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Hall

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(54) **RIGID PARTICULATE MATTER SENSOR**

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(73) Assignee: **Board of Regents, The University of Texas System**, Austin, TX (US)

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G01N 37/00 (2006.01)

(52) **U.S. Cl.** **73/28.01**

(58) **Field of Classification Search** 73/28.01, 73/28.02

See application file for complete search history.

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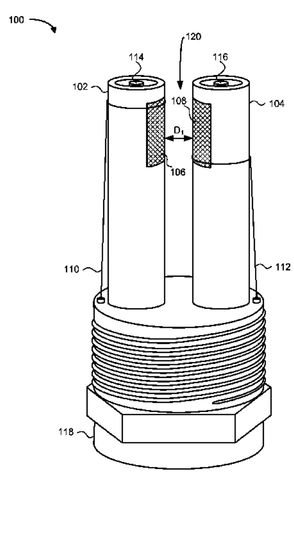
(57) **ABSTRACT**

A sensor to detect particulate matter. The sensor includes a first rigid tube, a second rigid tube, a detection surface electrode, and a bias surface electrode. The second rigid tube is mounted substantially parallel to the first rigid tube. The detection surface electrode is disposed on an outer surface of the first rigid tube. The detection surface electrode is disposed to face the second rigid tube. The bias surface electrode is disposed on an outer surface of the second rigid tube. The bias surface electrode is disposed to face the detection surface electrode on the first rigid tube. An air gap exists between the detection surface electrode and the bias surface electrode to allow particulate matter within an exhaust stream to flow between the detection and bias surface electrodes.

33 Claims, 5 Drawing Sheets



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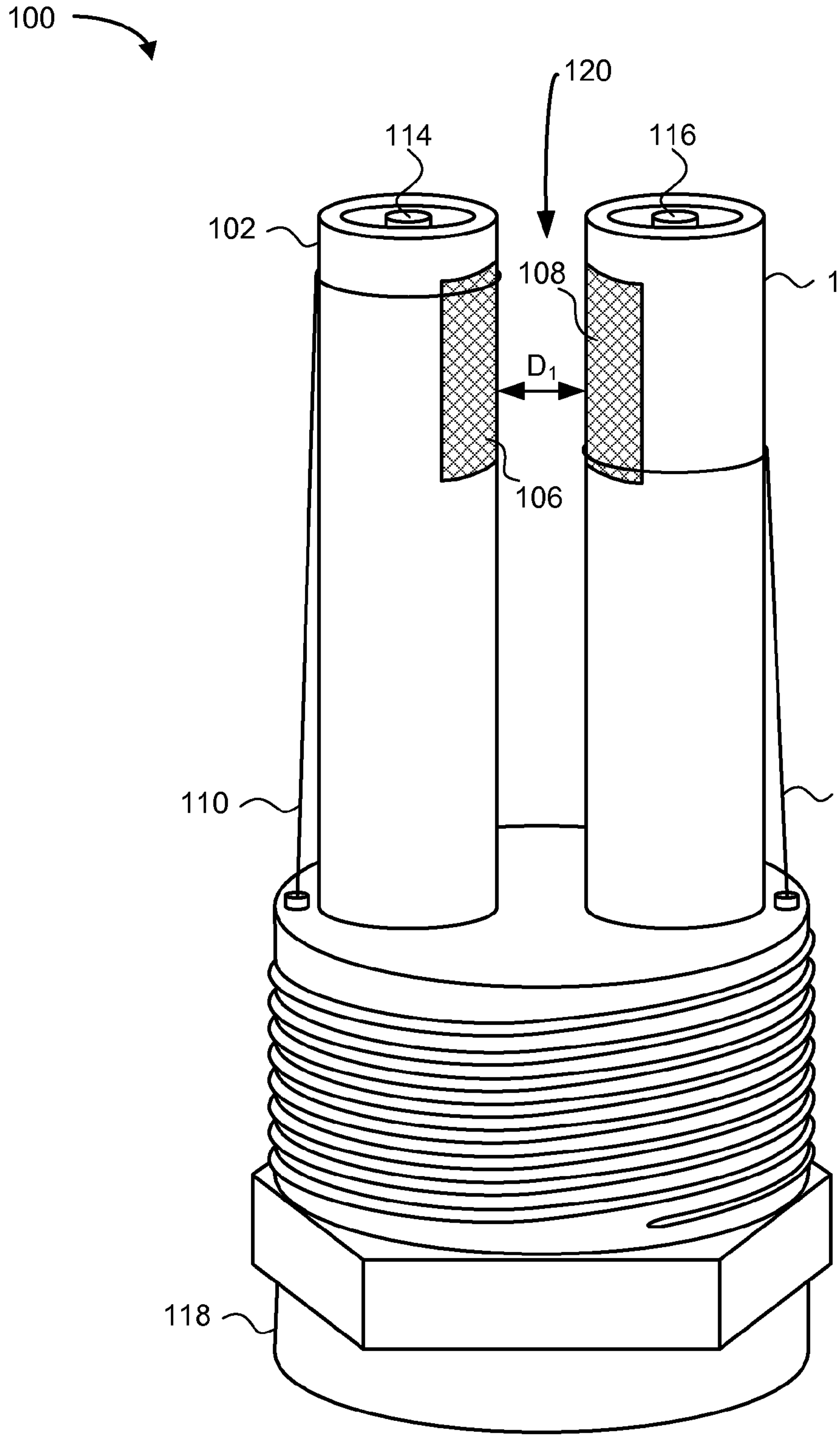

FIG. 1

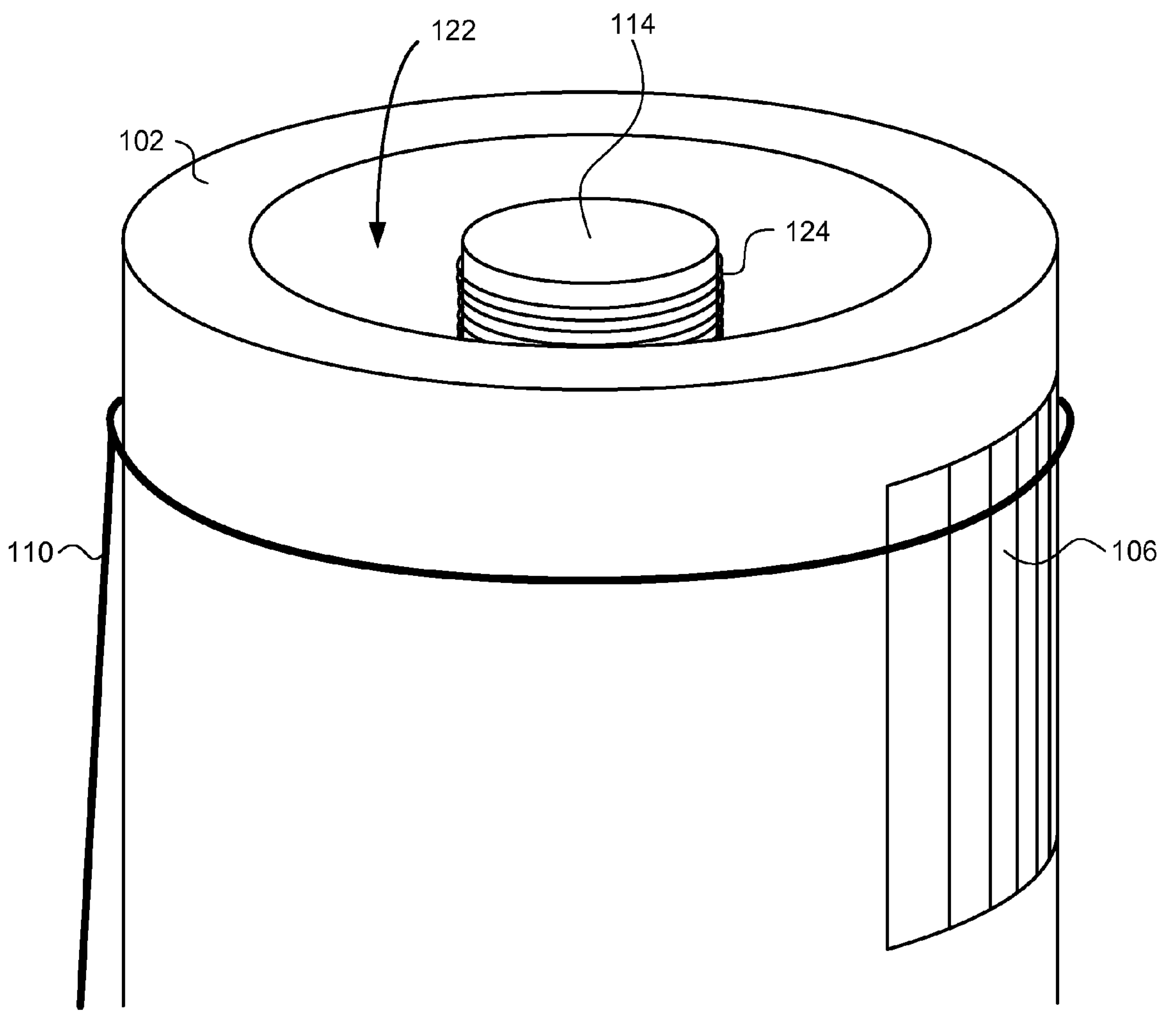

FIG. 2

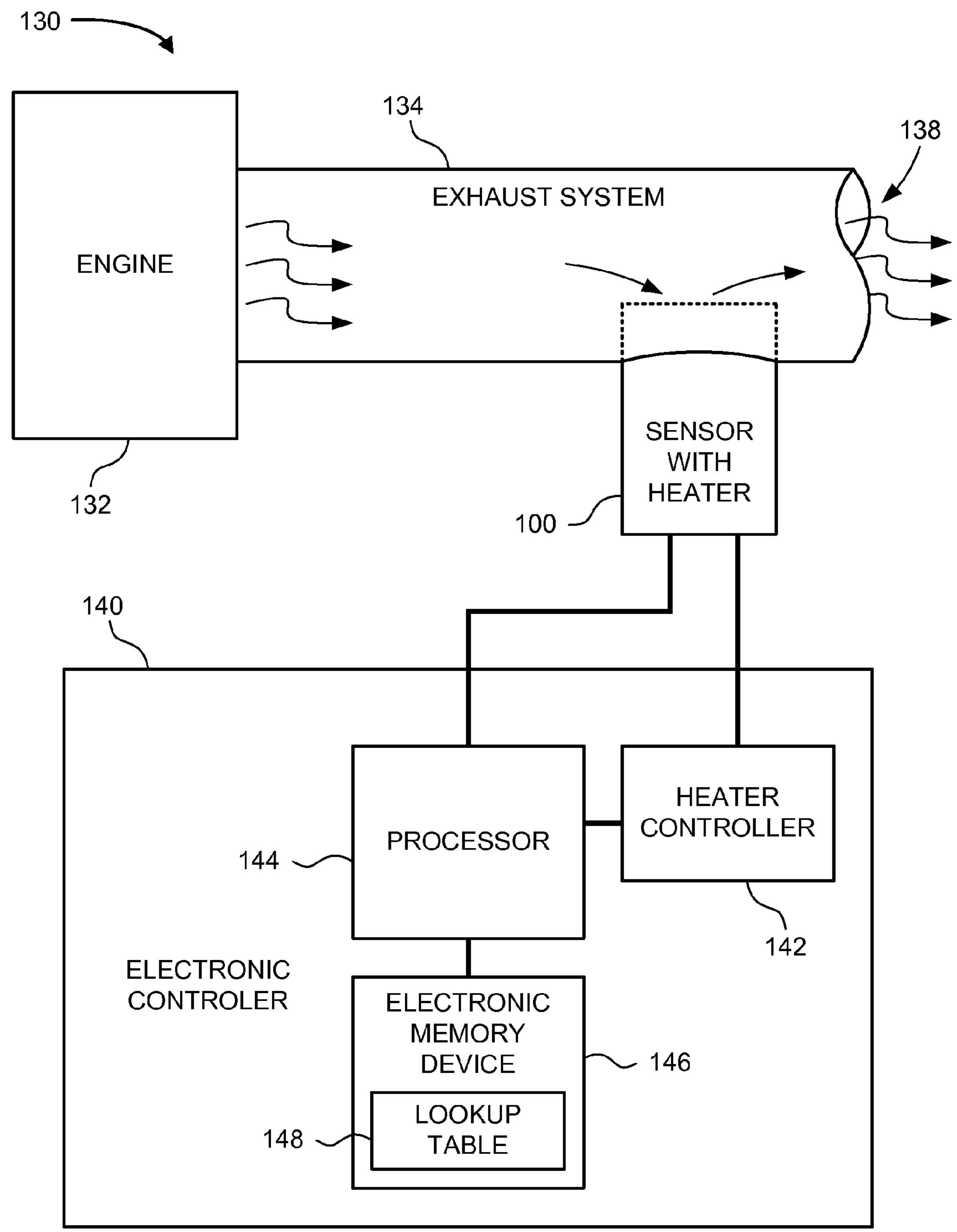
130
134
138
EXHAUST SYSTEM
ENGINE
132
SENSOR WITH HEATER
100
140
PROCESSOR
144
HEATER CONTROLLER
142
ELECTRONIC CONTROLER
ELECTRONIC MEMORY DEVICE
146
LOOKUP TABLE
148

FIG. 3

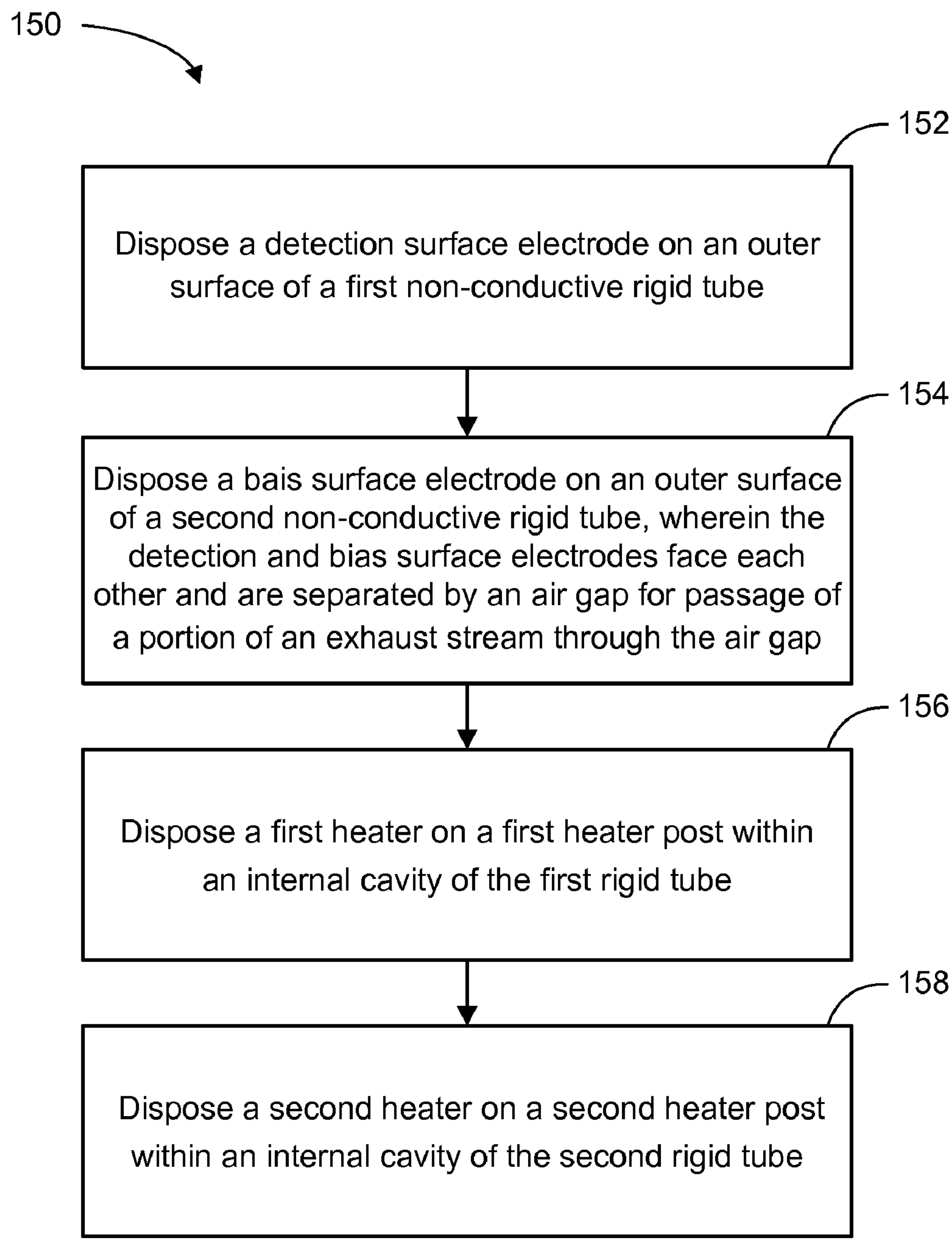
150
152
Dispose a detection surface electrode on an outer surface of a first non-conductive rigid tube
154
Dispose a bais surface electrode on an outer surface of a second non-conductive rigid tube, wherein the detection and bias surface electrodes face each other and are separated by an air gap for passage of a portion of an exhaust stream through the air gap
156
Dispose a first heater on a first heater post within an internal cavity of the first rigid tube
158
Dispose a second heater on a second heater post within an internal cavity of the second rigid tube

FIG. 4

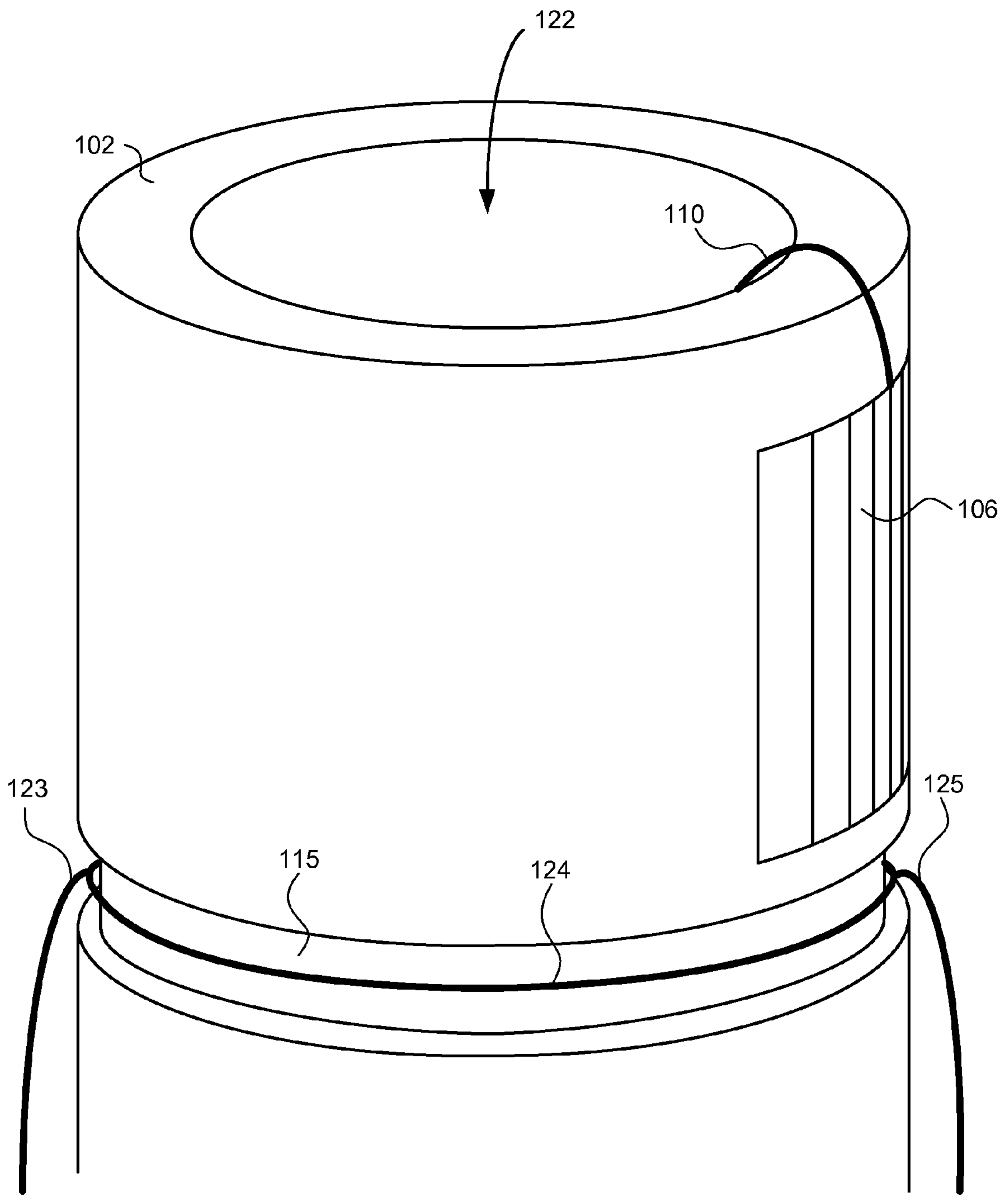

FIG. 5

RIGID PARTICULATE MATTER SENSOR

U.S. GOVERNMENT INTEREST

This invention was made with government support under Contract No. DE-FC26-06NT42966 awarded by the U.S. Department of Energy. The government has certain rights in the invention.

BACKGROUND

Internal combustion engines (e.g., diesel engines) typically generate an exhaust flow that contains varying amounts of particulate matter (PM). The amount and size distribution of particulate matter in the exhaust flow tends to vary with engine operating conditions, such as fuel injection timing, injection volume, injection pressure, or the engine speed to load relationship. Adjustment of these conditions may be useful in reducing particulate matter emissions and average particle size of the particulate matter from the engine. Reducing particulate matter emissions from internal combustion engines is environmentally favorable. In addition, particulate matter measurements for diesel exhaust is useful for on-board (e.g., mounted on a vehicle) diagnostics of PM filters and reduction of emissions through combustion control.

Conventional technologies that may be used for on-board monitoring of particulate matter in exhaust flow include the use of wire electrodes in sensor applications. Wire electrode sensors apply a high voltage between two electrodes and measure the current or charge between the electrodes. The electrode measurement is correlated with a specific particulate matter concentration. However, wire electrode sensors are subject to the de-calibration and baseline drift of the sensor due to accumulation of soot (i.e., particulate matter deposit) on and between the electrodes. Wire electrodes are also subject to vibration, which changes the distance between the electrodes. As the distance between the electrodes changes according to the vibration of the electrodes, the varying distance introduces error in the particulate matter reading.

SUMMARY

Embodiments of a sensor are described. In one embodiment, the sensor includes a first rigid tube, a second rigid tube, a detection surface electrode, and a bias surface electrode. The second rigid tube is mounted substantially parallel to the first rigid tube. The detection surface electrode is disposed on an outer surface of the first rigid tube. The detection surface electrode is disposed to face the second rigid tube. The bias surface electrode is disposed on an outer surface of the second rigid tube. The bias surface electrode is disposed to face the detection surface electrode on the first rigid tube with a gap between the detection surface electrode and the bias surface electrode. Other embodiments of the sensor are also described.

Embodiments of a system are also described. In one embodiment, the system is a system for detecting particulate matter. The system includes a sensor and an electronic controller. The sensor is configured to detect the particulate matter within an exhaust stream. The sensor includes a pair of non-conductive rigid tubes, a detection surface electrode, and a bias surface electrode. The detection surface electrode is disposed on one of the rigid tubes and faces the other non-conductive rigid tube. The bias surface electrode is disposed on the other rigid tube. The bias surface electrode faces the detection surface electrode and is separated from the detection surface electrode by an air gap for passage of a portion of the exhaust stream through the air gap. The electronic controller is configured to determine an amount of the particulate matter within the exhaust stream. Other embodiments of the system are also described.

Embodiments of a method are also described. In one embodiment, the method is a method for making a particulate matter sensor. The method includes disposing a detection surface electrode on an outer surface of a first non-conductive rigid tube. The method also includes disposing a bias surface electrode on an outer surface of a second non-conductive rigid tube. The bias and detection surface electrodes face each other and are separated by an air gap for passage of a portion of an exhaust stream through the air gap. The method also includes disposing a first heater on a first heater post within an internal cavity of the first rigid tube. The first heater applies heat to burn off particulate matter from the first non-conductive rigid tube. The method also includes disposing a second heater on a second heater post within an internal cavity of the second rigid tube. The second heater applies heat to burn off particulate matter from the second non-conductive rigid tube. Other embodiments of the method are also described.

Other aspects and advantages of embodiments of the present invention will become apparent from the following detailed description, taken in conjunction with the accompanying drawings, illustrated by way of example of the principles of the invention.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** depicts a schematic diagram of one embodiment of a sensor assembly.

FIG. **2** depicts a schematic diagram of one embodiment of the heater post within the first rigid tube of the sensor assembly of FIG. **1**.

FIG. **3** depicts a schematic block diagram of one embodiment of a particulate matter detection system.

FIG. **4** depicts a flow chart diagram of one embodiment of a method for making a particulate matter concentration sensor.

FIG. **5** depicts a schematic diagram of another embodiment with the heater element mounted to the outside of the first rigid tube of the sensor assembly of FIG. **1**.

Throughout the description, similar reference numbers may be used to identify similar elements.

DETAILED DESCRIPTION

It will be readily understood that the components of the embodiments as generally described herein and illustrated in the appended figures could be arranged and designed in a wide variety of different configurations. Thus, the following more detailed description of various embodiments, as represented in the figures, is not intended to limit the scope of the present disclosure, but is merely representative of various embodiments. While the various aspects of the embodiments are presented in drawings, the drawings are not necessarily drawn to scale unless specifically indicated.

The present invention may be embodied in other specific forms without departing from its spirit or essential characteristics. The described embodiments are to be considered in all respects only as illustrative and not restrictive. The scope of the invention is, therefore, indicated by the appended claims rather than by this detailed description. All changes which come within the meaning and range of equivalency of the claims are to be embraced within their scope.

Reference throughout this specification to features, advantages, or similar language does not imply that all of the features and advantages that may be realized with the present invention should be or are in any single embodiment of the invention. Rather, language referring to the features and advantages is understood to mean that a specific feature, advantage, or characteristic described in connection with an embodiment is included in at least one embodiment of the present invention. Thus, discussions of the features and advantages, and similar language, throughout this specification may, but do not necessarily, refer to the same embodiment.

Furthermore, the described features, advantages, and characteristics of the invention may be combined in any suitable manner in one or more embodiments. One skilled in the relevant art will recognize, in light of the description herein, that the invention can be practiced without one or more of the specific features or advantages of a particular embodiment. In other instances, additional features and advantages may be recognized in certain embodiments that may not be present in all embodiments of the invention.

Reference throughout this specification to “one embodiment,” “an embodiment,” or similar language means that a particular feature, structure, or characteristic described in connection with the indicated embodiment is included in at least one embodiment of the present invention. Thus, the phrases “in one embodiment,” “in an embodiment,” and similar language throughout this specification may, but do not necessarily, all refer to the same embodiment.

While many embodiments of a particulate matter sensor are described herein, at least some of the described embodiments detect particulate matter within an exhaust stream. The sensor includes two surface electrodes on two rigid tubes. The surface electrodes are oriented to face each other. An air gap between the two surface electrodes allows exhaust to flow between the two surface electrodes. In some embodiments, the first surface electrode is a detection electrode. The detection electrode is disposed on the first rigid tube. The second surface electrode is a bias electrode and is disposed on the second rigid tube. The bias surface electrode has an applied voltage, also referred to as a bias voltage. As the particulate matter in the exhaust stream passes between the bias and detection surface electrodes, a charge builds up or a current flows on the detection surface electrode. An electronic controller measures an electrical characteristic in the form of a charge, current, or voltage, and determines an amount of particulate matter in the exhaust.

Additionally, as exhaust passes through the sensor, particulate matter may build up on the surfaces of the sensor. Deposits on the detection and bias surface electrodes can distort particulate matter measurements. In some embodiments, each rigid tube of the sensor includes a heater post located in an internal cavity within the tube. A wire heater may be wrapped around the heater post. The wire heater is configured to generate heat sufficient to burn off the particulate matter deposits on the surfaces of the rigid tube. In particular, the heaters may burn off particulate matter deposits on the detection and bias surface electrodes.

Also, in some embodiments, by locating the surface electrodes on two separate rigid tubes, typical problems relating to electrical leakage through intermediate ceramic layers can be avoided. While conventional ceramic sensors which include electrodes separate by an intermediate ceramic layer can exhibit electrical leakage at high voltages and/or high operating temperatures (due to decreased electrical insulating properties of the intermediate ceramic layer), embodiments of the particulate matter sensor described herein do not have an intermediate ceramic layer interposed between the electrode layers and, therefore, do not exhibit electrical leakage between the surface electrodes. In other words, embodiments with the surface electrodes mounted on separate structures (e.g., rigid tubes) have reduced charge leakage which results in reduced signal distortion, compared with conventional ceramic particulate matter sensors made from a single stack of ceramic and conductive layers.

FIG. **1** depicts a schematic diagram of one embodiment of a sensor assembly **100**. The illustrated sensor assembly **100** includes a first rigid tube **102**, a second rigid tube **104**, a detection surface electrode **106**, a bias surface electrode **108**, a first electrical connection **110**, a second electrical connection **112**, a first heater post **114**, a second heater post **116**, and a sensor base **118**. Although the sensor assembly **100** is shown and described with certain components and functionality, other embodiments of the sensor assembly **100** may include fewer or more components to implement less or more functionality.

In some embodiments, the first rigid tube **102** is made of non-conductive ceramic. For example, the first rigid tube **102** may be made of alumina (Al2O3), magnesia (MgO), magnesium aluminate spinell ($MgAl_2O_4$), or other types of spinells. Other embodiments may use other types of ceramics and/or non-conductive materials. In one embodiment, the first rigid tube **102** has a substantially cylindrical geometry. The first rigid tube **102** has an outer diameter that is constant along the length of the first rigid tube **102**. In some embodiments, the first rigid tube **102** has an inner diameter to retain the structural stability of the first rigid tube **102**. In one embodiment, the outer diameter of the first rigid tube **102** is between about 6 to 7 mm (approximately 0.25 inch). In other embodiments, the outer diameter of the first rigid tube **102** is between about 5 to 10 mm. In some embodiment, the wall thickness of the first rigid tube **102** is about 1 mm (approximately 30 to 40 thousandths of an inch). In other embodiment, the wall thickness of the first rigid tube **102** is about 0.5 to 2 mm. The inner diameter of the first rigid tube **102** depends on the outer diameter and the wall thickness of the first rigid tube **102**. However, at least some embodiments of the first rigid tube **102** have an inner diameter that is sufficiently large to fit the first heater post **114** within the interior cavity of the first rigid tube **102**. The size of the first heater post **114** may depend on the type of heating element which is implemented by the first heater post **114**. Other embodiments may use other dimensions for the inner or outer diameters, or the wall thickness, of the first rigid tube **102**.

The first rigid tube **102** is aligned parallel to the second rigid tube **104**. The second rigid tube **104** is substantially similar to the first rigid tube **102**. In some embodiments, the first and second rigid tubes **102** and **104** are formed of the same ceramic materials. In other embodiments, the first and second rigid tubes **102** and **104** are formed of different ceramic or non-conductive materials. The first and second rigid tubes **102** and **104** define an air gap **120**. The air gap **120** allows air, or exhaust, to flow between the first and second rigid tubes **102** and **104**. The air gap **120** separates the first and second rigid tubes **102** and **104**, as well as the corresponding detection and bias surface electrodes **106** and **108** by a distance D_1.

The detection surface electrode **106** is disposed on the outer surface of the first rigid tube **102**. The detection surface electrode **106** is made of a conductive material. The detection surface electrode **106** may include, for example, a metallic foil made of platinum, gold, tungsten, nickel, or a mullite-based material. Other embodiments may use or include other types of conductive materials. In some embodiments, the detection surface electrode **106** is painted onto an outer surface of the first rigid tube **102**. In another embodiment, the detection surface electrode **106** is printed onto the outer surface of the first rigid tube **102**. In other embodiments, the detection surface electrode **106** is chemically or physically deposited onto the outer surface of the first rigid tube **102**.

The bias surface electrode **108** is substantially similar in structure and material to the detection surface electrode **106**. In particular, the bias surface electrode **108** is disposed on an outer surface of the second rigid tube **104**. The detection and surface electrodes **106** and **108** may be between about 1.0 to 2.0 square cm. In another embodiment, the surface area of each of the surface electrodes **106** and **108** is between about 0.5 to 4.0 square cm. Other embodiment may have surface electrodes **106** and **108** with smaller or larger surface areas.

In some embodiments, the bias surface electrode **108** is biased and generates an electric field. In one embodiment, a bias voltage is applied to the bias surface electrode **108**. The bias voltage of the bias surface electrode **108** may be, for example, between about 1 to 10,000 Volts. Alternatively, the bias voltage may be between about 500 to 5,000 Volts. Other embodiments may use other bias voltages. By biasing the bias surface electrode **108**, the particulate matter passing in the exhaust stream between the bias surface electrode **108** and the detection surface electrode **106** affects a charge or current on the detection surface electrode **106**. The charge or current (or voltage) on the detection surface electrode **106** can be correlated with a particulate matter concentration within the exhaust stream. In this way, the detection surface electrode **106** facilitates detection of the particulate matter in the exhaust stream.

The detection and bias surface electrodes **106** and **108** are connected to the first and second electrical connections **110** and **112**, respectively. In one embodiment, the first electrical connection **110** is used to measure the charge, current, or voltage on the detection surface electrode **106**. The second electrical connection **112** is used to supply the bias voltage to the bias surface electrode **108**. FIG. **1** shows the first and second electrical connections **110** and **112** looped around the outside of the rigid tubes **102** and **104** and the surface electrodes **106** and **108** to mechanically connect to the surface electrodes **106** and **108**. In another embodiment, the electrical connections **110** and **112** may be connected to the surface electrodes **106** and **108** by a thermal process such as brazing. The electrical connections **110** and **112** extend down to the sensor base **118**. Other embodiments may implement other connection configurations for the first and second electrical connections **110** and **112**.

In order to measure the charge on the detection surface electrode **106**, some embodiments of the sensor **100** include a charge amplifier (not shown) coupled to the detection surface electrode **106** via the first electrical connection **110**. The charge amplifier may be calibrated to measure an accumulated electric charge on the detection surface electrode **106** as particulate matter flows within the exhaust stream between the detection and bias surface electrodes **106** and **108**. The electric charge that accumulates on the detection surface electrode **106** varies with the mass concentration of particulate matter in the exhaust conduit. Thus, the charge amplifier may generate an output voltage corresponding to the measured accumulated electric charge. In general, the charge amplifier obtains a voltage proportional to the charge and yields a low output impedance. Hence, the charge amplifier also may be referred to as a charge-to-voltage converter.

Alternatively, in some embodiments, current flow on the detection surface electrode **106** and through the first electrical connection **110** may be measured in order to determine an amount of particulate matter in the exhaust stream. In another embodiment, voltage or another electrical parameter may be measured to determine the amount of particulate matter in the exhaust stream.

In one embodiment, although not depicted in detail in FIG. **1**, the detection and bias surface electrodes **106** and **108** are offset relative to each other to reduce the chance of an electrical short occurring between the electrical components of the first rigid tube **102** and the electrical components of the second rigid tube **104**. In particular, the detection and bias surface electrodes **106** and **108** are offset relative to each other, along a longitudinal axis of the first and second rigid tubes **102** and **104**, to reduce the chance of an electrical short occurring between the bias surface electrode **108** and the first electrical connection **110** or between the detection surface electrode **106** and the second electrical connection **112**. However, it should be noted that offsetting the surface electrodes **106** and **108** may reduce the amount of overlap between the surface electrodes **106** and **108** and, hence, reduce the effective size of the surface electrodes **106** and **108** (or, alternatively, increase the effective distance, D_1, between the surface electrodes **106** and **108**).

The first and second heater posts **114** and **116** are located within the internal cavities first and second rigid tubes **102** and **104**. The heater posts **114** and **116** are described in more detail below with reference to FIG. **2**. The sensor base **118** allows the sensor **100** to be mounted into an exhaust channel wall (e.g., an exhaust pipe).

FIG. **2** depicts a schematic diagram of one embodiment of the heater post **114** within the first rigid tube **102** of the sensor assembly **100** of FIG. **1**. In one embodiment, the heater post **116** and the second rigid tube **104** are similar in structure and function to the heater post **114** and the first rigid tube **102**, respectively.

The shape of the first rigid tube **102** forms an internal cavity **122**. In one embodiment, the heater post **114** is centrally mounted within the internal cavity **122**. Alternatively, the heater post **114** may be offset, for example, to be near the detection surface electrode **106**. A heater element **124** is disposed on the outer surface of the first heater post **114**. In one embodiment, the heater element **124** is separated by a distance from the first rigid tube **102**. More specifically, there may be an air gap between the heater element **124** and the ceramic structure of the first rigid tube **102**. By having the air gap between the heater element **124** and the first rigid tube **102**, the temperature of the first rigid tube **102** can be maintained lower so that the first rigid tube **102** does not get too hot and become electrically conductive. If the first rigid tube **102** were to become electrically conductive, then a disruptive current can flow from the heater element **124** to the surface electrode **106** if the heater element **124** were to contact the inner surface of the first rigid tube **102**.

In one embodiment, the heater element **124** is a resistive heater element. For example, the heater element **124** may be a resistive wire wrapped around the heater post **114**. In one embodiment, the heater element **124** is configured to generate heat substantially continuously. In some embodiments, the heater element **124** is configured to generate heat intermittently. Some embodiments may incorporate a timing scheme to control the heater element **124**, as described in more detail below with reference to FIG. **3**.

In one embodiment, the heater element **124** maintains specific operating temperatures for the corresponding rigid tube **102** and, in particular, the corresponding detection surface electrode **106**. The heater **124** may operate continuously, periodically, or on some other non-continuous basis. In one embodiment, the heater element **124** operates within a temperature range of approximately 200° C. or higher to burn off particulate matter from the rigid tube **102**, which may include burning off particulate matter accumulated on the detection surface electrode **106**. In some embodiments, the heater element **124** operates within a temperature range of approximately 400° C. or higher. Other embodiments of the heater element **124** may operate at other temperatures.

FIG. **3** depicts a schematic block diagram of one embodiment of a particulate matter detection system **130**. The illustrated embodiment includes the particulate matter sensor **100**, an engine **132**, and an exhaust system **134**. The engine **132** produces exhaust which moves through the exhaust system **134**. The exhaust system **134** facilitates flow of the exhaust gases to an exhaust outlet **138**. The sensor **100** is at least partially inserted into the exhaust system **134** to detect particulate matter in the exhaust stream. As the exhaust in the exhaust system **134** passes over and through the sensor **100**, the sensor **100** detects the particulate matter within the exhaust by measuring changes in the electrical characteristics at the sensor **100**, as described above.

The particulate matter detection system **130** also includes an electronic controller **140**. The electronic controller **140** includes a heater controller **142**, a processor **144**, and an electronic memory device **146**. The sensor **100** relays the sensor signal to the processor **144** of the electronic controller **140**. In some embodiments, the processor **144** analyzes the sensor signal from the sensor **100**. If the sensor signal is corrupted, the processor **144** sends a control signal to the heater controller **142**. The heater controller **142** activates one or more heaters on the sensor **100** to burn off particulate matter deposits that might corrupt the sensor signal from the sensor **100**. In some embodiments, the processor **144** sends the control signal to the heater controller **142** to activate the heater on the sensor **100** according to a timing scheme or on some other substantially continuous or non-continuous basis.

If the sensor signal from the sensor **100** is not corrupt, the processor **144** compares the sensor signal with data stored in a lookup table **148** on the electronic memory device **146** to determine one or more qualities of the exhaust in the exhaust system **134**. For example, the processor **144** may determine an amount of particulate matter in the exhaust stream. The processor **144** also may compare the sensor signal from the sensor **100** with data from the lookup table **148** to estimate, for example, a mass concentration of particulate matter in the exhaust stream. In other embodiments, the electronic controller **140** facilitates detection of one or more other qualities of the exhaust in the exhaust system **134**.

Some embodiments of the particulate measurement system **130** also may include one or more emissions control elements (not shown) to emit neutralizing chemicals into the exhaust system **134** either before or after the sensor **100**. It should also be noted that embodiments of the sensor **100** may be tolerant of fluctuations of certain gaseous constituents in an exhaust gas environment. In this way, the sensor **100** may be calibrated to measure particular chemicals or materials within an exhaust stream.

It should also be noted that the sensor **100** may be used, in some embodiments, to determine a failure in another component of the particulate matter detection system **130**. For example, the sensor element **100** may be used to determine a failure of a particulate matter filter (not shown) within the exhaust system **134**. In one embodiment, a failure within the particulate matter detection system **130** may be detected by an elevated signal generated by the sensor **100**. In some embodiments, the particulate matter detection system **130** includes an alarm to indicate a detected failure of the sensor **100** or other component of the particulate matter detection system **130**. In some embodiments, the sensor **100** also could be coupled to another sensor or detector such as a mass flow meter.

FIG. **4** depicts a flow chart diagram of one embodiment of a method **150** for making a particulate matter sensor such as the sensor **100** of FIG. **1**. Although the method **150** is described in conjunction with the sensor **100** of FIG. **1**, other embodiments of the method **150** may be implemented with other particulate matter sensors.

The illustrated method **150** includes disposing **152** a detection surface electrode **106** on an outer surface of a first non-conductive rigid tube **102**. The method **150** also includes disposing **154** a bias surface electrode **108** on an outer surface of a second non-conductive rigid tube **104**. The detection and bias surface electrodes **106** and **108** face each other and are separated by an air gap **120** with a distance D_1. The air gap **120** allows a portion of an exhaust stream to pass between the detections and bias surface electrodes **106** and **108**. The method **150** also includes disposing **156** a first heater **124** on a first heater post **114** within an internal cavity **122** of the first rigid tube **102**. The method **150** also includes disposing **158** a second heater on a second heater post **116** within an internal cavity of the second rigid tube **104**. The heaters may be operated according to the electronic controller **140** of FIG. **3** to burn off particulate matter on the rigid tubes **102** and **104** and/or the detection and bias surface electrodes **106** and **108**. The depicted method **150** then ends.

FIG. **5** depicts a schematic diagram of another embodiment with the heater element **124** mounted to the outside of the first rigid tube **102** of the sensor assembly **100** of FIG. **1**. In some embodiments, the rigid tube **102** includes a surface groove **115**, which at least partially contains the heater element **124**. The heater element **124** may be located on the exterior of the first rigid tube **102** (e.g., within the groove **115**) to substantially reduce carbon tracks around the heater element **124**. In some embodiments, the heater element **124** is a closed loop with a source (i.e., supply) connection **123** and a ground connection **125**. The source and ground connections **123** and **125** may be attached to opposite sides of the heater element **124** (e.g., approximately 180 degrees around the first rigid tube **102**) so that current flows through both sides of the wire heater element **102**. By placing the heater **124** on the outside of the first rigid tube **102**, as explained herein, some embodiments prevent formation of a carbon track between the coils of a helical wound wire. In the depicted embodiment, the first electrical connection **110** is connected to the surface electrode **106** by a wire which runs through the internal cavity **122** of the first rigid tube **102**. Other embodiments may use other types of connections for the heater element **124** and/or the surface electrode **106**.

Although the operations of the method(s) herein are shown and described in a particular order, the order of the operations of each method may be altered so that certain operations may be performed in an inverse order or so that certain operations may be performed, at least in part, concurrently with other operations. In another embodiment, instructions or sub-operations of distinct operations may be implemented in an intermittent and/or alternating manner.

In the above description, specific details of various embodiments are provided. However, some embodiments may be practiced with less than all of these specific details. In other instances, certain methods, procedures, components, structures, and/or functions are described in no more detail than to enable the various embodiments of the invention, for the sake of brevity and clarity.

Although specific embodiments of the invention have been described and illustrated, the invention is not to be limited to the specific forms or arrangements of parts so described and illustrated. The scope of the invention is to be defined by the claims appended hereto and their equivalents.

What is claimed is:

1. A sensor comprising:

a first rigid tube;

a second rigid tube mounted substantially parallel to the first rigid tube;

a detection surface electrode disposed on an outer surface of the first rigid tube, wherein the detection surface electrode is disposed to face the second rigid tube; and

a bias surface electrode disposed on an outer surface of the second rigid tube, wherein the bias surface electrode is disposed to face the detection surface electrode on the first rigid tube with a gap between the detection surface electrode and the bias surface electrode.

2. The sensor of claim **1**, wherein the detection and bias surface electrodes each comprise a conductive foil disposed on the outer surfaces of the first and second rigid tubes.

3. The sensor of claim **1**, wherein the detection and bias surface electrodes each comprise a conductive material printed on the outer surfaces of the first and second rigid tubes.

4. The sensor of claim **1**, wherein the detection surface electrode is offset, along a longitudinal axis of the first rigid tube, relative to the bias surface electrode.

5. The sensor of claim **1**, wherein the detection surface electrode is electrically connected to an electrical connection within a central cavity of the first rigid tube.

6. The sensor of claim **1**, wherein the bias surface electrode is electrically connected to an electrical connection within a central cavity of the second rigid tube.

7. The sensor of claim **1**, wherein a bias voltage is applied to the bias surface electrode.

8. The sensor of claim **7**, wherein the bias voltage comprises a voltage within a range of approximately 1 to 10,000 Volts.

9. The sensor of claim **8**, wherein the bias voltage comprises a voltage within a range of approximately 500 to 5,000 Volts.

10. The sensor of claim **1**, wherein the first and second rigid tubes each comprise a ceramic material.

11. The sensor of claim **1**, further comprising a heater mounted within a surface groove of at least one rigid tube of the first and second rigid tubes, wherein the heater is configured to apply heat to approximately a surface electrode location on the at least one rigid tube.

12. The sensor of claim **11**, further comprising:

a source electrical connection coupled to a first side of the heater, the source electrical connection to provide a source voltage to the heater; and

a ground electrical connection coupled to a second side of the heater approximately on an opposite side of the heater, wherein the source electrical connection and the ground electrical connection facilitate current flow through the entire heater during operation of the heater.

13. The sensor of claim **1**, further comprising a heater mounted within at least one rigid tube of the first and second rigid tubes, wherein the heater is configured to apply heat to approximately a surface electrode location on the at least one rigid tube.

14. The sensor of claim **13**, wherein the heater comprises a resistance heater comprising a metal wire wound around the heater post.

15. The sensor of claim **13**, wherein the heater is configured to generate heat substantially continuously.

16. The sensor of claim **13**, wherein the heater is configured to generate heat intermittently.

17. The sensor of claim **13**, wherein the heater is located at a distance from an interior surface of the at least one rigid tube of the first and second rigid tubes to define an air gap between the heater and the interior surface of the at least one rigid tube.

18. The sensor of claim **1**, further comprising:

a first heater disposed on a first heater post within an internal cavity of the first rigid tube, the first heater to apply heat to the detection surface electrode; and

a second heater disposed on a second heater post within an internal cavity of the second rigid tube, the second heater to apply heat to the bias surface electrode.

19. A system for detecting particulate matter, the system comprising:

a sensor to detect the particulate matter within an exhaust stream, the sensor comprising:

a pair of non-conductive rigid tubes;

a detection surface electrode disposed on one of the rigid tubes,

wherein the detection surface electrode faces the other non-conductive rigid tube; and

a bias surface electrode disposed on the other rigid tube, wherein the bias surface electrode faces the detection surface electrode and is separated from the detection surface electrode by an air gap for passage of a portion of the exhaust stream through the air gap; and

an electronic controller to determine an amount of the particulate matter within the exhaust stream.

20. The system of claim **19**, wherein the detection and bias surface electrodes are disposed on outer surfaces of the rigid tubes.

21. The system of claim **19**, further comprising a plurality of heaters, wherein at least one heater is disposed within each rigid tube, wherein the heaters are configured to apply heat to the detection and bias surface electrodes on the rigid tubes.

22. The system of claim **21**, wherein the electronic controller is further configured to control a frequency of operation of the heaters.

23. The system of claim **21**, wherein the electronic controller is further configured to control a temperature of operation of the heaters.

24. The system of claim **19**, further comprising a heater to burn off particulate matter from the detection and bias surface electrodes.

25. The system of claim **19**, further comprising a sensor base to at least partially enclose an end of the sensor, the sensor base to allow the portion of the exhaust stream to pass between the detection and bias surface electrodes.

26. The system of claim **19**, further comprising an electrical connection to each of the detection and bias surface electrodes, wherein each electrical connection comprises a metallic wire along an outside surface of the corresponding non-conductive rigid tubes.

27. A method of operation of the system of claim **19**, the method comprising detecting a failure of a particulate matter filter within the exhaust stream based on the amount of the particulate matter within the exhaust stream.

28. A method of operation of the system of claim **19**, the method comprising controlling a combustion parameter of an engine from which the exhaust stream originates based on the amount of the particulate matter within the exhaust stream.

29. A method of operation of the system of claim **19**, the method comprising controlling the amount of particulate matter within the exhaust stream from an engine based on the amount of the particulate matter within the exhaust stream.

30. A method for making a particulate matter sensor, the method comprising:

disposing a detection surface electrode on an outer surface of a first non-conductive rigid tube;

disposing a bias surface electrode on an outer surface of a second non-conductive rigid tube, wherein the detection and bias surface electrodes face each other and are separated by an air gap for passage of a portion of an exhaust stream through the air gap;

disposing a first heater on a first heater post within an internal cavity of the first rigid tube, the first heater to apply heat to burn off particulate matter from the first non-conductive rigid tube; and

disposing a second heater on a second heater post within an internal cavity of the second rigid tube, the second heater to apply heat to burn off particulate matter from the second non-conductive rigid tube.

31. The method of claim 30, wherein disposing the detection and bias surface electrodes further comprises painting each surface electrode onto the outer surface of the corresponding non-conductive rigid tube.

32. The method of claim 30, wherein disposing the detection and bias surface electrodes further comprises printing each surface electrode onto the outer surface of the corresponding non-conductive rigid tube.

33. The method of claim 30, wherein disposing the detection and bias surface electrodes further comprises chemically depositing each surface electrode onto the outer surface of the corresponding non-conductive rigid tube.

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