United States Patent [19]

Hummel

[11] **3,879,658**

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[54] **APPARATUS FOR MEASURING MAGNETIC SUSCEPTIBILITY**

[76] Inventor: **Heinz Hummel,** Fasanenweg 14, 6240 Konigstein-Johanniswald, Germany

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[52] **U.S. Cl.** **324/36**

[51] **Int. Cl.** **G01r 33/12**

[58] **Field of Search** .... 324/36; 73/27 A

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Primary Examiner—Stanley T. Krawczewicz
Attorney, Agent, or Firm—Ralf H. Siegemund

[57] **ABSTRACT**

Two magnetic circuits are provided with two gaps penetrated normally by similar magnetic fields and having similar zones of inhomogeneities as effective on two test bodies which are interconnected rigidly but in a manner permitting deflection, rotational or linear. The gaps are surrounded by gas, and one of the test bodies forms a combined system with an additional material as far as paramagnetically or diamagnetically produced deflective forces for that body is concerned. The gas may be a reference gas with the additional material being a liquid sample, or the gas may be a test gas to be investigated while the additional material is a reference gas, encapsuled in that one body; the other body is either hollow with access for the test gas to its interior or solid, but smaller. The interconnected bodies experience different deflections in the two gaps resulting in a deflection which is monitored and converted into an amplified control current which, in turn, is fed back to unbalance the magnetic fields in the gaps for returning the bodies to the equilibrium position. The current needed for unbalancing the fields is an indication of magnetic susceptibility of the sample.

29 Claims, 16 Drawing Figures

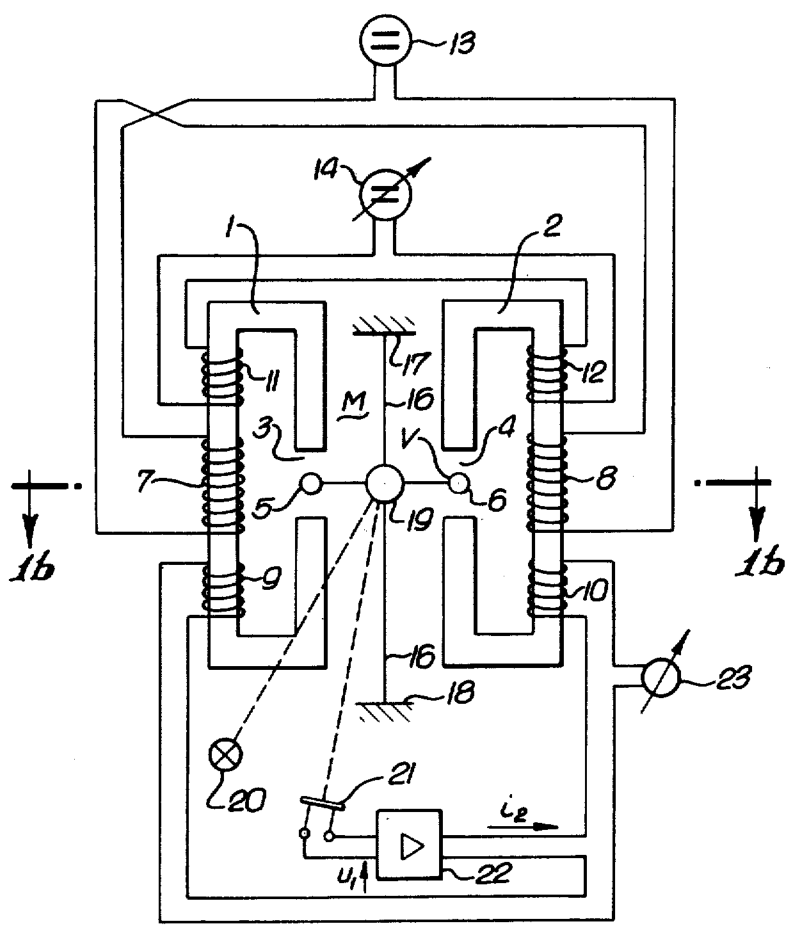


FIG. 1a.

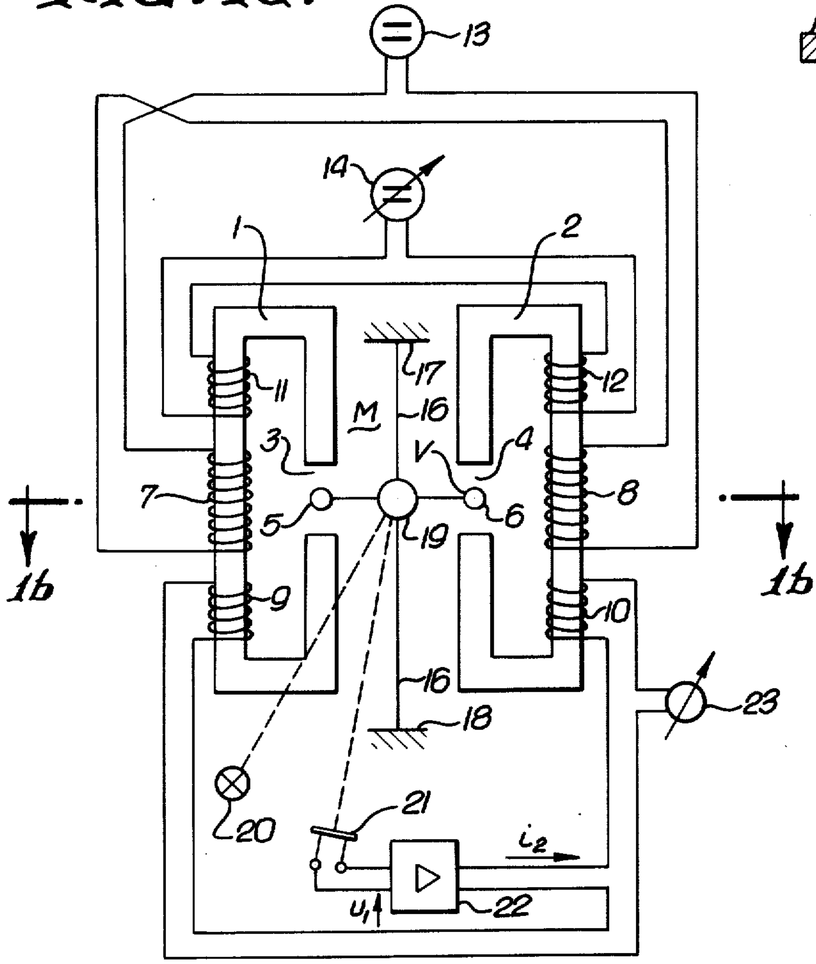


FIG. 1b.

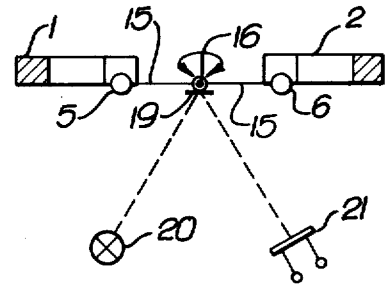


FIG. 2.

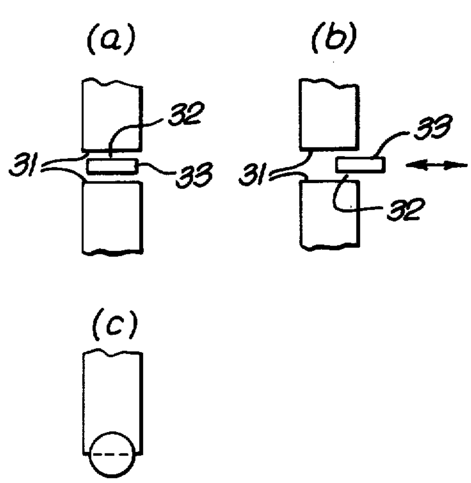


FIG. 3.

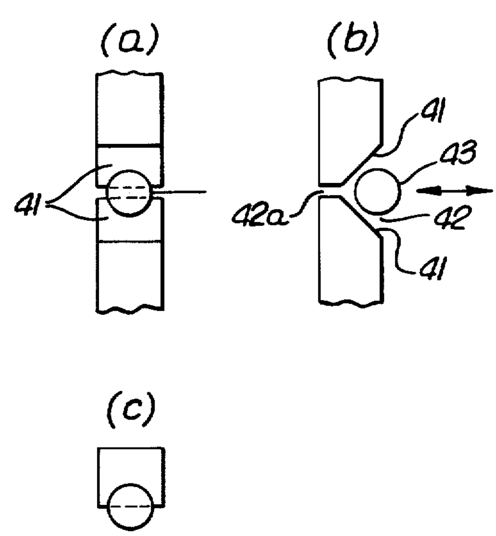


FIG. 4a.

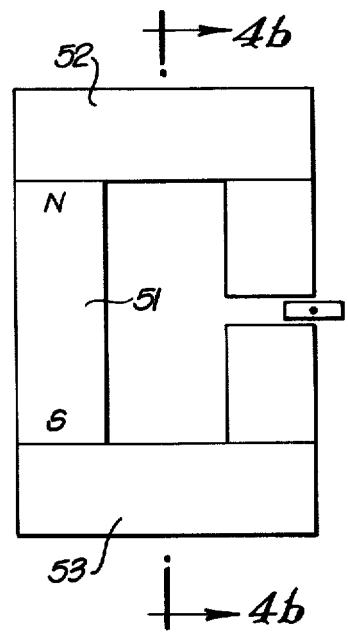


FIG. 4b.

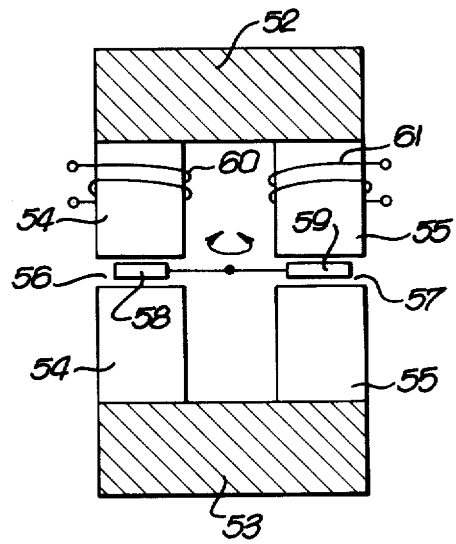


FIG. 5a.

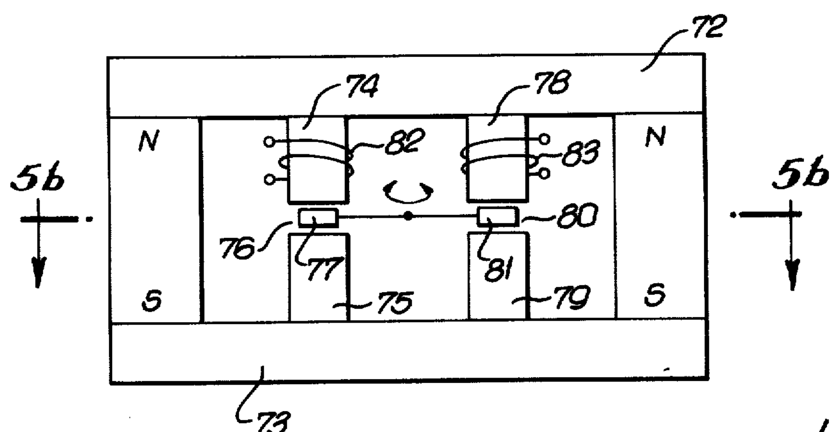


FIG. 5c.

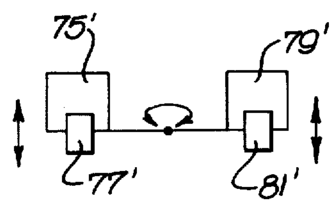


FIG. 5b.

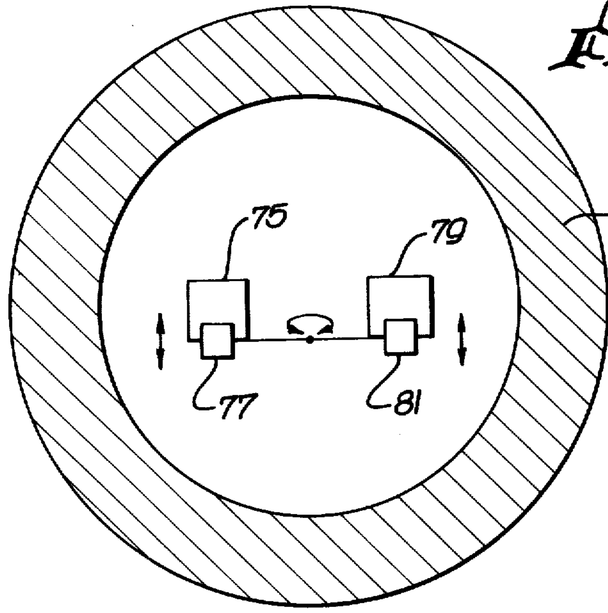


FIG. 6b.

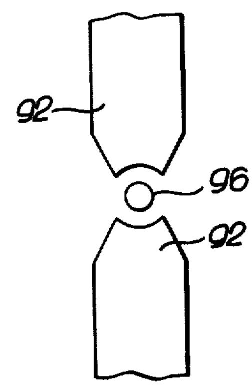


FIG. 6a.

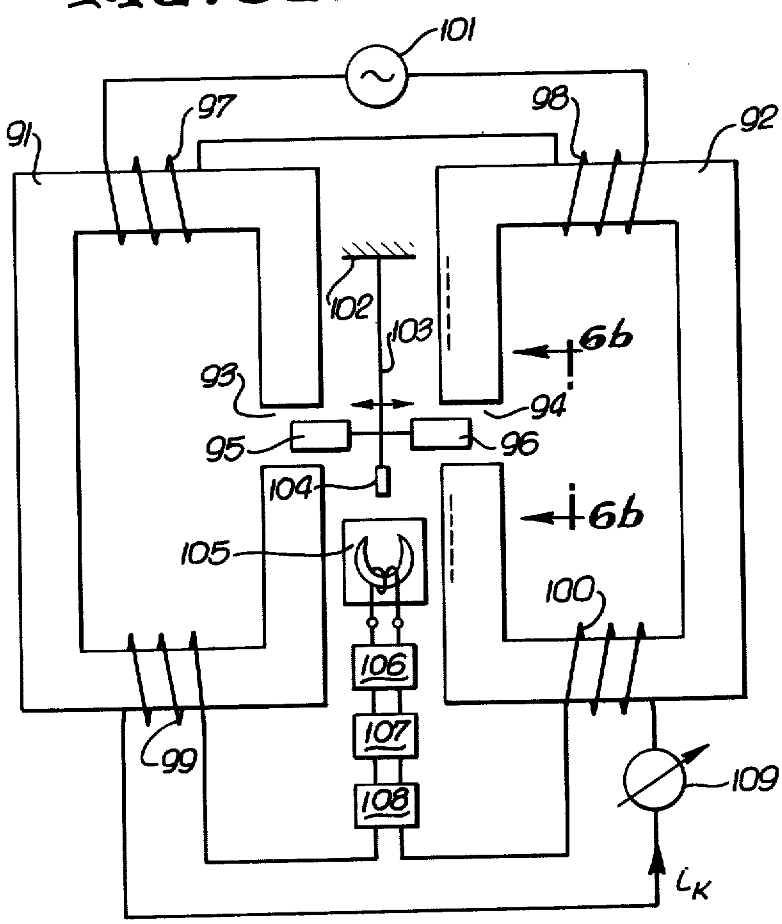


FIG. 7.

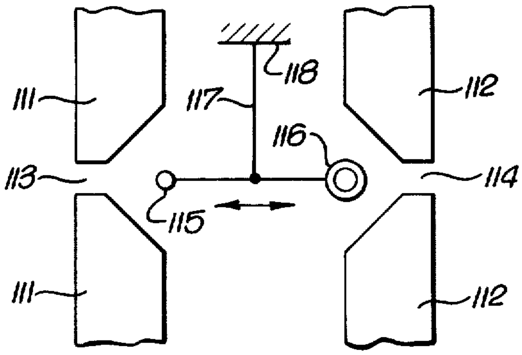


FIG. 7a.

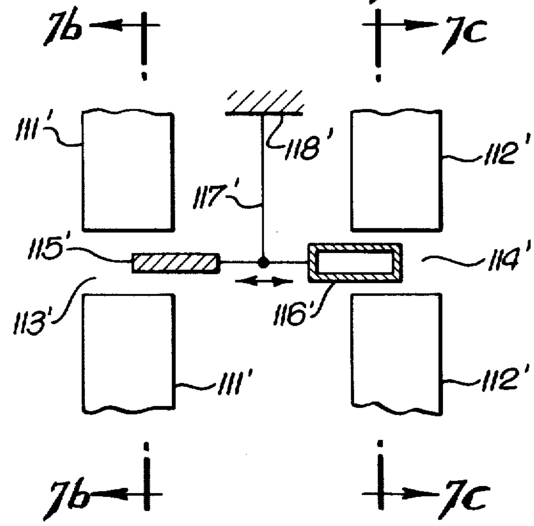


FIG. 7b.

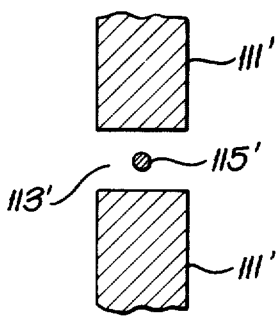


FIG. 7c.

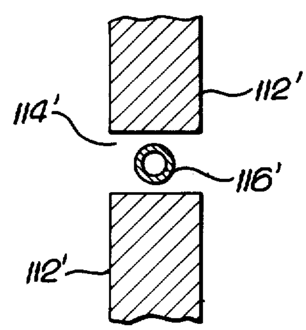
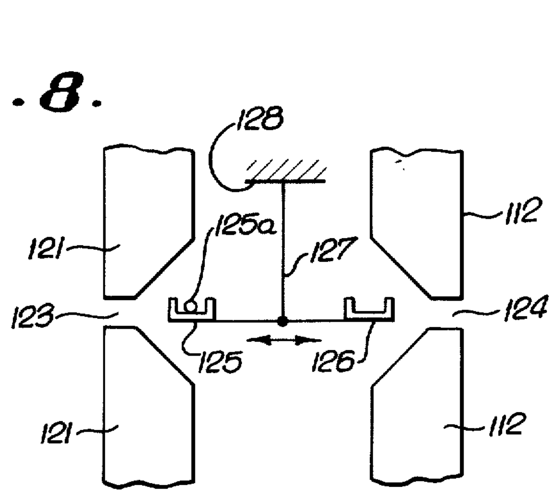


FIG. 8.



APPARATUS FOR MEASURING MAGNETIC SUSCEPTIBILITY

BACKGROUND OF THE INVENTION

The present invention relates to measuring magnetic susceptibility of material, such as mixtures of gases, liquids, etc.

The state of the art in this particular field includes particularly (1) a Handbook by Hengstenberg, Sturm and Winkler "Messen und Regeln in der chemischen Technik", 1964; (2) U.S. Letters Patent No. 2,416,344; (3) German printed patent application No. 1,951,342; (4) German printed patent application No. 2,000,212; and (5) a report by Munday in the Society of Instrument, Technology Conference in Swansea/England, September 1957.

The various methods as described in these prior art publications exhibit certain drawbacks resulting from the specific employment in each instance. Either they operate on the basis of deflection of a pointer or the like, or they operate on the basis of compensation and nulling. In the first instance, it is unavoidable to have significant dependeny of the measuring value on the operating parameters in the instrument such as strength of the magnetic field, its gradient, gain etc., The nulling or compensation method as practiced, for example, by Munday, suffers in that the zero point shifts significantly upon changes in the field strength with time, for example, due to aging or upon changes in ambient temperature or for other reasons. Additionally, the test body assembly (dumbbell) is difficult to make, particularly with regard to the wire for the electric current loop around the test bodies and further with regard to feeding current to such a loop. Mass production of such an instrument is close to impossible.

SUMMARY OF THE INVENTION

It is an object of the present invention to avoid the aforementioned drawbacks and to provide for a new and improved system for measuring magnetic susceptibility under additional advantages. Moreover, the measurements particularly as far as related to gas mixtures, should be more readily amenable to adaptation to conditions outside of the laboratory.

In accordance with the preferred embodiment of the present invention, the combination of the following features is suggested:

1. two magnetic circuits are provided, each having a measuring gap traversed by a magnetic field;

2. two test bodies are respectively arranged in or at the gaps, one body per gap, whereby the two test bodies are either similar or have similar integral volume susceptibility;

3. the two test bodies are arranged in similar field zones of the two gaps;

4. the two bodies are mechanically rigidly interconnected to establish a dumbbell configuration;

5. the two test bodies are provided to cooperate in conjunction with a reference gas so that the deflective forces as acting on the test bodies may differ, but only on account of the difference in magnetic susceptibility between test material and reference gas. Specific features of the invention relate to aspects as to how to provide for such differences to materialize;

5a. The two test bodies are similar and open containers, one of them receiving a test sample (liquid or solid) while both of them are surrounded by a reference gas, or one of the containers is completely closed for containing a reference gas while the other one is either open for penetration by surrounding test gas, or solid. In the latter case, the solid test body is smaller in displacement volume than the reference body, but they have similar body mass.

6. The dumbbell structure is suspended and positioned so that for similar field strength in the gaps, forces or torques acting on the dumbbell and resulting from occupancy of space in the fields by the solid material of the test bodies, have a zero resultant of force and, thus, tend to balance the dumbbell in an equilibrium position. Only those forces or torques are effective for obtaining a dumbbell displacement, which result from the effect of the sample or from susceptibility difference of sample and reference material or from the difference in effective displacement volume.

7. The material for the test bodies is chosen so that the magnetic effect (force) as acting on the individual body is larger than the respective effect and force acting on the measuring and test sample or acting by virtue of the larger displacement as resulting from the one larger body. The force ratio is to be about 1:10 or even 1:100, for the respective largest magnetic effect of the effective range for liquid sample or gas masses.

8. Assuming all conditions outlined under points 1 to 7 are met, the magnet fields acting in the gaps on the bodies, samples and gases can be changed to provide for compensation of these resulting forces. This is specifically carried out by means of a position scanner for the dumbbell, amplification of the scanner pick-up and feedback for control of a current flow in at least one compensating coil. The compensation is different in the two magnetic circuits, because the test body-gas-sample-magnetic field interactions in the two gaps of the two circuits differ, and it is the function of that unequal compensation to offset the imbalance of resulting interaction in the gaps for the stated reasons. For reasons of point 7, only a relatively small magnetic compensating field, i.e., a small field imbalance is needed in the gaps to obtain a large restoring force on the test body material to offset the imbalance of the differences in test body-reference and test body-test material interactions.

9. The current flowing through such a compensating coil represents the susceptibility of the sample or test gas to be measured.

The basic aspect of the invention is to be seen in that the susceptibility of the test gas or sample, i.e., the difference in susceptibility between, e.g., test and reference gases, is related to the constant susceptibility of the test bodies under conditions bringing forth a deflection of the dumbbell, and compensation is provided for under conditions in which the test body material itself is no longer an influence parameter, provided for the two test bodies themselves produce a zero deflective force resultant. This method provides for the following advantages:

The equipment does not require loops around the dumbbell bodies so that there is no problem of feeding current into such a displaceable system (see prior art reference 5, supra). This is not only a simplification in the construction, but also important for corrosion proofing of the system. Moreover, there is no danger of electrically overloading the system which is of advantage if, as is frequently the case, explosion proofing of the instrument is required.

In each of the cases considered, the magnetic effects on the test body, on the sample, on test gas, on the reference gas and/or on the displaced test gas depends on the product of magnetic field strength and field gradient. Therefore, uniform changes in the magnetic induction, and any resulting changes in the effective field and gradient in the gaps, have very little influence on the equilibrium position of the dumbbell and on the measuring output. Such changes in the induction must be expected upon changes in ambient temperature and upon aging. The prior art dumbbell constructions under reference 1 with compensation as per reference 5, provide a compensation which is proportionate to the gradient only, not the field itself, while the force acting on the displaced gas is proportional to the product of field and gradient.

DESCRIPTION OF THE DRAWINGS

While the specification concludes with claims particularly pointing out and distinctly claiming the subject matter which is regarded as the invention, it is believed that the invention, the objects and features of the invention and further objects, features and advantages thereof will be better understood from the following description taken in connection with the accompanying drawings in which:

FIG. 1*a* is a schematic side view and circuit diagram of an instrument in accordance with the preferred embodiment of the invention;

FIG. 1*b* is a view along lines 1*b*—1*b* in FIG. 1*a;*

FIGS. 2 and 3 show the magnetic field gap with test bodies in two configurations, wherein in each Figure section (a) shows a side view, section (b) shows a front view and section (c) shows a section view through the measuring gap, transverse to the magnetic field;

FIGS. 4*a* and 4*b* show side and plan views of a modification of the system with permanent magnet energization rather than electromagnetically of FIG. 1*a;*

FIG. 5*a* is a section view into a modified system with permanent magnetic energization;

FIG. 5b is a section view along lines 5*b*—5*b* of FIG. 5*a;*

FIG. 5*c* shows a modification of a detail in FIGS. 5*a*, 5*b;*

FIG. 6*a* shows an instrument in plan view with a.c. energization (rather than d.c. as in FIG. 1) and an inductive pick-up;

FIG. 6*b* shows a view along lines 6*b*—6*b* of FIG. 6a;

FIG. 7 shows a modification in the test body construction useable also in the instrument configurations of FIGS. 1a, 4*a*, 5*a* and 6*a;*

FIG. 7*a* shows a modification of the test body construction of FIG. 7 for use in parallel gaps;

FIGS. 7*b* and 7*c* are respectively views along lines 7*b*—7*b* and 7*c*—7*c* in FIG. 7*a;* and

FIG. 8 shows a further modification in the test body construction also usable in any of the instrument configurations of FIGS. 1*a*, 4*a*, 5*a* and 6*a*.

Proceeding now to the detailed description of the drawings, FIGS. 1*a* and 1*b* show two ferromagnetic yokes 1 and 2, each establishing a measuring gap, denoted respectively by reference numerals 3 and 4. Test bodies 5 and 6 are disposed in these gaps. These test bodies are of hollow construction, for example, hollow spheres or flat hollow cylinders made of glass or quartz and each defines a gas chamber.

Test body 5 has small apertures for gas exchange flow with the surrounding gas M to be investigated. Body 6 serves as reference and is sealed and contains a reference gas V. Alternatively, body 6 can be evacuated. However, from standpoint of establishing a reference, this is actually not a true or qualitative alternative, because the decisive point is that the susceptibility of the interior of body 6 must be a known quantity so that an evacuated space differs from a reference gas only quantitatively. Except for their content, the two bodies 5 and 6 are to be similar as much as possible. Both of them should be made of a material of low magnetic susceptibility and quartz is quite suitable here.

Yoke element 1 carries coils 7, 9 and 11; yoke element 2 is analogously provided with coils 8, 10 and 12. Again, it can be said that these coils are similar in pairs, i.e., coil 7 should be similar to coil 8, coil 9 should correspond to coil 10 and the same similarity should prevail as between coils 11 and 12. Coils 7 and 8 each should have a number of turns large as compared with the number of turns of the other coils.

Coils 7 and 8 are connected serially to each other and across a source 13 of d.c. potential, while coils 11 and 12 are also connected serially to each other and across a second source of d.c. potential, 14. As schematically depicted in the wiring diagram, the coils 7 and 8 provide for a d.c. magnetization of similar directions whereas the fields as provided by trimmer coils 11 and 12 are opposed. Source 14 is adjustable to obtain adjustment in the trimming function. It may be advisable to provide for a switch (not shown) which permits easy change in polarity of the voltage as applied by source 14 to the coils 11, 12, because it is basically uncertain in which direction trimming is needed. In either case, it is the function of the trimming coils to provide for supplementing magnetic fields so that the magnetic fields in the two gaps are similar in spite of any unintentional structural differences in the two magnetic circuits.

Bodies 5 and 6 are physically interconnected by a bar 15 or the like, to establish a dumbbell-like structure. This structure is suspended by a torsion fiber or filament 16 being connected to the casing of the instrument or otherwise at 17, 18. The suspension is such that the fringes of the magnetic fields in the gaps respectively traverse the centers of the test bodies, as can be seen from FIG. 1*b*. This is the normal, zero position and that this position is dynamically maintained will be explained shortly.

The center of the dumbbell carries a mirror 19 for scanning the angular disposition of the test bodies in conjunction with a stationary light source 20. The optical system may include suitable lenses or the like for establishing a beam (dashed line).

The scanning system includes, additionally, a twin or dual photoelement detector 21, cooperating with an amplifier 22 in a differential mode. The differential input voltage for amplifier 22 is denoted U_1, and the amplifier 22 provides a corresponding, amplified output current i_2 serving as compensating current in serially connected coils 9 and 10, and flowing also through an indicating instrument 23. The compensating coils 9 and 10 are connected so that their magnetic fields oppose the respective principle, energizing fields as provided by the principle coils 7 and 8. In other words, current flow through both coils 9 and 10 tends to unbalance the balanced magnetic fields in the two gaps 3 and 4.

The gaps 3 and 4 and the dumbbell system 5, 6, 16–19 are enclosed in a casing for establishing a chamber into which measuring or sample gas M is fed. That gas M particularly will penetrate the gaps 3 and 4 and interact magnetically with the magnetic fields therein, and will be surrounded by the test bodies 5 and 6.

In order to explain the function of the arrangement, it shall be assumed at first that the gas M has negligible magnetic susceptibility. It may be, for example, nitrogen. It may be assumed further that the reference gas V is also nitrogen. Presently, it shall be neglegted that nitrogen is actually diamagnetic. A magnetic field is provided in the gaps 3 and 4 by operation of current flow in the principle energizer coils 7 and 8. If the bodies 5 and 6 are made of diamagnetic glass, that magnetic field will tend to push the bodies 5 and 6 out of their respective gaps. At this point, it is assumed that the effective forces are similar so that the resulting torque on the dumbbell structure is zero and the dumbbell assumes a corresponding equilibrium position. This assumption is based on the proposition that bodies 5 and 6 are similar in mass and location vis-a-vis the magnetic fields and their gradients. As a consequence, current i_2 is also zero. In view of the high gain of the optical-electronic scanning system 19 through 22, the equilibrium position is positively maintained. That is to say any deflection of the dumbbell structure from this equilibrium position brings about immediately a high current tending to restore the equilibrium and zero or near zero output current of the differential amplifier.

Now, it shall be assumed that the gas M includes O_2; for example, 10 percent O_2, the remainder still being N_2. Since O_2 is not diamagnetic, body 5 is pulled into the magnetic field of gap 3, while no such pulling force is exerted on the body 6. As a consequence, a non-zero torque is exerted upon thread or filament 16, mirror 19 deflects, and the illumination as well as the output of differential detector 21, changes so that the amplifier 22 receives a non-zero input U_1. As a consequence, a current i_k is produced which changes the effective magnetic fields in gaps 3 and 4, so that a compensating torque is produced tending to return the dumbbell to the equilibrium position.

The new equilibrium results from a balance between the non-zero torque as resulting from magnetic field interaction between the paramagnetic gas M in body 5, and the non-zero torque as resulting from unequal magnetic field strengths in the gaps 3 and 4, and the difference in these two forces as now acting on the diamagnetic reference body 6 is brought to zero by the feedback loop action.

The force resulting from interaction of the now prevailing field difference in the gaps, on the solid material of the test bodies, is quite large, even for a rather small difference in magnetic field strength. Hence, only a relatively small current i_k is needed to produce that force which maintains near normal equilibrium position of the dumbbell with a small residual error to maintain a non-zero current i_k. The reference body content could be paramagnetic but in that case the sign of the difference in the two fields must be reversed. The angular position which the dumbbell assumes in that state of equilibrium is practically independent from the oxygen content in gas M because the optical-electronic system has a very high gain. It should be noted further that the scanning system as such is known, see for example prior art citation 1, supra, but new is the employment thereof in the specific configuration as outlined above.

The equilibrium condition is maintained in that the current I_k can be deemed proportional to the oxygen content of the gas M, so that this current is a quantitative representation of the oxygen content. The apparatus as described actually functions on basis of a comparison of the magnetic volume susceptibility of the reference gas compared with the volume susceptibility of gas M in body 5, and that comparison, in turn, is referenced against the volume susceptibility of the test body material to obtain again the balanced position of the dumbbell. The magnetic force (current i_k) needed for that restauration or compensation is then used as indication for the volume susceptibility of the test gas M.

Trimmer coils 11 and 12, in conjunction with the adjustable d.c. source 14, trims and adjusts individually the fields in the two gaps in opposite directions so that the operational zero point of the system (usually for zero content of oxygen) is established by exactly zero torque on the dumbbell. The purpose of the trimmer circuit is to offset and to compensate for any differences in the coil and in the branches of the dumbbell system when not measuring. However, the trimmer circuit can be used also for range and threshold adjustment, for example, for suppressing a low oxygen content of, e.g., 8 to 10 percent.

FIGS. 2 and 3 show two different versions for the measuring gaps, as well as for the test bodies. In each instance, however, the gaps are similar and so are the bodies among themselves (except for the openings in the body for the gas M). Thus, only one gap and one body needs to be shown in each instance. The double arrows denote the respective direction of movement and displacement. In each of the figures part (a) shows a front view, part (b) shows a side view and part (c) shows a top view, one pole of the gap being removed.

Turning first to FIG. 2, the particular gap 32 illustrated (be it 3 or 4), is established by flat; parallel surfaces 31 of the respective yoke. The test body is identified here by 33 and is a cylindrical, flat, hollow body. FIG. 3 shows a gap 42 with bevelled portions of the pole shoes surfaces, 41, and a narrow gap 42*a*. The test body (5 or 6) is shown here as a sphere 43. Either arrangement can be chosen in the system of FIG. 1*a*.

The optical scanning and pick-up system can be replaced by a capacitive pick-up. For example, a vane can be mounted on a rod or pin which extends transverse to both, connecting bar 15 and filament 16. The vane is made of plastic or metal. The vane extends and moves transverse to the axis of rotation of the dumbbell, inside of a differential plate capacitor having its plates likewise extending transverse to the said axis of rotation.

This differential capacitor is a component of a bridge circuit which is biased symmetrically with hf voltage. The bridge signal is representative of the angular position of the vane and after amplification the signal can serve for control of the magnetic compensating coils and fields in the same manner as described.

Still analogously, one can use an hf transformer wherein the coupling between the coils is controlled through movement of such a vane, (see, for example, German printed patent application No. 2,000,212, as well as the handbook by Rohrbach, "Handbuch fer elektrisches Messen mechanischer Gressen", published by VDI Publishing Company, 1967). These variations are mentioned here to indicate that different pick-up means for the dumbbell position can be used to obtain a compensation current which represents the difference of the dumbbell position from the equilibrium position.

The circuit in FIG. **1** et seq. can be modified by feeding a.c. to coils **7** and **8** or by feeding a d.c. current with an a.c. component superimposed to these coils. Usually, one would not need any longer the trimmer coils **11** and **12** in that case (see e.g. FIGS. **4** and **5** of German printed patent application No. 2,000,212). An a.c. bias as principle source for magnetic energization will require a pick-up means which is responsive to the variations in position and oscillations of the dumbbell, to produce a correspondingly periodically variable signal which, in turn, is fed to an amplifier **22,** which now must be an a.c. amplifier whose output may require phase correction and is then used as a.c. compensating signal in coils **9** and **10.**

In the case of an a.c. superimposed d.c. bias for the magnetic energizing system **7, 8,** one will still use an a.c. amplifier but the output current thereof can be used either as a.c. compensation current, or, after phase correct rectification, one can use a d.c. compensation current in coils **9** and **10.**

In the case of a.c. energization, the dumbbell will oscillate and the zero position of the oscillation will shift. Compensation by means of a.c. renders in effect the magnetization field variations unequal with a resulting return shift to the zero position, or a d.c. field compensation shifts directly the zero point of the oscillator or vibrator of the dumbbell.

Turning now to FIGS. **4***a* and **4***b*, the magnetic biasing system shown here includes a permanent magnet **51,** obviating the need for electromagnetic bias. The figures show the dumbbell only without suspension and scanning pick-up, which have been omitted merely for reasons of simplifying illustration. The magnetic circuit includes the permanent magnet **51**; yokes **52** and **53**; pole shoes **54, 55**; gaps **56, 57**; test bodies **58** in gap **56**; and reference body **59** in gap **57.** The pick-up and dumbbell scanning system controls current flow through compensating coils **60** and **61.**

In spite of the high magnetic resistance of magnet **51,** the magnetic shunt circuit **52-55-57-55-53-54-56-54-52** has only rather low magnetic resistance. Moreover, current changes in coils **60,** 61, are related linearly to the corresponding changes in the magnetic field, and the permanent magnet does not introduce hysteresis distortions into this relation.

Proceeding now to FIGS. 5a and 5b, the system shown therein uses a cylindrical permanent magnet **71,** ferromagneticflux transmission plates **72, 73,** pole shoes **74, 75,** with measuring gap **76,** and test body **77** for the test gap. Additionally, there are pole shoes **78,** 79, with gap **80** for a reference body **81,** and finally, the system includes compensating coils **82, 83.** The bodies **81** and **77** are flat as before but have flat prism-shaped configuration.

FIG. **5***c* shows modified, hollow test bodies **77'** and **81'** of cylindrical configuration, the cylinder axis extends transversely to the direction of the magnetic field and parallel to the direction of displacement in each instance. The displacement is illustrated by the double arrows. Otherwise, the same permanent magnetic energization is used as in FIGS. **5***a* and **5***b*.

The arrangement of FIGS. **5***a*, **5***b* and **5***c* with prism-shaped or cylindrical test bodies differs from the bodies shown in FIGS. **2** and **3** in a rather advantageous fashion. The forces acting on the test bodies are quite independent from the position of the dumbbell for a larger angular range than in the cases of FIGS. **2** and **3.** Accordingly, the optical-electronic amplification, i.e., the scanner gain generally, can be samller, assuming similar negative feedback by means of such compensating coils in each instance. This specific advantage results from the contour of the test bodies (prism or cylindrical) because the solid material volume as well as the hollow space volume that occupies part of the zone of magnetic field inhomogeneity remain constant for a large displacement range (angular) in the case of FIGS. **5***a*, **5***b*, **5***c* than in the case of FIGS. **2** or **3.**

Additionally, utilization of a cylindrical test body offers the advantage that for similar mechanical strength the ratio of solid material volume to the volume of the interior space of the respective test body has a minimum in the zone of magnetic field inhomogeneity as compared with other types of hollow bodies. This holds true even when the comparison is made with a hollow sphere.

The embodiments as described have dumbbell systems which do not require any directive force. However, the system should have a definite position of equilibrium for an open loop state, and a directive force for a return-to-zero is desirable accordingly. It may be advantageous to have a resonance rise and the directive or return force will then be chosen to obtain the desired resonance frequency under consideration of the moment of inertia of the dumbbell. For this, one will particularly chose the torsion spring-filament of the dumbbell suspension system.

Another example of the preferred embodiment of the invention is shown in FIGS. **6***a* and **6***b*. This particular system is constructed for operation of a linearly displaced dumbbell system (rather than rotational). The respective position of the dumbbell is scanned by means of a magnetic inductive pick-up. Turning first to the basic layout, the system includes two magnet yokes **91, 92,** respectively carrying energizing coils **97, 98,** which are serially connected to each other and to a source **101** of a.c. potential for obtaining alternating magnetic fields and induction in the two yokes. The magnetic yokes have respectively gaps **93** and **94,** and the test gas body **95** (with apertures) cooperates with gap **93,** while the hollow reference test body **96** (without aperture) cooperates with gap **94.** Test bodies **95,** 96, are mechanically interconnected to establish a dumbbell structure which is connected to a spring **103** which, in turn, is anchored at **102.** The double arrow denotes the directions of displacement and oscillation.

FIG. **6***b* shows a suitable configuration for the pole shoes as used in conjunction with cylindrical test bodies.

A bar magnet **104** is connected to the dumbbell and an inductive pick-up transducer **105** has disposition so that upon oscillation of the dumbbell, the bar magnet **104** oscillates in front of and in the pick-up range of transducer **105.** Upon occurrence of such oscillation, transducer **105** produces an a.c. output. This a.c. signal is amplified in a.c. voltage amplifier **106** providing an output whose frequency is divided-by-two in circuit

107, and the corresponding signal is phase shifted at 108 to obtain a compensation a.c. current i_k whose phase is correct for obtaining negative feedback in the magnet system. This compensation current i_k passes through coils 99 and 100 as well as through an indicating instrument 109.

In the case of diamagnetic test bodies, coil 99 has a sense of winding so that compensation current i_k increases the alternating magnetic field across gap 93, while the sense of winding for coil 100 is in the reverse for decreasing the magnetic field in gap 94. The same effect can be obtained, regardless of the actually present sense of winding of the coils through suitable selection of the direction and phase of the current flow.

It follows that the function and operation of the system of FIG. 6a is otherwise the same as outlined above with reference to FIG. 1a as far as deflection of the test bodies and their return to equilibrium position is concerned.

Proceeding next to FIGS. 7 and 8, two other embodiments are shown in these Figures having in each case the same pick-up, feedback and compensation circuit and devices as shown in FIG. 6a. Also, the magnetic yoke system (except for the pole shoes) are similar and a.c. magnetization is also assumed.

FIG. 7 shows pole shoes 111 and 112, respectively, for gaps 113 and 114, for co-action with the test gas and reference bodies 115, 116. The test bodies 115 and 116 are also interconnected in a dumbbell structure and suspended at 118 by means of a spring 117.

The test gaps are subjected to test gas analogously as aforedescribed. However, the test body construction differs from the earlier embodiments. Test gas body 115 is a solid sphere and reference body 116 is a hollow sphere filled with reference gas of low susceptibility (or vacuum). Both bodies are made of similar material, e.g., quartz and have the same mass as far as solid material is concerned. Thus, sphere 115 is smaller than sphere 116.

As long as the two bodies lodge in zones of similar magentic field strength and similar field gradient, the forces as acting on the solid substance of the bodies balance as before. However, the two bodies have different volume, e.g. 1 mm^3 for 115 and 5 mm^3 for 116. The volumes of displaced measuring and test gas differ accordingly. The O_2 content thereof provides for additional force components, tending to displace the spheres from the respective field in each instance. These forces do not balance if the susceptibilities of test and reference gas differ, and a resultant component acts on the dumbbell corresponding to the difference in volume of the spheres and further corresponding to the O_2 content in the test gas. This difference in force is measured by means of the feedback system as aforedescribed and representing quantitatively the O_2 content of the test gas through its susceptibility. In particular, one will again measure the compensating current as was outlined with reference to FIGS. 1 and 6a.

FIGS. 7a, 7b, 7c show a modification of the structure of FIG. 7a with parallel (rather than bevelled) gaps 113', 114', and correspondingly contoured pole shoes 111', 112'. The test gas body is a solid cylindrical rod 115', and the reference body is a closed hollow cylinder 116'. The masses of the two test bodies are similar so that their dimensions differ accordingly. The cross sections of the two test bodies are selected so that again similar cross sections of solid material and similar volumes accordingly are located in the relatively small zone of field inhomogeneities at the pole shoe fringes. The operation and function of this apparatus is otherwise similar to operation and function of the apparatus as per FIG. 7.

The construction of FIG. 7a could be modified further by using prism-shaped test bodies, one solid one hollow, under similar cross section conditions as described.

The pole shoe system 121, 122, with gaps 123, 124, in FIG. 8 are similar to the pole shoe systems and gap configurations of FIG. 7. However, the test bodies differ and a measuring chamber is not needed, because test body 125 is a flat dish for receiving a solid or liquid sample 125a, whose susceptibility is to be determined. The measuring chamber is charged with a reference gas of low susceptibility. If the sample 125a exhibits substantial susceptibility, it is no longer critical to have a low susceptibility environment in which gas of correspondingly low susceptibility is used; rather, one could use just air. But depending on the quantities involved, the susceptibility is air (which is known) should enter into the calculations for the system parameters and their precalibration determination. The two test bodies are similar here, they should also be made of quartz. Reference dish 126 just remains empty, because in this example reference gas constitutes the environment for the dumbbell and penetrates both gaps.

If one assumes that the solid body volume of the test bodies 125, 126, each is 60 mm^3, such volume corresponds in volume half of a hollow sphere with 8 mm diameter and 0.4 mm wall thickness. It may further be assumed that the sample 125a has a susceptibility of 3.10^{-6}. If the sample 125a has a volume of 2 mm^3 its volume susceptibility is $6 \cdot 10^{-6}$ mm^3 as compared with $60 \cdot 10^{-6}$ or $6 \cdot 10^{-5}$ mm^3 volume susceptibility of each test body. The resulting compensation in the magnetic field can be calculated accordingly (infra). Conversely, the compensation energization (current i_k times number of turns of the compensation coils) can be calculated first and if the sample is unknown, except for its volume, the volume or mass susceptibility can now be determined.

The equipment in accordance with the various examples and embodiments of the invention, and the method realized therewith, has very fast response in principle. That response, however, is reduced, if the test body which receives the test gas has only a small aperture. Therefore, it is desirable to have bodies with large apertures, which are dimensioned so that the same integral volume susceptibility as in the hollow reference body is present. In the case of cylindrical body for the test gas top and bottom are just omitted, and the cylinder walls are slightly thicker to maintain similarity in solid mass as between reference and test gas bodies.

In the case of parallel gaps (FIGS. 7a and 2), only a rather small zone of an inhomogeneous field is present; it is, therefore, required only that the two test bodies agree as to mass and to the extent they penetrate these zones. The opening(s) of the test gas body are, preferably, located outside of the respective zone and can, thus, be quite large without introducing any distortion in the relationship between body and field (gradient!).

After having described various versions for equipment to practice the inventive method, and after having described more qualitatively how the various parameters interrelate, quantitative and theoretical considerations on a more exact basis are in order.

The equations to be written below use the following terms:

K—force as acting on a test body;

H—local magnetic field strength at the location of a test body;

grad H—magnetic field strength gradient thereat;

Ho—constant magnetic field as resulting from d.c. energization if a.c. energization is also present;

H~—variable magnetic field as a result of a.c. electromagnetic energization;

Q—cross section (generally)

Q*m*—specific test gas cross section in the inhomogeneous zone of a magnetic field, used only for hollow prismshaped test bodies;

Q*q*—cross section through the solid material of such a prism-shaped test body, also in the inhomogeneous field zone;

V—volume of a test body;

V*m*—volume of the measuring gas inside of the test gas test body;

V*q*—volume of solid substance of a hollow test body;

—magnetic susceptibility;

m—magnetic susceptibility of the test or measuring gas;

ν—magnetic susceptibility of the reference gas;

q—magnetic susceptibility of the solid material of a test body;

O_2—magnetic susceptibility of oxygen under test conditions;

No—number of turns of each of the two principle energizing coils (e.g. **7**, **8**, of FIG. **1***a*);

N*k*—number of turns of each of the two compensating coils (e.g. **9** and **10**);

I*o*—d.c. current component through the principle energizing coils;

I~—a.c. current component through the principle energizing coils;

i_k—compensating current (d.c.);

i_k~—compensating current (a.c.);

θ—induction as produced by the permanent magnet;

C_{o2}—concentration of oxygen.

The following equation is basic and describes the force acting on a body in a non-homogeneous field:

$$K = H \cdot \text{grad}\, H \cdot V \cdot \kappa \quad (1)$$

If the body is a prism and if the inhomogeneous field is established at the fringes of a parallel gap (FIGS. **2**, **7***a*), the formula reduces to:

$$K = 0.5\, H^2 Q\kappa. \quad (2)$$

For $\nu = 0$, equilibrium is established when:

$$(\kappa m \cdot Qm) \cdot (Io \cdot \kappa o) \approx 4\,(\kappa q \cdot Qq)\,(i_k \cdot Nk) \quad (3)$$

under the assumption that:

$$\kappa m \cdot Q \leq 0.1 \kappa q \cdot Qq \quad (4)$$

It follows from equation (3) that:

$$(5) \qquad C_{o2} = 4\, \frac{i_k \cdot Nk}{Io \cdot No} \cdot \frac{\kappa a \cdot Qg}{\kappa O_2 \cdot Qm} \qquad \text{or}$$

$$(6) \qquad C_{o2} = K1 \cdot \frac{i_k}{Io}$$

One can readily see that for $C_{o2} = 0$, $i_k = 0$, and that zero condition is not dependent on Io and is, therefore, independent from the excitation of the system through the main energizing coils.

Furthermore, the sensitivity of measuring oxygen concentration depends only on the ratio i_k/Io and is linear as to i_k as long as Io is maintained constant. Thus, changes in the magnetic force flux, which are not caused by Io or i_k have no influence on the measuring result.

For a test body in an inhomogeneous field generally, one will find analogously:

$$(7) \qquad C_{o2} = K2\, \frac{i_k}{Io}$$

under the assumption

$$\kappa m \cdot Vm \leq 0.1 \kappa q \cdot Vq \quad (8)$$

In addition to the advantages just mentioned, one can add here that the measurement is no longer dependent on the field gradient. This is of advantage for null stability.

The embodiment of FIG. **4***a* used permanent magnets for energization. In these cases one has to use the permanent energization θ*o* in lieu of No·Io in the formulas above. This then yields the expression:

$$(9) \qquad C_{o2} = K3 \cdot \frac{i_k}{\theta o}$$

For a.c. energization, the calculations have to be modified, and one finds that Ho^2 has to be replaced by 2·Ho·H~. Depending now on the compensation, whether carried out on an a.c. basis or with d.c., one obtains:

$$(10) \qquad C_{o2} = K4 \cdot \frac{i_k}{Io} \text{ for d.c. compensation; and}$$

$$(11) \qquad C_{o2} = K5 \cdot \frac{i_k\sim}{Io} \text{ for a.c. compensation.}$$

The advantages of the invention can be summarized as follows, particularly when applied for measuring O_2 concentrations on a continuous basis.

1. The measuring result is actually independent from the carrier gas composition, except, of course, any magnetic properties thereof.

2. Through-flow has little influence on measurements if carried out with a.c. energization.

3. In the case of a.c. magnetization, a very fast response and result is obtained.

4. The zero point and sensitivity are quite constant.

5. One can readily change measuring ranges because the compensating current i_k linearly proportional to the O_2 concentration. The range can be changed, e.g. by changing N*k*, for example, by tappinng different numbers of turns of the compensating coils. Alternatively Io can be adjusted.

6. One can readily construct the instrument to obtain explosion proofing without significant expenditure.
7. The most sensitive parts in the instrument are simpler to make and more easily adjustable than comparable parts in the prior art.

The invention is not limited to the embodiments described above but all changes and modifications thereof not constituting departures from the spirit and scope of the invention are intended to be included.

What is claimed is:

1. In an instrument for measuring magnetic susceptibility and which includes a first and a second magnet circuit respectively with a first and second gap and a first and second test body, respectively located in the first and second gaps, and being interconnected to form a dumbbell configuration which is resiliently suspended but without enveloping current loops, the improvement comprising:

the test bodies disposed in the gaps so that forces acting on them due to the solid material of the test bodies and interaction thereof with the magnetic fields in the gap, have zero resultant; the test bodies differing in interior content, so that the first test body in conjunction with a reference gas, and the second body in conjunction with a test material experiences additional, deflective forces in the gaps which act at different magnitudes on the bodies with a non-zero resultant force for similar magnetic field strength in the gaps;

compensating means including at least one stationary coil disposed for acting on at least one of said magnetic circuits outside of said gaps to provide for at least one magnetic compensating field, effective respectively in at least one of said gaps, for unbalancing the magnetic fields in the gaps for offsetting said non-zero resultant force;

pick-up means responsive to the deflection of the dumbbell configuration in response to said deflective force, to provide for control of said compensating means to obtain said magnetic compensating field; and

indicating means connected to the pick-up means to provide an indication of the control as provided to the compensating means in representation of the difference in magnetic susceptibility between said test material and said reference gas.

2. In an instrument as in claim **1**, wherein the magnetic circuits include adjustable electromagnetic means modifying the magnetic fields in the gaps in opposite directions to obtain correction and similar magnetic fields in the fields.

3. In an instrument as in claim **1**, wherein the compensating means includes two stationary coils, including said one coil and one for each of said magnetic circuits, to provide oppositely effective compensating fields in the gaps to produce a composite force counteracting said non-zero resultant.

4. In an instrument as in claim **1**, wherein the two magnetic circuits are a.c. energized, the dumbbell being suspended for undergoing oscillation, the pick-up means responsive to said oscillation.

5. In an instrument as in claim **1**, the magnetic circuits being biased by permanent magnet means.

6. In an instrument as in claim **5**, the magnetic circuits including at least one permanent magnet and magnetic conductive means leading to said gaps; the conductive means holding two coils, including the one coil, to obtain said unbalancing of the magnetic fields.

7. In an instrument as in claim **1**, and including at least trimming coil with adjustible energization in at least one of said circuits to obtain the zero resultant in the absence of said additional deflective force.

8. In an instrument for measuring magnetic susceptibility and which includes a first and a second magnetic circuit respectively with a first and second gap and a first and second test body, respectively located in the first and second gaps, and being interconnected to form a dumbbell configuration which is resiliently suspended but without enveloping current loops, the improvement comprising:

the test bodies disposed in the gaps so that forces acting on them due to the solid material of the test bodies and interaction thereof with the magnetic fields in the gaps, have zero resultant;

the first and second gaps being penetrated by a test gas and surrounding said bodies, the first body being hollow and closed, and containing a reference gas, and displacing a larger volume of the test gas than the second body does, so that the test bodies experience additional deflective force in the gaps, the additional deflective force resulting from the different displacement volume of test gas as produced by the first and second bodies, there being a nonzero resultant deflecting force on the dumbbell for similar magnetic field strengths in the gaps accordingly;

compensating means including at least one coil not being deflected with said dumbbell and disposed for acting on at least one of said magnetic circuits outside of said gaps to provide for at least one magnetic compensating field, effective respectively in at least one of said gaps to unbalance the magnetic fields in the gaps for offsetting said non-zero resultant force;

pick-up means responsive to the deflection of the dumbbell configuration in response to said deflective force, to provide for control of said compensating means to obtain said magnetic compensating field; and

indicating means connected to the pick-up means to provide an indication of the control as provided to the compensating means in representation of the difference in magnetic susceptibility between said test material and said reference gas.

9. An instrument as in claim **8**, wherein the second body is smaller than the first body, so that the additional force is the result of the difference in displacement volume for test gas, as provided by the two bodies.

10. An instrument as in claim **8**, wherein the second body is hollow and open to be penetrated by the gas.

11. In an instrument for measuring magnetic susceptibility and which includes a first and a second magnetic circuit respectively with a first and second gap and a first and second test body, respectively located in the first and second gaps, and being interconnected to form a dumbbell configuration which is resiliently suspended but without enveloping current loops, the improvement comprising:

the test bodies disposed in the gaps, so that forces acting on them due to the solid material of the test bodies and due to interaction thereof with the magnetic fields in the gap, have zero resultant;

the first and second gaps being penetrated by a gas surrounding the bodies, the first body only holding a material separated from the gas and of different susceptibility, so that the first and second bodies experience additional different deflective forces on account of said difference in susceptibility with a non-zero resultant force for similar magnetic field strengths in the gaps;

compensating means including at least one coil not moving with said dumbbell and disposed for acting on at least one of said magnetic circuits outside of said gaps to provide for at least one magnetic compensating field, effective respectively in at least one of said gaps to unblance the magnetic fields in the gaps for off-seeting said non-zero resultant force;

pick-up means responsive to the deflection of the dumbbell configuration in response to said deflective force, to provide for control of said compensating means to obtain said magnetic compensating field; and

indicating means connected to the pick-up means to provide an indication of the control as provided to the compensating means in respresentation of the difference in magnetic susceptibility between said test material and said reference gas.

12. An instrument as in claim **11**, wherein the first body and the second body are similar open containers, the first body holding a sample, the gas being a reference gas.

13. An instrument as in claim **11**, wherein the first body is a closed container holding a reference gas, the gas being a test gas.

14. In an instrument as in claim **11**, wherein the two bodies have different volume for displacing different amounts of test gas, the mass and material of the test bodies being at least approximately similar so that the additional force is provided by the difference in magnetic interaction with the different displacement volume in the gaps.

15. In an instrument for measuring magnetic susceptibility and which includes a first and a second magnetic circuit respectively with a first and second gap and a first and second test body, respectively located in the first and second gaps, and being interconnected to form a dumbbell configuration which is resiliently suspended but without enveloping current loops, the improvement comprising:

the test bodies disposed in the gaps so that forces acting on them due to the solid material of the test bodies and interaction thereof with similar magnetic fields in the gaps, have zero resultant;

the first body being a container for a sample, the second body being without a sample, the test bodies being surrounded by a reference gas, so that a deflective non-zero resultant force acts on the dumbbell for similar fields in the gaps;

compensating means disposed for acting on at least one of said magnetic circuits to provide for at least one magnetic compensating field, respectively in at least one of said gaps to unbalance the magnetic fields in the gaps for offsetting said non-zero resultant force;

pick-up means responsive to the deflection of the dumbbell configuration in response to said deflective force, to provide for control of said compensating means to obtain said magnetic compensating field; and

indicating means connected to the pick-up means to provide an indication of the control as provided to the compensating means in representation of the difference in magnetic susceptibility between said test material and said reference gas.

16. In an instrument for measuring magnetic suceptibility and which includes a first and a second magnetic circuit respectively with a first and second gap and a first and second test body, respectively located in the first and second gaps, and being interconnected to form a dumbbell configuration which is resiliently suspended but wihtout enveloping current loops, the improvement comprising:

the test bodies disposed in the gaps so that forces acting on them due to the solid material of the test bodies and interaction thereof with similar magnetic fields in the gaps have zero resultant;

the first body being an open container for receiving a test gas surrounding the dumbbell and penetrating the gaps and into the first body, the second body being a closed container holding a reference gas so that the test body experiences additional deflective force in the gaps with a non-zero resultant deflection force on the dumbbell and as the result of difference in magnetic susceptibility of test and reference gases and for similar magnetic field strength in the gaps;

compensating means including at least one coil not moving with said dumbbell and disposed for acting on at least one of said magnetic circuits outside of said gaps to provide for at least one magnetic compensating field, effective respectively in at least one of said gaps to unbalance the magnetic fields in the gaps for offsetting said non-zero resultant force;

pick-up means responsive to the deflection of the dumbbell configuration in response to said deflective force, to provide for control of said compensating means to obtain said magnetic compensating field; and

indicating means connected to the pick-up means to provide an indication of the control as provided to the compensating means in representation of the difference in magnetic susceptibility between said test material and said reference gas.

17. In an instrument as in claim **16**, wherein said test bodies are of similar construction and dimension with the exception of open access for test gas to the interior of the first body.

18. In an instrument as in claim **17**, said test bodies beint flat, hollow cylinders.

19. In an instrument as in claim **17**, said test bodies being hollow spheres.

20. In an instrument for measuring magnetic susceptibility and which includes a first and a second magnetic circuit respectively with a first and second gap and a first and second test body, respectively located in the first and second gaps, and being interconnected to form a dumbbell configuration which is resiliently suspended but without enveloping current loops, the improvement comprising:

the test bodies disposed in the gaps so that forces acting on them due to the solid material of the test bodies and interaction thereof with similar magnetic fields in the gaps have zero resultant;

the first body being solid and having a smaller displacement than the second body which is filled with a reference gas, both bodies being surrounded by test gas which penetrates the gaps, the second body displacing a larger volume so that a non-zero resultant force acts on the dumbbell for the similar field strength in the gaps;

compensating means, including at least one coil not moving with said dumbbell and disposed for acting on at least one of said magnetic circuits outside of said gaps to provide for at least one magnetic compensating field, effective respectively in at least one of said gaps to unbalance the magnetic fields in the gaps for offsetting said non-zero resultant force;

pick-up means responsive to the deflection of the dumbbell configuration in response to said deflective force, to provide for control of said compensating means to obtain said magnetic compensating field; and

indicating means connected to the pick-up means to provide an indication of the control as provided to the compensating means in representation of the difference in magnetic susceptibility between said test material and said reference gas.

21. In an instrument for measuring magnetic susceptibility and which includes a first and a second magnetic circuit respectively with a first and second gap and a first and second test body, respectively located in the first and second gaps, and being interconnected to form a dumbbell configuration which is resiliently suspended but without enveloping current loops, the improvement comprising:

the test body disposed in the gaps so that forces acting on them due to the solid material of the test bodies and intaction thereof with the magnetic fields in the gaps, have zero resultant;

the first and second gaps being penetrated by a test gas and surrounding said bodies, the first body being hollow and closed, and containing a reference gas, and displacing a larger volume of the test gas than the second body does, so that the test bodies experience additional deflective force in the gaps, the additional deflective force resulting from the different displacement volume of test gas as produced by the first and second bodies, there being a non-zero resultant deflecting force on the dumbbell for similar magnetic field strengths in the gaps accordingly.

coil means effective in at least one of said magnetic circuits, but not moving with said dumbbells nor being disposed in said gaps to augment the field of at least one of said magnetic circuits as effective in the respective gap;

current driver means connected to the coil means so that said additional deflective force results from the difference in magnetic interaction of the fields in the gaps and the contents of the bodies to unbalance the fields in the gaps for offsetting said non-zero resultant force thereby causing the dumbbell to return to a particular disposition wherein the balancing forces acting on said test bodies are proportional to the product of magnetic field and magnetic field gradient in each of said gaps and where respectively acting on the test bodies in the particular disposition; and

indicating means connected to be responsive to provide an indication of the electric current as provided by said current driver means in representation of the difference in magnetic susceptibility between said test material and said reference gas.

22. In an instrument as in claim **21**, wherein said test bodies are of similar configuration, the second body being hollow with access for the test gas to its hollow interior, so that said additional deflective force results from the difference in magnetic interaction of the fields in the gaps and the contents of the bodies.

23. In an instrument as in claim **21**, wherein said second test body is solid and smaller than said first test body, so that the additional deflective force results from the difference in displacement volume of test gas by the two bodies.

24. In an instrument as in claim **21**, wherein said dumbbell is deflected linearly.

25. In an instrument as in claim **21**, wherein said two test bodies have different volume but similar mass and material, so that the additional force results from a difference in displacement volume by the bodies of test gas surrounding them.

26. In an instrument as in claim **21**, wherein the magnetic circuits have a common permanent magnet for energization, the circuits having separate joke and poleshoe structures for the two gaps, the structures each having a coil as the said coil means to provide additional magnetization to both circuits, the current driver means providing current to said coils to be effective in opposite direction as to the magnetic field components as resulting from this additional energization.

27. In an instrument as in claim **26**, the test bodies being similar in configuration and material, one being filled with reference gas and closed, the other one being open to the test gas.

28. In an instrument as in claim **21**, the coil means including one coil for each said circuits to provide additional magnetization to both circuits, the current driver means providing current to said coils to be effective in opposite direction as to the magnetic field components as resulting from this additional energization.

29. In an instrument as in claim **21**, the circuits having separate permanent magnets, common yoke structure and separate poleshoes.

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