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Gourdine et al.

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[54] **ELECTROSTATIC MASS PER UNIT VOLUME DUST MONITOR**

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[21] Appl. No.: **109,145**

[52] **U.S. Cl.**.....**73/28,** 324/32, 324/71 PC, 55/138, 55/139, 55/149, 55/155, 55/270

[51] **Int. Cl.**.....**G01n 15/00,** B01d 53/30, B03c 3/00

[58] **Field of Search** ...73/23, 28, 194 F, 432 PS, 421, 73/421.5; 324/32, 71 PC, 72, 72.5; 204/312; 310/6; 55/155, 138, 139, 136, 149, 270; 209/127, 129

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[57] **ABSTRACT**

Electrogasdynamic methods and apparatus for measuring the mass of particulate matter entrained in a gaseous flow per unit volume of such flow are disclosed. The gaseous flow is passed down a bounded flow path and the entrained particles are exposed to and charged by a corona discharge. The charged entrained particles are carried downstream to a collection section where the particles are repelled by a charged deposition electrode and driven toward a grounded electrode. A portion of the charged particles are collected on a dielectric surface positioned in front of the grounded electrode. The accumulated charge on the dielectric surface is then measured by an induction electrode and an electrometer to show the particle mass per unit volume of the flow.

33 Claims, 9 Drawing Figures

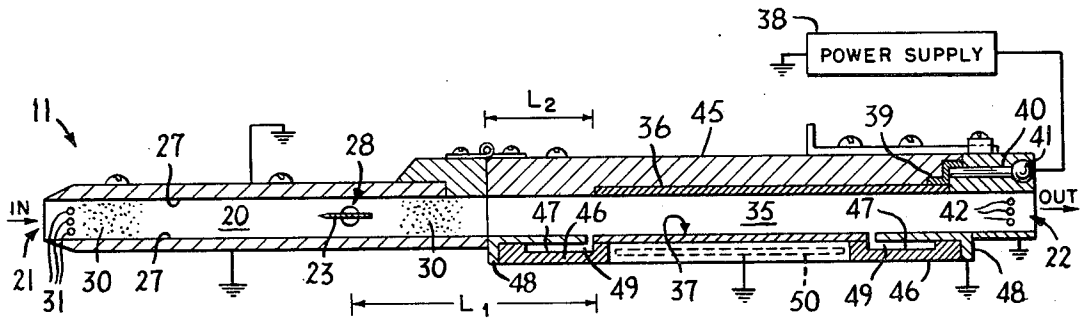
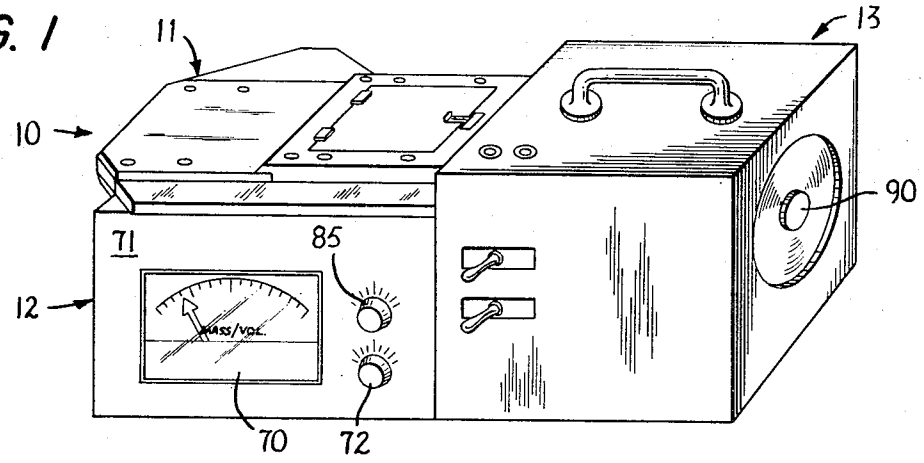


FIG. 1



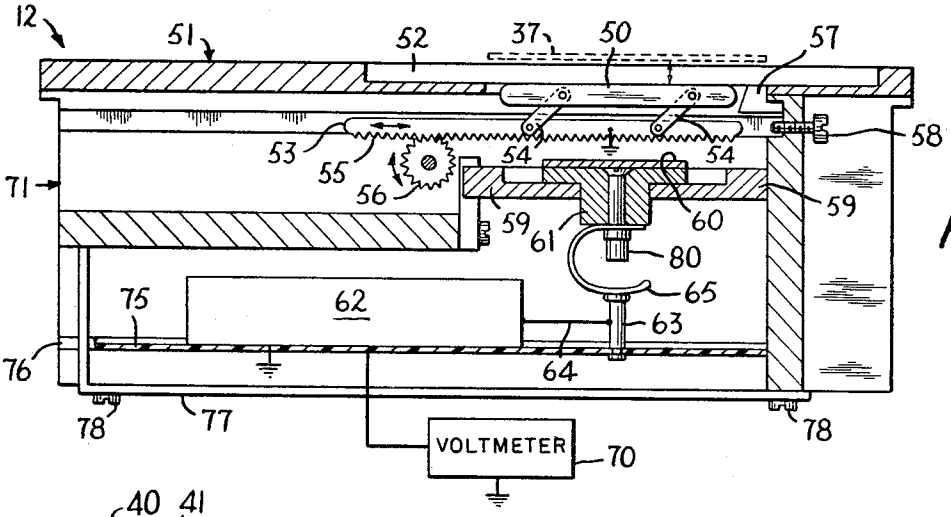


FIG. 4

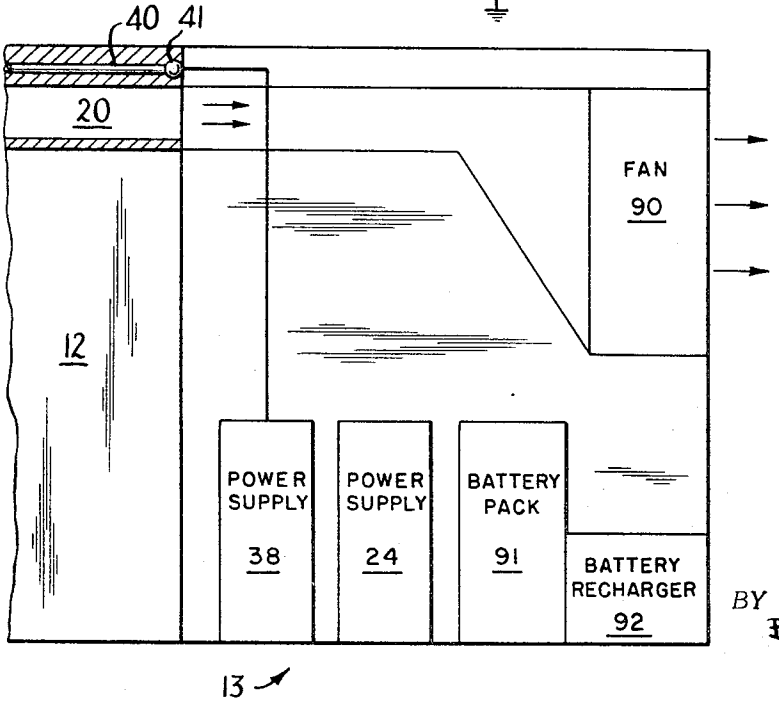
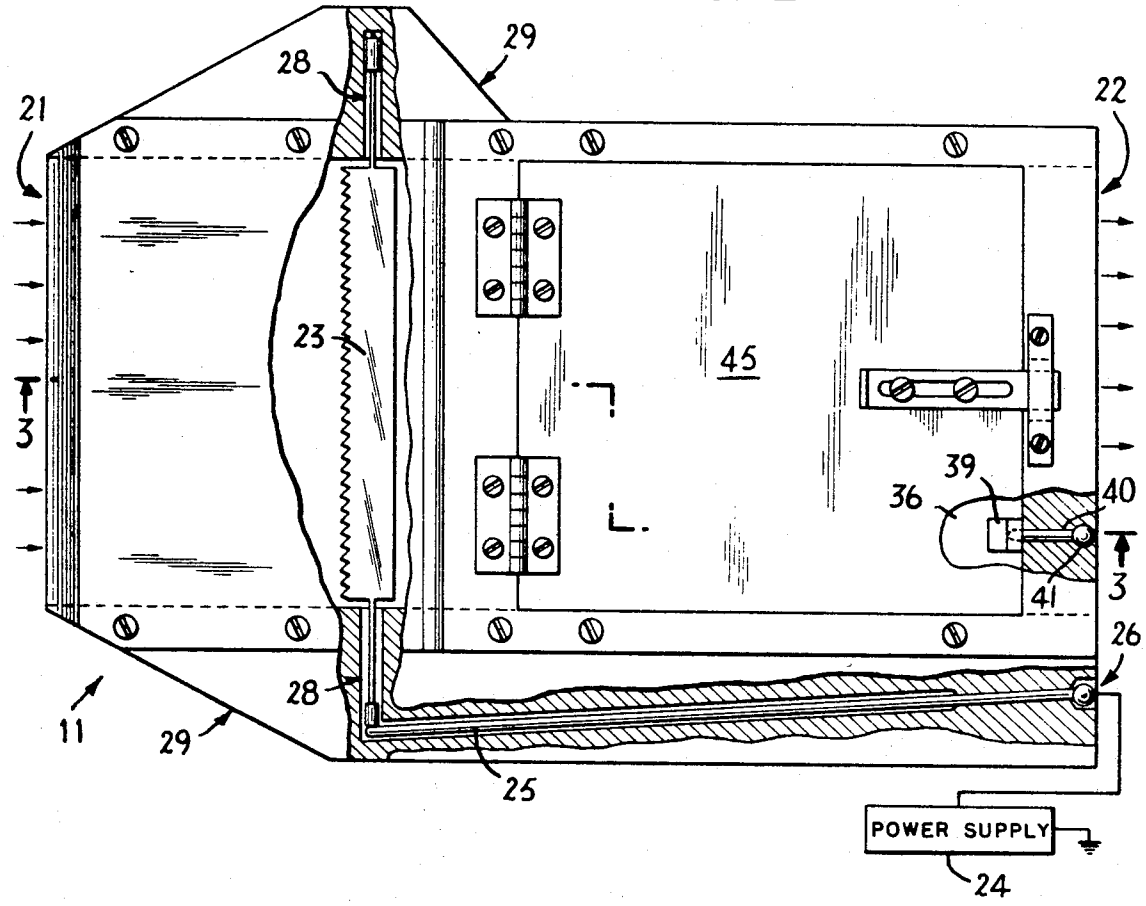


FIG. 5

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FIG. 2



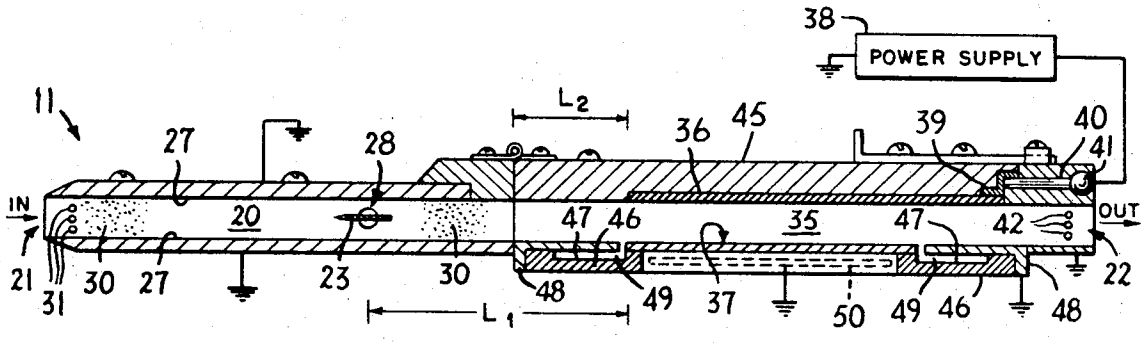
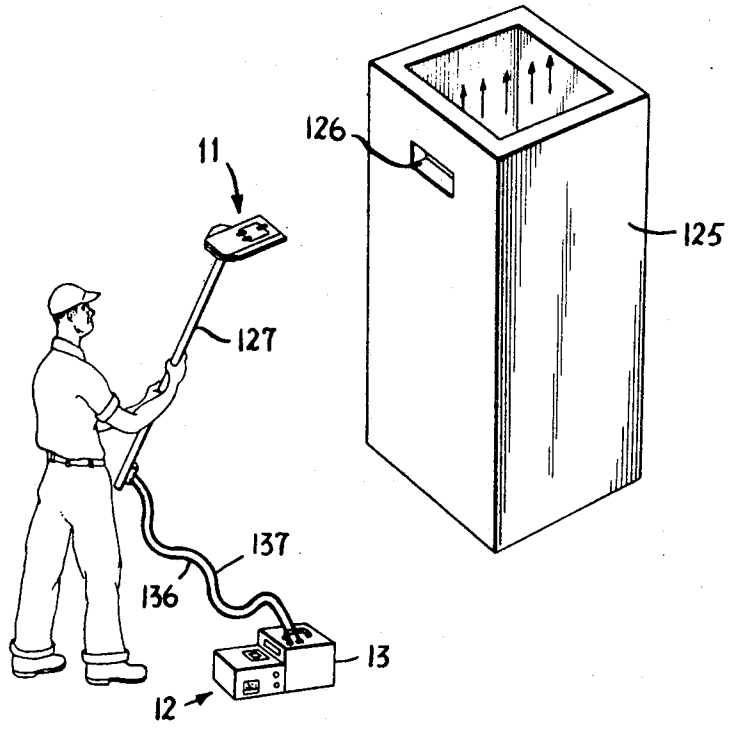


FIG. 3

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FIG. 6



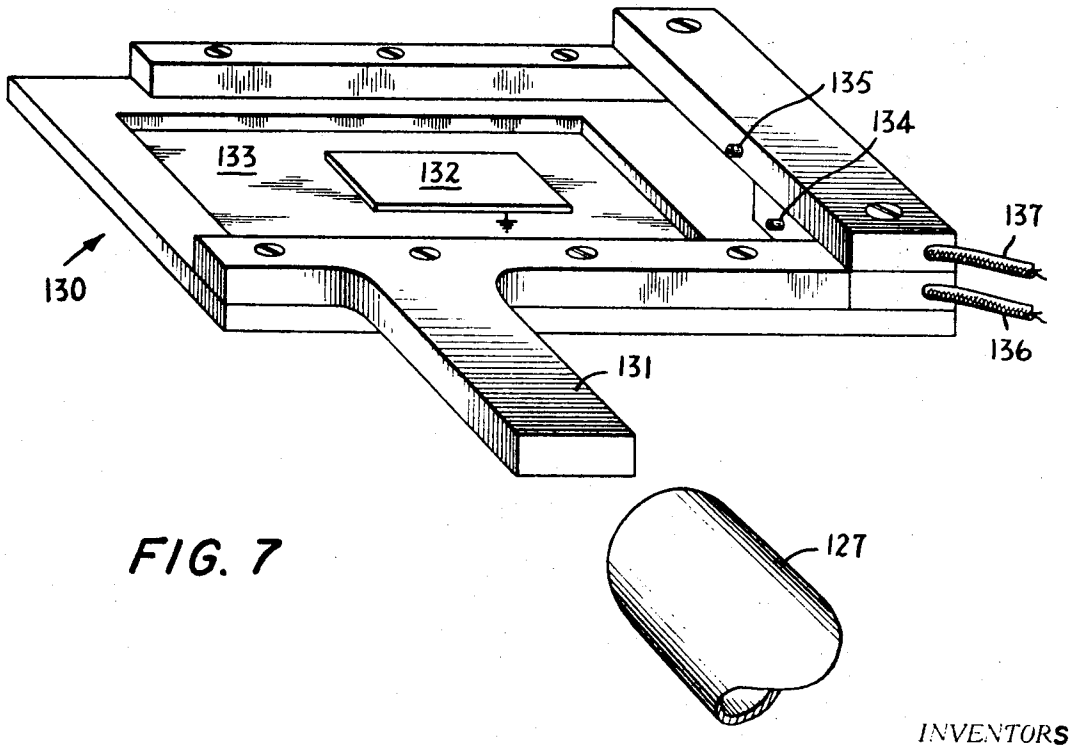


FIG. 7

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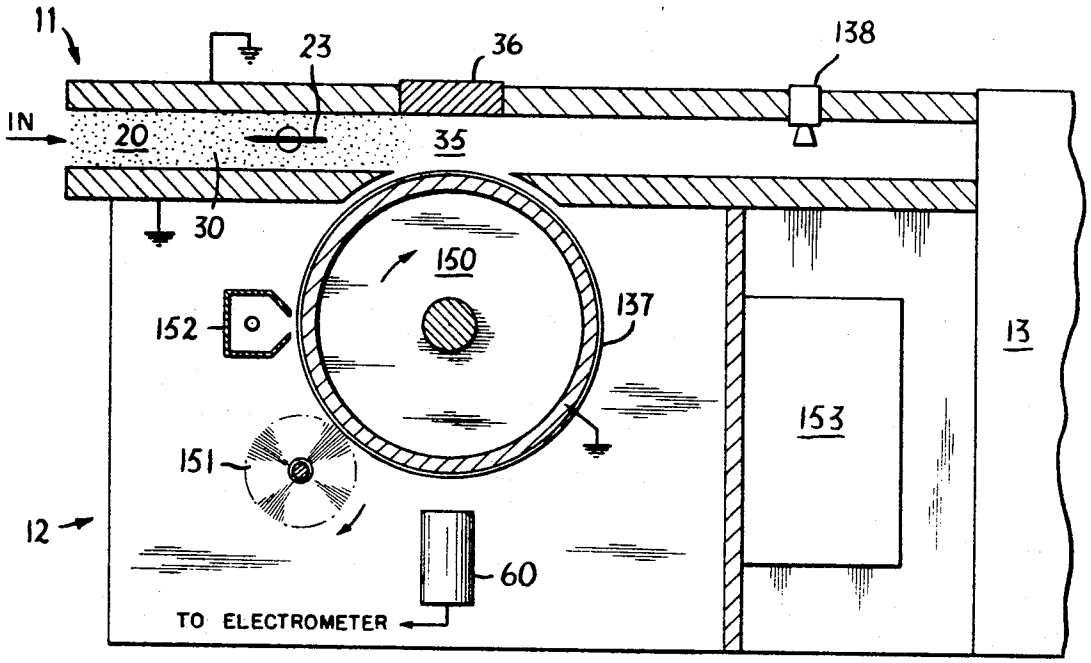


FIG. 8

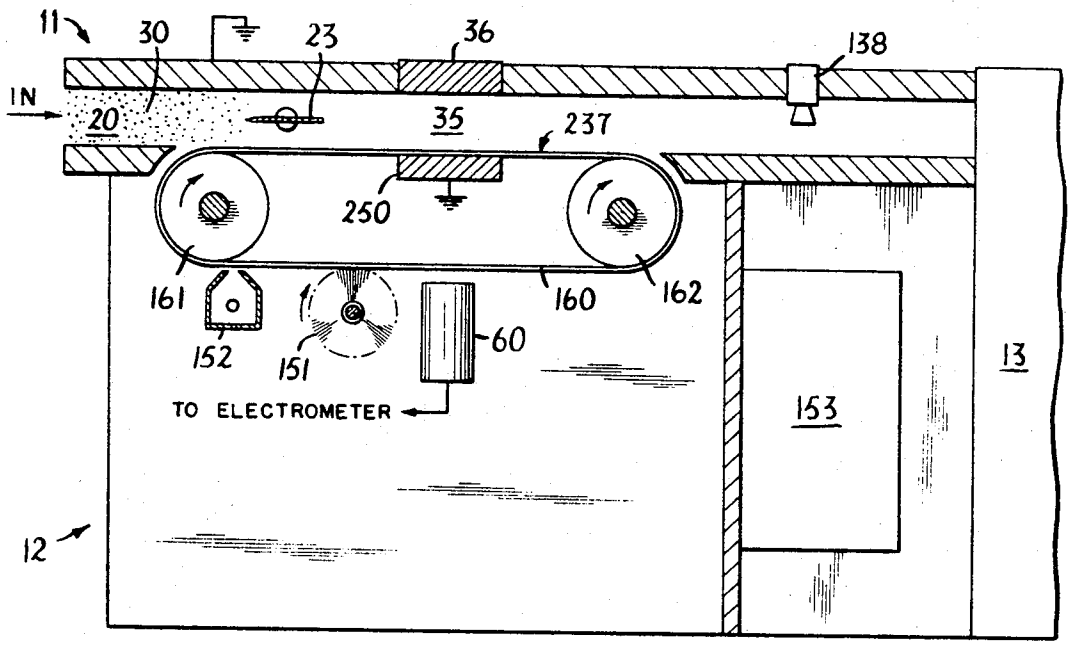


FIG. 9

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ELECTROSTATIC MASS PER UNIT VOLUME DUST MONITOR

BACKGROUND OF THE INVENTION

The present invention relates to improved methods and apparatus for measuring the mass of particulate or aerosol matter entrained in a flowing gaseous system. Specifically, the invention deals with improved methods and apparatus of this type employing electrogasdynamic techniques for measuring the mass of the entrained particulate matter per unit volume of the gas sampled.

Pollution of our environment has become an increasingly important problem in recent years. In this respect, most municipalities have standards regulating the amount of particulate emissions allowable from industrial stacks, diesel and reciprocating engines, and the like. The amount of particulate matter in the air in mines also is of much concern.

Many legislative regulations relating to the permissible amount of particulate matter in such emissions and mines, however, are specified in terms of particulate mass per unit volume (mass/volume) of gas flowing from the source. There are a few methods and instruments presently used for such mass/volume measurements, but they generally require much time and are costly and have definite shortcomings.

The most commonly employed method for mass/volume measurement is the gravimetric method. The gravimetric method involves the forced flow of the particulate gas mixture through a filter or filters porous only to the gas. After sampling a known volume of gas, the collected mass on the filters is removed and weighed on a delicate analytical balance. The primary disadvantage of this method is the length of time necessary to ascertain the mass/volume measurement.

Another technique used for mass/volume measurement involves the beta-ray backscatter instrument. The particulate mass collected on a porous filter is measured directly by a beta-ray backscatter. This technique is very expensive, however, and also requires a permanent installation.

Other techniques for air pollution measurements have also been used which operate on the basis of opacity or light scattering theories. These techniques have large measurement errors, however, due to their strong dependence upon particulate size.

The present invention overcomes all of the aforementioned disadvantages as it provides a particulate monitor which gives a direct meter readout in mass/volume in a short period of time, for example, on the order of one minute. The monitor is less expensive than other instruments, can be completely portable (i.e., hand carried and battery operated), and has a signal output which is independent of the particulate diameter.

SUMMARY OF THE INVENTION

The advantages of the invention are attained by flowing the gaseous fluid containing the suspended particles down a bounded flow path, ionizing the fluid at an upstream portion of the flow path to charge the particles, repelling the charged particles from a charge deposition electrode and thus driving the charged particles toward a grounded electrode, and collecting (depositing) a portion of the charged particles on a dielectric surface positioned in front of the grounded electrode. The surface potential built upon the dielectric surface is then measured after a given sampling time by a static charge induction electrode which is connected to an electrometer. Since the current density is a linear function of the particulate mass concentration per unit volume of the gaseous flow, and also is independent of the particulate size, the mass/volume of the particulate matter can be read directly from the electrometer.

BRIEF DESCRIPTION OF THE DRAWINGS

The invention may be more effectively understood by referring to the drawings, wherein:

FIG. 1 illustrates a particulate sampling apparatus utilizing the present invention;

FIG. 2 is a top-view of the sampling module of the apparatus shown in FIG. 1;

FIG. 3 is a cross-sectional view of the sampling module taken along the line and in the direction of the arrows 3—3 in FIG. 2.

FIG. 4 is a side-view in partial section and with the side wall removed of the electrometer module of the apparatus shown in FIG. 1;

FIG. 5 is a schematic view of the support module of the apparatus shown in FIG. 1;

FIG. 6 illustrates an operator using an embodiment of the invention;

FIG. 7 is a schematic view of a holding plate and lance for use with the embodiment of the invention shown in FIG. 6;

FIG. 8 is a schematic view of a continuous particulate sampling apparatus in accordance with the present invention; and

FIG. 9 is a schematic view of another continuous particulate sampling apparatus in accordance with the present invention.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

FIG. 1 illustrates the preferred embodiment of a mass/volume particulate measuring apparatus 10 utilizing the present invention. The apparatus includes three sections which for illustrative purposes will be described and discussed separately. The three sections are an electrogasdynamic sampling module 11, an electrometer module 12, and a support module 13. For operation, the three sections are connected together to form one unit 10 which can be either portable or permanently installed.

FIGS. 2 and 3 illustrate the electrogasdynamic sampling module 11. The sampling module forms a flow channel 20. The particulate-laden gas which is to be sampled enters the channel 20 at the upstream end 21 and exits at the downstream end 22. In the channel 20 near its upstream end is an unipolar corona discharge electrode (ionizing element) 23. Such element 23 can be a wire, sawblade, or the like, and is charged by a constant current power supply 24 of any conventional type. For unit 10 the power supply 24 can be located in the support module 13. The electrode 23 is connected to the power supply 24 by means of a high-voltage connecting rod 25. To facilitate the separability of the three modules of the unit 10, the connecting rod 25 terminates at the outside perimeter of the sampling module 11 in an anti-corona metal sphere 26. When

the sampling module **11** is placed adjacent the support module **13**, the metal sphere **26** comes in contact with the constant current power supply **24**.

The current supplied by the power supply **24** is preferably on the order of 100 μA. A constant current source is used because the ionization current flowing from a corona element supplied by a constant voltage decreases with increasing moisture content of the gas (relative humidity). It is well known that the electrical mobility of molecular ions is reduced by water vapor attachment. The constant current power supply thus maintains the particle charging current constant as relative humidity varies.

The top and bottom surfaces **27** of the channel **20** are constructed of any conductive metal and are maintained at ground potential. The side surfaces (walls) **29** are constructed of a non-conducting material, such as Teflon. During operation, a corona discharge is established between the corona discharge element **23** and the grounded surfaces **27**. The corona element **23** should be well insulated from the channel surfaces **27** and this is accomplished in the preferred embodiment by terminating the element **23** at supports (not shown) located near the end of clearance tunnels **28** and by having non-conductive side surfaces **29**.

The particles **30** entrained in the gaseous flow are charged to a prespecified fractional charge as they pass through the ionized field between the corona element **23** and the surfaces **27**. To insure neutrality of the particles prior to entering the ionizing field and thus to achieve a more theoretically perfect sampling, the particles **30** can be discharged upstream of the field by a discharge electrode **31**. The discharge electrode **31** can be, for example, a series of grounded corona wires stretched across the channel **20** and can be maintained at a voltage by the power supply **24** or any other conventional power supply means. Such initial discharge electrode is not required, however, as the amount of particles charged and the strength of such charges are insignificant in most instances.

Charged molecular gas ions swept from the corona region by the channel gas flow are drawn by the grounded surfaces **27** along length L_1 of the channel **20** and neutralized before they can be collected (deposited) downstream on a dielectric collection surface.

The charged particles **30** are carried by the gaseous flow downstream to the deposition region **35**. In such region **35**, a deposition field electrode **36** and dielectric collecting surface **37** are positioned. The electrode **36** is made of conductive metal and electrically charged by a constant voltage power supply **38** of any conventional type. The power supply **38** is preferably capable of supplying 600 to 5,000 volts. For unit **10** the power supply **38** can be positioned in the support module **13**. The electrode **36** is connected to the power supply **38** by means of a metal tab **39** and a conductor **40**. To facilitate separability of the three modules, the conductor **40** preferably terminates in metal sphere **41**. The charge on the electrode **36** is of the same sign potential as the corona element and thus of the charged particles **30** so that the particles **30** will be repulsed (repelled) by the electrode **36** and driven toward the dielectric collecting surface **37**.

The surface **37** can be any good dielectric having mechanical strength in a thin section, high electrical resistivity, and the ability to operate in high temperature environments, such as 450°–500°F. Such dielectrics can be, for example, glass or ceramic plates. Excellent results have been obtained using glass microscope slide covers.

The surface **37** is accessible for cleaning and discharging after sampling by means of an access door **45**. The door **45** forms the upper surface of the channel **20** in the deposition region **35** and contains the electrode **36**. The surface **37** can be cleaned and discharged, for example, by wiping it with an electrically grounded paper wetted with methyl alcohol or the like.

When the unit **10** is assembled and the sampling module **11** is placed in contact with the electrometer module **12**, a grounded metal backing plate **50**, which is shown in dashed lines in FIG. **3** and explained in more detail with reference to FIG. **4**, is positioned slightly below the sampling surface **37**. An electric deposition (collection) field is established between electrode **36** and the grounded plate **50** by power supply **38** and such field drives a portion of the charged particles **30** towards the sampling surface **37** where they are deposited thereon. The charge accumulated onto the surface **37** during a specified sampling time (typically one minute) is then measured by reading its voltage with an electrometer and induction probe (FIG. **4**) positioned below the surface **37**.

The surface **37** is embedded flush with the lower surface of the channel **20** and is insulated from ground. The sampling surface **37** is bonded by an adhesive or any other means to the insulated support **46**. The support **46** is constructed of a highly resistive material to maintain a low leakage path from the deposited charged particles to ground. The support **46** is provided with surfaces **47** which are protected ("hidden") from soiling by the particles **30** by a grounded metal shield cover **48** and an air space **49**. The cover **48** and air space **49** help maintain a highly resistive surface leakage path. When the particles **30** are very conductive, the charge leakage can be lessened by constructing the support **46** of a highly resistive material, for example, Teflon.

At the downstream end **22** of the channel **20**, a discharge electrode **42** can be provided if it is desired to neutralize the charged, undeposited particles entrained in the exhaust gaseous flow. The electrode **42** can be, for example, a series of wires stretched across the channel **20**. The corona electrode **42** can be maintained at a voltage by power supply **24** or any other conventional power supply means.

If it is desired to insure separation of non-respirable particles from the total airborne particles so that only the respirable size particles will arrive at and be deposited on the sampling surface **37**, the length of the deposition electrode **36** can be extended an additional distance L_2. By proper setting of the velocity of the gaseous flow and the strength of the deposition field, the phenomenon of electrostatic deflection of charged particles can be utilized to deposit the larger, more electrically mobile particles onto the lower channel wall and onto the grounded shield cover **48**.

FIG. 4 illustrates the preferred form of the electrometer module 12 for the unit 10. The module 12 is constructed so that the sampling module 11 can be placed on its top surface 51 for direct measurement. This feature eliminates any measurement error which might result if the test surface 37 had to be removed from the module 11 for measurement.

To facilitate placing and correctly positioning the sampling module 11 upon the module 12, a well ("seat") 52 is provided on the top surface 51. The well 52 is constructed to mate with the insulated support 46 and the cover 48, both of which extend below the lowermost surface of the channel 20 (see FIG. 3). The remainder of the lowermost surface of the module 11 rests on the surface 51.

When the modules 11 and 12 are mated, the deposition surface 37 is positioned approximately at the location shown by the dashed lines in FIG. 4. For testing, the grounded plate 50 is positioned directly below the deposition surface 37, as heretofore described.

The plate 50 is adjustable in order to facilitate alternately sampling the flow and measuring the accumulated charge on the surface 37. The grounded plate 50 is attached to a grounded sliding shield 53 by parallel linkages 54. The shield 53 is movable by any conventional means, such as the rack 55 and pinion 56 arrangement illustrated in FIG. 4. When the pinion 56 is rotated, the engagement of the pinion 56 with the rack 55 causes the shield 53 to travel horizontally. As the shield 53 travels rightwardly in FIG. 4 the plate 50 strikes a sharply inclined ramp 57 made preferably of very low friction material, such as Teflon, and causes the plate 50 to move vertically. The plate 50 is moved upwardly until it is near but not in contact with the sampling surface 37. The horizontal travel of the shield 53 and thus the vertical travel of the plate 50 is stopped by an adjustable screw 58. The screw 58 is adjusted so that an air gap is left between the plate 50 and the surface 37. The air gap, preferably on the order of one-sixteenth of an inch, is necessary to prevent conduction of the charge through the surface 37 to the plate 50.

During the sampling stage, the shield 53 is in its extreme rightward position and the plate 50 is in position for sampling of the shield 53 gaseous flow. After sampling, the movement of the shield 53 is reversed from that described above and the shield 53 and plate 50 are moved to a position not directly beneath the surface 37. The surface 37 is then exposed to measurement by an induction electrode 60 which is fixed permanently in vertical alignment with the well 52 and thus the surface 37.

The electrode 60 can be any static charge detection probe, such as the No. 2501 and 2503 model probes manufactured by Keithley Instruments, Inc.

Prior to movement of the shield 53 and plate 50 after sampling, however, the induction electrode 60 should be "zeroed" at ground potential. An electrical field-free space for zeroing is provided below the shield 53 when such shield is in position for sampling.

The induction electrode 60 is supported by a base 61 which in turn is supported by support 59. The base 61 is constructed of a highly non-conductive material which maintains the high input impedance necessary for the electrometer circuit 62. As illustrated in FIG. 4, the base 61 is designed to expose only a minimum amount of its surface for a residence of free charge.

When the electrode 60 is exposed to the surface 37, the accumulated charge on such surface induces a potential onto the electrode 60. The strength of the induced signal depends on the following factors: (1) the surface of the electrode 60; (2) the voltage on the surface 37; and (3) the input capacitance of the electrometer circuit 62. This induced voltage signal is the input to the electrometer circuit 62 which can be of any conventional type. The signal can be conducted to the circuit 62 by, for example, contact 65, rod 63 and conductor 64. The contact 65 is depicted for illustrative purposes as a spring contact to facilitate easy removal of the circuit 62 from the module 12, but can be of any conventional type. The output from the electrometer 60 in turn drives a voltmeter 70 of any conventional type whose deflection is a linear function of the potential on the sampling surface 37. The voltmeter can have many ranges of measurement and the appropriate range can be used depending on the potential of the charge on the surface 37. When the electrometer module 12 is constructed, the panel of the voltmeter 70 can be mounted on an outside surface (wall) 71 of the module 12 (as shown in FIG. 1) for easy viewing. The arc-type scale can be calibrated to read out in units of mass/volume, for example, milligrams per cubic meters, grains per cubic feet, or the like. As shown in FIG. 1, a control 72 for switching the range of the meter 70 also can be mounted on the wall 71 of the module 12.

The electrometer circuit 62 preferably is mounted on a slidable base 75 but it is understood that the circuit 62 can be mounted in a fixed position also. The base 75 can be constructed of any nonconductive material with good mechanical strength characteristics, such as fiberglass board. Groves 76 are provided on the inside of the walls 71 of the module 12 to facilitate sliding of the base 75. In this manner the circuit 62 is readily accessible for repair or replacement. The base 75 can be held in place by, for example, a cover-plate 77 secured by screws 78.

The induction electrode 60 and the circuit 62 can be grounded for zeroing by, for example, a panel push rod (not shown) which contacts and grounds a leaf spring 80 in contact with electrode 60. The electrode 60 can also be grounded by attaching a spring contact (not shown) to the bottom of the slide 53 which grounds the circuit 62 when the slide 53 is in position for sampling.

Since, as hereinafter discussed, the particulate mass/volume readout is independent of the specific size of material being measured, the particulate volume/gas volume readout, when multiplied by the true bulk density of the material being measured, gives the mass/volume. The multiplication is done electronically by the electrometer circuit 62. A control knob 85 can be provided, as shown in FIG. 1, to adjust the circuit 62 to the proper bulk density of the specific material being measured. When the knob 85 is set at unity, the meter 70 will provide the particulate volume/gas volume.

FIG. 5 illustrates the support module 13 of the unit 10. The use of the module 13 facilitates the containment of the power supplies, the fan and the like in one easily accessible unit. It is understood, however, that any other type of means can be used for these elements or they may all be attached separately to the electrogasdynamic sampling device and the electrometer device.

In module 13, the following elements can be located: the constant current power supply 24; the constant voltage deposition power supply 38; a fan or impeller 90; a battery pack 91; a battery recharger 92; and the voltage output connections (not shown) corresponding to and adapted to mate with metal spheres 26 and 41 (FIG. 2). The power supplies 24 and 38 are described above with reference to FIGS. 1–3. The fan 90 can be of any convention type and its purpose is to induce a gaseous flow of a specified velocity in channel 20, especially when stagnant atmospheres are measured. For portable operation of the invention, battery pack 91 can be provided. If a battery pack is utilized, it is preferable also to provide a battery recharger 92.

To maintain the velocity of the flow in the channel 20 at a specified velocity, a transducer 138 (shown in FIGS. 8 and 9) can be provided. The transducer 138 is in communication with the fan 90 and is adapted to measure the flow velocity in the channel and to adjust the speed of the fan 90 accordingly to maintain the channel velocity constant.

It will be beneficial at this point to examine in more detail the theory of operation of the sampling apparatus.

Consider an applied electric field E (volts/m) established between two parallel plate conducting electrodes. Let the gas filling the space between the electrodes contain a mass concentration M (kg/m^3) of particulate matter per unit volume. Mathematically, it can be demonstrated that the current density J (amperes/m^2) flowing between the plates is a linear function of the particulate mass/volume concentration M.

The current density J is the product of the numerical density of the particulates n_p (number of particles/m^3), the particle charge q_p (coulombs), and the particulate velocity v_p (m/sec):

$$J = n_p q_p v_p \tag{1}$$

But

$$v_p = k_p E \tag{2}$$

where k_p is the mobility of the charged particulate (m^2/volt-sec), and also,

$$k_p = q_p / 6\pi\eta a \tag{3}$$

where η is the gas viscosity (kg/m-sec) and a is the particulate radius (m). Thus,

$$J = n_p q_p^2 E / 6\pi\eta a \tag{4}$$

And from particulate charging theory,

$$q_p = (12\pi\epsilon_o E_o a^2) \quad (f) \tag{5}$$

where ϵ_o is the permittivity of the gas (coul^2/nt-m^2), E_o is the corona charging field (volt/m) and f is the fraction of saturation charge attained on the particulate. Thus,

$$J = \left[\frac{24\pi\epsilon_o^2 E_o^2}{\eta}\right] f^2 n_p E a^3 \tag{6}$$

Since,

$$m_p = 4/3\ \pi a^3 \delta \text{ or } a^3 = 3m_p/4\pi\delta \tag{7}$$

where m_p is the mass of a single particulate (kg) and δ is the bulk density of the particulate matter (kg/m^3), then,

$$J = \left[\frac{24\pi\epsilon_o^2 E_o^2}{\eta}\right] f^2 E \frac{3m_p n_p}{4\pi\delta} \tag{8}$$

But,

$$n_p m_p = M \tag{9}$$

and thus,

$$J = \left[\frac{18\epsilon_o^2 E_o^2}{\eta}\right]\left[\frac{f^2 E}{\delta}\right](M) \tag{10}$$

For a given type of particulate matter, with a given corona charging system and a given particulate deposition field, this becomes;

$$J = KM \tag{11}$$

where K is a constant.

Thus for any particular system, the current density J is a linear function of the particulate mass concentration per unit volume of gas. Experiments have proved the correctness of this theory.

The foregoing analysis also illustrates that the current density is independent of the particulate size (or size distribution).

The determination of particulate mass/volume by measuring the current density directly has two complications, namely, the extremely small currents dealt with and the length of time required for highly resistive particulates to transfer their charges to a metal electrode. As described above, the present sampling apparatus utilizes a dielectric surface backed by a grounded metal electrode as the deposition surface and the resultant build-up of potential (volts) on the dielectric is measured quickly and easily.

Appropriate restrictions regarding the sampling time must be observed, however, in order to insure that the output from the apparatus remains a linear function of the mass concentration M. The range of linearity of the present apparatus has been established theoretically; but before stating the results, it will be helpful to examine the theory.

Consider placing a dielectric material, for example, glass or Mylar, having a thickness d_m (m) and permittivity ϵ_m onto the lower of two parallel plate conducting (metal) electrodes. The upper plate is charged by a high-voltage source to a voltage V and the lower plate is grounded, thus establishing an electric field E_a in the air-dielectric system between the plates. The total voltage drop across the system is,

$$V = E_a d_a + E_m d_m \tag{12}$$

where d_a (m) is the distance between the upper plate and the uppermost surface of the dielectric (d_a thus is the air gap) and E_m is the electric field (volts/m) established in the dielectric.

Further, at the air-dielectric interface, the discontinuity of the normal component of the electric displacement vector is equal to the surface charge density ρ_s (coul/m^2) of the free charge on the interface, Thus,

$$\epsilon_m E_m - \epsilon_a E_a = \rho_s \tag{13}$$

where ϵ_a is permittivity of the air (coul^2/nt-m^2).

Equations (12) and (13) can be used to derive an equation for the electric field E_a in the air which is driving the charged particulates toward the dielectric as,

$$E_a = \left[\frac{\epsilon_m V}{\epsilon_a d_m + \epsilon_m d_a}\right] - \left[\frac{\rho_s d_m}{\epsilon_a d_m + \epsilon_m d_a}\right] \tag{14}$$

where the first parenthetical expression is due only to the applied field V which is constant and the second parenthetical expression is due to the build-up on the dielectric surface as a function of time.

Now the current density, from Ohm's Law is,

$$J=\sigma_a E_a \tag{15}$$

where σ_a is the conductivity of the air (mho/m), and also,

$$J=d\rho_s/dt \tag{16}$$

where t is time in seconds.

Thus, from equations (14), (15) and (16), the following first order, linear, differential equation is derived;

$$\left(\frac{d\rho_s}{dt}\right)+\left(\frac{\sigma_a d_m}{\epsilon_a d_m+\epsilon_m d_a}\right)=\left(\frac{\sigma_a \epsilon_m V}{\epsilon_a d_m+\epsilon_m d_a}\right) \tag{17}$$

By separation of variables and integration, the surface charge density build-up on the dielectric deposition surface can be expressed as a function of time,

$$\rho_s=(\epsilon_m V/d_m)(1-e^{-t/\tau}) \tag{18}$$

where the dielectric surface-charging time constant τ (sec) characterizes the time at which the surface has attained 63 percent of its final maximum value of $\epsilon_m V/d_m$ and is given by the expression,

$$\tau=\epsilon_a d_m+\epsilon_m d_a/\sigma_a d_m \tag{19}$$

From Ohm's Law ($\sigma_a = J/E_a$), equation (10) can furnish ρ_a for substitution into equation (19), and thus,

$$\tau=\frac{\epsilon_a d_m+\epsilon_m d_a}{\left\{\frac{18\epsilon_o^2 E_o^2 f^2 M}{\eta\delta}\right\} d_m} \tag{20}$$

Equation (18) for the surface charge density has an asymptotic growth. For $t << \tau$ the growth is practically linear, that is, the slope ($J = d\rho_s/dt$) is nearly constant with time. Therefore, for a collection (deposition) time T small compared with τ,

$$\rho_s=\int \delta J dt \cong JT \tag{21}$$

Combining equations (21) and (11),

$$\rho_s=(KT)M \tag{22}$$

or

$$\rho_s=K_1 M \tag{23}$$

where K_1 is a constant.

Further, the potential ϕ_s (volts) of the dielectric surface is a linear function of the surface charge density ρ_s, so,

$$\phi_s=K_2 M \tag{24}$$

where K_2 is a constant.

From the above analysis, the surface charge density ρ_s and the surface potential ϕ_s of the dielectric deposition surface are theoretically shown to be practically linear functions of the particulate mass/volume M, provided the particle collection time T is restricted to a value which is small compared with a time constant τ as given by equation (20).

To meet this requirement the present apparatus preferably should operate at collection times less than one-half a time constant as calculated by equation (20) for the maximum anticipated M value. In most instances, the time will be on the order of one to a few minutes.

Accordingly, the method and apparatus of the present invention provide an instrument response characterized by a short measurement time, an independence from particle diameter, and a direct signal readout which is a linear function of mass/volume over a wide range of particulate concentrations. Further, since current density is measured, it is not necessary to collect all of the particulate mass from the gaseous flow in order to measure M. In fact, the particles **30** themselves can be eroded from the sampling surface **37** by the gas velocity without affecting the measure of M so long as the particles leave their charge on such surface.

In order to insure uniform particle deposition along the length of the surface **37** for a specified channel gaseous flow velocity v_g, the maximum deposition voltage V is determined by the following equation,

$$V=v_g\eta^d a^2/2\epsilon_o E_o f L a \tag{25}$$

where L is the length of the dielectric sampling surface **37**. The maximum V permissible is that which allows the largest anticipated particle to just traverse the entire air gap (d_a) as it travels the length L. This insures that all of the smaller particles are uniformly deposited along the length of the surface **37**.

When the three modular units are jointed together to form a complete sampling apparatus, as shown in FIG. **1**, the apparatus is used primarily to sample open atmospheres. The fan **90** is utilized, if necessary, to provide the requisite gaseous flow through the channel **20**. However, when the apparatus is used for monitoring the emission of industrial stacks and the like where the temperatures of the gases are high and the gases naturally have a velocity, another embodiment can be used. This embodiment is shown in FIGS. **6** and **7**.

The temperature of the gases in industrial stacks is typically on the order of 400° to 500°F. The embodiment shown in FIGS. **6** and **7** alleviates the deleterious effects that such temperatures would have on the operation of the different parts of the apparatus. As shown in FIG. **6**, the sampling module **11** is detached from the electrometer module **12** and the support module **13** and is adapted for insertion into a stack or duct **125**. A small hole **126**, slightly larger than the cross-sectional area of the module **11**, can be provided in stack **125** for the insertion. A lance **127** allows the operator to remain at a safe distance from the stack **125** during this sampling. In the preferred construction of the stack sampling apparatus, the lance **127** is about six feet long and is comprised of an aluminum tube 1 inch in diameter. The handle area of the lance **127** can be made of or covered with an insulated material, for example, wood or rubber, to ensure protection and safety of the operator. The lance **127** also can be bent along its length to facilitate ease of insertion of the module **11** into the stack **125**.

For the embodiment shown in FIGS. **6** and **7**, the sampling module **11** must be constructed of materials capable of withstanding the high temperatures in stacks. For example, preferably the metal parts are aluminum and the non-conductive parts are Teflon, but these parts can be made of any other materials with similar properties.

Attached to the lance **127** and adapted to hold the module **11** is a holding plate **130**. In FIG. **7**, finger **131** of holding plate **130** is designed for insertion into the end of the lance **127** by, the plate **130** being securely attached to the lance **127** by, for example, one or more screws (not shown). The holding plate **130** has a grounded plate **132** which is positioned so that it will be directly beneath the sampling surface **37** (FIG. **3**) when the module **11** is mounted on such plate. The plate **132** is similar to the grounded plate **50** discussed above in reference to FIGS. **2**, **3** and **4** and performs the same function. Also provided in plate **130** is a well **133** which acts as a seat for mating with the sampling module **11** (FIG. **2**). The grounded plate **132** is attached to the bottom of the well **133**.

The ionizing constant current voltage supply **24** and the deposition voltage supply **28** are connected to the module **11** by spring loaded "bullet" contacts **134** and **135**, respectively. Contact **134** makes contact with metal sphere **26** (FIG. **2**) of module **11** and contact **135** makes contact with metal sphere **41** (FIG. **2**). The contacts **134** and **135** are, in turn, connected to wire conductors **136** and **137**, respectively, which are carried by lance **127** to the support module **13**. If desired, the conductors **136** and **137** can be coaxial. The electrostatic operation of the module **11** when it is placed in the holding plate **130** at the end of the lance **127** is the same as that described above with reference to FIGS. **2** and **3**.

The naturally occurring velocity of the gaseous flow in the stack **125** provides the necessary flow for sampling. The velocity of the gases in most industrial stacks is in the range of 10 ft/sec to 100 ft/sec and experiments have shown that the present apparatus operates excellently within this range. The module **11** samples the flow transversely to the gaseous flow in the stack **125**, but this does not affect the operation of the apparatus nor the accuracy of the resulting measurement.

At the conclusion of the sampling stage, the module **11** is removed from the stack **125**, detached from the holding plate **130** and placed upon the electrometer module **12**. The charge on the surface **37** and thus the mass/volume of the particulate matter in the flow is then measured and read in the same manner as that described above with reference to FIG. **4**.

In some instances, it is preferable to have a sampling apparatus which provides a continuous measurement of the amount of particulate matter in the particular environment. One such instance involves mining operations where for safety reasons the amount of dust in the mine shafts should be known at all times. Even the few minutes needed to secure a sampling by the apparatus illustrated in FIGS. **1–5** possibly could be undesirable and hazardous. Continuous or automatic sampling apparatus are illustrated schematically in FIGS. **8** and **9**.

In FIG. **8**, the particles **30** entrained in the gaseous flow in the channel **20** are charged by an ionizing element **23** in the same manner as that described above with reference to FIGS. **2** and **3**. Also similarly, the charged particles are repelled in a deposition region **35** and are driven toward and deposited upon a sampling surface **137**. The sampling element in this embodiment, however, comprises a rotatable, grounded metal cylinder or drum **150** covered on its outside surface with a dielectric surface **137**. The surface **137** can be any dielectric, such as a 3.5 mil Kapton tape which is self-adhesive and can be bonded to the drum **150**.

The drum **150** is rotated in the direction of the arrow in FIG. **8** and continuously presents a portion of the surface **137** to flow for sampling. The tangential velocity of the drum **150** preferably is adjusted to be the same as the velocity of the gaseous flow in the channel **20**. To measure the accumulated charge on the surface, a static charge induction electrode **60** connected to an electrometer (not shown) is provided. The electrode **60** is positioned adjacent the drum **150**, preferably at the position illustrated in FIG. **8**. The electrode **60** and the manner of achieving the resultant mass/volume measurement are the same as that described above with reference to FIG. **4**.

After the surface **137** is "read" by the electrometer, it reconditioned (cleaned and neutralized) for further sampling. The reconditioning phase can comprise of, for example, a counter-rotating brush **151** which physically contacts the surface **137** and cleans the particles therefrom, and an A.C. corona **152** which discharges the surface **137** to zero volts (or to a base reference level). The surface **137** can also be neutralized by wiping it with a methanol wetted grounded roller (not shown). With this latter method of discharging the drum surface **137**, however, it is preferable to remove the drum from the electrometer module **12**. Mechanical means (not shown) for automatically sliding the drum **150** out of the module **12** can be provided.

To operate the drum **150** and cleaning brush **151**, a small drive motor **153** of any conventional type is provided. The A.C. corona discharge **152** can be operated by the deposition power supply **38** (FIGS. **3** and **5**) which can be contained in a supply module **13** similar to that described above.

Inserted into the channel **20** is an air velocity transducer **138** which is described above with reference to FIG. **5**. In addition to being in communication with the fan and thus regulating the velocity of the flow in the channel, the velocity transducer **138** can also or alternatively be in communication with the drive motor **153** and utilized to adjust the rotation of the drum **150**. In the latter instance, where the flow in the channel is caused by the gas itself, the transducer **138** can maintain the speed of rotation of the dielectric surface in a prespecified relationship to the velocity of the flow.

A second embodiment of a continuous sampling apparatus is illustrated in FIG. **9**. In this design an endless dielectric belt **160** is rotated by two rollers **161** and **162**. The belt **160** can be of any dielectric material, such as Mylar. One or both of the rollers **161** and **162** can be driven by a drive motor **153** of any conventional type. Positioned underneath the upper portion **237** of the belt **160** is a grounded metal plate **250**. The operation of apparatus of FIG. **9** is the same as that with respect to the earlier described embodiments. The charged entrained particles **30** are driven by a deposition electrode **36** toward the grounded plate **250** and are deposited upon the portion of the belt designated by numeral **237**. Also in a similar manner to that heretofore described with reference to FIG. **8**, the accumulated charge on the surface **237** is measured and the belt **160** is cleaned and discharged for resampling.

For continuous sampling, the three phases of the sampling operation (the collection, measurement and discharge phases) are preferably carried out simultaneously but they do not have to be. For example, first the apparatus could be run for a period of time with only the collection phase and its corresponding power supplies operating. Then, the collection power supply could be turned off and the electrometer section put into operation. Finally, the electrometer power could be turned off and the cleaning and discharging phase put into effect, either by operating the A.C. corona **152** or by sliding out the drum **150** or belt **160** for wiping.

If any of the above embodiments (FIGS. 1–9) are used for sampling respirable dust, it is sometimes preferable to attach a particle size separation unit (not shown) at the inlet **21** of the channel **20**. Such separation unit could be, for example, a cyclone unit, and would exclude from sampling all particles over a certain diameter. Alternately, an electrostatic deflection technique could be used to deposite out the more mobile, larger charged dust particles prior to entrance of the flow in the channel **20**.

Although the invention has been described with reference to specific embodiments thereof, it is understood that substitutions, modifications and variations, both in form and detail, will occur to those skilled in the art. All such substitutions, modifications and variations, therefor, are intended to be included within the scope of the invention as defined in the appended claims.

We claim:

1. A method for determining the mass per unit volume of particles entrained in an ionizable gas, comprising the steps of
   - flowing the gas through a bounded flow path;
   - charging the particles to a given electrical polarity by means of a first corona discharge field at an upstream portion of the flow path;
   - exposing the charged particles to a deposition electrical field at a downstream portion of the flow path, the deposition electrode of said field having the same polarity as the polarity of the charged particles;
   - driving the charged particles toward the ground electrode of said field;
   - depositing a portion of said charged particles on a dielectric surface positioned in said field, and
   - determining by induction the accumulated charge on the dielectric surface.

2. A method in accordance with claim **1** wherein the first corona discharge field is established by a constant current power supply.

3. A method in accordance with claim **1** comprising the additional step of discharging the particles by means of a second corona discharge field positioned upstream of said first corona discharge field.

4. A method in accordance with claim **1** comprising the additional step of discharging the charged particles by means of a third corona discharge field positioned downstream of said deposition electric field.

5. A method in accordance with claim **1** comprising the additional step of separating out from the gas substantially all particles above a certain size, the separation taking place upstream of said first corona discharge field.

6. A method in accordance with claim **1** wherein the accumulated charge on the dielectric surface is determined by measurement by an induction electrode and the measurement of the accumulated charge is linearly related to the mass of the particulate matter per unit volume of the gas and is independent of the size of the particulate matter.

7. A method in accordance with claim **1** wherein the maximum voltage V permissible for said deposition electrical field is given by the relation

$$V = v_g \eta d_a^2 / 2\epsilon_o E_o f L a$$

where v_g is the velocity of the gas in the bounded flow path, η is the viscosity of the gas, d_a is the distance from the deposition electrode to the dielectric surface, ϵ_o is the permittivity of the gas, E_o is the first corona charging field, f is the fraction of saturation charge attained on the particulate matter, L is the length of the dielectric surface, and a is the average radius of the particulate matter.

8. A method for determining the mass per unit volume of particles entrained in an ionizable gas, comprising the steps of
   - flowing the gas through a bounded flow path;
   - charging the particles to a given electrical polarity by means of a first corona discharge at an upstream portion of the flow path;
   - exposing the charged particles to a deposition electrical field at a downstream portion of the flow path, the deposition electrode of said field having the same polarity as the polarity of the charged particles;
   - driving the charged particles toward the ground electrode of said field;
   - depositing a portion of said charged particles on a dielectric surface positioned in said field, and
   - determining by induction the accumulated surface charge density on the dielectric surface, the surface charge density ρ_s being determined as a function of time by the equation

$\rho_s = (\epsilon_m V/d_m)(1-e^{-t/\tau})$ for measurement times of t $<<\tau$, where ϵ_m is the permittivity of the dielectric surface, V is the voltage of the deposition electrical field, d_m is the thickness of the dielectric surface, t is the time, and τ is the dielectric surface-charging time constant given by the relation

$$\tau = \frac{\epsilon_a d_m + \epsilon_m d_a}{\left\{\frac{18\epsilon_o^2 E_o^2 f^2 M}{\eta\delta}\right\} d_m},$$

where ϵ_a is the permittivity of the air, d_a is the distance between the deposition field electrode and the dielectric surface, ϵ_o is the permittivity of the gas, E_o is the first corona charging field, f is the fraction of saturation charge attained on the particulate matter, η is the viscosity of the gas, δ is the bulk density of the particulate matter, and M is the mass of the particulate matter per unit volume of the gas.

9. A method in accordance with claim **8** comprising the additional step of converting electrically the accumulated charge determined by induction to a measurement of the particulate mass per unit volume of the gas.

10. An apparatus for determining the mass per unit volume of particles entrained in an ionizable gas comprising

means defining a bounded flow path for passage of the gas, the flow path having at least two conductive grounded surfaces,

means for establishing a first electrical discharge in the upstream end of the flow path to charge the entrained particles,

means for establishing a deposition electric field at a downstream portion of the flow path, said deposition electric field having a deposition electrode and a ground electrode,

a dielectric surface for collecting the charges associated with the particles, the dielectric surface positioned in the deposition electric field adjacent the ground electrode, and

an induction electrode for measuring the accumulated charge on the dielectric surface.

11. An apparatus as defined in claim 10 wherein the means for establishing the first electrical discharge in the upstream end of the flow path comprise a corona discharge electrode and a constant current power supply.

12. An apparatus as defined in claim 10 further comprising means for establishing a second electrical discharge in the flow path, the second electrical discharge means positioned upstream of the first electrical discharge means.

13. An apparatus as defined in claim 12 wherein the second electrical discharge means comprises at least one corona discharge electrode and an electrical power supply.

14. An apparatus as defined in claim 10 further comprising means for establishing a third electrical discharge in the flow path, the third electrical discharge means positioned downstream of the deposition electric field means.

15. An apparatus as defined in claim 14 wherein the third electrical discharge means comprises at least one corona discharge electrode and an electrical power supply.

16. An apparatus as defined in claim 10 further comprising means for separating out from the gas substantially all particles above a certain size, the separation means positioned at the upstream end of the flow path.

17. An apparatus as defined in claim 10 wherein the induction electrode is positioned below the ground electrode and the ground electrode is adapted to be adjustably removed from adjacent the dielectric surface.

18. An apparatus as defined in claim 10 wherein the accumulated charge measured by the induction electrode is converted electrically to a measurement of the mass of the particulate matter by an electrometer circuit, the accumulated charge and the mass of the particulate matter per unit volume of the gas measurements being linearly related and the accumulated charge measured being independent of the size of the particulate matter.

19. An apparatus as defined in claim 10 further comprising means for inducing a flow of the gas in the flow path.

20. An apparatus as defined in claim 19 wherein the flow inducing means comprises a fan positioned adjacent the downstream end of the flow path.

21. An apparatus for determining the mass per unit volume of particles entrained in an ionizable gas comprising

means defining a bounded flow path for passage of the gas,

means for establishing an electrical discharge in the upstream end of the flow path to charge the entrained particles,

means for establishing a deposition electric field at a downstream portion of the flow path, said deposition electric field having a deposition electrode and a ground electrode,

a dielectric surface for collecting the charges associated with the particles, the dielectric surface positioned in the deposition electric field between the deposition electrode and the ground electrode, and

induction means for determining the accumulated surface charge density on the dielectric surface, the surface charge density ρ_s being determined as a function of time by the equation

$$\rho_s = (\epsilon_m V/d_m)\,(1-e^{-t/\tau})$$

for measurement times of $t << \tau$, where ϵ_m is the permittivity of the dielectric surface, V is the voltage of the deposition electrical field, d_m is the thickness of the dielectric surface, t is the time, and τ is the dielectric surface-charging time constant given by the relation

$$\tau = \frac{\epsilon_a d_m + \epsilon_m d_a}{\left\{\frac{18\epsilon_o^2 E_o^2 f^2 M}{\eta\delta}\right\} d_m},$$

where ϵ_a is the permittivity of the air, d_a is the distance between the deposition field electrode and the dielectric surface, ϵ_o is the permittivity of the gas, E_o is the first corona charging field, f is the fraction of saturation charge attained on the particulate matter, η is the viscosity of the gas, δ is the bulk density of the particulate matter, and M is the mass of the particulate matter per unit volume of the gas.

22. An apparatus as defined in claim 21 wherein the accumulated surface charge density determined is converted electrically to a measurement of the mass of the particulate matter per unit volume of the gas by an electrometer circuit.

23. An apparatus for continuously determining the mass per unit volume of particles entrained in an ionizable gas comprising

means defining a bounded flow path for passage of the gas,

means for establishing an electrical discharge in the upstream end of the flow path to charge the entrained particles,

means for establishing a deposition electric field at a downstream portion of the flow path, said deposition electric field having a deposition electrode and a ground electrode,

a dielectric surface for collecting the charges associated with the particles, the dielectric surface being movable, endless and positioned with at least one portion thereof in the deposition electric field,

means for moving the endless dielectric surface, and

an induction electrode for measuring the accumulated charge on the dielectric surface.

24. An apparatus as defined in claim 23 wherein the endless dielectric surface is attached to a rotatable cylinder, the means for moving the endless dielectric surface is connected to the cylinder, and the cylinder is grounded and acts as the ground electrode for the deposition electric field.

25. An apparatus as defined in claim 23 further comprising means for discharging the accumulated charge on the endless dielectric surface.

26. An apparatus as defined in claim 23 wherein the endless dielectric surface comprises an endless belt positioned around at least two rollers and the means for moving the surface is connected to at least one of the rollers.

27. An apparatus for determining the mass per unit volume of particles entrained in an ionizable gas comprising

means defining a bounded flow path for passage of the gas, the flow path having at least two grounded conductive surfaces,

a first corona discharge electrode,

power supply means for establishing a corona discharge from the first corona discharge electrode to the grounded conductive surfaces in the upstream end of the flow path to charge the entrained particles,

a deposition field electrode and a deposition field ground electrode positioned at a downstream portion of the flow path,

power supply means for establishing a deposition electric field between the deposition electrode and the ground electrode,

a dielectric surface for collecting the charges associated with the particles, the dielectric surface positioned in the deposition electric field adjacent the ground electrode,

an induction electrode for measuring the accumulated charge on the dielectric surface, the induction electrode positioned below the ground electrode, and

an electrometer circuit for receiving the accumulated charge measured by the induction electrode and converting the measurement to a measurement of the particulate mass per unit volume of gas.

28. An apparatus as defined in claim 27 wherein the means defining the bounded flow path, the corona discharge electrode, the deposition field electrode and the dielectric surface are contained in a sampling module, the deposition field ground electrode, the induction electrode and the electrometer circuit are contained in an electrometer module, and the corona discharge power supply means and the deposition field power supply means are contained in a supply module, the three modules adapted to be separable.

29. An apparatus as defined in claim 28 wherein the power supply means for the first corona discharge electrode is a constant current power supply means.

30. An apparatus as defined in claim 28 further comprising a fan for inducing a flow of gas in the flow path, the fan positioned in the supply module and in communication with the downstream end of the flow path.

31. An apparatus as defined in claim 27 further comprising a second corona discharge electrode in the flow path to discharge the charged entrained particles, the second corona discharge electrode positioned upstream of the first corona discharge electrode.

32. An apparatus as defined in claim 27 further comprising a third corona discharge electrode in the flow path to discharge the charged entrained particles, the third corona discharge electrode positioned downstream of the deposition electric field.

33. An apparatus as defined in claim 27 further comprising a holding plate and a lance attached to the holding plate, the means defining the bounded flow path, the corona discharge electrode, the deposition field electrode and the dielectric surface contained in a sampling module, and the sampling module positioned on the holding plate whereby the mass per unit volume of particles entrained in the gas in a stack can be determined.

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