the fluid line will alter the dielectric loading and cause a consequent change in the resonant characteristics of the cavity **12**. By monitoring the cavity's resonant characteristics, certain fluid properties can be determined.

In one embodiment, the transmission probe **22** imparts a small amount of electromagnetic energy (less than one milliwatt) to the cavity at a microwave frequency; for example 5.0 GHz. Because of the transmission probe's geometry, size, location and orientation, when energy is introduced into the cavity at or near its fundamental resonant frequency, the focusing post **18** will cause a localized electric field to be produced in the region between the top of the post **18** and the cover **16**. The electric field is focused on the segment of fluid line **20** and the fluid therein. In this embodiment, the cavity structure is such that the fluid line is disposed perpendicular to the electric field. One purpose of the focusing post is to cause the fluid line segment **20** to be the major determinant of the dielectric loading of the cavity **12**. Small changes in the fluid line **20** and fluid therein will significantly affect the dielectric loading of the cavity. Thus, the sensitivity of the monitor is increased.

The cavity **12** acts as a filter in that energy at or near particular frequencies, such as the fundamental resonant frequency of the cavity, will be efficiently imparted to the fluid. The resonant characteristics of the cavity,

which is surrounding the fluid line segment filled with a fluid, will remain stable as long as the parameters which are responsible for determining the cavity's resonant characteristics remain constant. However, should the dielectric properties of the fluid within the focused region of the electric field within the cavity change, or the volume of the fluid within the focused region of the electric field change, an accompanying change in resonant characteristics will also occur.

Although shown as a rectangularly shaped cavity with coupling loops for feeds, other cavity shapes and feed devices may be used. Those shown in FIGS. **1** through **3** are for purposes of illustration only and depict a cavity structure wherein the fluid line **20** is disposed perpendicular to the electric field in the focused region. In FIG. **4**, a cross-sectional view of an alternative resonant cavity structure **30** is shown in which the fluid line **20** is disposed parallel to the electric field in the focused region. Such a sensor is constructed in a manner which allows the fluid line to be properly installed; for example, the cavity may be split symmetrically along the axis of the fluid line **20** into two halves **32** and **34** and a clamping mechanism (not shown) provided for electrical contact and mechanical stability.

Additionally, although a cavity is shown as the dielectrically-loaded electromagnetic filter device used, other filter devices may be used. For example, in applications where large changes in fluid composition or large pressure excursions, such as +800 to −250 mm mercury, need to be monitored, a sensor based on the monitoring of dielectric loading, but of lower sensitivity than the cavity type, can be utilized.

In another embodiment, instead of using a cavity resonator with the electromagnetic field enclosed, an open planar microstrip or stripline resonant structure can be employed. In FIG. **5**, there is shown a microstrip resonator device **36** with the resonant microstrip line element **38** supported by the substrate **40**, which is backed by the ground plane **42**. Two microstrip line elements **44** and **46** form the input and output coupling ports. The fluid line segment **20** is disposed over the resonant element **38** at or near the region of maximum electric field and thus forms a part of the dielectric loading of the resonator. When resonating in its fundamental resonant mode, for example, the electric field that is generated has its maximum amplitude at the center of the resonating element **38**. Any changes in dielectric loading caused by a change in fluid composition, the presence of air or other gas, or changes in fluid volume will therefore perturb the resonant characteristics in an identifiable manner.

Although FIG. **5** illustrates an open microstrip resonator, a shielded configuration may be used in another embodiment. In FIG. **6**, a modified stripline resonator **48** is illustrated. In this case, a resonant stripline element **50** is supported by the lower substrate **52**, which is backed by a ground plane **54**. Two stripline elements **56** and **58** form the input and output coupling ports. The fluid line segment **20** is disposed over the resonant element **50** at or near the region of maximum electric field and is sandwiched between the lower substrate **52** and the upper substrate **60**. The upper substrate **60** is backed by a second ground plane **62**. The two ground planes **54** and **62** together provide greater shielding than in a microstrip structure. An appropriate channel must be cut into the upper substrate **60** to accommodate the fluid line segment. As the fluid line **20** is disposed such that it forms a major part of the dielectric loading of the resonator, changes in the composition and/or pressure of the fluid within will perturb the structure's resonant characteristics.

In yet another embodiment, a dielectrically-loaded electromagnetic transmission device may be employed as the sensing element rather than a filter device. In FIG. **7** there is shown a microstrip delay device **64** over which is disposed the fluid line segment **20**. The transmission element **66** is supported by the substrate **68** which is backed by ground plane **70**. The fluid line segment **20** is disposed in a manner which allows the electromagnetic field created by the energized transmission element **66** to encompass a significant portion of the fluid line segment. Thus the fluid line segment and fluid within form a part of the dielectric loading of the delay device. An alternative to the microstrip transmission device would be a modified stripline transmission device. Although, in these cases, the transmission devices do not act as filters, as in the cavity embodiment, they do use the dielectric loading imparted by the fluid line segment and fluid therein and may be used to determine changes in the fluid composition and/or pressure.

Each fluid possesses particular dielectric properties. When different fluids are mixed together, a new fluid is formed that will probably possess different dielectric properties from the two separate fluids. Moreover, gases, such as air, possess radically different dielectric properties than that of liquids. Water, for example has a dielectric constant approximately eighty times higher than that of air. Thus, referring to the resonant cavity embodiment of FIGS. **1** through **3**, the presence of air bubbles in a liquid will cause a radical change in the dielectric loading of the cavity. This change in dielectric properties will cause a significant and identifiable change in the filtering characteristics of the cavity.

Referring again to FIGS. **1** through **3**, when compliant tubing is used as the section of fluid line **20**, an increase or decrease in fluid pressure will cause the tubing to expand or contract accordingly and the fluid volume within the cavity at the focused region of the resonant cavity will change. This change in volume causes a change in the dielectric loading of the resonant cavity and will cause a change in the cavity's filtering characteristics. By this arrangement, the in-line fluid monitor can determine fluid pressure.

A schematic/block diagram of an in-line fluid monitor system **72** in accordance with the principles of the invention is shown in FIG. **8**. The circuit **72** generally comprises three main functional blocks, the sensor oscillator block **74**, the discriminator block **76**, and the processing block **78**. The sensor block **74** contains the resonant cavity **12**.

The sensor oscillator block **74** is used to provide a signal representative of the fluid characteristics (e.g., presence of air or other gas in the line, changes in fluid composition, pressure), and comprises a sensor delay element **80** connected to the sensor output cable **28**, a bandwidth-limited amplifier **82** connected to the delay element **80**, a coupler **84** which receives the output of the amplifier **82** and directs a portion of the output from the amplifier **82** to the input cable **26** of the resonant cavity **12**. The coupler **84** also directs a portion of the output from the amplifier **82** to the discriminator circuit **76**. Thus, a circuit is formed in sensor oscillator block **74** wherein the energy of the amplifier is coupled to the resonant cavity **12** via the coupler **84** and the input cable **26** and coupling loop **22**. Energy is then coupled through the cavity **12** which surrounds a portion of the

fluid path **20** and the fluid. The output coupling loop **24** then couples energy from the cavity **12** to the delay element **80** and to the input of the amplifier **82**. The power level in the sensor oscillator block **74** is low (less than one milliwatt in one embodiment) so that the fluid characteristics can be "interrogated" and the fluid not appreciably heated. In the preferred embodiment, the bandwidth of amplifier **82** is limited such that oscillations in the primary (fundamental) resonant mode of the cavity are sustained and oscillations at higher modes are suppressed.

In order to sustain oscillation, the output of the amplifier **82** must supply positive feedback to its input. An additional requirement for oscillation is that the gain of the sensor oscillator block **74**, the "loop gain", must be greater than one, that is, the gain in the amplifier must be greater than the sum of the losses of the components in the loop. This gain is sufficient to initiate stable oscillation quite rapidly, on the order of microseconds or less. The frequency of the oscillator block is determined primarily by the resonant characteristics of the cavity and the total delay around the loop from amplifier output to amplifier input, as well as the gain of the loop. Thus, changes in the dielectric loading of the cavity due to changes in fluid composition, including the presence of air of other gas, and/or pressure (volume) within the focused region of the cavity will result in a change in oscillation frequency.

The discriminator block **76** processes the oscillation signal and includes a signal splitter **86** which receives a portion of the output from the sensor amplifier **82** through the coupler **84** and a discriminator input line **88**. The discriminator signal splitter **86** has an output **90** to a delay element **92** which is connected to one port of a phase detector **94**, such as the R.F. port of a double-balanced mixer, and the discriminator signal splitter also has an output **96** which is connected to the L.O. port of the double balanced mixer. The output from the double balanced mixer **94** (phase detector) is directed to a low frequency amplifier **98** capable of amplifying signals from D.C. to a frequency consistent with the rate of fluid property changes which are being monitored. The amplifier **98** has an output which is provided to the signal processor block **78**. The discriminator delay element **92** may alternatively be an appropriate phase shifting reactive element, and although the mixer/amplifier arrangement is provided to convert changes in frequency of the sensor oscillator block **74** to changes in voltage, other types of conversion to a signal suitable for analysis by the signal processor block **78** may also be used.

Operation of the frequency discriminator block **76** can be described by simple mathematical relationships. Given that F is the oscillating frequency of the cavity **12** in Hertz, and that the delay element **92** provides a delay T in seconds, the output of the discriminator is ideally equal to $K\cos(2\pi FT)$, where K is a gain constant depending on the amplitude of oscillation and other circuit details. For example, for F=4.02 GHz and T=20.1 nanoseconds, the discriminator output would be 0.321K. If the oscillating frequency is perturbed to 4.025 GHz, the resulting output of the discriminator would be 0.818K. The delay element **92** is chosen such that the discriminator sensitivity is high in the frequency region of operation. It was found that near frequencies where $\cos(2\pi FT)=0$, the best sensitivity exists; poor sensitivity exists near frequencies where $\cos(2\pi FT)=+1$ or -1. In the specific case outlined above, good sensitivity exists in the range of from 4.0 GHz to 4.025 GHz. FIG. **9** illustrates the relationship between discriminator **76** output voltage and oscillating frequency, for the particular case of T=20.1 nanoseconds in the frequency range of from 4.0 GHz to 4.12 GHz. The range **100** represents a high sensitivity discrimination frequency sensing range, and the range **102** represents a low sensitivity discrimination frequency sensing range.

When normal fluid characteristics exist within the resonant cavity, the delay line **92** in the discriminator block **76** is adjusted so that an output of zero volts is produced at the output of the mixer **94**. Referring again to FIG. **9**, it can be seen that this is the steepest part of the discriminator **76** output, thereby yielding the highest sensitivity.

Once the change in frequency has been converted to a change in voltage, it is amplified **98**. The electrical signals supplied by the discriminator block **76** of the in-line fluid monitor **72** must be processed or analyzed in order to determine and quantify important fluid characteristics. Preferably, this task is implemented by a microprocessor included as part of the signal processor **104**. As a great many instruments currently produced incorporate a microprocessor, the signal processing requirement of this in-line fluid monitor do not represent a large cost. In industry and in hospital fluid delivery, microprocessors perform many computational and control tasks, including communications with the operator of the instrument, allowing the operator to intelligently interact with the instrument in setting desired parameters and limits. Additionally, the microprocessor can easily perform the calculations necessary for "closed loop control", where a desired pressure can be maintained by controlling a pumping mechanism.

In the preferred embodiment, the signal processor **104** receives the electrical output signal from the discriminator block **76**, which represents the oscillating frequency of the resonant cavity **12**. The microprocessor can make determinations based on changes to the oscillating frequency. The existence of a small amount of air in the fluid line segment can be determined by comparing the frequency change to parameters that are either fixed, or "entered in" by the operator of a system which utilizes the in-line fluid monitor. The signal processor **104** includes conventional circuitry and programming for comparing the discriminator output voltage signal with a reference value and for determining the magnitude of perturbation of the oscillating frequency. The signal processor **104** is also preferably constituted so as to provide an output signal either to a display and/or printer unit **106**, such as a display monitor for viewing a real time graph of waveforms of the perturbation of oscillations in the resonant cavity **12**, and the signal processor may be adapted to simultaneously generate a signal to an alarm device **108**, for indicating an alarm condition when the magnitude of perturbation is greater than a predetermined threshold value. The alarm device **108** may aurally indicate an alarm and may also be coupled to the pump controller to automatically stop pump operation.

Referring now to FIG. **10**, a volumetric flow rate data source **110** provides data representative of the volumetric flow rate of the fluid in the fluid line **20** to the signal processor **104**. The in-line fluid monitor **112** is also coupled to the signal processor **104** for providing fluid property data as described above. By knowing the volumetric flow rate of the fluid, the size of detected

bubbles can be assessed. This feature can provide important information in a medical infusion and permits the operator to monitor the infusion process more accurately. This is important in sensitive applications such as infusing fluid to a neonate where even small air bubbles can be fatal. In one embodiment, the volumetric flow rate data is provided by the electronic control system which operates a precision fluid pumping mechanism. In another embodiment, a flow meter may be provided to provide the flow data, such as that disclosed in U.S. Pat. No. 4,938,079 to Goldberg.

Because changes in the dielectric loading can be detected, changes in fluid composition can be detected. Varying concentrations can also be detected as is illustrated in FIG. **11**, where varying concentrations of both sodium chloride **114** and dextrose **116** in water produce a change in frequency. Although not shown, radical changes in frequency accompany the presence of a gas in the liquid.

Another feature of the system is the ability to detect impurities, or contaminants other than air, such as blood. As an impurity passes through the sensor, the filtering characteristics of the cavity change. Blood has a notably different dielectric character than most common infusates, such as sodium chloride solution, so that if blood were to back up into the administration set, its presence could be detected by observing the perturbation of the oscillation frequency. In addition, if two or more different fluids were to be infused successively through the same line, the sensor could detect the perturbation of the cavity loading, assuming the fluids have different dielectric characters, in order to verify that the changeover between fluid types was successful.

In actual practice, the change in dielectric loading caused by the presence of air in the line is so great, that a system of the type shown in FIG. **8** may cease to oscillate while a large amount of air is within the sensing region of the cavity. The range of possible oscillation frequencies at which the system can oscillate depends largely on the bandwidth of the amplifier **82**. This bandwidth must be chosen such that oscillation is supported whenever a bubble of a size which the user needs quantified passes through the cavity. For bubbles that are so large that oscillations cease, the signal processor **104** will preferably initiate an alarm **108**. Depending on the size of the bubble, frequency shifts from 0.1 MHz to 400 MHz have been observed in practice.

When a polyurethane tubing of 0.105" inner diameter and 0.145" outer diameter is utilized, pressure change of the order of ±300 mm mercury, for example, causes oscillating frequency changes in the range of ±3 MHz. This frequency shift is generally less than that caused by the passage of an air bubble of significant size. Pressure change can also be distinguished from air bubble passage because the frequency changes due to pressure change are far less abrupt than those caused by air bubble passage. Although frequency shifts due to fluid compositional changes overlap the range of frequency shifts caused by pressure change, those caused by compositional variations are generally not transient in nature. When a fluid type changeover takes place, for example, the signal processor **104** is programmed to expect a frequency change which is sustained for the duration of the infusion or until a subsequent changeover takes place, rather than a transient change as may take place when the pressure varies.

Another embodiment of an in-line fluid monitor system **118** in accordance with the principles of the invention is illustrated in a schematic/block diagram of FIG. **12**. A stable frequency source **120**, such as a dielectric resonator oscillator (D.R.O.) is used, and is shown driving an amplifier **122** the output of which produces sufficient power for sensor operation, for example 10 dBm. The power from the amplifier is then fed through a quarter-wavelength directional coupler, such as a microstrip coupler **135**, to the input port **137** of a microstrip resonator **36**, which may be similar to that described above in relation to FIG. **5**. The fluid line **20** and fluid therein are positioned to dielectrically load the resonator **36**. The output port **129** of the resonator **36** is coupled to a signal return through a load **130**, which is shown as a fifty ohm resistor in this case.

The directional coupler **135** is arranged such that it is responsive to the reflected power from the input port **137** of the microstrip resonator **36**. Proper termination, shown to be a fifty ohm resistor **139** in this case, is provided at the terminated port **143** of the directional coupler **135**, and the reflected power from the resonator **36** is monitored with a detector, such as a diode detector **132** at the reflected power port **141** of the coupler **135**. The diode detector **132** may be thought of as a first processor and the signal developed by the detector **132** is amplified **134** and coupled to the signal processor **104**. In the embodiment of FIG. **12**, the amplitude of the reflected power at port **141** is affected by the dielectric loading on the resonator **36**. Changes in that dielectric loading caused by fluid property changes will be detected by detector **132** and provided to the processor **104**. The arrangement of FIG. **12** may incorporate a rigid fluid line segment **20** over the resonator **36** and can be used to determine the existence of an air bubble in the fluid line.

From the foregoing, it will be appreciated that the in-line fluid monitor system and method in accordance with the principles of the invention provides a simple, cost effective, and accurate way of detecting fluid properties and pressure. The fluid line may be disposable while the monitor system can be reused.

Although specific embodiments of the invention have been described and illustrated it is clear that the invention is susceptible to numerous modifications and embodiments within the ability of those skilled in the art, and without the exercise of inventive faculty. Thus, it should be understood that various changes in form, detail and application of the present invention may be made without departing from the spirit and scope of the invention.

We claim:

1. An apparatus for monitoring fluid in a fluid line, the apparatus comprising:

a compliant fluid line segment coupled to the fluid line such that the fluid flows through the segment;

a dielectrically loaded electromagnetic sensing device coupled to the compliant segment such that the segment and fluid therein provide dielectric loading on the sensing device, the sensing device providing a sensor signal representative of the dielectric loading;

a flow data source which provides a flow signal representative of the volumetric flow rate of the fluid in the fluid line; and

a processor, having predetermined gas data representative of a gas in the fluid, which receives the sensor signal from the sensing device, provides a loading signal representative of the dielectric loading, compares the loading signal to the predetermined

gas data to detect the presence of the gas and upon detecting the gas, determines the time period that the sensing device detects the gas and processes the detection time period with the flow signal and provides a signal indicative of the size of the gas bubble.

2. The apparatus of claim 1 wherein:

the predetermined data comprises data representing a solute in the fluid; and

the second processor compares the loading signal to the predetermined solute data and provides a signal representative of the concentration of the solute in the fluid.

3. An apparatus for monitoring fluid in a fluid line, the apparatus comprising:

a dielectrically loaded resonant electromagnetic sensing device coupled to a segment of the fluid line such that the segment and fluid therein form part of the dielectric loading on the sensing device, the sensing device provides a sensor signal representative of the dielectric loading;

a flow data source which provides a flow signal representative of the volumetric flow rate of the fluid in the fluid line;

a processor, having predetermined gas data representative of a gas in the fluid, which receives the sensor signal from the sensing device, provides a loading signal representative of the dielectric loading, compares the loading signal to the predetermined gas data to detect the presence of the gas and upon detecting the gas, determines the time period that the sensing device detected the gas, processes the detection time period with the flow signal and provides a signal indicative of the size of the gas bubble.

4. The apparatus of claim 3 wherein the dielectrically loaded resonant device comprises a resonant cavity having an electric field and a focusing post which focuses the electric field onto the segment of fluid line such that the segment provides a substantial part of the dielectric loading of the cavity.

5. The apparatus of claim 3 wherein:

the resonant device comprises a microstrip resonator;

the fluid line segment is disposed to provide dielectric loading to the microstrip resonator; and

the sensor signal represents the dielectric loading of the microstrip resonator.

6. The apparatus of claim 3 wherein:

the resonant device comprises a stripline resonator;

the fluid line segment is disposed to provide dielectric loading to the stripline resonator; and

the sensor signal represents the dielectric loading of the stripline resonator.

7. An apparatus for monitoring fluid in a fluid line, the apparatus comprising:

a dielectrically loaded electromagnetic sensing device having a planar structure and coupled to a segment of the fluid line such that the segment and fluid therein provide dielectric loading on the sensing device, the sensing device provides a sensor signal representative of the dielectric loading;

a processor having predetermined gas data representative of a gas in the fluid, which receives the sensor signal from the sensing device, provides a loading signal representative of the dielectric loading, compares the loading signal to the predetermined gas data to detect the presence of the gas and provides a signal indicative of the gas detection.

8. The apparatus of claim 7 wherein the planar sensing device comprises a resonant device, a resonant characteristic of which varies in response to the dielectric loading;

the segment is disposed to provide dielectric loading to the resonant device;

the sensor signal is responsive to the resonant characteristic; and

the processor provides the loading signal in response to the resonant characteristic.

9. The apparatus of claim 8 wherein:

the planar sensing device comprises a microstrip resonator;

the segment is disposed to provide dielectric loading to the microstrip resonator; and

the sensor signal represents the dielectric loading of the microstrip resonator.

10. The apparatus of claim 8 wherein:

the planar sensing device comprises a stripline resonator;

the segment is disposed to provide dielectric loading to the stripline resonator; and

the sensor signal represents the dielectric loading of the stripline resonator.

11. The apparatus of claim 7 wherein:

the planar sensing device comprises a transmission device, the delay through which varies in response to the dielectric loading;

the segment is disposed to provide dielectric loading to the transmission device;

the sensor signal is responsive to the delay through the transmission device; and

the processor provides the loading signal in response to the delay.

12. A method of monitoring fluid in a fluid line, comprising the steps of:

forming a segment of the fluid line of complaint material;

sensing the volumetric flow rate of the fluid in the fluid line and providing a flow signal representative of the rate;

disposing the compliant segment such that it and the fluid therein provide dielectric loading on a sensing device;

sensing the dielectric loading of the sensing device;

providing a loading signal which is representative of the sensed dielectric loading of the sensing device;

comparing the loading signal to predetermined gas data which is representative of a gas in the fluid to detect the presence of the gas and upon detecting the gas, processing the time period that the gas is detected with the flow signal and providing a signal indicative of the size of the gas bubble passing through the fluid line in response to said comparison.

13. A method of monitoring fluid in a fluid line, comprising the steps of:

disposing a segment of the fluid line such that it and the fluid therein provide dielectric loading on a resonant electromagnetic sensing device, a resonant characteristic of which varies in response to the dielectric loading;

sensing the resonant characteristic of the sensing device;

providing a loading signal which is representative of the sensed resonant characteristic of the sensing device;

sensing the volumetric flow rate of the fluid in the fluid line and providing a flow signal representative of the rate; and

comparing the loading signal to predetermined gas data which is representative of a gas in the fluid, to detect the presence of the gas and upon detecting the gas, processing the time period that the gas is detected with the flow signal and providing a signal indicative of the size of the gas bubble passing through the fluid line in response to the comparison.

14. The method of claim **13** further comprising the steps of:

providing a resonant cavity as the resonant device;

forming an electric field in the cavity; and

focusing the electric field onto the compliant segment of fluid line such that the segment forms a substantial part of the dielectric loading of the sensing device.

15. The method of claim **13** further comprising the steps of:

providing a microstrip resonator as the resonant device;

disposing the fluid line segment to provide dielectric loading to the microstrip resonator;

monitoring a resonant characteristic of the microstrip resonator; and

providing the loading signal in response to the resonant characteristic.

16. The method of claim **13** further comprising the steps of:

providing a stripline resonator as the resonant device;

disposing the fluid line segment to provide dielectric loading to the stripline resonator;

monitoring a resonant characteristic of the stripline resonator; and

providing the loading signal in response to the resonant characteristic.

17. An apparatus for monitoring fluid in a fluid line, the apparatus comprising:

a dielectrically loaded transmission electromagnetic sensing device coupled to a segment of the fluid line such that the segment and fluid therein form part of the dielectric loading on the sensing device, the sensing device having a delay which varies in response to the dielectric loading and provides a sensor signal representative of the delay;

a flow data source which provides a flow signal representative of the volumetric flow rate of the fluid in the fluid line;

a processor, having predetermined gas data representative of a gas in the fluid, which receives the sensor signal from the sensing device and in response to the delay, provides a loading signal representative of the dielectric loading, compares the loading signal to the predetermined gas data to detect the presence of the gas and upon detecting the gas, determines the time period that the sensing device detects the gas, processes the detection time period with the flow signal and provides a signal indicative of the size of the gas bubble.

18. A method of monitoring fluid in a fluid line, comprising the steps of:

disposing a segment of the fluid line such that it and the fluid therein provide dielectric loading on a transmission electromagnetic sensing device, the delay through which varies in response to the dielectric loading;

sensing the delay of the sensing device;

providing a loading signal which is representative of the sensed delay of the sensing device;

sensing the volumetric flow rate of the fluid in the fluid line and providing a flow signal representative of the rate; and

comparing the loading signal to predetermined gas data which is representative of a gas in the fluid, to detect the presence of the gas and upon detecting the gas, processing the time period that the gas is detected with the flow signal and providing a signal indicative of the size of the gas bubble passing through the fluid line in response to the comparison.

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ARAŞTIRMA RAPORU

Başvuru Sahibi: **HAVELSAN HAVA ELEKTRONİK SAN. VE TİC. A. Ş.**		
Başvuru No: **2020/21733**	Başvuru Tarihi: **25/12/2020**	(İlk) Rüçhan Tarihi -
Patent Sınıfı (IPC[8]): **G01N 33/28, C02F 1/00, G01N 27/00 (2006.01)**		

GENEL GÖZLEMLER

Buluş Bütünlüğü

☒ Var (başvuru sadece bir buluş konusunu içermektedir)

☐ (başvuru birden çok buluş konusunu içermektedir) (Bakınız: Bölüm III)

Tarifname Takımı

☒ Rapor aşağıda belirtilen tarifname takımı esas alınarak düzenlenmiştir.

Tarifname 3 sayfa (Orijinal)

İstem 2 adet (Orijinal)

Resim 1 sayfa (Orijinal)

Açıklık

☒ Tüm istemler araştırılabilir niteliktedir.

☐ **...** nolu istemler araştırılabilir nitelikte değildir. (Bakınız: Bölüm IV)

☐ Başvuruyla ilgili diğer görüşler (Bakınız: Bölüm II)

Raporun Tamamlandığı Tarih: **17/03/2022**

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Başvuru Numarası:
2020/21733

A. BULUŞUN PATENT SINIFI (IPC[8])
G01N 33/28, C02F 1/00, G01N 27/00 (2006.01)

B. ARAŞTIRILAN ALANLAR
G01N, C02F

Araştırma esnasında kullanılan elektronik veritabanları ve -uygun olduğu durumlarda- kullanılan bazı anahtar kelimeler

EPODOC, WPI, EPOQUE İngilizce Tüm-metin Veritabanları (TXTE, TXTDE), Türk Patent Veritabanı, Espacenet

"analyze, control, magnetic, mems, micro-electromechanic, sensor, detecort, fluid, lubricant, oil, lubricating, dielectric" ve bunların uygun kombinasyonları

C. İLGİLİ DOKÜMANLAR

Kategori	Dokümanlar	İlgili Olduğu İstem
X	**US2006105467A1** (PREDICT INC) 18 Mayıs 2006 (18.05.2006) Özet, Tarifname: özellikle Paragraf 1, 2	1-2
A	**US6459995B1** (LUBRIGARD LTD) 1 Ekim 2002 (01.10.2002) Tüm Doküman	1-2
A	**US5260665A** (IVAC CORP) 9 Kasım 1993 (09.11.1993) Tüm Doküman -----	1-2

☐ İlgili Dokümanlar sonraki sayfadan devam etmektedir. ☐ Patent Ailesi Üyeleri ekine bakınız.

Kategorilerin Açıklaması:

"X"	Buluşun yeni olmadığını veya buluş basamağı içermediğini tek başına gösteren doküman	"E"	Başvuru tarihinde veya başvuru tarihinden sonra yayımlanan doküman
"Y"	Buluşun buluş basamağı içermediğini başka bir dokümanla bir araya getirildiğinde gösteren doküman	"T"	Buluşun altında yatan ilke veya teoriyi anlamak için belirtilen doküman
"A"	Tekniğin bilinen durumunu belirten ama buluşla tam olarak ilgili olmayan doküman	"L"	Başka nedenlerle belirtilen doküman
"O"	Yazılı olmayan açıklama	"D"	Başvuruda belirtilen doküman
"P"	Başvuru tarihi ile rüçhan tarihi arasında yayımlanan doküman	"&"	Aynı patent ailesinin dokümanı

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