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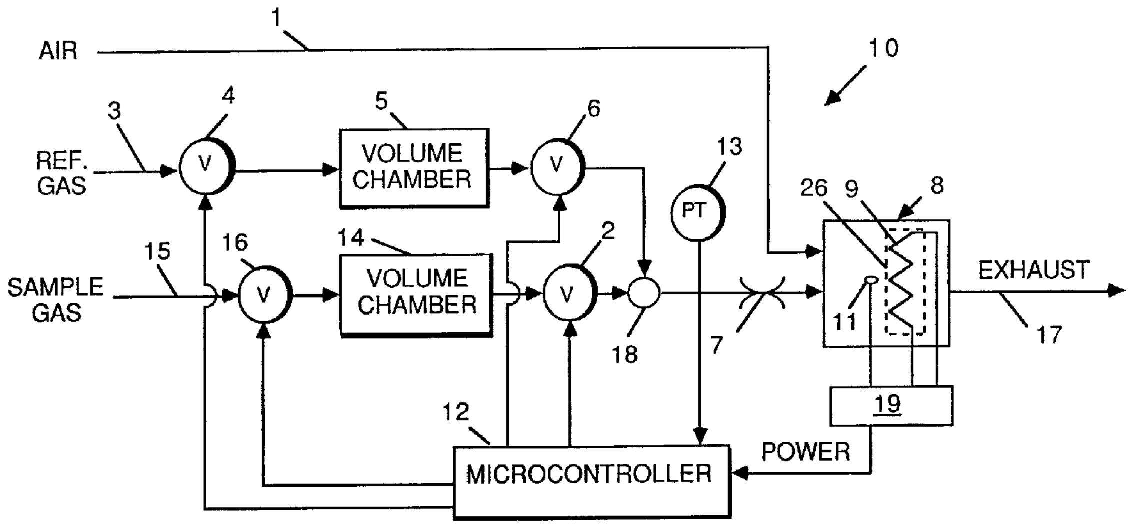
(54) **MESURE DE LA VALEUR CHAUFFANTE D'UN GAZ AU MOYEN D'UNE COMBUSTION SANS FLAMME**

(54) **MEASURING HEATING VALUE OF A GAS USING FLAMELESS COMBUSTION**



(57) On calcule la valeur chauffante d'un gaz échantillon au moyen d'un microcontrôleur (12) à partir de la valeur chauffante d'un gaz de référence et à partir de débits et de niveaux de puissance déterminés au moment de la combustion du gaz par un processus de combustion sans flamme. Le gaz combustible est mélangé à un gaz de support de combustion, par exemple de l'air, et il est amené à s'écouler jusqu'à un bloc de matériau (26, 52), lequel est chauffé à une température suffisante pour provoquer l'oxydation du mélange gazeux. La taille des espaces dans un dispositif chauffant (9, 11, 25, 26) selon une première réalisation et dans un dispositif chauffant

(57) The heating value of a sample gas is calculated by a microcontroller (12) from the heating value of a reference gas, and from flow ratios and power levels determined as the gas is combusted by a flameless combustion process. The combustible gas is mixed with a combustion supporting gas, such as air, and flowed to a body of material (26, 52) which is heated to a temperature sufficient for oxidation of the gas mixture. The size of spaces in a first embodiment of a heater device (9, 11, 25, 26) and in a second embodiment of a heater device (50) are limited to prevent formation of an open flame. In a preferred "lean mixture" embodiment,

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(50) selon une seconde réalisation est limitée pour empêcher la formation d'une flamme ouverte. Dans une réalisation préférée à mélange pauvre, le mélange gaz-air du gaz de référence et le mélange gaz-air du gaz échantillon, respectivement, sont chacun ajustés jusqu'à ce qu'un niveau de puissance sélectionné de combustion à une température inférieure au point de combustion stoechiométrique soit atteint. Dans une seconde réalisation à mélange riche, le mélange gaz-air du gaz de référence et le mélange gaz-air du gaz échantillon, respectivement, sont chacun ajustés à partir d'un mélange riche pour atteindre un point de combustion stoechiométrique. Sur la base des débits et du taux de puissance sélectionné, la valeur chauffante du gaz échantillon est calculée par le microcontrôleur (12) et délivrée à un visuel ou à tout autre dispositif de sortie.

the gas-air mixture of the reference gas, and the gas-air mixture of the sample gas, respectively, are each adjusted until a selected power level of combustion at a temperature lower than the point of stoichiometric combustion is reached. In a second, "rich mixture" embodiment, the gas-air mixture of the reference gas, and the gas-air mixture of the sample gas, respectively, are each adjusted from a "rich mixture" to reach a point of stoichiometric combustion. Based on flow rates and the selected power ratio, the heating value of the sample gas is calculated by the microcontroller (12) and output to a visual display or other output device.

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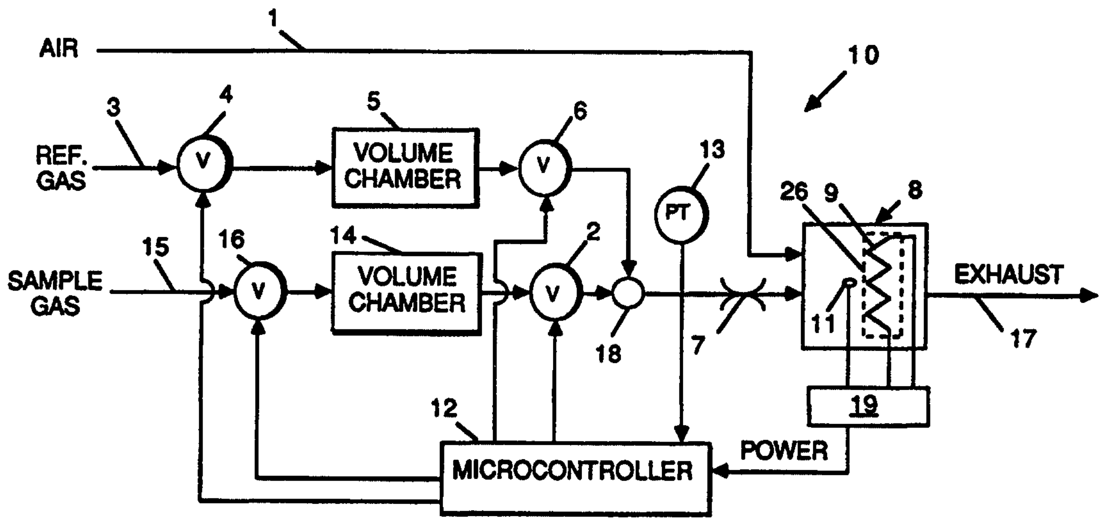
(54) Title: MEASURING HEATING VALUE OF A GAS USING FLAMELESS COMBUSTION



(57) Abstract

The heating value of a sample gas is calculated by a microcontroller (12) from the heating value of a reference gas, and from flow ratios and power levels determined as the gas is combusted by a flameless combustion process. The combustible gas is mixed with a combustion supporting gas, such as air, and flowed to a body of material (26, 52) which is heated to a temperature sufficient for oxidation of the gas mixture. The size of spaces in a first embodiment of a heater device (9, 11, 25, 26) and in a second embodiment of a heater device (50) are limited to prevent formation of an open flame. In a preferred "lean mixture" embodiment, the gas-air mixture of the reference gas, and the gas-air mixture of the sample gas, respectively, are each adjusted until a selected power level of combustion at a temperature lower than the point of stoichiometric combustion is reached. In a second, "rich mixture" embodiment, the gas-air mixture of the reference gas, and the gas-air mixture of the sample gas, respectively, are each adjusted from a "rich mixture" to reach a point of stoichiometric combustion. Based on flow rates and the selected power ratio, the heating value of the sample gas is calculated by the microcontroller (12) and output to a visual display or other output device.

MEASURING HEATING VALUE OF A GAS USING FLAMELESS COMBUSTION

TECHNICAL FIELD

The field of the invention is methods and apparatus for determining the heating value of gases.

DESCRIPTION OF THE BACKGROUND ART

The measurement of the heating value of natural gas is important in controlling combustion and is a necessary measurement in the distribution and sale of natural gas. There are four useful methods for measuring heating value.

The first method for measuring heating value is calorimetric measurement in which a volume of the gas is combusted. An amount of heat is liberated by the complete combustion and is carefully accumulated and measured. The amount of heat liberated is manifested by a change in temperature. This method is the original method employed and usually requires extreme control of flows and temperatures. The apparatus usually requires extensive maintenance.

The second method for measuring heating value is constituent analysis. Using a gas chromatograph, the fraction of each chemical constituent in the gas is determined. Then heating value is determined by summing the heating values for the individual constituents according to their fractional presence. The problem with constituent analysis is the reliability of the apparatus and its linearity. Gas chromatographs require constant maintenance and have a limited range for heating value measurement unless calibrated with a reference gas that is very similar to the sample gas.

The third method is stoichiometry, in which combustion is substantially completed with a perfect amount of oxygen. In this case, natural gases are combusted with air and the fuel-to-air ratio is adjusted until combustion results in either a maximum flame temperature or the stoichiometric point of perfect combustion, i.e., the knife edge when there is no remaining oxygen.

Clingman, U.S. Patent No. 3,777,562, is an example of the third method. In Clingman, heating value is measured by combustion of a gas with amounts of air that are adjusted to obtain the maximum flame temperature. This is further disclosed in Clingman, U.S. Patent Nos. 4,062,236, 4,125,018 and 4,125,123. In each of these patents, the combustion of the air-gas mixture is accomplished with a combustion flame on a burner top and with a temperature sensing device such as a thermocouple. Certain environments cannot be served by equipment that presents an open flame.

The fourth method utilizes catalytic combustion. Gas is passed over a heated catalyst and oxidized. The amount of heat liberated can be measured either by temperature changes related to the catalytic reaction, by changes in power supplied to heat the catalyst or by measuring the temperature of the catalytic material. Catalytic combustion or catalytic oxidation is a known phenomenon with hydrocarbons. A mixture of hydrocarbon gas and air in the presence of platinum and/or palladium material will produce an oxidation reaction. The reaction occurs at temperatures below the auto-ignition temperature associated with a hydrocarbon. For example, methane when mixed with air will ignite at a temperature of about 730°C. and reach an open flame at a temperature exceeding 1600°C. Catalytic oxidation can take place at catalyst temperatures as low as 400°C. although efficient catalytic activity is achieved at temperatures near 500-600°C.

One problem with catalytic oxidation is the potential for poisoning the catalyst. Certain chemicals such as sulfur or lead and numerous others, can combine with and disable a catalyst and therefore eliminate its usefulness in heating value measurement. In many processes, such as land fill gas recovery, the gases contain "poisons" in sufficient quantity to have a high probability of disabling the measurement process.

SUMMARY OF THE INVENTION

The present invention provides methods and apparatus for measuring the heating value of a gas utilizing non-catalytic flameless combustion and variable molar flow rates for sample gas mixtures fed to the combustion apparatus.

The present invention utilizes a body of inert material for receiving and combusting mixtures of gases and a carrier gas, such as air. Under normal conditions, the gas would be oxidized or combusted and a flame would form. In the present invention, inert material is formed with only small voids, so that an open flame is prevented by the quenching of rapid heat transfer.

The combustion process operates at a temperature above the auto-ignition temperature of a gas mixture and yet combusts the gas without producing an open flame, thereby making the process suitable for operation in special environments.

In most heating value measurements, extreme stability of gas and air volumes is required to achieve accuracy. Many of the previously described methods use constant flow rates or constant gas volumes. The present invention eliminates the need for such constant values.

In addition, the oxidation or combustion of the present invention can be performed with mixture concentrations over a wide range that extends beyond the stoichiometric mixture of the gas. This process cannot be "poisoned" in the catalytic sense, because no catalyst is involved in the combustion.

The gas combustion power or the combustion temperature, is measured as the gas mixture flows in the combustion device. The associated molar flow rate of the gas is also measured. A reference gas and the sample gas are measured alternately and repeatedly. The only requirement is that the molar flow rate of the sample and reference gas be compared at an appropriate combustion power or at a maximum combustion temperature for the combustion device.

In one embodiment, air flow is established well in excess of the air required to combust the gas, a lean gas condition. The combustion gas is mixed with air, and the mixture is flowed over or through a heated body of solid material and the mixture is oxidized. The combustion power and the gas molar flow rate vary with time. At a selected combustion power, the molar flow rate of the gas is measured by appropriate sensors, and these parameters are used to calculate the heat value of a reference combustion gas and later, a sample combustion gas.

In a second embodiment, air flow is established below the air flow required to combust the gas at stoichiometric conditions, to provide a rich gas mixture. The combustion gas is again mixed with the air, and the gas-air mixture is flowed into contact with a heated body of solid material where the mixture is oxidized. The combustion power is measured continuously. The molar flow rate of the gas is determined when the combustion power reaches a minimum value corresponding to the maximum value of combustion. At this maximum combustion power, the molar flow rate of the gas is measured by appropriate sensors.

In both a "lean mixture" embodiment and a "rich mixture" embodiment, a reference gas cycle is followed by one or more sample gas cycles.

For the embodiment using the lean gas mixture, heating value of the sample gas is calculated based on the known heating value of the reference gas, the power levels of combustion selected for the reference gas and the sample gas, the flow rates of the reference gas and the sample gas at the selected power levels, and in some instances a ratio of the power levels for the reference gas and the sample gas.

For the embodiment using the rich gas mixture, heating value of the sample gas is calculated based on the known heating value of the reference gas, the power level of combustion corresponding to stoichiometric combustion, and the flow rates of the reference gas and the sample gas at the power level for stoichiometric combustion.

In either embodiment, the fuel-to-air mixture may be varied by allowing pressure in a volume chamber to decay, to produce a decreasing flow of fuel that progressively leans out the fuel-to-air mixture. Molar flow rates are measured for a reference gas and a sample gas during respective combustion cycles occurring within the heated body of solid material. The heating value for the reference gas is typically a value stored in memory. The fuel-air mixture may also be varied by direct control of the flow rates of the air and gases using conventional pressure controllers, for example.

Various objects and advantages will be apparent to those of ordinary skill in the art from the description of the preferred embodiment which follows. In the description, reference is made to the accompanying drawings, which form a part hereof, and which illustrate examples of the invention. Such examples, however, are not exhaustive of the various embodiments of the invention, and, therefore, reference is made to the claims which follow the description for determining the scope of the invention.

BRIEF DESCRIPTION OF THE DRAWINGS

Fig. 1 is a block diagram of an apparatus for practicing the method of the present invention;

Fig. 2 is a detail schematic diagram of an electrical circuit in the catalytic apparatus of Fig. 1;

Fig. 3a is a schematic diagram of a combustion device used in the apparatus of Fig. 1;

Fig. 3b is a graph of temperature versus longitudinal displacement within the combustion device of Fig. 3a;

Fig. 3c is a schematic diagram of a second embodiment of a combustion device used in the apparatus of Fig. 1;

Fig. 4a and 4b are graphs of power and molar flow rate versus time illustrating operation of the apparatus of Fig. 1; and

Fig. 5 is a flow chart of the operation of a microcontroller in the apparatus of Fig. 1.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

Referring to Fig. 1, an apparatus 10 for practicing the method of the present invention receives air from an external supply through supply line 1. The air is used as a carrier gas and to flush other gases from combustion apparatus 8. A reference gas is received from an external supply through supply line 3. A sample gas, for which the heating value is to be determined, is received from an external supply through supply line 15.

The reference gas and the sample gas are to be mixed with varying amounts of air and combusted in a combustion apparatus 8 that includes a heating element 9, a temperature sensor 11 and a porous body of inert solids (26 in Fig. 3) which are heated by heating element 9.

The porous body of inert solids 26 is composed of solids having high temperature and high heat capacity and is usually formed of ceramic materials. The heating element 9 is located at or in the central section of the porous body 9 to provide an initial starting temperature for the reaction. The inert solids 26 are typically heated to a temperature of 800°C. or more.

Heating element 9 is energized by electricity from a power supply circuit 19 (Fig. 1). Temperature sensor 11 is embedded in the porous material to sense the temperature at the reaction surface of the porous material. Temperature sensor 11 generates a signal as an input to power source 19. This signal is recognized by the power source 19 as representative of reaction temperature.

The products of combustion are exhausted from the combustion apparatus 8 in an exhaust stream 17. Additional steps may be taken to process the exhaust stream.

Microcontroller 12 is a suitable microelectronic CPU (central processing unit) with A-to-D and D-to-A interface circuitry. Microcontroller 12 operates by executing program instructions, some of which are represented by blocks in the flow chart in Fig. 5, the instructions being stored in a memory also represented generally by reference 12.

The apparatus 10 includes elements for producing variable flow rates of air and combustible gas to vary the mixtures for the reference gas and the sample gas, respectively. The apparatus 10 more particularly includes outlet control valves 2 and 6 for controlling the flow of sample gas or reference gas, respectively, to restrictor 7. The outlet flow rate is determined by the initial charging pressure in volume chamber 5, 14 and the flow properties of flow restrictor 7. It is preferred that the flow rates of the air-gas mixtures be continuously variable over some range. However, the invention could also be employed with constant flow rates in other embodiments. And, although the preferred embodiments described more fully herein adjust the mixtures by adjusting the flow rates of the combustible gases, it is also known that such mixtures can be adjusted by adjusting the flow rate of the air.

The supply line 3 for the reference gas is connected through inlet flow control valve 4 to volume chamber 5. Flow control valve 6 is closed during filling of volume chamber 5 to close the outlet. When gas pressure in volume chamber 5 reaches a predetermined but non-critical level, usually set by the pressure of the external supply line 3, then inlet control valve 4 is closed.

Following closure of valve 4, outlet control valve 6 is opened allowing flow of gas from volume chamber 5 through flow restrictor 7, where it is then mixed with air flow from supply line 1 and passed through a porous body of inert solids 26.

One way to measure the temperature of combustion is to monitor the electrical power that is provided to the heater device 8 from power supply circuit 10 to maintain a constant temperature at sensor 11. Changes in this electrical power supplied to heater 9 are a measure of the change in combustion power or combustion temperature of the combustion process in combustion apparatus 8.

As gas flows out of volume chamber 5, the pressure in volume chamber 5 is reduced. Microcontroller 12 monitors the changes in pressure in volume chamber 5 using a pressure transducer 13. At a preselected level of combustion, as sensed through power supply circuit 19, a molar flow rate or a change in molar content in chamber 5 is measured or calculated and stored by microcomputer 12. When the gas pressure in volume chamber 5 reaches a predetermined, but not critical, low level, control valve 6 is closed, thereby stopping the flow of the reference gas to the combustion apparatus 8.

While reference gas has been flowing to combustion apparatus 8, control valve 16 has been open to fill the volume chamber 14 with sample gas from supply line 15. Flow into volume chamber 14 increases pressure in volume chamber 14 until a predetermined but non-critical pressure is reached, usually determined by the pressure in supply line 15, and then inlet control valve 16 is closed. When sample gas is to be flowed to combustion apparatus 8, microcontroller 12 opens control valve 2 to establish flow of sample gas through restrictor 7 to combustion apparatus 8, where the mixture of sample gas and air is combusted.

Power supply circuit 19 continuously adjusts power to heater 9 to maintain a constant temperature as sensed by sensor 11. As the gas flow rate reduces, power changes to the heater 9 are inversely proportional to the heat energy of combustion in apparatus 8. Depending on the embodiment, the molar flow rate from volume chamber 14 is calculated and stored by microcomputer 12 for a) a predetermined combustion power level or b) a predetermined change in combustion power level or c) at the maximum temperature condition.

It should be noted that measurement of molar flow rate using the rate of change of pressure in volume chamber 5, 14, is of the type disclosed in Kennedy, U.S. Pat. No. 4,285,245 for sensing molar flow rate in response to pressure changes due to flow of gas out of a chamber. This eliminates the molecular weight of the gas from consideration in the gas measurements. Such a flow meter is incorporated in a product commercially offered by the assignee under the trade designation "TRU-THERM".

The use of two volume chambers, 5 and 14, is not required but is a preferred embodiment. Using one chamber would slow the measurement process because a single chamber utilizing two gases would require several cycles to exhaust a residue of a combustible gas remaining in the chamber from a previous cycle. If speed of response is not a primary goal of design, the measurement can be modified to use reference gas only infrequently and a single volume chamber can be used.

Fig. 2 illustrates the power supply circuit 19, temperature sensor 11 and heater 9 described earlier in relation to Fig. 1. The circuit 19 is a bridge that maintains a constant resistance by heating and cooling by electrical means.

In the preferred embodiment, resistance 9 in Fig. 2 is provided by a platinum coiled-wire resistor. Platinum is selected due to its stable temperature coefficient over a wide temperature range. The resistance is $R_h = R_{h0}\ (1+\alpha\Delta T)$. The value of resistor 20 and resistor 9 are selected to provide the desired temperature of operation at the power levels selected for the operation of the porous body of solids 26 (Fig. 3a). The coiled-wire resistor provides both the resistance heating element 9 and the temperature sensor 11 for the porous material 26. Resistors 21 are a pair of resistors that divide the voltage 24 applied to the bridge. In Fig. 2, the resistors 21 are shown with equal values, R_0, which is not a strict requirement.

In Fig. 2, operational amplifier 22 senses the difference between the center tap voltages on each section of the bridge and amplifies that difference. The result is applied to power FET 23 and changes the voltage 24 on the bridge until the center tap voltages of the two sections become equal.

Therefore, the electrical power level into the heater-sensor 9, 11 is that required to hold the resistance and temperature of heater-sensor 9, 11 constant. If gas combustion takes place, the heat of combustion will raise the temperature of material 26 and the applied electrical power will be proportionately reduced to maintain the a constant temperature for the heater-sensor 9, 11.

Fig. 3a depicts the general construction of a heater device by forming a column of porous inert material 26. A tube 25 holds the porous material, in this example, beads 26 of different sizes, and forms a column. Ceramic beads or foam can be used as the porous solids 26, and if foam is used, the body may be a unitary body. Beads can be graduated in size as well as have a changing surface character to control emission of radiation components, which affect the heat transfer rate from the combustion products. The heater-sensor 9, 11 is located in the central section of the porous material 26 and through resistance heating raises the temperature of the material 26 to a lever greater than the auto-ignition temperature of the gas-air mixture.

The small voids in the porous body of solid material 26 are selected and characterized by having a linear dimension on the order of the quenching dimension of the gas flame. With methane, for example, the quenching dimension is about 2.5 millimeters (0.060"). The methane does not burn with an open flame when the voids in the body of solid materials 26 are smaller than 2.5 mm. Heat is transferred through the solid material 26 at a sufficient rate to prevent the large increases in temperature that would accompany an open flame.

Combustion produces combustion products such as CO_2 and H_2O vapor. A flame is a visual indication that the combustion products have insufficient heat capacity to carry away the heat of combustion by convection and conduction alone. The temperature of the combustion products must then rise until the radiation level is high enough to radiate the excess heat. The rate of conduction and convection increases in linear relation to temperature. Radiation responds in proportion to the fourth power of temperature, and provides an additional and stabilizing factor to the heat transfer rate. The temperature of the burned gases increases until the heat of combustion equals the heat losses. For natural gases, the gas temperature reaches radiation frequencies in the visible spectrum and the flame is visible.

In the present invention, gas flow rates through the combustion apparatus 8 are also limited by design to limit the total available heat of the combustion reaction. If the energy available from combustion is too great, electrical power cannot be reduced enough to control the combustion. Therefore, limits are placed on the flow rate of the gas-air mixture to limit the heating power available by combustion to less than the electrical power required to heat the solid material 26 above the auto-ignition temperature.

The solids structure surrounding the small voids allows the heat transfer rate between the combustion gas products and the heater to be sufficiently high to prevent large temperature increases and thereby stabilize the combustion temperature. The body of material 26 must have sufficient heat transfer capacity to quench the flame without requiring high radiation temperatures.

The air and the gas are introduced at the base of the column and travel through the body of material 26. Because of heat flow from the central section, the temperature 28 (Fig. 3b) of the inlet section of the combustion material 26 increases and the gas-air mixture heats and mixes as it flows toward the reaction zone at the center.

Beyond the reaction zone, the temperature 29 (Fig. 3b) in the column 25 cools as the gases pass to the exhaust 17. The temperature profile of the porous bed is indicated in the accompanying graph in Fig. 3b.

When the air-gas mixture reaches the reaction zone, and when the temperature is above the auto-ignition point, the gas oxidizes or combusts to release energy as the heat of combustion. The released heat raises the temperature of the reaction zone and raises the resistance of the platinum heater 9. The power supply circuit 19 for the heating element 9 senses this increasing temperature and reduces the electrical power to maintain a constant temperature in the reaction zone. The change in electrical power corresponds to the increased combustion power or porous bed temperature and is the indicator of porous bed activity.

Fig. 3c illustrates an alternative embodiment of a heater device 50. A coil of platinum wire 51 is cast into a body of ceramic material 52. An outer structure for the heater device 50 comprises upstanding wall(s) 53, and the device is cylindrical, but may be rectangular or other shapes in cross section in other embodiments. Filter elements 54, 55 are made of porous metal to allow passage of gas mixtures, while filtering out particulate matter. The filter elements 54, 55 form the upper and lower end walls of the heater device 50. The upstanding wall 53 and filter elements 54, 55 are closely spaced from the heating element 51, 52, so as to provide spaces 56, 57 of suitably small dimension to quench any higher temperature reactions before a flame is formed.

The spaces 56, 57 are selected and characterized by having a linear dimension on the order of the quenching dimension of the gas flame. With methane, for example, the quenching dimension is about 2.5 millimeters (0.060"). The methane does not burn with an open flame when the spaces 56, 57 are smaller than 2.5 mm. Heat is transferred through the solid material 52 at a sufficient rate to prevent the large increases in temperature that would accompany an open flame.

In operation, the coil 51 is supplied by electrical power from power circuit 19 (Fig. 1). As the mixed gas flows through the heater 50, it oxidizes and produces heat in a normal fashion but the heat transfer rate to the surrounding wall 53 is sufficiently rapid to enable the gases to cool without significantly increasing the combustion product temperatures. This is known as "quenching" the flame. If the heater is operated at a constant temperature above the auto-ignition temperatures for the mixed gases, then as combustion power increases, the electrical power must be decreased to reflect the magnitude of the combustion power liberated by the mixed gases.

In a preferred "lean mixture" embodiment, the gas-air mixture of the reference gas, and the gas-air mixture of the sample gas, respectively, are each variably decreased until a selected power level of combustion at a temperature lower than the point of stoichiometric combustion is reached. In a second, "rich mixture" embodiment, the gas-air mixture of the reference gas, and the gas-air mixture of the sample gas, respectively, are each variably decreased from a "rich mixture" to reach a point of stoichiometric combustion, which corresponds to the highest power of combustion within the body of solids 26, 52.

The molar heating value, H_m, is defined as the amount of heat which can be liberated by combustion of a mole of the gas. Molar heating value is expressed in units of energy per mole. In the "lean mixture" embodiment, the molar flow rate of a gas, $\dot{n}_g$, with units of moles per second, is multiplied by molar heating value. The result is the power of combustion described as $P_{gas} = H_m \dot{n}_g$ and the change in combustion power between two selected power levels can be written as $\Delta P_{gas} = H_m \Delta\dot{n}_g$. If the combustion power changes of the sample gas and reference gas are measured between the same two selected power levels (See Fig. 4a), then equating the two combustion power changes results in Eq. 1 as follows:

$$H_{m\ s} = H_{m\ r}\left(\frac{\Delta\dot{n}_r}{\Delta\dot{n}_s}\right) \qquad (1)$$

where the subscripts r and s refer to the reference gas and the sample gas, respectively.

A desirable feature of this invention is that speed of response can be improved by terminating the individual measurement cycles prior to completion. If the changes in combustion power during the reference cycle and the sample cycle are not equal, but are related by a known ratio, then Eq. 1 can be modified introducing a correction factor, η, which is the ratio of the changes in combustion power and Eq. 1 can be restated as:

(2) $$H_{m\ s} = \eta\ H_{m\ r} \left(\frac{\dot{n}_r}{\dot{n}_s}\right)$$

where η is the ratio of the two changes in combustion power. It should be clear that η can take on values that range between zero and unity.

A mole of gas contains a fixed number of molecules, known as Avogadro's number, and occupies a defined volume, Vm, which is a function of temperature and pressure. At 0°C. and 14.696 psia, the volume for an ideal gas is 22.4138 liters. The effect of compressibility must be recognized and used to define the molar volume of a real gas as $V_{m\ real} = V_{m\ ideal} Z_{real}$ with units of volume per mole and where the compressibility, Z_{real}, is calculated at the temperature and pressure of the measurement. Therefore the volume heating value (energy per unit volume) of the gas is stated as:

(3) $$H_{v\ s} = \frac{\eta\ H_{m\ r} \left(\frac{\Delta\dot{n}_r}{\Delta\dot{n}_s}\right)}{V_{m\ ideal}\ Z_{real}}$$

The heating value, as defined in Eqs. (1) through (3), is related to a standard temperature and pressure according to the general gas laws and factors known in art of gas physics and gas measurement.

The molar flow rate of the gas flowing from volume chambers 5, 14 is sensed by measuring the rate of change or change of pressure in the volume as the gas is withdrawn. The relation between the molar flow rate of the gas and the rate of change of pressure is obtained from the general gas law and is expressed as follows:

(4) $$\dot{n} = \frac{\dot{P}\ V}{Z^2\ R\ T}$$

where $\dot{n}$ is the molar flow rate, $\dot{P}$ is the rate of change of pressure, and Z is the compressibility factor.

For the "rich mixture" embodiment, the reference gas is introduced at sufficiently frequent intervals to assure that humidity has not changed, and this allows ambient air to be used as the combustion supporting gas. If the reference gas is not introduced at such sufficiently frequent intervals, then the air is preferably dried to a very low humidity, such as less than 5% relative humidity. In the "rich mixture" embodiment, the maximum combustion temperature corresponding to the minimum power input level (See Fig. 4b) identifies the stoichiometric point of combustion. This embodiment requires the measurement of the molar flow rate of the gas, $\dot{n}_g$ in units of moles per second. Since the stoichiometric points of the sample gas and reference gas are measured, the heating value is formed using a ratio of the molar flow rates ($\dot{n}$) and the volume heating value (H) of the reference gas according to Eq. 5 as follows:

$$(5) \qquad H_{v\,s} = H_{v\,r}\left(\frac{\dot{n}_r}{\dot{n}_s}\right)$$

where the subscripts r and s refer to the reference gas and the sample gas, respectively.

Figs. 4a and 4b illustrate the rate of combustion vs. molar flow rate for the "lean gas" mixture embodiment and the "rich mixture" embodiment, respectively.

When the gas flow is not present, only air is supplied to the combustion material and the electrical power (P) supplied to the heated body of material is maximum and stable. The temperature of the combustion material is constant, and this is represented by the constant levels of electrical power in Figs. 4a and 4b. When reference gas or sample gas is flowed to the combustion heater, the combustion process adds heat to the body of material and the power controller reduces the electrical power (P) to the heater in the exact amount as gas energy is added. As the gas flow rate reduces due to reduced gas pressure in the volume chambers 5, 14, the combustion gas energy is reduced. The electrical power must then be increased to maintain a constant temperature in the heated material. When the temperature of combustion is at a maximum, the minimum electrical power needs to be supplied to heat the material, as shown in Fig. 4b.

As shown in Fig. 4a, molar flow rates for the reference gas are determined for two selected power levels. The molar flow rates for the sample gas are then determined for the same two selected power levels.

As shown in Fig. 4b, a rich gas mixture of the reference gas, containing more gas molecules than necessary for stoichiometric combustion, is flowed to the combustion material. As the reference gas flow rate reduces, the maximum temperature state and maximum gas power of combustion (minimum electrical power level) is reached. There, the molar flow rate of the reference gas is measured. This cycle is then repeated for the sample gas, until the maximum temperature state and maximum gas power of combustion (minimum electrical power level) is reached and the molar flow rate of the reference gas is measured. This data is read by the microcontroller 12, which then calculates heat content of the sample gas.

The flow rate of air through the porous material 26 is not critical and can vary by ±10% in a slow fashion, but must be stable between the reference and sample cycles.

Fig. 5 shows the operation from the viewpoint of the microcontroller 12 in executing its control program. The start of the operation is represented by start block 30. The microcontroller 12 executes instructions to select either the reference gas cycle or the sample gas cycle, as represented by process block 31. If the reference gas cycle is selected, the microcontroller 12 executes further instructions, represented by process block 32, to open valve 16 and allow sample gas to fill volume chamber 14 in preparation for the sample gas cycle. Next, as represented by process block 33, the microcontroller 12 executes further instructions to open valve 6 to allow reference gas to flow to the combustion device 8. The microcontroller 12 then executes instructions represented by process block 34 to begin to sample molar flow rate ($\dot{n}$) and the changes in the electrical power (ΔP) required by the combustion device 8. The microcontroller 12 then executes instructions represented by decision block 35 to test for a molar flow rate corresponding to a maximum temperature and gas power of combustion (minimum electrical power) (Fig. 4b) or for molar flow rates corresponding to two selected power levels during the same cycle (Fig. 4a). If the result is "NO," it loops back to continue with another sample. If the result is "YES," it proceeds to execute instructions represented by block 36 to end the first cycle and prepare for the next cycle.

As represented by process block 36, microcontroller 12 executes instructions to stop the gas flow of the reference gas by closing valve 6. The microcontroller 12 then executes instructions represented by process block 37 to change the selection to the other gas cycle. The microcontroller 12 then executes instructions represented by process block 38 to flush chamber 5 and combustion apparatus 8. Next, the microcontroller 12 then executes instructions represented by process block 39 to store the final flow rate and power values for the cycle just completed. A check is then made, as represented by decision block 40, to see if both a reference cycle and a sample gas cycle have been completed within a recent time period. If the result is "YES," the data can be used calculate heating value as represented by process block 41. The heating value is then output to a visual display (not shown in Fig. 1) or another type of output device. If the data is not complete, the result from decision block 40 is "NO," and program returns to start a new gas measurement cycle, such as the sample gas cycle, at block 32.

This has been a description of examples of how the invention can be carried out. Those of ordinary skill in the art will recognize that various details may be modified in arriving at other detailed embodiments, and these embodiments will come within the scope of the invention.

Therefore, to apprise the public of the scope of the invention and the embodiments covered by the invention, the following claims are made.

CLAIMS

We claim:

1. A method of measuring heating value of a combustible gas, the method characterized by the steps of:

flowing a first mixture of a reference gas and a combustion supporting gas into contact with a heated body of material (26, 52) to cause flameless combustion of the reference gas;

varying the first mixture of the reference gas and the combustion supporting gas to obtain a changing combustion power level;

detecting a flow rate of the reference gas at one or more first selected combustion power levels;

flowing a second mixture of a sample gas and a combustion supporting gas into contact with the heated body of material (26, 52) to cause flameless combustion of the sample gas;

varying the second mixture of the sample gas and the combustion supporting gas to obtain a changing combustion power level;

detecting a flow rate of the sample gas at one or more second selected combustion power levels; and

calculating the heating value of the sample gas in response to a ratio of the reference gas flow rate and the sample gas flow rate at the first and second selected combustion power levels, respectively.

2. The method of claim 1, further characterized in that the selected combustion power levels correspond to a first selected electrical power level for combustion of the reference gas at maximum combustion power, and a second selected electrical power level for combustion of the combustible gas at maximum combustion power, respectively.

3. The method of claim 1 or 2, further characterized in that the body of material (26, 52) is heated to a temperature

that is above the auto-ignition temperature of the gas-air mixture.

4. The method of claim 1, further characterized in that the flow rate of the sample gas is limited to supply less combustion energy than an amount of electrical power supplied to heat the body of material.

5. The method of claim 1 or 2, further characterized in that the combustion supporting gas is air.

6. The method of claim 1 or 2, further characterized in that the step of varying the first mixture and the step of varying the second mixture further comprises regulating the supply of at least one of said gases in said mixtures.

6. The method of claim 1 or 2, further characterized in that the step of varying the first mixture and the step of varying the second mixture further comprises regulating the supply of the combustion supporting gas.

7. The method of claim 1 or 2, further characterized in that a supply of combustion supporting gas in the reference gas flow is equal to a supply of combustion supporting gas in the sample gas flow.

8. The method of claim 1 or 2, further characterized in that the flow rates of the reference gas and sample gas are molar flow rates.

9. The method of claim 1, further characterized in that the steps of varying the first mixture of the reference gas and varying the second mixture of the sample gas each further comprises allowing a variable decrease in pressure of the reference gas and the sample gas, respectively.

10. The method of claim 1, further characterized in that at least one of said first mixture and said second mixture is varied to obtain at least two combustion power levels having a common power value for two different compositions of a respective one of said mixtures.

11. The method of claim 1 or 2, further characterized in that said method is performed at ambient temperatures from approximately -40°F. to 130°F.

12. The method of claim 1 or 2, further characterized by heating the body of material (26, 52) and sensing temperature of the body of material through a constant resistance bridge circuit (19).

13. The method of claim 1 or 2, further characterized by the step of flowing air only through the body of material (26, 52) to establish a baseline value for measurement of combustion.

14. An apparatus for determining the heating value of a combustible gas, the apparatus being characterized by:

a heated body of material (26, 52) for combusting gas-air mixtures without the formation of a flame;

first flow means (1, 7, 8) for flowing a mixture of the combustible gas and a combustion supporting gas into contact with said heated body of material to cause oxidation of said mixture;

second flow means (2, 5, 6, 14) for selectively flowing either a reference combustible gas or a sample combustible gas to said first means;

first sensing means (19) for sensing a combustion power of said combustible gas when said combustible gas is flowed into contact with said body of material;

second sensing means (13) for sensing at least one molar flow rate of said combustible gas corresponding to at least one selected combustion power of said combustible gas; and

means (12) responsive to said first sensing means (19) and said second sensing means (13) for calculating the heating value of said sample combustible gas.

15. The apparatus of claim 14, further characterized in that said first sensing means (19) is operable for sensing an electrical level corresponding to a maximum power of combustion for said sample combustible gas; and further characterized in that said second sensing means (13) is operable for sensing at least one molar flow rate of said combustible gas corresponding to a maximum power of combustion for said sample combustible gas.

16. The apparatus of claim 14 or 15, further characterized in that the body of material (26, 52) is heated to a temperature that is above the auto-ignition temperature of the gas-air mixture.

17. The apparatus of claim 14, further characterized by means for limiting the gas flow rate (12) to supply energy less than an amount of electrical power supplied to heat the body of material.

18. The apparatus of claim 14 or 15, further characterized in that said first sensing means (19) includes a sensor for sensing the power of flameless combustion.

19. The apparatus of claim 14 or 15, further characterized in that said second flow means (2, 5, 6, 14) includes means for providing a variable, decreasing flow rate for said combustible gas to obtain varying combustion power of said combustible gas.

20. The apparatus of claim 14 or 15, further characterized in that said first flow means (1, 7, 8) is controlled separately from said second flow means (2, 5, 6, 14).

21. The apparatus of claim 14 or 15, further characterized in that said means for separately controlling the flow of said combustible gas (2, 5, 6, 14) includes a molar flow meter (12, 13).

22. The apparatus of claim 14 or 15, further characterized in that said combustion supporting gas is air.

23. The apparatus of claim 14 or 15, further characterized in that said first flow means includes means for interrupting the flow of combustible gas (12, 4, 16) to flow only a combustion supporting gas into contact with the body of material to establish a baseline value for temperature of combustion.

24. The apparatus of claim 14 or 15, further characterized in that said heated body of material (26) further comprises a plurality of solids (26) held together so as provide a porous body of solid material.

25. The apparatus of claim 14 or 15, further characterized in that said heated body of material (52) further comprises a heater element (52) enclosed by closely spaced walls (53) for preventing any flame as said gas-air mixtures are oxidized.

26. An apparatus of the type for determining the heating value of a combustible gas, the apparatus comprising:

a porous body of material (26, 52, 53) containing one or more spaces with linear dimensions (56, 57) not greater than a quenching dimension for the combustible gas;

a heater element (11, 51) disposed in the porous body of material (26, 52) to heat a portion of the porous body of material (26, 52) to at least the auto-ignition temperature of the combustible gas;

a sensor (9, 19) for sensing the level of combustion and for generating a signal responsive thereto; and

a processor (12) responsive to signals from the sensor (9, 19) for calculating the heating value of the combustible gas.

27. The apparatus of claim 26, further characterized in that said porous body of material (26, 52) is formed of non-catalytic material.

28. The apparatus of claim 27, further characterized in that said porous body of material (26) further comprises a plurality of solids (26) arranged in a column so as provide a porous body of material with a plurality of spaces between said solids.

29. The apparatus of claim 28, further characterized in that said spaces have a linear dimension of not greater than about 2.5 mm (0.060").

30 The apparatus of claim 29, further characterized in that said plurality of solids (26) are beads of ceramic material.

31. The apparatus of claim 30, further characterized in that said beads (26) of ceramic material are graduated in size.

32. The apparatus of claim 30, further characterized in that said beads (26) of ceramic material are formed of non-catalytic material.

33. The apparatus of claim 26, further characterized in that:

said porous body of material (52, 53) further comprises a casing (53) and a body of ceramic material(52) disposed in said casing;

further characterized in that said heater element (51) is disposed in said body of ceramic material (52); and further characterized in that the porous body of material (52, 53) has an interior space (56, 57) between said casing (53) and said body of ceramic material (52) with linear dimensions which are not greater than the quenching dimension for the combustible gas.

34. The apparatus of claim 33, further characterized in that said casing (53) and said ceramic material (52) are formed of non-catalytic material.

35. The apparatus of claim 34, further characterized in that said heater element (51) further comprises a coil of platinum wire contained in a body of ceramic material.

36. The apparatus of claim 33 or 35, further characterized in that said interior space (56, 57) has linear dimensions of not greater than about 2.5 mm (0.060").

37. The apparatus of claim 33 or 36, further characterized in that said casing (53) has opposite ends with an entrance for gas in one opposite end and an exit for gas in another opposite end and wherein said combustion device further comprises filters (54, 55) disposed in said opposite ends of said casing (53).

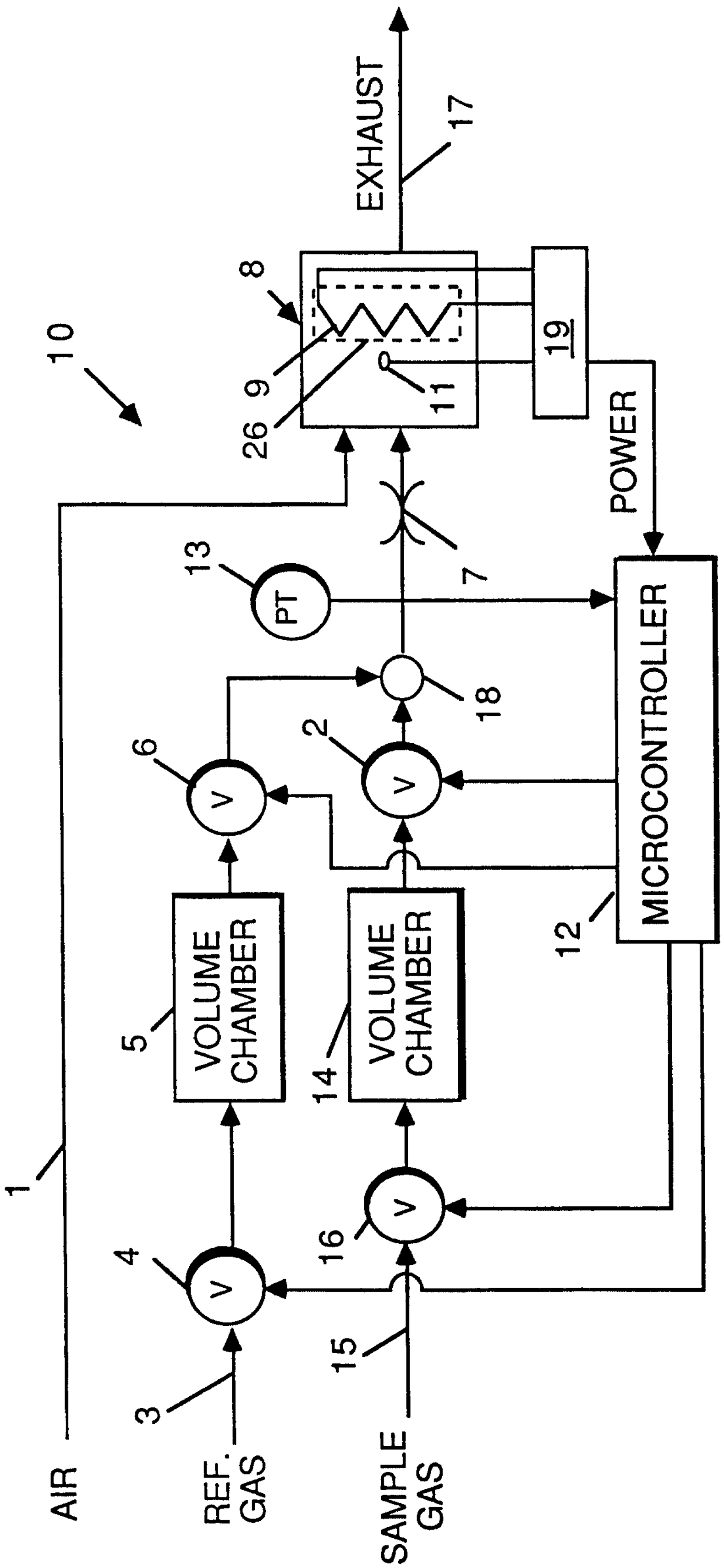

EXHAUST
17
8
10
9
26
11
19
POWER
13
PT
7
18
6
V
2
V
MICROCONTROLLER
12
VOLUME CHAMBER
5
VOLUME CHAMBER
14
1
4
V
16
V
3
15
AIR
REF. GAS
SAMPLE GAS

FIG. 1

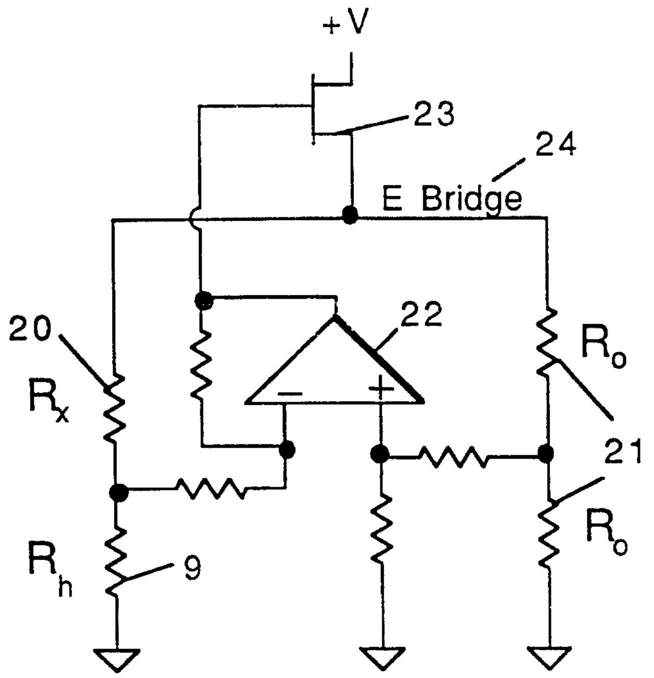


FIG. 2

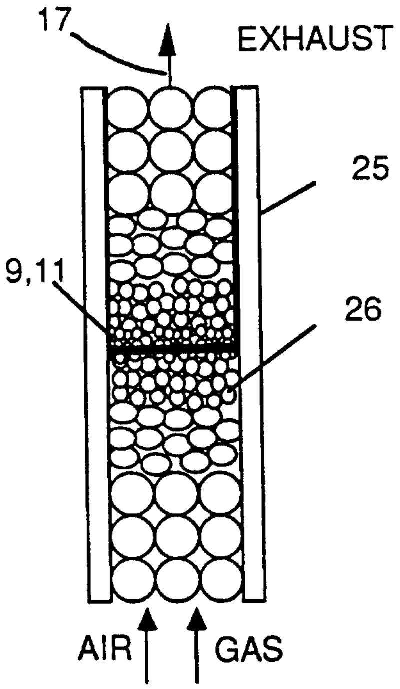


FIG. 3a

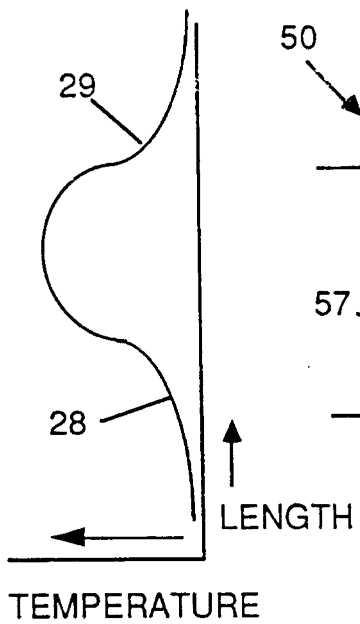


FIG. 3b

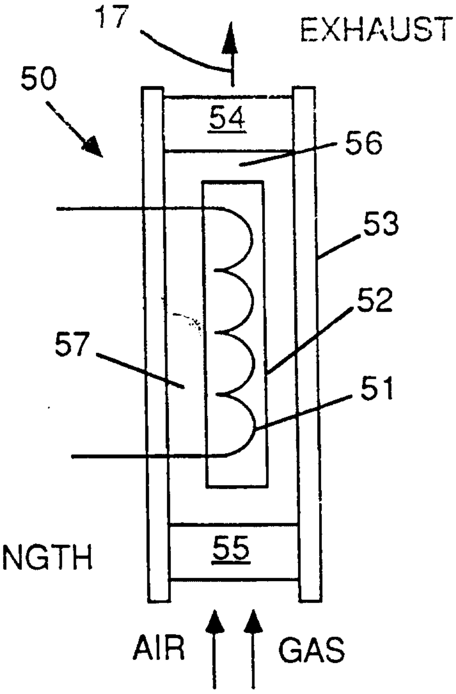


FIG. 3c

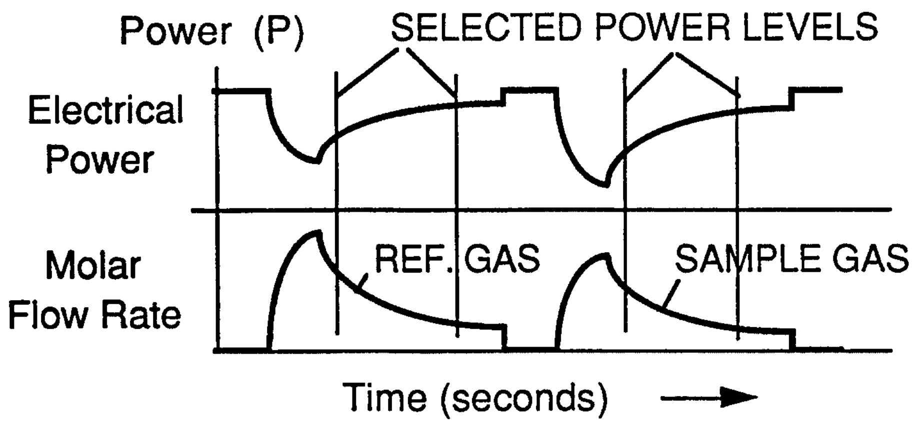

Power (P)
SELECTED POWER LEVELS
Electrical Power
Molar Flow Rate
REF. GAS
SAMPLE GAS
Time (seconds)

FIG. 4a

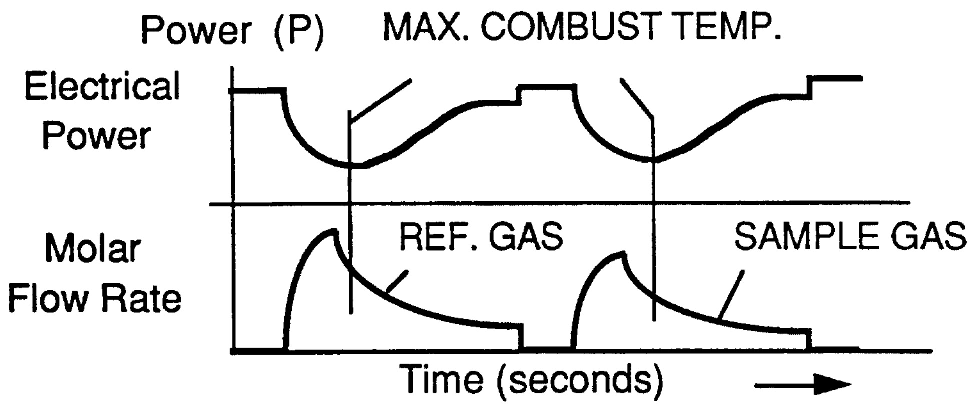

Power (P)
MAX. COMBUST TEMP.
Electrical Power
Molar Flow Rate
REF. GAS
SAMPLE GAS
Time (seconds)

FIG. 4b

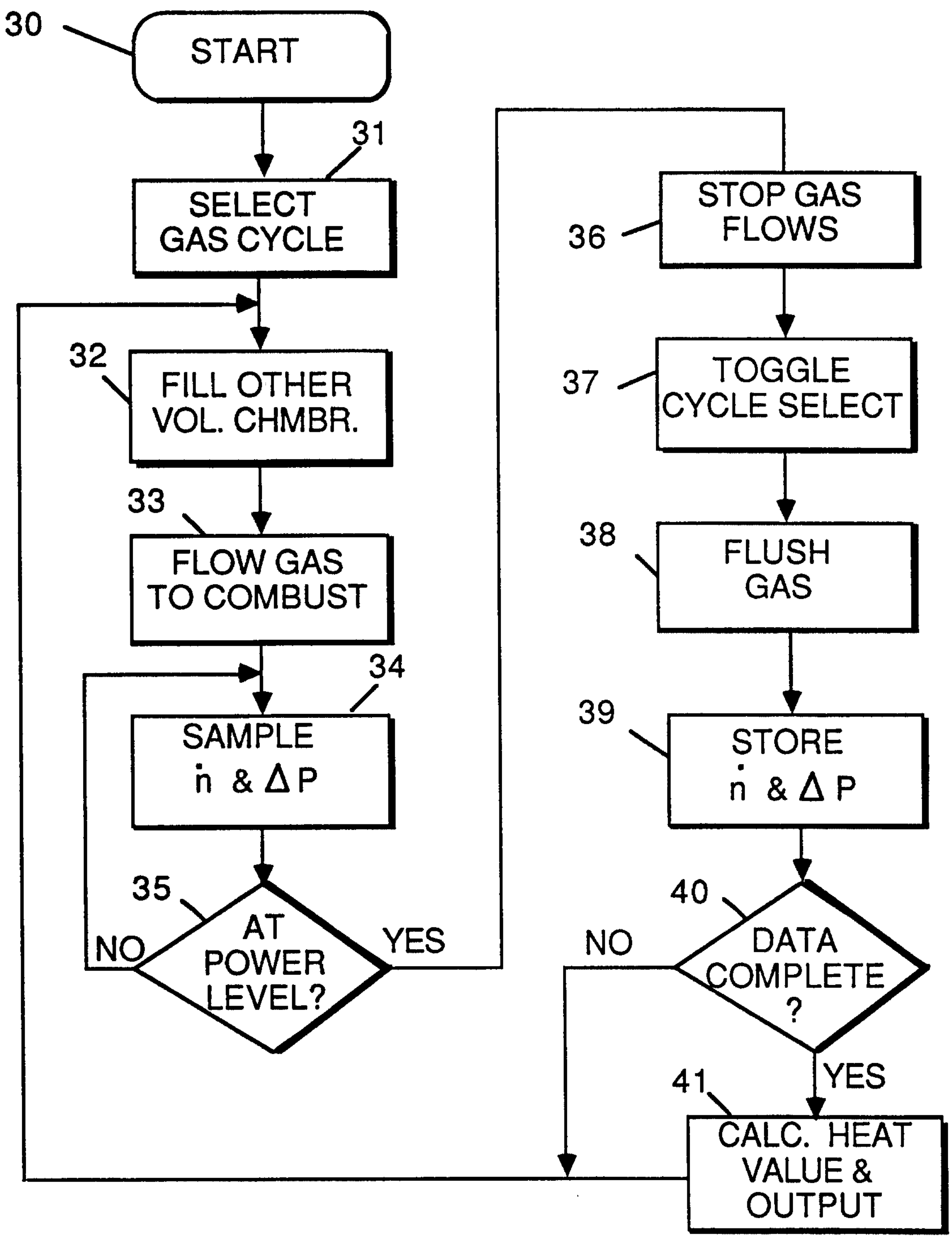
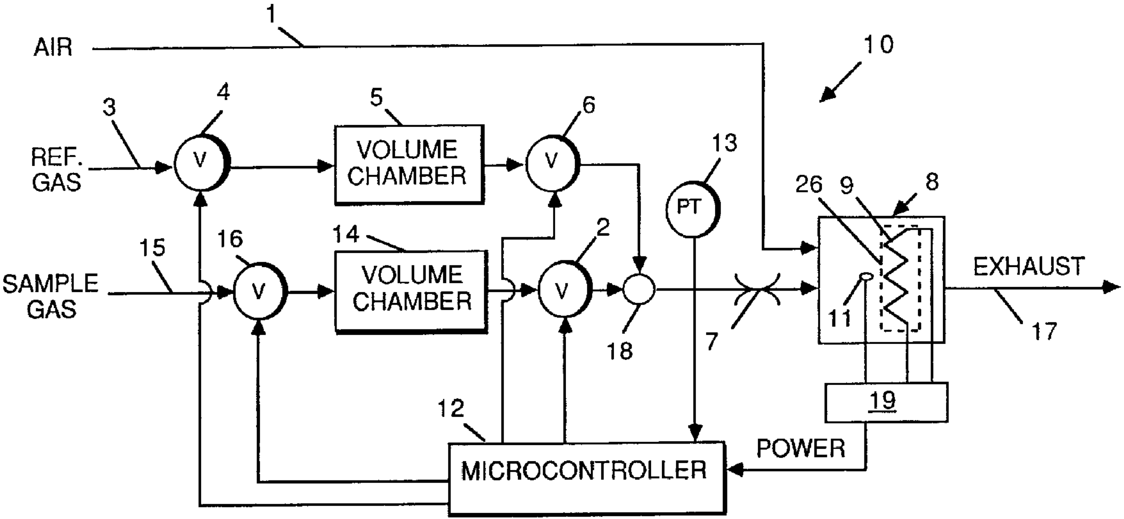

30
START
31
SELECT GAS CYCLE
32
FILL OTHER VOL. CHMBR.
33
FLOW GAS TO COMBUST
34
SAMPLE $\dot{n}$ & ΔP
35
NO
AT POWER LEVEL?
YES
36
STOP GAS FLOWS
37
TOGGLE CYCLE SELECT
38
FLUSH GAS
39
STORE $\dot{n}$ & ΔP
40
NO
DATA COMPLETE ?
YES
41
CALC. HEAT VALUE & OUTPUT

Fig. 5


AIR
1
10
REF.
GAS
3
4
V
5
VOLUME
CHAMBER
6
V
13
PT
26
9
8
SAMPLE
GAS
15
16
V
14
VOLUME
CHAMBER
2
V
18
7
11
EXHAUST
17
19
12
MICROCONTROLLER
POWER