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Hankins

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[54] **FLUE GAS CONDITIONING METHOD FOR INTERMITTENTLY ENERGIZED PRECIPITATION**

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Related U.S. Application Data

[63] Continuation of Ser. No. 254,937, Jun. 7, 1994, abandoned.

[51] **Int. Cl.**^{6} **B03C 3/013**

[52] **U.S. Cl.** **95/6**; 95/7; 95/58; 95/81; 96/23; 96/52; 96/80

[58] **Field of Search** 95/6, 7, 58, 80, 95/81, 2; 96/22–24, 52, 74, 80, 82; 323/903; 110/216, 217, 345; 423/242.1

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[57] **ABSTRACT**

A method is used for preconditioning flue gas to be treated in an electrostatic precipitator having a set of electrostatic elements which are intermittently energized by a power supply. The method uses a current sensor and a voltage sensor to detect the current and the voltage supplied to the electrostatic elements during an energized half-cycle of the power delivered to the electrostatic precipitator and develops an indication of the intermittent power supplied to the electrostatic elements from the current and voltage sensor measurements. The amount of a conditioning agent added to the flue gas is controlled to maintain the power indication at a substantially predetermined level.

15 Claims, 4 Drawing Sheets

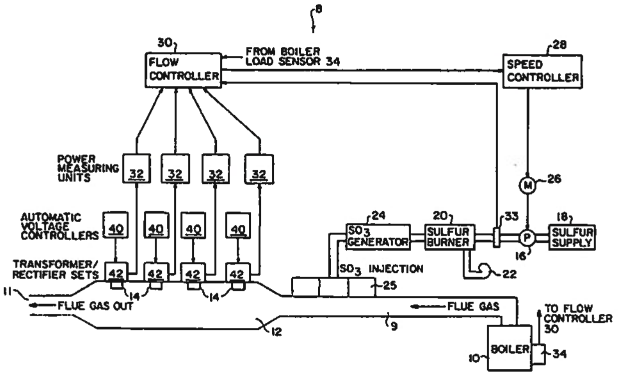


FIG. 1

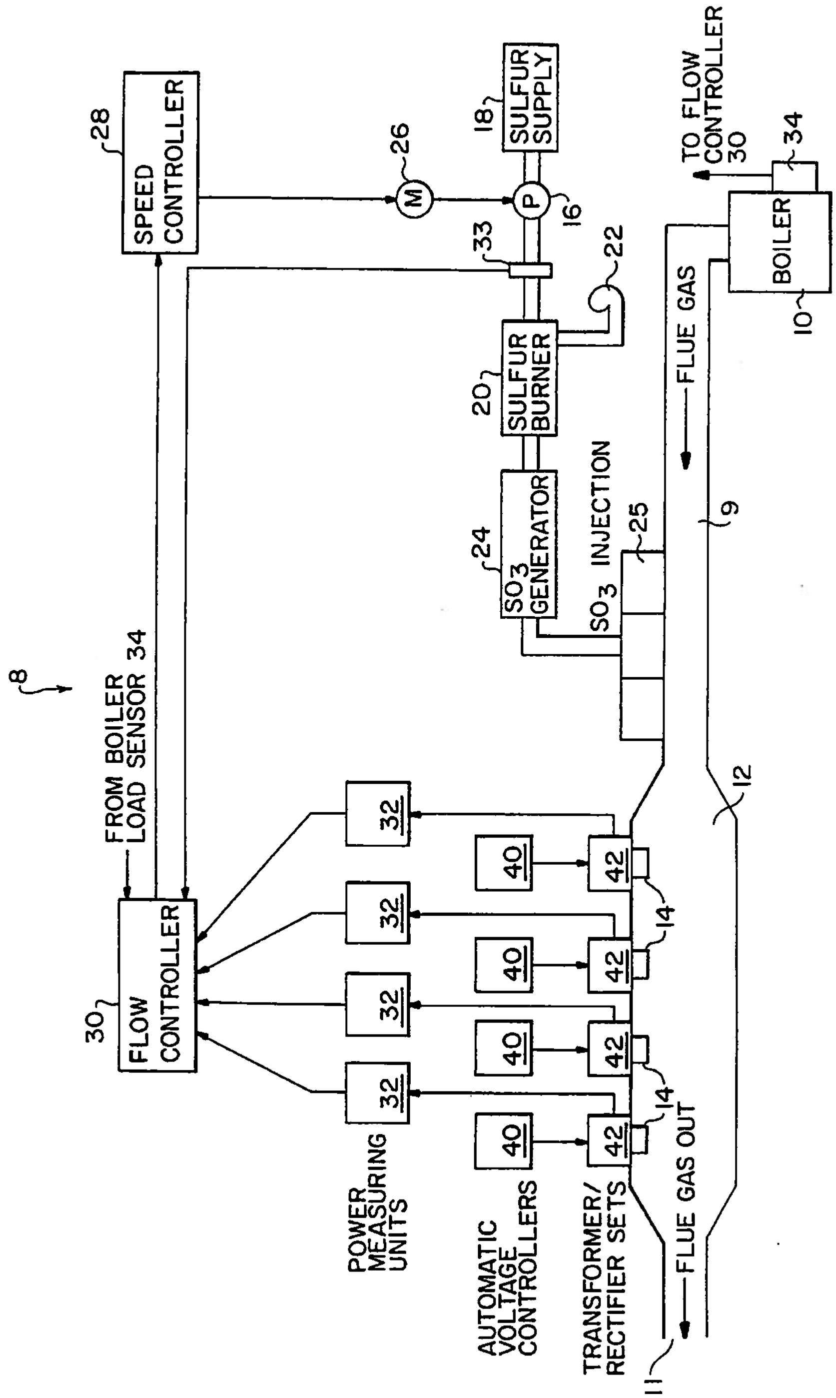

8
FROM BOILER LOAD SENSOR 34
SPEED CONTROLLER
28
M
26
P
16
SULFUR SUPPLY
18
33
22
SULFUR BURNER
20
SO3 GENERATOR
24
SO3 INJECTION
25
SO3
TO FLOW CONTROLLER 30
34
BOILER
10
FLUE GAS
9
12
FLOW CONTROLLER
30
32
32
32
32
POWER MEASURING UNITS
40
40
40
40
AUTOMATIC VOLTAGE CONTROLLERS
42
42
42
42
14
14
TRANSFORMER/ RECTIFIER SETS
FLUE GAS OUT
11

FIG. 2

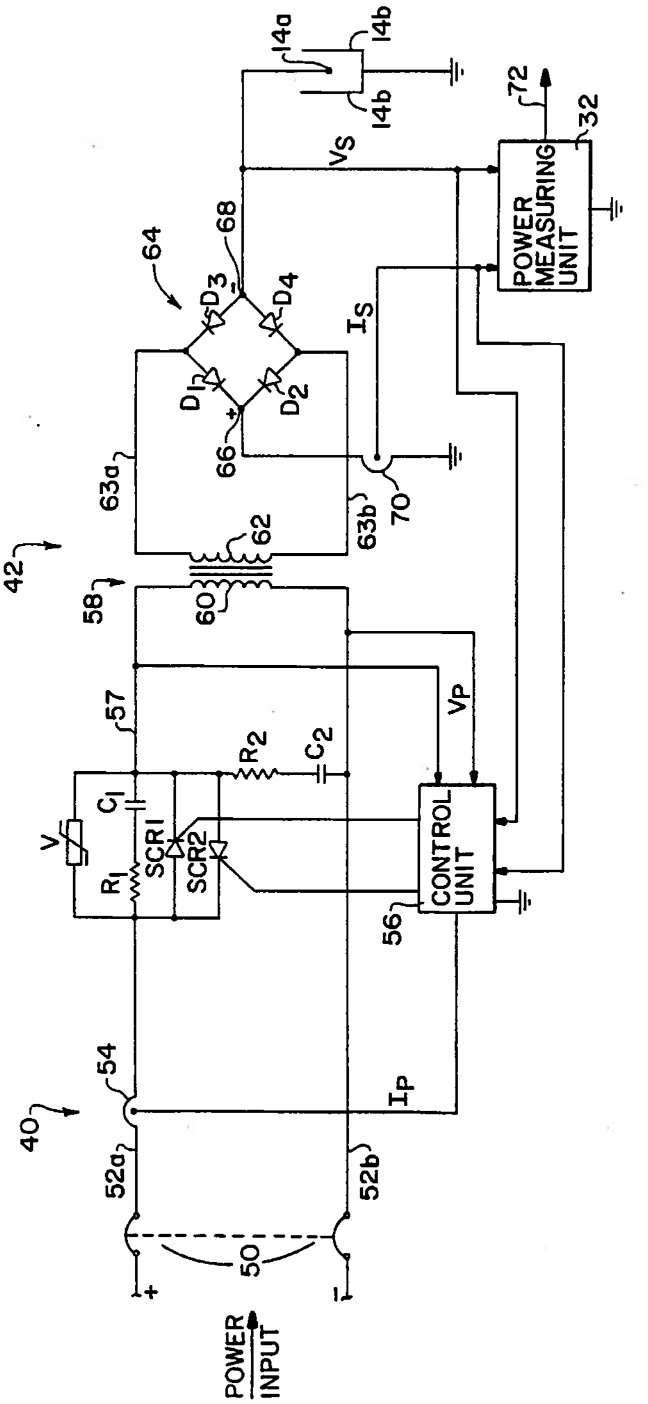

14a
14b
14b
72
32
POWER MEASURING UNIT
VS
64
68
D3
D4
D1
D2
+
−
IS
66
70
63a
63b
62
42
58
60
57
VP
R2
C2
C1
V
R1
SCR1
SCR2
CONTROL UNIT
56
54
40
IP
52a
52b
50
+
−
POWER INPUT

FIG. 3

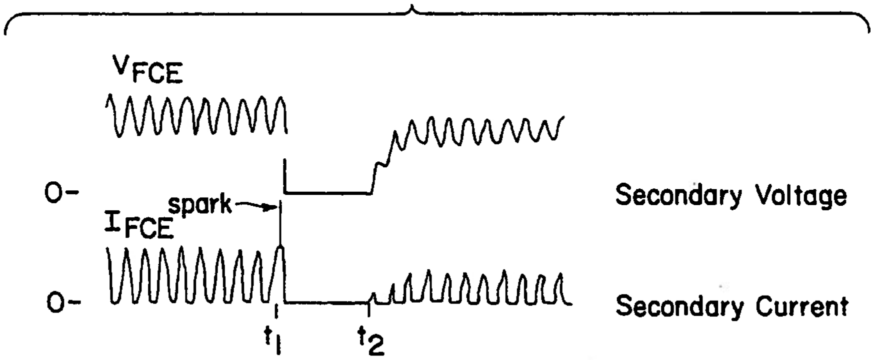

V_{FCE}
0-
spark
I_{FCE}
0-
t_1
t_2
Secondary Voltage
Secondary Current

FIG. 4

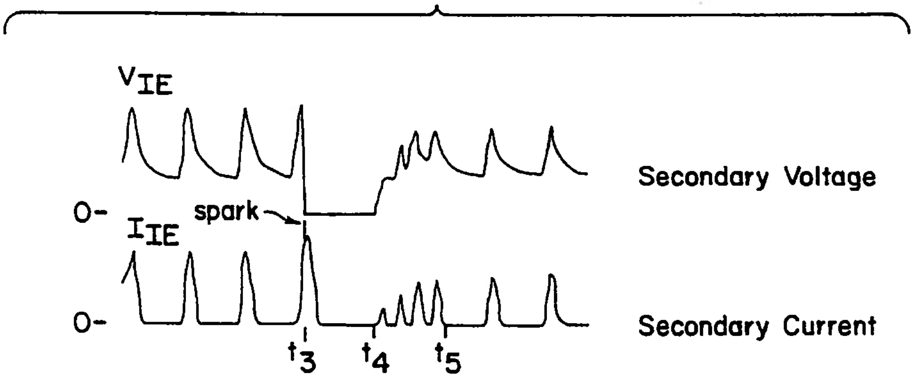
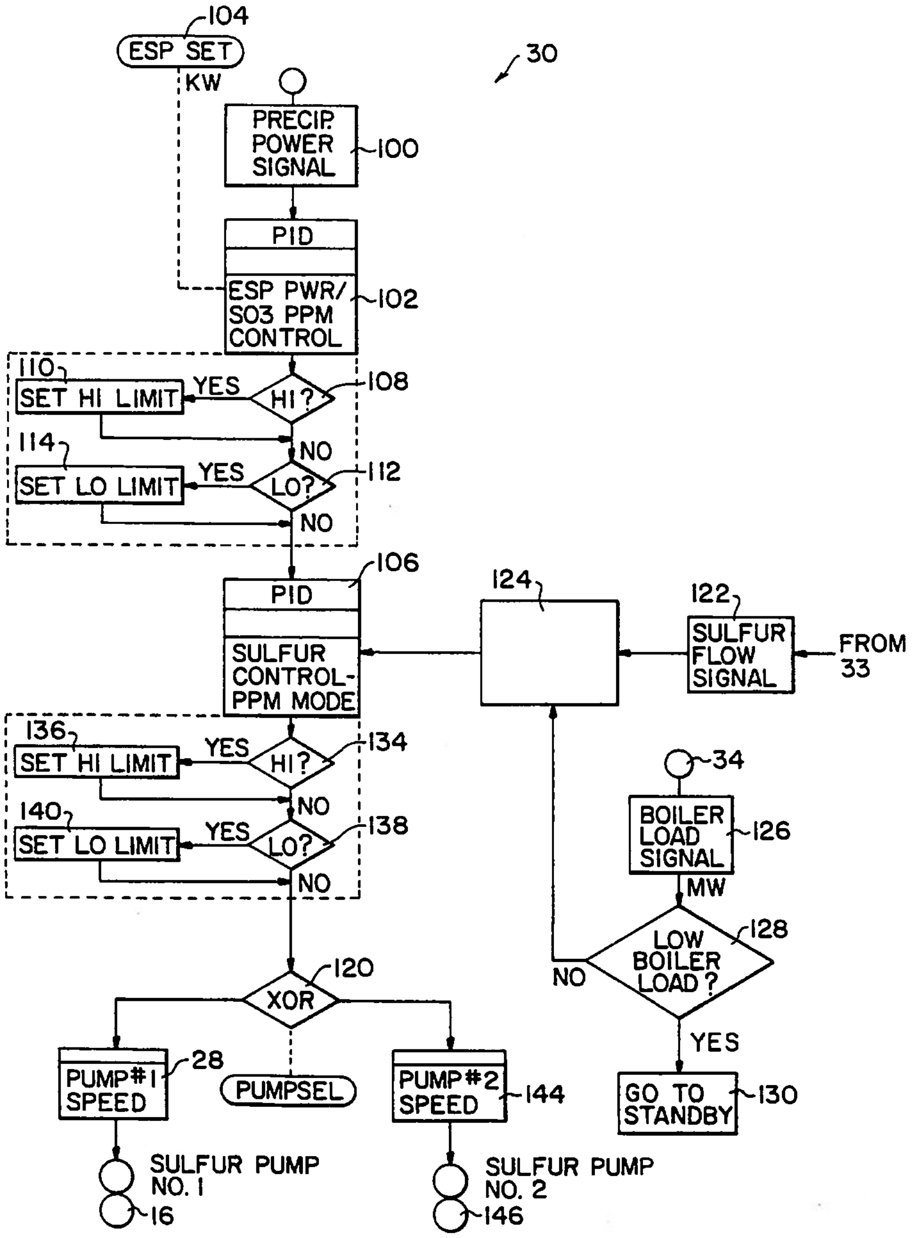

V_{IE}
0-
spark
I_{IE}
0-
t_3
t_4
t_5
Secondary Voltage
Secondary Current

FIG. 5


104
ESP SET
KW
30
PRECIP. POWER SIGNAL
100
PID
ESP PWR/ SO3 PPM CONTROL
102
110
SET HI LIMIT
YES
HI ?
108
NO
114
SET LO LIMIT
YES
LO?
112
NO
106
PID
SULFUR CONTROL-PPM MODE
124
122
SULFUR FLOW SIGNAL
FROM 33
136
SET HI LIMIT
YES
HI ?
134
NO
140
SET LO LIMIT
YES
LO?
138
NO
34
BOILER LOAD SIGNAL
126
MW
LOW BOILER LOAD ?
128
NO
YES
120
XOR
PUMP#1 SPEED
28
PUMPSEL
PUMP#2 SPEED
144
GO TO STANDBY
130
SULFUR PUMP NO. 1
16
SULFUR PUMP NO. 2
146

FLUE GAS CONDITIONING METHOD FOR INTERMITTENTLY ENERGIZED PRECIPITATION

This is a Continuation of U.S. application Ser. No. 08/254,937, filed Jun. 7, 1994, now abandoned.

FIELD OF THE INVENTION

The present invention relates to a system for conditioning flue gas with a conditioning agent such as SO_3 in order to improve the efficiency of an electrostatic precipitator in collecting ash and other particulate matter from the flue gas, and more particularly, to such a system which is controlled by monitoring the power delivered to the electrostatic elements of an electrostatic precipitator.

BACKGROUND OF THE INVENTION

The flue gas of furnaces and boilers, such as those used in power generation plants, carries matter including ash and other particulates which pollute the atmosphere. Electrostatic precipitators are used to remove ash and other particulates carried in the flue gas. Electrostatic precipitators operate by causing the individual particles in the flue gas to accept an electrical charge and by attracting the charged particles to collector plates for disposal.

Electrostatic precipitation has been used primarily in connection with the burning of coal. As coal burns, it produces H_2O, CO_2, CO, SO_2, SO_3, ash and other particulate matter and products of combustion. The H_2O and SO_3 combine to form H_2SO_4 (sulfuric acid) which coats the particulate matter. The coating of H_2SO_4 reduces the resistance of the ash and other particulate matter and thereby facilitates the electrical charging of this particulate matter so that the charged particulate matter can be more easily attracted to the collector plates of the electrostatic precipitator. If combustion produces insufficient H_2SO_4, however, the resistance of the particulate matter is high which reduces the efficiency of the electrostatic precipitator in charging the particulate matter suspended in the flue gas and, as a result, in collecting particulate matter from the flue gas.

When coal having a relatively high sulfur content is burned, sufficient SO_3 is produced to form the proper amount of H_2SO_4. However, high sulfur coal also produces excess SO_2 which, if exhausted to the atmosphere, is a pollutant that has been linked to acid rain.

In order to reduce SO_2 emissions, the operators of coal fired boilers and furnaces have burned coal having a low sulfur content. However, low sulfur coal results in the production of less SO_3 than that required to efficiently operate the electrostatic precipitators. Accordingly, one must balance the need for lower SO_2 emissions and the need for an adequate supply of SO_3 to maintain the efficiency of electrostatic precipitators at a relatively high level. To provide this balance, the operators using lower sulfur content coal have injected a controlled amount of SO_3 into the flue gas to compensate for the inadequate amount of SO_3 produced by combustion of the low sulfur coal. Thus, SO_2 emissions are held relatively low while electrostatic precipitator efficiency is increased.

As is apparent, the efficiency of some electrostatic precipitators is dependent upon the concentration of SO_3 in the flue gas. That is, if the SO_3 concentration in the flue gas is too low, an electrostatic precipitator may operate at less than optimal efficiency and an unacceptable plume of particulates may result. Flue gas that has less than optimal SO_3 concentrations as the flue gas enters the electrostatic precipitator constitutes an emissions problem. Coal fired power generation plants that are operating out of compliance with emission regulations can be forced to reduce their power output until the emissions are brought back into compliance. Accordingly, it is important to keep the emissions concentrations within an acceptable range while minimizing the power consumption of the electrostatic precipitator.

One prior art method of decreasing the power consumption of an electrostatic precipitator is to measure the opacity of the flue gas as it exits from a stack of the flue gas conditioning system and to control the amount of power supplied to the electrostatic precipitator accordingly. For example, Reese, et al., U.S. Pat. No. 4,284,417 discloses a system for controlling the electric power supplied to an electrostatic precipitator having an opacity-sensitive transducer which produces an output signal proportional to the opacity of the flue gas exiting from the precipitator. The system also includes a comparator which compares the output signal with preset upper and lower limits and a controller which controls the power supplied to the precipitator in order to restore the flue gas opacity to a permissible range when the output signal falls outside of the preset upper and lower limits. Krigmont, et al., U.S. Pat. No. 4,987,839 discloses a system including a source of SO_3 which adds SO_3 to flue gas before it enters an electrostatic precipitator and a controller which controls the rate at which the SO_3 is added to the flue gas. The controller is responsive to the opacity of the flue gas exiting the electrostatic precipitator and to the power supplied to the electrostatic precipitator.

Measuring the opacity of the flue gas as it leaves the flue gas conditioning system, however, is not necessarily the best method of controlling the level of ash and other particulates in flues because the opacity of the flue gas is not a good indicator of the need for the addition of a particular additive, such as SO_3.

Another method of increasing the efficiency of an electrostatic precipitator is to employ, as a control for the amount of SO_3 delivered to the flue, the power delivered to the electrostatic precipitator. A system employing this method is disclosed in Woracek, et al., U.S. Pat. No. 4,779,207, wherein a flue gas conditioning system includes automatic voltage controllers (AVCs) which supply power to transformer/rectifier sets which, in turn, provide a stepped-up and rectified voltage to elements or plates of an electrostatic precipitator. Power measuring elements produce signals indicative of the power delivered by each of the AVCs to each of the transformer/rectifier sets, and these signals are combined to produce an indication of the average power delivered to the electrostatic precipitator. The average power indication is used to control the amount of SO_3 delivered to the flue so as to keep the average power delivered to the electrostatic precipitator within a predetermined range.

It is also known in the prior art to intermittently energize the elements of an electrostatic precipitator, which may include plates, electrodes and the like, in order to increase the electrostatic precipitator efficiency. A flue gas conditioning system which is utilized for an electrostatic precipitator system with intermittent energization typically has an AVC which supplies an intermittent voltage, having a predetermined duty cycle, to a transformer/rectifier circuit which, in turn, provides a stepped-up, rectified, intermittent voltage to the electrostatic elements. Krigmont, et al., U.S. Pat. No. 4,987,839 discloses an intermittently energized system having a control which is responsive to the duty cycle of the power delivered to an electrostatic precipitator and which uses this duty cycle to estimate the power delivered to the flue gas by the electrostatic elements.

Intermittent energization, however, creates a control problem in flue gas conditioning systems like that disclosed in the Krigmont, et al. patent and those which control the amount of SO_3 delivered to the flue in accordance with a power signal developed from the duty cycle of the intermittent power supplied to the electrostatic precipitator. This problem occurs because neither (a) the duty cycle of the intermittent power nor (b) the actual power developed by the precipitator power source with which the flue gas conditioning system is used, are reliable indications of the power actually delivered to the flue gas by the electrostatic elements. As such, an average power signal developed from the duty cycle of the intermittent power is an inaccurate determination of the amount of SO_3 which needs to be provided to the flue gas entering the electrostatic precipitator. This problem becomes particularly acute when the duty cycle of the power source is periodically changed during operation of the flue gas conditioning system. In such a system, therefore, other means must be provided for measuring the power absorbed by the electrostatic elements of the electrostatic precipitator.

SUMMARY OF THE INVENTION

The power absorbed by the electrostatic elements of an electrostatic precipitator is an indication of the resistivity of the particulate matter within a flue and, therefore, the need for SO_3. When a flue gas conditioning system is operated in a constant energization mode, one may normally use the power developed by a power source and delivered to the electrostatic precipitator as an accurate measure of the power absorbed by the electrostatic elements and, therefore, as a reliable indicator of the amount of flue gas conditioning agent (SO_3) required to treat the particulates in the flue gas.

If the electrostatic elements of the electrostatic precipitator are intermittently energized, however, the power developed by the power source and the duty cycle of the intermittent energization are not reliable indications of the power absorbed by the electrostatic elements. Therefore, when intermittent energization is employed, other means must be provided for measuring the power absorbed by the electrostatic elements. According to one embodiment of the present invention, certain parameters of the power delivered directly to the electrostatic elements are measured, and these parameters are used to develop a power signal which, in turn, is used to regulate the amount of SO_3 delivered to the flue gas.

Thus, the present invention relates to a system for preconditioning flue gas to be treated in an intermittently energized electrostatic precipitator having a power source which supplies an intermittent power to electrostatic elements of an electrostatic precipitator. One aspect of this system includes a source of a conditioning agent, such as SO_3, and a detection device which detects first and second parameters of the power supplied to the electrostatic elements. The system also includes a component which is responsive to the first and second parameters, and which develops an indication of the power supplied to the electrostatic elements. In addition, the system includes a controller, responsive to the power indication, which controls the amount of conditioning agent added to the flue gas in order to maintain the power at a substantially predetermined level.

The power source may include circuitry for delivering an intermittent voltage to a primary winding of a transformer having a transformer output coupled to the electrostatic elements. The power source may also include a circuit for selecting the intermittent duty cycle delivered to the transformer.

The detection device may include a current sensor for measuring the current flowing through the transformer input or the transformer output and a voltage sensor for measuring the voltage at the transformer input or the transformer output. Specifically the current sensor may include circuitry for measuring the half-cycle root mean squared (RMS) current, the peak current or the average current flowing through the transformer during one or more energized half-cycles of the intermittent power, while the voltage sensor may include circuitry for measuring the average voltage, the peak voltage, the half-cycle RMS voltage or the minimum voltage across transformer during one or more energized half-cycles of the intermittent power. Preferably, a multiplier multiplies the RMS, peak or average current with the average, peak, RMS or minimum voltage to produce the power indication.

Another aspect of the present invention is directed to an improvement in a flue gas conditioning system in which a source of a conditioning agent is added to flue gas, and in which an electrostatic precipitator, having a set of electrostatic elements which receive a power, treats the flue gas. Furthermore, a controller, responsive to an indication of the power, controls the amount of the conditioning agent added to the flue gas, and a power source, which operates in an intermittent energization mode, delivers a power having a duty cycle to the electrostatic elements. The improvement includes a measuring device which measures first and second parameters of the power delivered to the electrostatic elements, and circuitry, responsive to the first and second parameters, which derives the indication of the power.

Preferably, the first and second parameters are current and voltage, respectively, and the measuring device includes a first sensor which detects current flowing into the electrostatic elements to produce a current signal and a second sensor which detects voltage developed across the electrostatic elements to produce a voltage signal. The circuitry combines the current signal and the voltage signal to produce the indication of the power.

Yet another aspect of the present invention is directed to a method of controlling a flue gas conditioning system which includes a source of a conditioning agent, a component which adds the conditioning agent to flue gas, and an electrostatic precipitator having a set of electrostatic elements which receive a power, for treating the flue gas. The system further includes a controller, responsive to a signal indicative of the power, which controls the amount of conditioning agent added to the flue gas. According to one embodiment of the method, a power source is operated in an intermittent energization mode to develop an input power having a duty cycle which delivers the power to the electrostatic elements. Furthermore, first and second parameters of the power are measured and are used to derive the signal indicative of the power.

These and other features and advantages will become more apparent from a detailed consideration of the invention when taken in conjunction with the following drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 comprises a block diagram of a flue gas exhaust and conditioning system according to an embodiment of the present invention;

FIG. 2 comprises a combined block and simplified schematic diagram of a portion of the system of FIG. 1;

FIG. 3 comprises a set of waveform diagrams illustrating the operation of the system of FIG. 1 in a full-cycle energization mode;

FIG. 4 comprises a set of waveform diagrams illustrating the operation of the system of FIG. 1 in an intermittent energization mode; and

FIG. 5 comprises a flow chart illustrating a flue gas flow controller employed in the system of FIG. 1.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENT

Referring initially to FIG. 1, a flue gas conditioning system is indicated generally at **8** and is used with a flue **9** connected to a boiler **10**, such as a boiler in a coal burning power generation plant, which discharges by-products of combustion through flue **9**. An electrostatic precipitator **12** is disposed in flue **9** and has multiple sets of electrostatic elements **14**, which include electrodes and/or electrostatic plates, which are disposed parallel to the flow of the flue gas through the flue **9**, for removing ash and other particulate material from the flue gas.

In order to increase the efficiency of electrostatic precipitator **12** in precipitating out the ash and other particulate matter from the flue gas in flue **9**, a conditioning agent in the form of gaseous sulfur trioxide, SO_3, is supplied to the flue gas in flue **9**. This SO_3 is produced by burning sulfur with oxygen to produce sulfur dioxide, SO_2, and then converting the SO_2, by the use of a catalytic converter, into SO_3 which then can be supplied to flue **9**. Accordingly, a pump **16** delivers molten sulfur provided by a sulfur supply **18** to a sulfur burner **20** which burns the sulfur in the presence of oxygen in order to produce sulfur dioxide, SO_2. Oxygen is supplied to the burner **20** in the form of air from an air blower **22**. A gas mixture including SO_2 exits the sulfur burner **20** and is supplied to an SO_3 generator **24**, such as a catalytic converter, which converts the sulfur dioxide, SO_2, into sulfur trioxide, SO_3, typically by employing excess oxygen in the mixture exiting sulfur burner **20**. SO_3 generator **24** delivers SO_3 to a set of injectors **25** which inject the SO_3 into flue **9** where the SO_3 combines with water vapor in the flue gas to form sulfuric acid vapor which condenses and reacts with the ash and other particulate material in flue **9**. This process reduces the resistivity of the particles in the flue gas and allows electrostatic elements **14** of electrostatic precipitator **12** to remove the particles more efficiently. Burning sulfur in the presence of oxygen to form sulfur dioxide and then converting that sulfur dioxide into sulfur trioxide may all be done in a conventional manner.

Pump **16** is driven by a motor **26** under control of a speed controller **28**. Speed controller **28** is regulated by a flue gas flow controller **30** which is responsive to a set of power signals developed by power measuring units **32** which provide an indication of the requirement of SO_3 within the flue. Flow controller **30** may also be responsive to a flow signal produced by a flow rate sensor **33**, connected between pump **16** and burner **20**. Sensor **33** produces a signal indicative of the actual amount of sulfur being supplied to burner **20**. Flow controller **30** may also be responsive to a boiler load signal from a sensor **34** which reflects the amount of combustion occurring in boiler **10**.

A set of automatic voltage controllers (AVCs) **40** provide power in the form of AC voltage to a set of transformer/rectifier (T/R) sets **42**, each of which includes a transformer and a rectifier and each of which is connected to one of the sets of electrostatic elements **14**. Each of T/R sets **42** steps up the voltage supplied by the associated AVC **40** to produce a higher amplitude secondary voltage, rectifies the secondary voltage, and provides the rectified secondary voltage to the associated electrostatic elements **14**, which remove ash and other particulate matter from the flue gas in electrostatic precipitator **12**.

Power measuring units **32** are responsive to signals indicative of the voltage and current delivered to electrostatic elements **14** by T/R sets **42**, and units **32** produce power signals indicative of the power absorbed by electrostatic elements **14**. The power signals produced by power measuring units **32** are preferably indicative of the average power delivered to electrostatic elements **14** during each cycle or half-cycle of the AC voltage developed by AVCs **40**, but could, alternatively, comprise instantaneous power signals, power signals indicative of the average power absorbed by the electrostatic elements **14** over longer periods of time, or any other type of power signal, if so desired. Flow controller **30** is responsive to the power signals developed by each of the power measuring units **32** and produces an electrostatic precipitator power signal indicative of the total average power absorbed by all of the sets of electrostatic elements **14** over a predetermined length of time.

Flow controller **30** uses the electrostatic precipitator power signal as a process value to control the speed controller **28**. This control can be accomplished by comparing an electrostatic precipitator power signal process value to a power set point to produce a difference signal. If the electrostatic precipitator process value is greater than the set point, the flow controller **30** causes speed controller **28** to decrease the amount of sulfur being provided by sulfur supply **18** to burner **20** and decrease the amount of SO_3 injected at injectors **25**, which increases the resistivity of the particles in the flue gas, and thereby decreases the power absorbed by the electrostatic elements. If, however, the electrostatic precipitator process value is below the set point value, flow controller **30** causes the speed controller to increase the amount of sulfur being provided by sulfur supply **18** to burner **20** and increase the amount of SO_3 injected at injectors **25**, which reduces the resistivity of the particles in the flue gas and thereby increases the power absorbed by the electrostatic elements. In this manner, flow controller **30** measures the power dissipated by electrostatic elements **14** and regulates the speed of motor **26** to ensure that the proper amount of sulfur trioxide, SO_3, is supplied to flue **9** so as to maintain a substantially constant power usage within electrostatic elements **14** of the electrostatic precipitator **12**.

Flow controller **30** shown in FIG. **1** may be a programmable logic controller such as a Honeywell UDC 9000E which delivers a 4 to 20 milliamp signal to speed controller **28** which may be any suitable speed controller, such as a Westinghouse Acutrol Model 110, for accepting a 4 to 20 milliamp input and for providing a speed control output to motor **26**. Each of AVCs **40** shown in FIG. **1** may be, for example, an ABB Fläkt, Epic II automatic voltage controller system.

The amount of SO_3 supplied to flue **9** is proportional to the sulfur supplied to the burner **20** by pump **16** which is controlled by the speed of motor **26**. In one embodiment, the amount of air from blower **22**, which provides the oxygen for forming SO_2 and SO_3, can be preset to comprise a constant flow of air sufficient to produce the required supply of oxygen at maximum SO_3 demand. In another embodiment, air flow from blower **22** can be varied in response to variations in the amount of sulfur delivered by sulfur pump **16**. Typically, in both embodiments, there is always a surplus of air flow to burner **20** and to SO_3 generator **24** to deliver to flue **9**, a dilute mixture of gaseous SO_3.

FIG. **2** illustrates one AVC **40** in conjunction with one T/R set **42** and one power measuring unit **32**. An AC input voltage, typically having an RMS voltage of 480, is produced by an external power source (not shown) and is supplied through a circuit breaker **50** to lines **52***a* and **52***b*. A current sensor **54** produces a primary current signal I_p, indicative of the current flowing through line **52***a* and into AVC **40**, which is delivered to an AVC control unit **56**. The power developed on line **52***a* is provided to silicon controlled rectifiers SCR1 and SCR2 which are connected between line **52***a* and a line **57**, in a reverse parallel configuration. AVC control unit **56** is coupled to the gate inputs of SCR1 and SCR2 and controls the operation thereof.

A varistor V and a resistor R1 in conjunction with a capacitor C1 are connected in parallel across silicon controlled rectifiers SCR1 and SCR2, while a resistor R2 and a capacitor C2 are connected in series between the cathode of SCR1 and line **52***b*. Varistor V, resistors R1 and R2 and capacitors C1 and C2 operate as a protection circuit which filters out transients produced by SCR1 and SCR2 when switching from an on state to an off state, or vice-versa. This protection circuit prevents, for example, SCR1 from turning SCR2 on when SCR1 turns off. The values of varistor V, resistors R_1 and R_2 and capacitors C_1 and C_2 are dependent upon the particular type of silicon controlled rectifier used and may be chosen in any conventional manner.

The cathode of SCR1 and the anode of SCR2 are connected through line **57** to an input of a transformer **58** having a primary winding **60** and a secondary winding **62**. Transformer **58** steps up the voltage appearing between lines **52***b* and **57** to a higher, secondary level to produce a stepped-up voltage across lines **63***a* and **63***b*, which may comprise a transformer output. Transformer **58** may, however, include a rectifier **64** connected in a full-bridge configuration having diodes D1–D4 connected as shown in FIG. 2. Rectifier **64** is responsive to the stepped-up voltage appearing across lines **63***a* and **63***b* and produces a secondary voltage V_s across a positive transformer output **66** and a negative transformer output **68**. Positive transformer output **66** is connected to an electrical ground while negative transformer output **68** is connected to a discharge electrode **14***a* comprising one or more of a plurality of electrodes associated with one of the sets of electrostatic elements **14**. Electrostatic plates **14***b*, which comprise the other of the plurality of electrodes within one of the sets of electrostatic elements **14**, are connected to electrical ground.

According to one embodiment of the present invention, power measuring unit **32** is responsive to secondary voltage V_s appearing across transformer outputs **66** and **68** and to a current signal I_s, produced by a current sensor **70** connected to positive transformer output **66**. Power measuring unit **32** produces one signal, indicative of, for example, the root mean squared (RMS) current, the peak current or the average current flowing through the electrostatic elements **14** during one or more predetermined number of energized half-cycles of the input voltage. Power measuring unit **32** also produces a second signal indicative of, for example, the average voltage, the peak voltage, the RMS voltage or the minimum voltage appearing across electrostatic elements **14** during one or more predetermined number of energized half-cycles of the input voltage.

It should be noted, however, that power measuring unit **32** can also be connected across the primary winding **60** of the transformer **58** to measure the current and voltage during one or more energized half-cycles of the input voltage. For example, the power measuring unit **32** can measure the RMS, peak or average current flowing through the primary winding **60** of the transformer **58** during each energized half-cycle of the input voltage and measure the average, peak, RMS or minimum voltage appearing across the primary winding **60** over one or more predetermined number of energized half-cycles of the input voltage in order to measure the power being delivered to the electrostatic elements

Power measuring unit **32** combines the RMS, peak or average current signal and the average, peak, RMS or minimum voltage signal by multiplication, for example, to produce a signal indicative of the instantaneous, average or other power delivered to the electrostatic elements **14**. Preferably, however, voltage values which are below a preset threshold are not used to derive this power signal. Also preferably, the power measuring unit **32** develops a power signal which represents the power delivered to electrostatic elements **14** during each energized half-cycle or full cycle of the input voltage appearing across lines **52***a* and **52***b*. However, the power measuring unit **32** may develop a power signal which represents the power delivered to the electrostatic elements over longer periods of time, if so desired. In any event, power measuring unit **32** delivers the power signal to flow controller **30** via a line **72**.

In operation, the input voltage is delivered to lines **52***a* and **52***b* and thereby to silicon controlled rectifiers SCR1 and SCR2. Control unit **56** responds to current signal I_p, to primary voltage V_p appearing across primary winding **60** of transformer **58**, to secondary voltage V_s, and to secondary current signal I_s, and produces control signals at the gate inputs of SCR1 and SCR2. These control signals turn SCR1 and SCR2 on and off and thereby control the voltage delivered to transformer **58**.

More specifically, control unit **56** provides a control signal to the gate input of SCR1 which turns SCR1 on during the positive half-cycles of the input voltage appearing between lines **52***a* and **52***b* and which turns SCR1 off during the negative half-cycles of the input voltage. Likewise, control unit **56** provides a control signal to the gate input of SCR2 which turns SCR2 on during the negative half-cycles of the input voltage and which turns SCR2 off during the positive half-cycles of the input voltage.

Control unit **56** controls the specific amount of power delivered to transformer **58** by controlling the exact turn-on time of SCR1 and SCR2 during any particular half-cycle of the input voltage. Control unit **56**, for example, turns SCR1 on at the beginning of a particular positive half-cycle of the input voltage in order to deliver maximum power to transformer **58** and to produce a maximum peak voltage across secondary winding **62** of transformer **58** during that particular half-cycle. Control unit **56**, however, turns SCR1 on later in a particular positive half-cycle of the input voltage in order to supply less power to transformer **58** and to produce a lower peak voltage across secondary winding **62** of transformer **58** which, in turn, results in less power being delivered to the electrostatic elements **14**. Thus, turning SCR1 on later during a particular half-cycle of the input voltage results in less power being delivered to transformer **58** which, in turn, results in less power being delivered to electrostatic elements **14**. SCR1 and SCR2 automatically unlatch or turn off at the end of each half-cycle of the input voltage, i.e., when the input voltage goes through the zero point. In this manner, AVCs **40**, in conjunction with T/R sets **42**, supply a controlled pulsating DC power to the electrostatic elements **14**.

AVCs **40** in conjunction with T/R sets **42** may be operated in a full-cycle energization mode as is commonly known in the prior art. The waveform diagrams shown in FIG. 3 illustrate a voltage signal V_{FCE} and a current signal I_{FCE}

which represent the voltage and the current at the output of a T/R set 42 when an AVC 40 operates in a full-cycle energization mode, i.e., when electrostatic elements 14 are energized during all the positive half-cycles and the negative half-cycles of the input voltage. Voltage signal V_{FCE} and the current signal I_{FCE}, therefore, represent parameters of power delivered to an electrostatic element 14 of electrostatic precipitator 12. As illustrated in FIG. 3, AVC 40 gradually increases the peak voltage supplied to T/R set 42 over a plurality of input voltage half-cycles until the control unit 56 detects a spark within electrostatic precipitator 12. At this time, shown in FIG. 3 as a time T1, voltage signal V_{FCE} drops to a value of zero while current signal I_{FCE} increases until the end of that particular half-cycle and then drops to a value of zero. After a spark occurs in a particular set of electrostatic elements 14, the associated AVC 40 does not supply voltage to the associated T/R set 42 for a predetermined period of time. This delay allows the ionized path created by the spark to dissipate and prevents continuous sparking or sustained arcing within the particular set of electrostatic elements 14. At a time T2, AVC 40 begins to supply low amplitude voltage to the associated T/R set 42 and gradually increases the peak of the supplied voltage over a plurality of half-cycles until another spark occurs within the associated set of electrostatic elements 14. Each AVC 40 repeats this cycle so as to energize electrostatic elements 14 in a full-cycle energization mode.

It has been found, however, that the performance of electrostatic precipitator 12 can be improved and/or power can be saved, when AVCs 40 operate in an intermittent energization mode. During the intermittent energization mode, each AVC 40 provides voltage to associated T/R set 42 during some half-cycles (which may include both positive and negative half-cycles) of the input voltage while skipping other half-cycles. FIG. 4 illustrates a voltage signal V_{IE} and a current signal I_{IE} which represent the voltage and current appearing at the output of T/R set 42 when the associated AVC 40 operates in an intermittent energization mode, having a duty cycle of 33% (i.e., one half-cycle on and two half-cycles off). During the intermittent energization mode, the AVC 40 increases the voltage delivered to associated T/R set 42 until a current or voltage limit is reached or until a spark occurs within electrostatic elements 14. At that time, illustrated in FIG. 4 as a time T3, voltage signal V_{IE} drops to a value of zero while current signal increases until the end of that particular half-cycle and then drops to a value of zero. After the spark occurs, AVC 40 does not provide voltage to T/R set 42 for a predetermined period of time to allow the ionized path created by the spark to dissipate. After a predetermined delay, i.e., at a time T4, AVC 40 begins to provide a low amplitude voltage to T/R set 42. AVC 40 may then operate in a full-cycle energization mode for a number of half-cycles of the input voltage in order to increase the amplitude of voltage signal V_{IE} to a useful level in a short period of time. At a time T5, AVC 40 switches back into the intermittent energization mode, and once again, gradually increases the amplitude of voltage signal V_{IE} until another spark occurs within electrostatic elements 14. This cycle is repeated so as to energize electrostatic elements 14 in the intermittent energization mode.

In one embodiment of the present invention, AVCs 40 control the voltage delivered to T/R sets 42 in response to various input signals. These input signals may include, for example, a signal indicative of the boiler load developed by boiler load sensor 34 or a signal indicative of the sulfur flow rate developed by flow rate sensor 33 (FIG. 1). Specifically, AVCs 40 may choose an intermittent duty cycle in response to these signals, or other desired control signals, which results in the most efficient operation of electrostatic precipitator 12. Preferably, AVCs 40 may automatically change the intermittent duty cycle during operation of flue gas conditioning system 8.

As illustrated in FIG. 4, voltage signal V_{IE}, produced at transformer outputs 66 and 68, does not drop to a value of zero during the off half-cycles of the intermittent voltage supplied by AVC 40. This is a result of charge being stored in the electrostatic elements 14 during these off half-cycles. (The current signal I_{IE}, however, does drop to a value of zero during the off half-cycles of the intermittent voltage.) It should also be noted that the peaks of the voltage signal V_{IE} tend to be greater than those developed by the voltage signal V_{FCE} during the full-cycle energization mode shown in FIG. 3. It is this increase in the peaks of the voltage signal V_{IE}, in conjunction with zero current flow during the off half-cycles of the input voltage, which increases the performance of electrostatic precipitator 12 during the intermittent energization mode of operation.

The performance of electrostatic precipitator 12 during the intermittent energization mode, however, is not directly correlated to the operating duty cycle of AVC 40, because the peak voltages produced at transformer outputs 66 and 68 during intermittent energization are not linearly related to the duty cycle of AVC 40. Thus, as the ratio of energized half-cycles to deenergized half-cycles (the duty cycle) is changed, the performance of electrostatic precipitator 12 changes without a direct correlation in the change of average power supplied to electrostatic elements 14. For example, switching from the full-cycle energization mode to the intermittent energization mode with a duty cycle of 33% (i.e., one half-cycle on and two half-cycles off) generally results in the same performance of electrostatic precipitator 12 but also results in electrostatic elements 14 absorbing an average power that is approximately 40% of the average power absorbed by the same electrostatic elements during the full-cycle energization mode.

Thus, the duty cycle used during the intermittent energization mode is not a reliable indication of the power being dissipated by the electrostatic elements 14 and a change in the duty cycle by, for example, 50%, does not necessarily change the average power absorbed by electrostatic elements 14 by 50%. As a result, flow controller 30 cannot rely on a measure of power developed by AVC 40, such as the duty cycle, as an accurate indication of the average power being delivered to electrostatic elements 14, but must, instead, measure the actual power provided to electrostatic elements 14, as disclosed herein, in order to control the flow of SO_3 into the flue 9 in a precise manner.

It is, therefore, an important aspect of this invention to measure the precise voltage and the current developed by each T/R set 42 (e.g., the voltage appearing across and the current flowing through electrostatic elements 14) to produce an accurate indication of the power delivered to electrostatic elements 14. This power indication is, preferably, developed from the half-cycle RMS, peak or average value of current signal I_s during each of the energized half-cycles of the input voltage and from the average value of voltage V_s, the peak value of voltage V_s, the half-cycle RMS value of the voltage V_s or the minimum value of the voltage V_s over one or more energized half-cycles of the input voltage. This power indication could, however, also be developed from the half-cycle RMS, peak or average value of the current flowing through the primary of the transformer 58 and/or from the average, peak, half-cycle RMS or minimum value of the voltage across the primary of the transformer **58** over one or more energized half-cycles of the input voltage. Preferably, if a voltage measurement over a number of predetermined half-cycles is used, the power measuring unit **32** discards any voltage measurements from half-cycles which fall below a predetermined threshold because such measurements tend to occur during the half-cycles of the input voltage immediately following a spark within the electrostatic plates. A power signal, so developed, enables flow controller **30** to control flow of SO_3 into flue **9** in a precise and accurate manner, regardless of the intermittent energization duty cycle chosen by AVCs **40**. Furthermore, it should be noted that the duty cycle of the intermittent power supply can change during operation thereof without effecting the ability of the power measuring unit **32** to produce an accurate power signal, i.e., a signal which accurately indicates the power being delivered to the electrostatic elements.

FIG. **5** shows a preferred embodiment of flow controller **30** although any other desired flow controller can be used instead. An electrostatic precipitator power signal **100** is developed, for example, by averaging the outputs of power measuring units **32**. Signal **100** is supplied to a process variable input of a proportional-integral-derivative (PID) controller **102**. An electrostatic power set point **104** is supplied to a set point input of PID controller **102**. PID controller **102** subtracts one of either electrostatic power set point **104** or electrostatic precipitator power signal **100** from the other to develop an error or difference signal. PID controller **102** applies any desired combination of proportional, integral, and derivative control to this error signal to develop an electrostatic precipitator power control quantity for supply to a PID controller **106**.

If desired, a comparator **108** tests the electrostatic precipitator power control quantity from PID controller **102** against a high threshold. If the electrostatic precipitator power control quantity is above the high threshold, the electrostatic precipitator power control quantity is then set at a high limit **110**. The electrostatic precipitator power control quantity is also compared to a low threshold by a comparator **112**. If the electrostatic precipitator power control quantity is below the low threshold, the electrostatic precipitator power control quantity is set at a low limit **114**. Accordingly, the electrostatic precipitator power control quantity, or its high limit **110**, or its low limit **114** is supplied to PID controller **106**.

The output of the PID controller **102** or the output of the comparator **112**, which may, for example, represent a percentage, can be converted into a signal representative of any other desired unit before being input into the PID controller **106**.

PID controller **106** provides an SO_3 control signal, which is based upon a calculated SO_3 concentration quantity, to a connection point **120**. In order to calculate the SO_3 concentration quantity, flow controller **30** receives a sulfur flow signal **122** from, for example, flow rate sensor **33** (FIG. **1**). A block **124** applies a proportionality constant K to sulfur flow signal **122**.

Furthermore, a boiler load signal **126** is provided by boiler load sensor **34** (FIG. **1**), and the boiler load signal may be compared, if desired, by a comparator **128** to a low threshold. If the boiler load signal is below the low threshold, a block **130** initiates a standby condition, at the option of the operator. That is, if boiler **10** is operating at a substantially reduced boiler load, for example below 10% of its rated maximum capacity (i.e., the low threshold), the volume of the flue gas produced by boiler **10** is very low. Consequently, the amount of contaminants is sufficiently low at this volume of flue gas that the injection of SO_3 is unnecessary. Thus, in standby, sulfur pump **16** is stopped so that no sulfur is unnecessarily burned by sulfur burner **20** (FIG. **1**).

On the other hand, if boiler load signal **126** is not below the low threshold, the boiler load signal **126** is supplied to the block **124** which may comprise a microprocessor or other computing network. The Block **124** performs the following calculation:

$$SO_3PPM = \frac{(\text{Sulfur Flow})\,(460 + T_s)\,(\text{ConverterEff})\,(10^6)\,(387)}{(\text{ACFM})\,(60)\,(530)\,(32)} \tag{1}$$

where SO_3PPM is the SO_3 concentration quantity, Sulfur Flow is the sulfur flow signal **122** supplied by flow rate sensor **33**, 460 is 460° Rankin which converts the Fahrenheit temperature scale to the absolute temperature scale, T_s is the temperature in degrees Fahrenheit of the flue gas at injectors **25** at which SO_3 conditioning agent is injected, ConverterEff is the nominal efficiency of SO_3 generator **24** (which may typically be 95%), 10^6 converts the calculation to parts per million, 387 is the Ideal Gas Constant in cubic feet per pound mole, ACFM is the boiler load (representing the actual cubic feet per minute rate at which flue gas is produced), 60 converts the ACFM rate from cubic feet per minute to cubic feet per hour, 530 is a temperature reference equal to 460° Rankin plus the temperature base for the Ideal Gas Constant, i.e. 70° F., and 32 is the molecular weight of sulfur. Although the temperature of the flue gas may be measured by a sensor (not shown) to produce a signal for T_s, the design output temperature of boiler **10** at full boiler load may instead be used for T_s.

Equation (1) can be rewritten in a simplified form as follows:

$$C_{SO_3}=K(F_s/L_B) \tag{2}$$

where C_{SO_3} is the SO_3 concentration quantity in parts per million, F_s is the sulfur flow signal **122** supplied by flow rate sensor **33**, i.e., Sulfur Flow of equation (1), L_B is boiler load signal **126** supplied by boiler load sensor **34**, i.e., ACFM of equation (1), and K is the scaling factor applied to the sulfur flow signal **122** and is the collection of all terms on the right-hand side of equation (1) other than Sulfur Flow and ACFM.

Since other types of conditioning agents may be supplied to the flue gas produced by boiler **10**, since any type of burner **20** can be used for boiler **10**, and since it is possible to directly measure the rate at which the conditioning agent is supplied to the flue gas, equation (2) can be further generalized according to the following equation:

$$C_{CA}=K_1(F_{CA}/L_B') \tag{3}$$

where C_{CA} is the conditioning agent concentration quantity, F_{CA} is a flow rate related to the rate at which the conditioning agent is supplied to the flue gas, L_B' is boiler load (i.e., related to the rate at which flue gas is produced), and K_1 is a scaling factor appropriate to the sensors which measure F_{CA} and L_B' and to the particular conditioning agent which is selected for the treatment of the flue gas.

Referring again to FIG. **5**, the SO_3 concentration quantity calculated by block **124** is supplied to a process variable input of PID controller **106**. PID controller **106** produces an error signal by subtracting (a) the electrostatic precipitator power control quantity developed by the PID controller **102** from (b) the calculated SO_3 concentration quantity supplied by block **124**. PID controller **106** applies any desired combination of proportional, integral, and derivative control to this error signal to develop the SO_3 control signal delivered to connection point **120**.

If desired, a comparator **134** tests the SO_3 control signal against a high threshold. If the SO_3 control signal is above the high threshold, the SO_3 control signal is then set at a high limit **136**. The SO_3 control signal is also compared to a low threshold by a comparator **138**. If the SO_3 control signal is below the low threshold, the SO_3 control signal is set at a low limit **140**. Accordingly, the SO_3 control signal; or its high limit **136**, or its low limit **140** is supplied to connection point **120**.

The output of SO_3 connection point **120** is supplied to speed controller **28** in order to control sulfur pump **16**. Alternatively, the output of the connection point **120** may be supplied to a speed controller **144** in order to control a second pump **146**.

As indicated in FIG. **5**, the electrostatic precipitator power control quantity developed by PID controller **102** is used as the set point for PID controller **106**. As a result, the rate at which SO_3 is supplied to the flue gas in flue **9** is controlled in order to achieve a balance between sulfur flow signal **122**, boiler load signal **126**, and the electrostatic precipitator power consumed by electrostatic precipitator **12** as sensed by power measuring units **32**. Thus, if it is assumed, for example, that the power consumed by electrostatic precipitator **12** decreases, its efficiency in removing ash from the flue gas in flue **9** decreases. As the power consumed by electrostatic precipitator **12** decreases, electrostatic precipitator power signal **100** decreases. PID controller **102** is arranged so that a decrease in electrostatic precipitator power signal **100** results in an increase in the electrostatic precipitator power control quantity produced by PID controller **102**. An increase in the electrostatic precipitator power control quantity results in an increase of the set point of PID controller **106**. As the set point of PID controller **106** increases, the SO_3 control signal changes in a direction to increase the speed of pump **16** thereby to increase sulfur flow, i.e., the SO_3 control signal increases. As a result, SO_3 is supplied to the flue gas at a faster rate in order to increase the efficiency of electrostatic precipitator **12** and to consequently increase the power consumed by electrostatic precipitator **12**. As the flow of sulfur increases, sulfur flow signal **122** increases to increase the calculated SO_3 concentration quantity until a balance is achieved between sulfur flow signal **122**, boiler load signal **126**, and the electrostatic precipitator power consumed by electrostatic precipitator **12** as sensed by power measuring units **32**.

Flow controller **30** as disclosed in FIG. **5**, may be implemented utilizing known analog hardware elements. Alternatively, flow controller **30** may be implemented by a microprocessor and a program which performs the functions of the elements disclosed in FIG. **5**.

The source of sulfur trioxide is shown in FIG. **1** as comprising a source of sulfur **18**, a burner **20** for converting the sulfur to sulfur dioxide in the presence of oxygen (from an air blower **22**) and an SO_3 generator **24**, such as a catalytic converter, for converting the sulfur dioxide into sulfur trioxide. However, any suitable source of SO_3 can be used; for example, a source of liquid SO_2 may be provided which can be vaporized and combined with air to be converted by a catalytic converter into sulfur trioxide, SO_3; or sulfur trioxide (SO_3) can be supplied directly by vaporizing liquid SO_3 from a supply thereof. Electrostatic precipitator **12** may be any of the commercially available electrostatic precipitators. Also, an Allen-Bradley, Model 1771 controller may be used as the flow controller shown at **30** in FIG. **1**, instead of using the Honeywell UDC 9000E controller.

Furthermore, even though specific values for limits, constants, ranges and the like have been shown, it will be appreciated that any other desired values may be used. These and other modifications will be apparent to one skilled in the art and lie within the present invention, the scope of which is determined only by the following claims.

I claim:

1. A method of controlling a flue gas conditioning system including a source of a conditioning agent, means for adding the conditioning agent to a flue gas, an electrostatic precipitator for treating the flue gas and having a set of electrostatic elements which receive an intermittent input power, a power supply which operates in an intermittent energization mode to deliver the intermittent input power to the electrostatic precipitator, and a controller, for controlling the amount of the conditioning agent added to the flue gas, said method comprising the steps of:

measuring first and second parameters of the intermittent input power delivered to the electrostatic precipitator;

deriving a power signal, indicative of the intermittent input power delivered to the electrostatic precipitator, from the first and second parameters; and

controlling the amount of conditioning agent added to the flue gas according to the power signal; wherein

the input power includes a plurality of energized and non-energized half-cycles; and

the step of measuring includes the step of (a) detecting the first parameter existing at the electrostatic precipitator during an energized half-cycle of the input power and (b) detecting the second parameter existing at the electrostatic precipitator during an energized half-cycle of the input power.

2. The method of claim **1**, wherein:

the power supply includes a transformer having a secondary winding coupled to the electrostatic precipitator; and

the step of measuring includes the step of detecting the first and second parameters of the intermittent input power at the secondary winding of the transformer.

3. The method of claim **1**, wherein:

the power supply includes a transformer having a primary winding coupled to a power source; and

the step of measuring includes the step of detecting the first and second parameters of the intermittent input power at the primary winding of the transformer.

4. A method of controlling a flue gas conditioning system including a source of a conditioning agent, means for adding the conditioning agent to a flue gas, an electrostatic precipitator for treating the flue gas and having a set of electrostatic elements which receive an input power, a power supply which operates in an intermittent energization mode to deliver the input power to the electrostatic precipitator, and a controller, for controlling the amount of the conditioning agent added to the flue gas, said method comprising the steps of:

measuring first and second parameters of the input power delivered to the electrostatic precipitator;

deriving a power signal indicative of the input power delivered to the electrostatic precipitator from the first and second parameters; and

controlling the amount of conditioning agent added to the flue gas according to the power signal;

wherein:

the input power includes a plurality of energized and non-energized half-cycles;

the first and second parameters are current and voltage, respectively; and

the step of measuring includes the step of detecting a current flowing to the electrostatic precipitator during an energized half-cycle of the input power and detecting a voltage developed across the electrostatic precipitator during the energized half-cycle of the input power.

5. The method of claim **4**, wherein the step of detecting a current includes detecting one of the half-cycle RMS current, the peak current or the average current flowing to the electrostatic elements; and

the step of detecting a voltage includes detecting one of the peak voltage, the average voltage, the half-cycle RMS voltage or the minimum voltage developed across the electrostatic elements.

6. The method of claim **5**, wherein:

the step of deriving includes-the step of combining signals indicative of the detected current and the detected voltage to produce the power signal indicative of the input power.

7. The method of claim **6**, wherein the step of combining includes:

multiplying the current signal with the voltage signal to produce the power signal indicative of the input power.

8. The method of claim **4**, wherein:

the power supply includes a transformer having a secondary winding coupled to the electrostatic precipitator; and

the step of measuring includes the step of detecting the first and second parameters of the input power at the secondary winding of the transformer.

9. The method of claim **4**, wherein:

the power supply includes a transformer having a primary winding coupled to a power source; and

the step of measuring includes the step of detecting the first and second parameters of the input power at the primary winding of the transformer.

10. A method of controlling a flue gas conditioning system including a source of a conditioning agent, means for adding the conditioning agent to a flue gas, an electrostatic precipitator for treating the flue gas and having a set of electrostatic elements which receive an input power, a power supply which operates in an intermittent energization mode to deliver the input power to the electrostatic precipitator, and a controller, for controlling the amount of the conditioning agent added to the flue gas, said method comprising the steps of:

measuring first and second parameters of the input power delivered to the electrostatic precipitator;

deriving a power signal indicative of the input power delivered to the electrostatic precipitator from the first and second parameters; and

controlling the amount of conditioning agent added to the flue gas according to the power signal;

wherein:

the input power includes energized and non-energized half-cycles;

the first and second parameters are current and voltage, respectively; and

the step of measuring includes the step of detecting a current flowing to the electrostatic precipitator during a plurality of the energized half-cycles of the input power and detecting a voltage developed across the electrostatic precipitator during the plurality of the energized half-cycles of the input power.

11. The method of claim **10**, wherein the step of detecting a current includes detecting one of the half-cycle RMS current, the peak current or the average current flowing to the electrostatic elements; and

the step of detecting a voltage includes detecting one of the peak voltage, the average voltage, the half-cycle RMS voltage or the minimum voltage developed across the electrostatic elements.

12. The method of claim **10**, wherein:

the step of deriving includes the step of combining signals indicative of the detected current and the detected voltage to produce the power signal indicative of the input power.

13. The method of claim **12**, wherein the step of combining includes:

multiplying the current signal with the voltage signal to produce the power signal indicative of the input power.

14. The method of claim **10**, wherein:

the power supply includes a transformer having a secondary winding coupled to the electrostatic precipitator; and

the step of measuring includes the step of detecting the first and second parameters of the input power at the secondary winding of the transformer.

15. The method of claim **10**, wherein:

the power supply includes a transformer having a primary winding coupled to a power source; and

the step of measuring includes the step of detecting the first and second parameters of the input power at the primary winding of the transformer.

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