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(54) **SYSTEMS AND METHODS FOR DETECTING DISCREPANCY IN A COMBUSTION SYSTEM**

(57) A combustion system having burner tip plugging indication, comprising: a burner having a burner tip; a fuel pressure sensor generating fuel pressure data of a fuel source input into the burner; a processor; and, memory operatively coupled to the processor storing a burner tip monitor as computer readable instructions that when executed by the processor operate to: generate a calculated fuel heat release of the burner by executing a fired-systems model of the burner based on fuel information, a fuel pressure, and burner geometry, and compare the calculated fuel heat release of the burner to a measured heat release to generate a burner tip health indication of the burner tip.

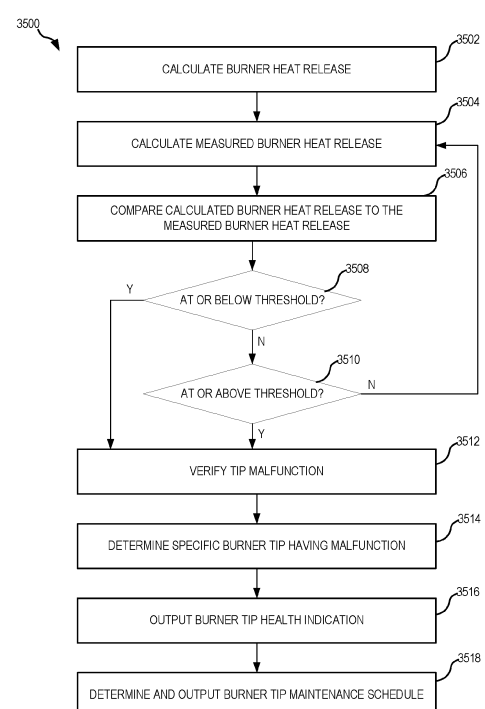


FIG. 35

Description

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application claims priority to, and benefits from each of: U.S. Provisional Application Serial No. 62/864,967, filed June 21, 2019, and U.S. Provisional Application Serial No. 62/864,997, filed June 21, 2019; and U.S. Provisional Application Serial No. 62/865,021, filed June 21, 2019. This application is also related to each of: U.S. Provisional Application Serial No. 62/864,954, filed June 21, 2019; U.S. Provisional Application Serial No. 62/864,992, filed June 21, 2019; U.S. Provisional Application Serial No. 62/865,007, filed June 21, 2019; and U.S. Provisional Application Serial No. 62/865,031, filed June 21, 2019. The entire contents of each of the aforementioned applications are incorporated herein as if fully set forth.

BACKGROUND

[0002] Combustion systems operate by converting fuel and air into thermal energy within a process heater. Downstream from this conversion location, various sensors operate to collect emissions and flue gas composition data such as Nitrous Oxide (NO_x), Oxygen (O₂), and Carbon Monoxide (CO). Many parameters are sensed by various sensors throughout the combustion system. Oxygen measurements, in particular, are indicative of the amount of air input into the system that is in excess of the required amount of air needed for the conversion of the fuel to thermal energy (stoichiometric air requirements). These oxygen measurements are used to control the input and ratio of fuel and air into the system. If these oxygen measurements are not correct, such as due to unwanted excess air entering the system at leaks in the system housing (sometimes referred to as tramp air), or extra fuel entering the system (via holes in the process tubes of the combustion system), or insufficient air being provided to the system (via malfunctioning or blocked air inlets at the burners), the control of the heater becomes inefficient and potentially unsafe.

[0003] Process heaters have multiple burners (sometimes up to 200+ burners per furnace) and each one has one or multiple burner tips, each configured to inject fuel according to a specific flow rate / pattern for combustion within the heater. Over time, these burner tips become clogged or begin to foul with "coke" and other material. This clogging (also known as plugging) causes the collective burner system to operate inefficiently. Additionally, plugged gas tips can cause an otherwise stable burner to lose its flame anchoring or relighting capability, causing substantial safety concerns if not maintained frequently or properly.

BRIEF DESCRIPTION OF THE FIGURES

[0004] The foregoing and other features and advantages

of the disclosure will be apparent from the more particular description of the embodiments, as illustrated in the accompanying drawings, in which like reference characters refer to the same parts throughout the different figures. The drawings are not necessarily to scale, emphasis instead being placed upon illustrating the principles of the disclosure.

Figure 1 depicts an example system of a process heater with automatic air register setting determination, in embodiments.

Figure 2 depicts a typical draft profile throughout a heater (e.g., the heater of Figure 1).

Figure 3 depicts a plurality of example process tube types.

Figure 4 depicts a diagram showing air temperature and humidity effects on sensed excess O₂ levels.

Figure 5 depicts a schematic of air and fuel mixture in a pre-mix burner, in embodiments.

Figure 6 depicts a schematic of air and fuel mixture in a diffusion burner, in embodiments.

Figure 7 depicts an example cutaway diagram of a burner, which is an example of the burner of Figure 1.

Figure 8 depicts an example air register handle and indicator plate 804 that is manually controlled.

Figure 9 depicts example burner tips with different shapes and sizes.

Figure 10 depicts example burner tips with the same shape, but different drill hole configurations.

Figure 11 depicts a block diagram of the process controller of Figure 1 in further detail, in embodiments.

Figures 12-16 depict various operating conditions result in sensed oxygen readings by the oxygen sensor of Figure 1 that cause incorrect control of the input fuel/air ratio to the burner of Figure 1, in examples.

Figure 17 depicts an air analyzer, which is an example of the air analyzer, of Figure 11, in an embodiment.

Figures 18 and 19 show example tramp air indicators, in embodiments (the cumulative difference between the calculated and the measured excess O₂).

Figure 20 depicts a method for determining air-flow discrepancy in a combustion system, in embodiments.

Figure 21 depicts an example of clogged fins on process tubes.

Figure 22 depicts an example draft analyzer including draft discrepancy identifier, in embodiments.

Figures 23-28 depict graphs indicating heater operation over time when the fins of process tubes become clogged due to harsh conditions in the heater, in an embodiment.

Figure 29 depicts data table represented by the graphs of Figures 23-28.

Figure 30 depicts a method for determining discrepancy in a combustion system, in embodiments.

Figure 31 depicts a burner having a burner tip that has completely failed, in an example.

Figure 32 depicts a fuel analyzer, which is an example of the fuel analyzer of Figure 11, in an embodiment.

Figure 33 depicts a comparison of a calculated heat release to a measured heat release.

Figure 34 depicts an example burner tip health indication in the form of a graph depicting the ratio of the measured heat release to the calculated heat release.

Figure 35 depicts a method for generating a combustion system burner tip health indication, in embodiments.

Figures 36 and 37 depict example data showing oxygen data used to verify that tip plugging was not occurring.

Figure 38 depicts a method for determining discrepancy in a combustion system, in embodiments.

DETAILED DESCRIPTION OF THE EMBODIMENTS

[0005] Figure 1 depicts an example system 100 of a process heater with intelligent monitoring system, in embodiments. The system 100 includes a heater 102 that is heated by one or more burners 104 located in the housing 103 thereof. Heater 102 can have any number of burners 104 therein, each operating under different operating conditions (as discussed in further detail below). Moreover, although Figure 1 shows a burner located on the floor of the heater 102, one or more burners may also be located on the walls and/or ceiling of the heater 102 without departing from the scope hereof (indeed, heaters in the industry often have over 100 burners). Further, the heater 102 may have different configurations, for example a box heater, a cylindrical heater, a cabin heater, and other shapes, sizes, etc. as known in the art.

[0006] Burner 104 provides heat necessary to perform chemical reactions or heat up process fluid in one or more process tubes 106 (not all of which are labeled in Figure 1. Any number of process tubes 106 may be located within the heater 102, and in any configuration (e.g., horizontal, vertical, curved, off-set, slanted, or any configuration thereof). Burner 104 is configured to combust a fuel source 108 with an oxidizer such as air input 110 to convert the chemical energy in the fuel into thermal energy 112 (e.g., a flame). This thermal energy 112 then radiates to the process tubes 106 and is transferred through the process tubes 106 into a material therein that is being processed. Accordingly, the heater 102 typically has a radiant section 113, a convection section 114, and a stack 116. Heat transfer from the thermal energy 112 to the process tubes 106 primarily occurs in the radiant section 113 and the convection section 114.

[0007] Airflow into the heater 102 (through the burner 104) typically occurs in one of four ways natural, induced, forced, and balanced.

[0008] A natural induced airflow draft occurs via a dif-

ference in density of the flue gas inside the heater 102 caused by the combustion. There are no fans associated in a natural induced system. However, the stack 116 includes a stack damper 118 and the burner includes a burner air register 120 that are adjustable to change the amount of naturally induced airflow draft within the heater 102.

[0009] An induced airflow draft system includes a stack fan (or blower) 122 located in the stack (or connected to the stack) 116. In other or additional embodiments, other motive forces than a fan are be used to create the induced draft, such as steam injection to educts flue gas flow through the heater. The stack fan 122 operates to pull air through the burner air register 120 creating the induced-draft airflow within the heater 102. The stack fan 122 operating parameters (such as the stack fan 122 speed and the stack damper 118 settings) and the burner air register 120 impact the draft airflow. The stack damper 118 may be a component of the stack fan 122, or separate therefrom.

[0010] A forced-draft system includes an air input forced fan 124 that forces air input 110 into the heater 102 via the burner 104. The forced fan 124 operating parameters (such as the forced fan 124 speed and the burner air register 120 settings) and the stack damper 118 impact the draft airflow. The burner air register 120 may be a component of the forced fan 124, but is commonly separate therefrom and a component of the burner 104.

[0011] A balanced-draft system includes both the air input forced fan 124 and the stack fan 122. Each fan 122, 124 operate in concert, along with the burner air register 120 and stack damper 118 to control the airflow and draft throughout the heater 102.

[0012] Draft throughout the heater 102 varies depending on the location within the heater 102. Figure 2 depicts a typical draft profile 200 throughout a heater (e.g., heater 102). Line 202 depicts a desired draft that is consistent with the design of the heater and components therein. Line 204 depicts a high draft situation where pressure in the heater is more negative than desired (and thus further negative compared to atmospheric pressure outside of the heater). Line 206 depicts a low draft situation where pressure in the heater is more positive than desired (and thus closer to or greater than atmospheric pressure outside of the heater). As shown, by line 202, heaters are often designed to have a -0.1 pressure at the arch of the heater.

[0013] Draft throughout the heater 102 is also be impacted based on the geometry of the heater and components thereon. For example, draft is strongly a function of heater 102 height. The taller the heater 102, the more negative the draft will be at the floor of the heater 102 to maintain the same draft level at the top of the heater 102 (normally -0.1 in H₂O). The components greatly impact the draft. For example, Figure 3 depicts a plurality of process tube types. The convection section process tubes 106 may or may not have heat sink fins thereon to man-

age the heat transfer from the thermal energy 112 to the process tube 106. These convection section fins may plug or corrode overtime-varying the required draft within a heater as compared to the designed draft for the same heater with the same components. As the convection section flue gas channel open area begins to decrease, a greater pressure differential is required to pull the same quantity of flue gas through the convection section.

[0014] Referring to Figure 1, pressure (indicating draft) within the heater 102 is measured at a variety of locations in the heater respectively via one of a plurality of pressure sensors. Floor pressure sensor 126(1) measures the pressure at the floor of the heater 102. Arch pressure sensor 126(2) measures the pressure at the arch of the heater 102 where the radiant section 113 transitions to the convection section 114. Convection pressure sensor 127 measures the pressure of the convection section 114. Stack pressure sensor 129, if included, measures the pressure of the stack 116.

[0015] The pressure sensors 126, 127, 129 may include a manometer, or a Magnehelic draft gauge, where the pressure readings are manually entered into process controller 128 (or a handheld computer and then transferred wirelessly or via wired connection from the handheld computer to the process controller 128) including a sensor database 130 therein storing data from various components associated with the heater 102. The pressure sensors 126, 127, 129 may also include electronic pressure sensors and/or draft transmitters that transmit the sensed pressure to the process controller 128 via a wired or wireless connection 133. The wireless or wired connection 133 may be any communication protocol, including WiFi, cellular, CAN bus, etc.

[0016] The process controller 128 is a distributed control system (DCS) (or plant control system (PLC) used to control various systems throughout the system 100, including fuel-side control (e.g., control of components associated with getting fuel source 108 into the heater 102 for combustion therein), air-side control (e.g., control of components associated with getting air source 110 into the heater 102), internal combustion-process control (e.g., components associated with managing production of the thermal energy 112, such as draft within the heater 102), and post-combustion control (e.g., components associated with managing the emissions after production of the thermal energy 112 through the stack 116). The process controller 128 typically includes many control loops, in which autonomous controllers are distributed throughout the system 100 (associated with individual or multiple components thereof), and including a central operator supervisory control.

[0017] Operating conditions within the heater 102 (such as draft, and the stoichiometry associated with creating the thermal energy 112) are further impacted via atmospheric conditions, such as wind, wind direction, humidity, ambient air temperature, sea level, etc. Figure 4 depicts a diagram 400 showing air temperature and humidity effects on sensed excess O₂ levels. The changes

in operating conditions are often controlled by monitoring and manipulating the draft conditions within the heater 102. The stack dampers 118 are commonly digitally controlled, and therefore often controllable from the operating room of the system 100, via the process controller 128. However, many systems do not include burner air registers 120 that are digitally controlled. Because of this, system operators often control draft within the heater 102 using just an electronic stack damper (e.g., stack damper 118) thereby avoiding timely and costly manual operation of each burner air register (e.g., burner air register 120) associated with each individual burner (e.g., burner 104). This cost grows depending on the number of burners located in each heater - each heater may have over 100 burners therein.

[0018] In addition to the draft as discussed above, burner geometry plays a critical role in managing the thermal energy 112 produced in the heater 102. Each burner 104 is configured to mix the fuel source 108 with the air source 110 to cause combustion and thereby create the thermal energy 112. Common burner types include pre-mix burners and diffusion burners. Figure 5 depicts a schematic 500 of air and fuel mixture in a pre-mix burner, in embodiments. In a pre-mix burner, kinetic energy of the fuel gas 502 draws some primary air 504 needed for combustion into the burner. The fuel and air mix to create an air/fuel mixture 504 having a specific air-to-fuel ratio prior to igniting to create the thermal energy 112. Figure 6 depicts a schematic 600 of air and fuel mixture in a diffusion burner, in embodiments. In a diffusion burner, air 604 for combustion is drawn (by induced- or natural-draft) or pushed (by forced-, or balanced-draft) into the heater before mixing with the fuel 602. The mixture burns at the burner gas tip 606.

[0019] Figure 7 depicts an example cutaway diagram of a burner 700, which is an example of the burner 104 of Figure 1. Burner 700 is an example of a diffusion burner. Burner 700 is shown located mounted in a heater at the heater floor 702. Proximate the burner 700 in the heater floor 702 is a manometer 704, which is an example of the pressure sensors 126, 127, 129 discussed above. The manometer 704 may be another type of pressure sensor without departing from the scope hereof. Burner 700 is shown for a natural or induced-draft heater system, and includes a muffler 706 and a burner air register 708. Ambient air flows through the muffler 706 from outside the heater system. In a forced or balanced-draft system, the muffler 706 may not be included and instead be replaced with an intake ducting from the forced fan (e.g., forced fan 124 in Figure 1). The burner air register 708 is an example of the burner air register 120 discussed above with respect to Figure 1, and may be manipulated via an air register handle 710 to one of a plurality of settings defining how open or closed the air register 708 is. As discussed above, the air register handle 710 is typically manually controlled (although sometimes is fitted with an actuator, or provided with mechanical linkage and an actuator so a single actuator manipulates a plurality

of burners). Figure 8 depicts an example air register handle 802 and indicator plate 804 that is manually controlled. The input air then travels through the burner plenum 712 towards the burner output 714 where it is mixed with input fuel and ignited to combust and produce thermal energy (e.g., thermal energy 112 of Figure 1).

[0020] The fuel travels through a fuel line 716, and is output at a burner tip 718. The fuel may be disbursed on a deflector 720. The burner tip 718 and deflector 720 may be configured with a variety of shapes, sizes, fuel injection holes, etc. to achieve the desired combustion results (e.g., flame shaping, emissions tuning, etc.). Figure 9 depicts example burner tips with different shapes and sizes. Figure 10 depicts example burner tips with the same shape, but different drill hole configurations. Furthermore, one or more tiles 722 may be included at the burner output 714 to achieve a desired flame shape or other characteristic.

[0021] Referring to Figure 1, control of the system 100 occurs both manually and digitally. As discussed above, various components, such as burner air register 120 are commonly manually controlled. However, the system 100 also includes a variety of sensors throughout the heater 102, the fuel-side input, and the air-side input used to monitor and control the system using the process controller 128.

[0022] At the stack 116, an oxygen sensor 132, a carbon monoxide sensor 134, and NO_x sensor 136 can be utilized to monitor the condition of the exhaust and emissions leaving the heater 102 via the stack 116. Each of the oxygen sensor 132, carbon monoxide sensor 134, and NO_x sensor 136 may be separate sensors, or part of a single gas-analysis system. The oxygen sensor 132, carbon monoxide sensor 134, and NO_x sensor 136 are each operatively coupled to the process controller 128 via a wired or wireless communication link. These sensors indicate the state of combustion in the heater 102 in substantially real-time. Data captured by these sensors is transmitted to the process controller 128 and stored in the sensor database 130. By monitoring the combustion process represented by at least one of the oxygen sensor 132, carbon monoxide sensor 134, and NO_x sensor 136, the system operator may adjust the process and combustion to stabilize the heater 102, improve efficiency, and/or reduce emissions. In some examples, other sensors, not shown, can be included to monitor other emissions (e.g., combustibles, methane, sulfur dioxide, particulates, carbon dioxide, etc.) on a real-time basis to comply with environmental regulations and/or add constraints to the operation of the process system. Further, although the oxygen sensor 132, carbon monoxide sensor 134, and NO_x sensor 136 are shown in the stack 116, there may be additional oxygen sensor(s), carbon monoxide sensor(s), and NO_x sensor(s) located elsewhere in the heater 102, such as at one or more of the convection section 114, radiant section 113, and/or arch of the heater 102. The above discussed sensors in the stack section may include a flue gas analyzer (not shown) prior

to transmission to the process controller 128 that extract, or otherwise test, a sample of the emitted gas within the stack 116 (or other section of the heater) and perform an analysis on the sample to determine the associated oxygen, carbon monoxide, or NO_x levels in the sample (or other analyzed gas). Other types of sensors include tunable laser diode absorption spectroscopy (TDLAS) systems that determine the chemical composition of the gas based on laser spectroscopy.

[0023] Flue gas temperature may also be monitored by the process controller 128. To monitor the flue gas temperatures, the heater 102 may include one or more of a stack temperature sensor 138, a convection sensor temperature sensor 140, and a radiant temperature sensor 142 that are operatively coupled to the process controller 128. Data from the temperature sensors 138, 140, 142 are transmitted to the process controller 128 and stored in the sensor database 130. Further, each section may have a plurality of temperature sensors-in the example of Figure 1, there are three radiant section temperature sensors 142(1)-(3). The above discussed temperature sensors may include a thermocouple, suction pyrometer, and/or laser spectroscopy analysis systems that determine the temperature associated with the given temperature sensor.

[0024] The process controller 128 may further monitor air-side measurements and control airflow into the burner 104 and heater 102. Air-side measurement devices include an air temperature sensor 144, an air-humidity sensor 146, a pre-burner air register air pressure sensor 148, and a post-burner air register air pressure sensor 150. In embodiments, the post-burner air pressure is determined based on monitoring excess oxygen readings in the heater 102. The air-side measurement devices are coupled within or to the air-side ductwork 151 to measure characteristics of the air flowing into the burner 104 and heater 102. The air-temperature sensor 144 may be configured to sense ambient air temperatures, particularly for natural and induced-draft systems. The air-temperature sensor 144 may also be configured to detect air temperature just prior to entering the burner 104 such that any pre-heated air from an air-preheat system is taken into consideration by the process controller 128. The air-temperature sensor 144 may be a thermocouple, suction pyrometer, or any other temperature measuring device known in the art. The air humidity sensor 146 may be a component of the air temperature sensor, or may be separate therefrom, and is configured to sense the humidity in the air entering the burner 104. The air temperature sensor 144 and air humidity sensor 146 may be located upstream or downstream from the burner air register 120 without departing from the scope hereof. The pre-burner air register air pressure sensor 148 is configured to determine the air pressure before the burner air register 120. The post-burner air register air pressure sensor 150 is configured to determine the air pressure after the burner air register 120. The post-burner air register air pressure sensor 150 may not be a sensor measuring the fur-

nance draft at the burner elevation, or other elevation and then calculated to determine the furnace draft at the burner elevation. Comparisons between the post-burner air register air pressure sensor 150 and the pre-burner air register air pressure sensor 148 may be made by the process controller to determine the pressure drop across the burner 104, particularly in a forced-draft or balanced-draft system. Air-side and temperature measurements discussed herein may further be measured using one or more TDLAS devices 147 located within the heater 102 (at any of the radiant section 113, convection section 114, and/or stack 116).

[0025] Burner 104 operational parameters may further be monitored using a flame scanner 149. Flame scanners 149 operate to analyze frequency oscillations in ultraviolet and/or infrared wavelengths of one or both of the main burner flame or the burner pilot light.

[0026] Figure 1 also shows an air handling damper 152 that is located prior to the burner air register 120. The air-handling damper 152 includes any damper that impacts air-flow into the heater 102, such as a duct damper, variable speed fan, fixed-speed fan with air throttling damper, etc.) In certain system configurations, a single air input (including a given fan 124) supplies air to a plurality of burners, or a plurality of zones within a given heater. There may be any number of fans (e.g., forced fan 124), temperature sensors (e.g., air temperature sensor 144), air humidity sensors (e.g., air humidity sensor 146), air pressure sensors (e.g., pre-burner air register air pressure sensor 148) for a given configuration. Further, any of these air-side sensors maybe located upstream or downstream from the air handling damper 152 without departing from the scope hereof.

[0027] The process controller 128 may further monitor fuel-side measurements and control fuel flow into the burner 104. Fuel-side measurement devices include one or more of flow sensor 154, fuel temperature sensor 156, and fuel-pressure sensor 158. The fuel-side measurement devices are coupled within or to the fuel supply line(s) 160 to measure characteristics of the fuel flowing into the burner 104. The flow sensor 154 may be configured to sense flow of the fuel through the fuel supply line 160. The fuel-temperature sensor 156 detects fuel temperature in the fuel supply line 160, and includes known temperature sensors such as a thermocouple. The fuel-pressure sensor 158 detects fuel-pressure in the fuel supply line 160.

[0028] The fuel line(s) 160 may have a plurality of fuel control valves 162 located thereon. These fuel control valves 162 operate to control the flow of fuel through the supply lines 160. The fuel control valves 162 are typically digitally controlled via control signals generated by the process controller 128. Figure 1 shows a first fuel control valve 162(1) and a second fuel control valve 162(2). The first fuel control valve 162(1) controls fuel being supplied to all burners located in the heater 102. The second fuel control valve 162(2) controls fuel being supplied to each individual burner 104 (or a grouping of burners in each

heater zone). There may be more or fewer fuel control valves 162 without departing from the scope hereof. Further, as shown, there may be a grouping of fuel-side measurement devices between individual components on the fuel supply line 160. For example, a first flow sensor 154(1), first fuel temperature sensor 156(1), and first fuel-pressure sensor 158(1) are located on the fuel supply line 160 between the fuel source 108 and the first fuel control valve 162(1). A second flow sensor 154(2), second fuel temperature sensor 156(2), and second fuel-pressure sensor 158(2) are located on the fuel supply line 160 between the first fuel control valve 162(1) and the second fuel control valve 162(2). Additionally, a third flow sensor 154(3), third fuel temperature sensor 156(3), and third fuel-pressure sensor 158(3) are located on the fuel supply line 160 between the second fuel control valve 162(2) and the burner 104. The third fuel temperature sensor 156(3), and third fuel-pressure sensor 158(3) may be configured to determine flow, temperature, and pressure respectively of an air/fuel mixture for pre-mix burners discussed above with respect to Figure 5.

[0029] The process controller 128 may also measure process-side temperatures associated with the processes occurring within the process tubes 106. For example, system 100 may further include one or more tube temperature sensors 168, such as a thermocouple, that monitor the temperature of the process tubes 106. The temperature sensor 168 may also be implemented using optical scanning technologies, such as an IR camera, and/or one of the TDLAS devices 147. Furthermore, the heater controller 128 may also receive sensed outlet temperature of the fluid within the process tubes 106 from process outlet temperature sensor (not shown), such as a thermocouple. The process controller 128 may then use these sensed temperatures (from the tube temperature sensors 168 and/or the outlet temperature sensor) to control firing rate of the burners 104 to increase or decrease the generated thermal energy 112 to achieve a desired process temperature.

[0030] Figure 11 depicts a block diagram of the process controller 128 of Figure 1 in further detail, in embodiments. The process controller 128 includes a processor 1102 communicatively coupled with memory 1104. The processor 1102 may include a single processing device or a plurality of processing devices operating in concert. The memory 1104 may include transitory and or non-transitory memory that is volatile and/or non-volatile.

[0031] The process controller 128 may further include communication circuitry 1106 and a display 1108. The communication circuitry 1106 includes wired or wireless communication protocols known in the art configured to receive and transmit data from and to components of the system 100. The display 1108 may be co-located with the process controller 128, or may be remote therefrom and displays data about the operating conditions of the heater 102 as discussed in further detail below.

[0032] Memory 1104 stores the sensor database 130 discussed above, which includes any one or more of fuel

data 1110, air data 1118, heater data 1126, emissions data 1140, process-side data 1170, and any combination thereof. In embodiments, the sensor database 130 includes fuel data 1110. The fuel data 1110 includes fuel flow 1112, fuel temperature 1114, and fuel-pressure 1116 readings throughout the system 100 regarding the fuel being supplied to the burner 104. For example, the fuel flow data 1112 includes sensed readings from any one or more of the flow sensor(s) 154 in system 100 transmitted to the process controller 128. The fuel temperature data 1114 includes sensed readings from any one or more of the fuel temperature sensor(s) 156 in system 100 transmitted to the process controller 128. The fuel-pressure data 1116 includes sensed readings from any one or more of the fuel-pressure sensor(s) 158 in system 100 transmitted to the process controller 128. In embodiments, the fuel data 1110 may further include fuel composition information that is either sensed via a sensor located at the fuel source 108 or that is determined based on an inferred fuel composition such as that discussed in U.S. Provisional Patent Application No. 62/864,954, filed June 21, 2019 and which is incorporated by reference herein as if fully set forth. The fuel data 1110 may also include data regarding other fuel-side sensors not necessarily shown in Figure 1, but known in the art.

[0033] In embodiments, the sensor database 130 includes air data 1118 regarding the air being supplied to the burner 104 and heater 102. The air data 1118 includes air temperature data 1120, air humidity data 1122, and air pressure data 1124. The air temperature data 1120 includes sensed readings from any one or more of the air temperature sensor(s) 144 in system 100 transmitted to the process controller 128. The air humidity data 1122 includes sensed readings from any one or more of the air humidity sensor(s) 146 in system 100, and/or data from local weather servers, transmitted to the process controller 128. The air pressure data 1124 includes sensed readings from any one or more of the pre-burner air register air pressure sensor 148, and a post-burner air register air pressure sensor 150 (or any other air pressure sensor) in system 100 transmitted to the process controller 128. The air data 1118 may also include data regarding other air-side sensors not necessarily shown in Figure 1, but known in the art.

[0034] In embodiments, the sensor database 130 includes heater data 1126. The heater data 1126 includes radiant-section temperature data 1128, convection-section temperature data 1130, stack-section temperature data 1132, radiant-section pressure data 1134, convection-section pressure data 1136, and stack-section pressure data 1138. The radiant-section temperature data 1128 includes sensed readings from the radiant temperature sensor(s) 142 of system 100 that are transmitted to the process controller 128. The convection-section temperature data 1130 includes sensed readings from the convection temperature sensor(s) 140 of system 100 that are transmitted to the process controller 128. The stack-section temperature data 1132 includes sensed

readings from the stack temperature sensor(s) 138 of system 100 that are transmitted to the process controller 128. The radiant-section pressure data 1134 includes sensed readings from the radiant pressure sensor(s) 126 of system 100 that are transmitted to the process controller 128. The convection-section pressure data 1136 includes sensed readings from the convection pressure sensor(s) 127 of system 100 that are transmitted to the process controller 128. The stack-section pressure data 1136 includes sensed readings from the stack pressure sensor(s) 129 of system 100 that are transmitted to the process controller 128. The heater data 1126 may also include data regarding other heater sensors not necessarily shown in Figure 1, but known in the art.

[0035] In embodiments, the sensor database 130 further includes emissions data 1140. The emissions data 1140 includes O₂ reading(s) 1142, CO reading(s) 1144, and NO_x reading(s) 1146. The O₂ reading(s) 1142 include sensed readings from the oxygen sensor 132 transmitted to the process controller 128. The CO reading(s) 1144 include sensed readings from the carbon monoxide sensor 134 transmitted to the process controller 128. The NO_x reading(s) 1146 include sensed readings from the NO_x sensor 136 transmitted to the process controller 128. The emissions data 1140 may also include data regarding other emissions sensors not necessarily shown in Figure 1, but known in the art.

[0036] In embodiments, the sensor database 130 includes process-side data 1170 regarding the conditions of the process tubes 106 and the process occurring. The process-side data 1170 includes process tube temperature 1172, and the outlet fluid temperature 1174. The process tube temperature 1172 may include data captured by the process tube temperature sensor 168, discussed above. The outlet fluid temperature 1174 may include data captured by an outlet fluid sensor (not shown), such as a thermocouple. The process-side data 1170 may also include data regarding other process-side sensors not necessarily shown in Figure 1, but known in the art.

[0037] Data within the sensor database 130 is indexed according to the sensor providing said readings. Accordingly, data within the sensor database 130 may be used to provide real-time operating conditions of the system 100.

[0038] The memory 1104, in embodiments, further includes one or more of a fuel analyzer 1148, an air analyzer 1150, a draft analyzer 1152, an emissions analyzer 1154, a process-side analyzer 1176, and any combination thereof. Each of the fuel analyzer 1148, air analyzer 1150, draft analyzer 1152, emissions analyzer 1154, and process-side analyzer 1176 comprise machine readable instructions that when executed by the processor 1102 operate to perform the functionality associated with each respective analyzer discussed herein. Each of the fuel analyzer 1148, air analyzer 1150, draft analyzer 1152, emissions analyzer 1154, and process-side analyzer 1176 may be executed in serial or parallel to one another.

[0039] The fuel analyzer 1148 operates to compare the fuel data 1110 against one or more fuel alarm thresholds 1156. One common fuel alarm threshold 1156 includes fuel-pressure threshold that sets a safe operation under normal operating condition without causing nuisance shutdowns of the system 100 due to improperly functioning burner 104 caused by excess or low fuel-pressure. The fuel alarm thresholds 1156 are typically set during design of the system 100. The fuel analyzer 1148 may analyze other data within the sensor database 130 not included in the fuel data 1110, such as any one or more of air data 1118, heater data 1126, emissions data 1140, process-side data 1170, and any combination thereof to ensure there is appropriate air to fuel ratio within the heater to achieve the stoichiometric conditions for appropriate generation of the thermal energy 112.

[0040] The air analyzer 1150 operates to compare the air data 1118 against one or more air alarm thresholds 1158. One common air alarm threshold 1158 includes fan operating threshold that sets a safe operation condition of the forced fan 124 and/or stack fan 122 under normal operating condition without causing nuisance shutdowns of the system 100 due to improper draft within the heater 102 caused by excess or low air pressure throughout the system 100. The air alarm thresholds 1158 are typically set during design of the system 100. The air analyzer 1150 may analyze other data within the sensor database 130 not included in the air data 1118, such as any one or more of fuel data 1110, heater data 1126, emissions data 1140, process-side data 1170, and any combination thereof to ensure there is appropriate air to fuel ratio within the heater to achieve the stoichiometric conditions for appropriate generation of the thermal energy 112.

[0041] The draft analyzer 1152 operates to compare the heater data 1126 against one or more draft alarm thresholds 1160. One common draft alarm threshold 1160 includes heater pressure threshold that sets safe operation conditions of the heater 102 under normal operating condition without causing nuisance shutdowns or dangerous conditions of the system 100 due to positive pressure within the heater 102 (such as at the arch of the heater 102). The draft alarm thresholds 1160 are typically set during design of the system 100. The draft analyzer 1152 may analyze other data within the sensor database 130 not included in the heater data 1126, such as any one or more of fuel data 1110, air data 1118, emissions data 1140, process-side data 1170, and any combination thereof to ensure there is appropriate operating conditions within the heater 102 to achieve the stoichiometric conditions for appropriate generation of the thermal energy 112.

[0042] The emissions analyzer 1154 operates to compare the emissions data 1140 against one or more emission alarm thresholds 1162. One emissions alarm threshold 1162 include a minimum and maximum excess oxygen level that sets safe operation conditions of the heater 102 under normal operating condition without causing

nuisance shutdowns or dangerous conditions of the system 100 due to too little or too much oxygen within the heater 102 during creation of the thermal energy 112. Other emission alarm thresholds 1162 include pollution limits set by environmental guidelines associated with the location in which system 100 is installed. The emission alarm thresholds 1162 are typically set during design of the system 100. The emissions analyzer 1154 may analyze other data within the sensor database 130 not included in the emissions data 1140, such as any one or more of fuel data 1110, air data 1118, heater data 1126, process-side data 1170, and any combination thereof to ensure there is appropriate operating conditions within the heater 102 to achieve the stoichiometric conditions for appropriate generation of the thermal energy 112.

[0043] The process-side analyzer 1176 operates to compare the process-side data 1170 against one or more process thresholds 1178. One common process threshold 1178 includes a desired outlet temperature to achieve efficient process conversion in the process tubes 106. Another example process threshold 1178 includes a maximum temperature threshold of the process tube 106 at which the process tube 106 is unlikely to fail. The process-side analyzer 1176 may analyze other data within the sensor database 130 not included in the process-side data 1170, such as any one or more of fuel data 1110, air-data 1118, heater data 1126, emissions data 1140, and any combination thereof to ensure there is appropriate air to fuel ratio within the heater to achieve the stoichiometric conditions for appropriate generation of the thermal energy 112.

[0044] The fuel threshold 1156, air threshold 1158, draft threshold 1160, emissions threshold 162 and process threshold 1178, and any other thresholds discussed herein may differ from system to system. They may be based on the amount of deviation from an expected value that an operator is willing to allow. The thresholds discussed herein may be set based on sensor and other hardware error tolerances. The thresholds discussed herein may be set based on regulations allowing certain tolerances for emissions or other operating conditions. The thresholds discussed herein may be set according to safety conditions for operating the heater 102.

[0045] The thresholds may also be set based on an uncertainty associated with calculated or predicted values, such as an artificial intelligence engine uncertainty. In such embodiments, the systems and methods herein may accommodate error ranges to provide a confidence region around the output of an expected value that is then compared to sensed values to trigger one or more of the control signals 1164, alarms 1166 and/or displayed operating conditions 1168 when the sensed value deviates from the expected value past one or more of the fuel threshold 1156, air threshold 1158, draft threshold 1160, emissions threshold 162 and process threshold 1178. The sensors used to capture sensed data (e.g., the real-time sensed data and/or historical data of the system) may not be entirely accurate resulting in a sensor-based

calculation uncertainty value. The sensor-based calculation uncertainty value is typically a fixed percentage that can change based on a calculated value (e.g., sensors are X% efficient when measuring temperatures across a first range, and Y% efficient across a second range). Similarly, the artificial intelligence engine may have an AI uncertainty that varies based on given inputs to the artificial intelligence engine. The AI engine, for example, models historical combined data distributions and analyzes statistical deviations of the current distribution on a scale of 0 to 100%. The confidence region allows a given prediction by the physics-based calculations and/or the AI-based engine to accommodate variances in the associated data. The confidence region may be calculated based on a predicted value plus or minus an uncertainty value based on one or both of the sensor-based calculation uncertainty value and/or the AI-engine uncertainty. The uncertainty value may be, for example, the sum of the sensor-based calculation uncertainty value and/or the AI-engine uncertainty. The uncertainty value may be, for example, the square root of the sensor-based calculation uncertainty, squared, plus the AI-engine uncertainty, squared. Use of an uncertainty value when comparing sensed and expected/predicted/calculated values prevents false identifications of conditions within the process heater 102 in the system. Use of a confidence region based on an uncertainty value as discussed above may apply to any one or more of the "expected", "modeled", "predicted", "calculated" values or the like discussed in this application.

[0046] The fuel analyzer 1148, the air analyzer 1150, the draft analyzer 1152, the emissions analyzer 1154, and the process-side analyzer 1176 operate to create one or more of control signals 1164, alarms 1166, and displayed operating conditions 1168. The control signals 1164 include signals transmitted from the process controller 128 to one or more components of the system 100, such as the dampers 118, air registers 120 (if electrically controlled), fans 122, 124, and valves 162. The alarms 1166 include audible, tactile, and visual alarms that are generated in response to tripping of one or more of the fuel alarm threshold 1156, air alarm threshold 1158, draft alarm threshold 1160, and emission alarm threshold 1162. The displayed operating conditions 1168 include information that is displayed on the display 1108 regarding the data within the sensor database 130 and the operating conditions analyzed by one or more of the fuel analyzer 1148, air analyzer 1150, draft analyzer 1152, emissions analyzer 1154, and process-side analyzer 1176.

[0047] Referring to Figure 1, one or more of the fuel analyzer 1148, the air analyzer 1150, the draft analyzer 1152, the emissions analyzer 1154 and the process-side analyzer 1176 may be entirely or partially implemented on an external server 164. The external server 164 may receive some or all of the data within the sensor database 130 and implement specific algorithms within each of the fuel analyzer 1148, the air analyzer 1150, the draft ana-

lyzer 1152, the emissions analyzer 1154 and the process-side analyzer 1176. In response, the external server 164 may transmit one or more of the control signals 1164, the alarms 1166, and/or the displayed operating conditions 1168 back to the process controller 128.

Determination of Airflow Discrepancy in a Combustion System

[0048] When unwanted excess air (also referred to as tramp air) enters the heater 102, the excess oxygen level sensed by the oxygen sensor 132 increases. Air is "unwanted" in that it is not expected during control of the system—all burners are controlled to have at least some amount of excess air to drive a desired amount of excess oxygen at the stack while maintaining safe and stoichiometric conditions for combustion. Conversely, the oxygen level sensed by the oxygen sensor 132 may lower for a variety of reasons such as: additional fuel entering the system (e.g., via a leak in the process tubes 106 causing excess material to enter the heater housing 102); when a burner air register is not moving when actuated; when something—e.g., debris, insulation, etc.—is blocking the air input at one or more burners 104, ambient air inlet blocked via insects and/or birds' nests, heater insulation falling into the burner 104 throat, etc.).

[0049] Figures 12-16 depict various operating conditions result in sensed oxygen readings by the oxygen sensor 132 that cause incorrect control of the input fuel/air ratio to the burner 104, in examples. Figure 12 shows a tile 1202 fallen from the interior of the housing and blocking air input to a burner. Figure 13 depicts one pin-hole that causes excess fuel to enter into the system for example as shown in the infrared image of Figure 14. Figure 15 shows a blown-open process tube 1502 causing significant release of fuel into the system as shown in Figure 16. The polished look 1504 of the tubes adjacent the failed process tube 1502 in Figure 15 indicates flame impingement causing inefficient or improper heating conditions within the process tube, which was likely the cause of the tube failure.

[0050] Significant excess air within the heater 102 or not enough air within the heater 102 causes an unbalanced stoichiometric condition for generating the thermal energy 112, thereby resulting in unfavorable (and often unsafe) operating conditions. Typically, the oxygen sensor output is trusted by operations personnel to be the primary indication that there is sufficient and proper air for combustion to occur safely. Currently, there are limited options for ensuring that the measured excess oxygen in the system is coming through the burners as designed. Visual analysis by a human operator is frequently required to check for conditions in the heater that may indicate excess or insufficient air. When there is excess tramp air in the system, if the operator is unaware and controlling based on the sensed oxygen levels by the oxygen sensor 132, the operator and/or heater controller 128, often reduces the input air to the burner because

the global oxygen sensor 132 indicates there is too much air. Thus, the flames (e.g., thermal energy 112) from the burner 104 may extend too far from the burner 104 because the oxygen in the excess tramp air is being used to burn the extra fuel (because the controlled input fuel/air ratio is too high). These extended flames cause the process tubes 106 in the system to heat improperly resulting in inefficient or dangerous operation. Blocked input air in the system (see Figure 12), or excess fuel in the system (see Figures 13-16) causes the operator or control system to increase the air flow through the burners, in attempts to raise the measured excess O₂. In doing so, the burner air fuel ratio will be unintentionally driven to a fuel lean condition (more excess air going through the burners than is being measured), which can result in unstable burners which is also dangerous and/or inefficient condition.

[0051] Figure 17 depicts an air analyzer 1700, which is an example of the air analyzer 1150, of Figure 11, in an embodiment. Air analyzer 1700 includes an air-flow discrepancy analyzer 1702. Air-flow discrepancy analyzer 1702 includes computer readable instructions that when executed by a processor (e.g., processor 1102), operate to identify air-flow discrepancy and output a remediation action 1704 based on the identified discrepancy.

[0052] In embodiments, to identify air-flow discrepancy, the air-flow discrepancy analyzer 1702 compares an expected oxygen level 1706 against a sensed oxygen level 1708. The expected oxygen level 1706 is determined by the air-flow discrepancy analyzer 1702 by performing physics-based modeling according to the measured operating parameters 1710 regarding operation within the heater 102 to generate a fired-systems model 1705. The measured operating parameters 1710 may include the firing rate of each burner 104, and a measured (e.g., as sensed by an air-flow sensor) or calculated air flow through each burner 104. The air flow through each burner may be calculated using the fired-systems model 1705 based on physics-based modeling that analyzes the operating parameters 1710 such as the draft within the heater 102 to determine a burner pressure drop, and use this variable in combination with one or more of the stack damper 118 setting, burner air register 120 setting, stack fan setting 122, forced fan setting 124, fuel control valve 162 settings, ambient air information etc. to determine the expected air flow rate through each burner. Using these expected air flow rates per burner and the measured or calculated heat release, the air-flow discrepancy analyzer 1702 executes a combustion chemistry calculation to determine what the expected cumulative oxygen levels would be at the location of the oxygen sensor 132. Combustion chemistry calculations may include, but are not limited to, those described in chapter 4 of the "John Zink Hamworthy Combustion Handbook", which is incorporated by reference in its entirety (Baukal, Charles E. The John Zink Hamworthy Combustion Handbook. Fundamentals. 2nd ed., vol. 1 of 3, CRC Press,

2013).

[0053] The physics modeling used to solve the fired-systems model 1705 may further be based on other information of the system 100 (such as one or more of fuel information 1712, heater geometry 1714, air-flow ductwork geometry 1716, and burner geometry 1718, weather information 1720, and any combination thereof). The fuel information 1712 includes the fuel composition that is either sensed, or inferred as discussed above, and may also include other information such as expected fuel temperature and other data within fuel data 1110. The heater geometry 1714 indicates the shape and dimensions of the heater 102. The heater geometry 1714 (such as the shape and height) of the heater housing plays an important role in defining how the draft within the heater will travel through the heater. This affects how the air will be input and output from the system through convection influenced by the draft. The heater geometry 1714 may include process tube geometry defining the orientation of the process tubes (e.g., tubes 106), as well as size, shape, etc. such as shown in Figure 3, above. As discussed above, the characteristics of the process tubes may influence the draft in the heater and thus influence the air-flow throughout the system 100 and available air-flow from each burner 104 therein. The air-flow ductwork geometry 1716 includes the geometry of the airflow ductwork (e.g., ductwork 151) throughout the system 100. This includes any air handling register (e.g., air handling register 152), the air-flow zones, and the geometry of each of the above. The burner geometry 1718 includes the number, location, and physical geometry of the burners, the burner zones within the heater, as well as burner settings for each burner, such as the controllable range of the burner air register (e.g., burner air register 120) such as the controllable range shown on indicator plate 804 in Figure 8. The weather information 1720 may be received at the fuel analyzer 1300 from a weather server, or generated on site using one or more sensors (e.g., precipitation, humidity, barometric, and/or temperature sensors at the heater 102).

[0054] The fired-systems model 1705 may be for an entire combustion system (e.g., from the air-input and the fuel-input through the exit of the stack), or may be for one or more specific components within a given combustion system (such as one or more of a burner model, an air ductwork model, a model of draft within the heater, a model of heat transfer surrounding process tubes, etc.). The fired-systems model 1705 model may be based on any one or more of combustion chemistry, combustion kinetics, air and fuel fluid dynamics, heat transfer, process side modeling, computational fluid dynamics modeling, and other various types of combustion modeling. The fired-systems model 1705 may account for various system constraints and operational characteristics and real-time changes of the system during use of the system (for example, the burner tips can develop coke therein that blocks the drilled holes causing the burners to operate slightly different than designed).

[0055] The sensed oxygen level 1708 may include the O₂ reading(s) 1142 sensed by the oxygen sensor(s) 132.

[0056] In embodiments, the sensed oxygen level 1708 includes a plurality of sensed oxygen levels at a plurality of locations within the heater 102. For example, the plurality of locations may include a plurality of heights within the heater 102. As another example, the plurality of locations may include a plurality of horizontal locations at a similar height, such as at a plurality of locations of the radiant section 113 of the heater 102. The expected oxygen level 1706 is then determined (using the physics and chemistry based models of the fired-systems model 1705) at each of the plurality of locations within the heater 102 such that individual sensed oxygen levels 1708 at each location is compared by the air-flow discrepancy analyzer 1702 to an expected oxygen level 1706 corresponding to that location. Analyzing a plurality of locations accommodates the realization that global oxygen readings are impacted by a variety of combustion conditions (such as tramp-air and/or excess fuel entering the heater 102). Thus, a global oxygen reading may indicate no discrepancy, or indicate a false or inaccurate discrepancy, where excess oxygen due to an amount of excess air (tramp-air) entering the heater 102 at one location is cancelled out, or otherwise compensated for, by additional fuel entering the heater 102 (and thus burning additional oxygen) at the same or other location of the heater 102.

[0057] When the sensed oxygen level 1708 is above the expected oxygen level 1706, the air-flow discrepancy analyzer 1702 generates an unwanted excess air quantifier 1722 (which may be a part of or separate from the remediation action 1704). The unwanted excess air quantifier 1722 is a display of the air leakage based on the delta between the expected oxygen level 1706 and the sensed oxygen level 1708. The unwanted excess air quantifier 1722 may be displayed in mass or volume per time, such as kg/seconds. Figures 18 and 19 show example unwanted excess air quantifier 1722, in embodiments.

[0058] In embodiments, the unwanted excess air quantifier 1722 indicates excess air in terms of leakage area 1724, such as square inches. This provides the advantage that operators may search for openings in the heater 102 that match, or approximately match, the area indicated. The leakage area 1724 may be determined based on the delta between the expected oxygen level 1706 and the sensed oxygen level 1708 and the sensed draft within the heater 102 as identified via in-heater air data 1726 (which is similar to the heater data 1126 discussed above).

[0059] Indeed, in some embodiments, the air-flow discrepancy analyzer 1702 compares the identified leakage area 1724 against a database of known components 1728 of the heater 102, such as input/output pipes that pass through the wall of the heater 102, access windows, and other potential leakage points of the heater 102. Accordingly, the unwanted excess air quantifier 1722

(and/or the remediation action 1704) may define a list of potential components 1730 of the known components 1728 that match, or match within an area-threshold 1732, the leakage area 1724. If no known components 1728 match, the unwanted excess air quantifier 1722 (and/or the remediation action 1704) indicates the identified leakage area 1724 such that an operator may perform a manual scan to identify potential holes in the heater 102 matching said area.

[0060] In embodiments, the unwanted excess air quantifier 1722 indicates an approximate location of the leak based on a correlation of the height at which the sensed oxygen level 1708 becomes above the expected oxygen level 1706. As discussed above, in certain embodiments, the oxygen level is sensed at a plurality of heights. Because the draft within the heater 102 creates a flow of air, excess air entering the heater 102 may not cause the sensed oxygen level 1708 to differ substantially from the expected oxygen level 1706 below the location of the leak.

[0061] In certain embodiments, the air-flow discrepancy analyzer 1702 may identify location of the tramp-air leak based on an optical scan data 1734 to further to pinpoint the cause of such discrepancy. In embodiments, the optical scan data 1734 includes data captured by one or more of the TDLAS devices 147, discussed above. Additionally, or alternatively, the optical scan data 1734 may include a visual, infrared, and/or ultraviolet wavelength data captured by one or more cameras within the heater 102. Knowledge of the field of view, or scanning path, of the optical device used to generate the optical scan data 1734 allows the air-flow discrepancy analyzer 1702 to correlate the field of view, or scanning path, to a specific location within the heater 102 and therefore provide the remediation action 1704 accordingly. The optical scan data 1734 may indicate tramp-air leak because the temperature is lower in the heater 102 at the location of the tramp-air leak.

[0062] In certain embodiments, when the sensed oxygen level 1708 is below the expected oxygen level 1706, the air-flow discrepancy analyzer 1702 may analyze the optical scan data 1734 to further to pinpoint the cause of such discrepancy. Knowledge of the field of view, or scanning path, of the optical device used to generate the optical scan data 1734 allows the air-flow discrepancy analyzer 1702 to correlate the field of view, or scanning path, to a specific location within the heater 102 and therefore provide the remediation action 1704 accordingly. The optical scan data 1734 may indicate a process tube 106 leak if there are flames exiting one of the process tubes 106, shown in Figures 14 and 16. The optical scan data 1734 may indicate a blocked burner 104 if there is a dark spot over a burner 104 that should be firing, or a bright spot adjacent a burner 104 indicating a burning or hot piece of insulation or tile adjacent the burner, such as shown in Figure 12. If, after analysis of the optical scan data 1734, there is no indication of a faulty burner 104 or process tube 106 leak, the remediation action

1704 may instruct the operator to analyze the inlet of ambient air to check for blocked air inlet. In embodiments, instead of an optical scan, the air-flow discrepancy analyzer 1702 analyzes one or more temperature sensors (e.g., thermocouples located on one or more of the process tubes 106) to correlate the location of a punctured process tube 106 or other inlet of fuel other than that intended by the control scheme of the system.

[0063] In embodiments, the air-flow discrepancy analyzer 1702 indicates an approximate location of a punctured process tube 106 based on a correlation of the height at which the sensed oxygen level 1708 becomes below the expected oxygen level 1706. As discussed above, in certain embodiments, the oxygen level is sensed at a plurality of heights. Because the draft within the heater 102 creates a flow of air, the punctured process tube 106 may not cause the sensed oxygen level 1708 to differ substantially from the expected oxygen level 1706 below the location of the punctured process tube 106.

[0064] In embodiments, the remediation action 1704 includes a safety control signal 1736 that changes operation of the system 100 to prevent further dangerous or inefficient operating conditions within the heater 102. For example, the control signal 1736 may alter the air/fuel ratio being supplied to one or more burners 104 by controlling the fuel control valve(s) 162. In some cases, for example, the tramp air indication may suddenly increase, and the controller may require operator approval before reducing the air flow in the firebox to allow time for operations to investigate the source of the rising tramp air indication. As another example, the control signal 1736 may alter the air/fuel ratio being supplied to one or more of the burners 104 by controlling the stack fan 122, forced fan 124, the stack damper 118, the air register 120 (automatically if capable, or via an instruction to manually change the air-register setting), or a combination thereof.

[0065] In embodiments, the air-flow discrepancy analyzer 1702 does not generate the remediation action 1704 unless the sensed oxygen level 1708 is above or below the expected oxygen level 1706 by a delta that meets or exceeds a discrepancy threshold 1738. The discrepancy threshold 1738 allows an operator to control the tolerance of tramp-air within the system before the air-flow discrepancy analyzer 1702 generates the remediation action 1704. Furthermore, there may be distinct discrepancy thresholds 1738 for a positive delta (indicating excess air in the heater 102) and a negative delta (indicating insufficient air in the heater 102, or excess fuel in the heater 102). Insufficient air in the heater 102 may present a more dangerous condition, and thus the discrepancy threshold 1738 for a negative delta needs to be a tighter threshold to prevent catastrophic failures.

[0066] In embodiments, the air-flow discrepancy analyzer 1702 is executed after the heater controller 128 verifies the fuel-side of the system 100. In other words, the heater controller 128 may execute computer readable

instructions that analyze the fuel data 1110 sensed against expected fuel data to verify no inconsistencies within the system 100. If no (or nominal) fuel inconsistencies exist, and the oxygen levels are not as expected, as discussed above, this condition indicates that the output remediation action 1704 is associated with an air-flow discrepancy, even if the specific air-flow discrepancy cannot be pinpointed via the optical scan discussed above (or some other in-heater sensed condition).

[0067] Additionally, the characterized and expected emissions data may be compared to the measured emissions data to provide further data necessary to point operators towards the likely root cause of the variation in tramp air indications. Furthermore, additional troubleshooting may be performed to verify the root cause of the tramp air. For example, historical data such as maintenance records may be utilized to identify potential areas of tramp-air leakage, or blocked airways.

[0068] Any portion of the heater controller 128, including the air analyzer 1700 of Figure 17 may be implemented using an edge computing scheme. For example, the air analyzer 1700 may be located at the external server 164, and data (such as the measured operating parameter 1710, fuel information 1712, heater geometry 1714, air-flow ductwork geometry 1716, burner geometry 1718, weather information 1720, in-heater air data 1726, known heater components 1729, area threshold 1732, optical scan data 1734, sensed oxygen level 1708, or any combination thereof) may be transmitted from the heater controller 128 (or another device) to the external server 164. This allows the fired-systems model 1705 to remain on the external server 164 for analysis thereon. The remediation action 1704 may then be transmitted from the external server 164 to the heater controller 128.

[0069] Figure 20 depicts a method 2000 for determining air-flow discrepancy in a combustion system, in embodiments. Method 2000 is implemented in the air-flow discrepancy analyzer 1702 discussed above, for example. In certain embodiments, method 2000 is implemented after verification of the fuel-side of the system associated with the method.

[0070] In block 2002, the method 2000 senses oxygen level inside the process heater. In one example of block 2002, the sensed oxygen level 1708 is captured by the oxygen sensor 132 and transmitted to, and received by, the heater controller 128. In certain embodiments of block 2002, the method senses the oxygen level inside the process heater at a plurality of locations. For example, the plurality of locations may include a plurality of heights within the heater 102. As another example, the plurality of locations may include a plurality of horizontal locations at a similar height, such as at a plurality of locations of the radiant section 113 of the heater 102.

[0071] In block 2004, the method 2000 calculates the expected oxygen level correlating to the location of the sensed oxygen level. In one example of block 2004, the air-flow discrepancy analyzer 1702 performs physics-based modeling according to the measured operating

parameters 1710 of the heater 102 to calculate the expected oxygen level 1706 thereby determine what the expected oxygen levels are at the location of the oxygen sensor 132. If block 2002 includes sensing oxygen levels at a plurality of locations, then block 2004 also includes determining expected oxygen level 1706 at corresponding plurality of locations.

[0072] In blocks 2006 and 2008, respectively, the method 2000 then determines if the sensed oxygen level from block 2002 is greater than or less than the expected oxygen level calculated in block 2004. In one example of block 2006, the air-flow discrepancy analyzer 1702 determines if the sensed oxygen level 1708 is greater than the expected oxygen level 1706 (at a single location, or at a plurality of locations). In one example of block 2008, the air-flow discrepancy analyzer 1702 determines if the sensed oxygen level 1708 is less than the expected oxygen level 1706 (at a single location, or at a plurality of locations).

[0073] If, at block 2006, the sensed oxygen level is greater than the expected oxygen level, method 2000 proceeds with block 2010. Else, method 2000 repeats block 2002.

[0074] At block 2010, the method 2000 displays an excess air indicator including the delta between the sensed oxygen level of block 2002 and the expected oxygen level at block 2004. In an example of block 2010, the air-flow discrepancy analyzer 1702 displays the unwanted excess air quantifier 1722 on the heater controller 128, or another device such as an operator mobile device, computer, or other electronic device. The displayed excess air indicator of block 2010 may be in kg/s.

[0075] In certain embodiments, method 2000 includes blocks 2012 which is a decision in which method 2000 determines if the sensed oxygen level is above the expected oxygen level beyond a discrepancy threshold. In one example of block 2012, the air-flow discrepancy analyzer 1702 determines if the sensed oxygen level 1708 is above the expected oxygen level 1706 by a delta that meets or exceeds a discrepancy threshold 1738.

[0076] In certain embodiments, the block 2010 includes sub-blocks that determine and analyze a leakage area of the discrepancy in air-flow. In block 2014, the method 2000 identifies a leakage area based on the delta between the sensed oxygen level and the expected oxygen level. In one example of block 2014, the air-flow discrepancy analyzer 1702 determines the leakage area 1724 based on the delta between the expected oxygen level 1706 and the sensed oxygen level 1708 and the sensed draft within the heater 102 as identified via in-heater air data 1726 (which is similar to the heater data 1126 discussed above).

[0077] In block 2016, the method 2000 displays the leakage area determined in block 2014. In one example of block 2016, the air-flow discrepancy analyzer 1702 displays the leakage area 1724 on the heater controller 128, or another device such as an operator mobile device, computer, or other electronic device.

[0078] In certain embodiments, the method 2000 further includes blocks 2018-2024. In block 2018, the method 2000 compares the leakage area to known components of the process heater. In one example of block 2018, the air-flow discrepancy analyzer 1702 compares the leakage area 1724 to known heater components 1728.

[0079] In block 2020, the method 2000 determines if there is a match between the leakage area and known components of the process heater. If so, method 2000 proceeds with block 2022, else method proceeds with block 2024.

[0080] In block 2022, the method 2000 outputs a remediation action including known component(s) that match the leakage area. In one example of block 2018, the air-flow discrepancy analyzer 1702 outputs the remediation action 1704 including the potential leak components 1730.

[0081] In block 2024, the method 2000 outputs the remediation action including one or more of the leakage area (similar to block 2016), and/or identification of the oxygen sensor (e.g., oxygen sensor 132) corresponding to the location at which the sensed oxygen level exceeded the expected oxygen level. Identifying the oxygen sensor allows the operator to determine whether the oxygen sensor needs to be calibrated (or is otherwise "drifting" from appropriate readings).

[0082] If, at block 2008, the sensed oxygen level is less than the expected oxygen level, method 2000 proceeds with block 2026. Else, method 2000 repeats block 2002.

[0083] In block 2026, the method analyzes in-heater data to narrow the location of the air-flow discrepancy. In one example of block 2026, the air-flow discrepancy analyzer 1702 analyzes optical scan data 1734 and/or other temperature data within the heater 102 (such as thermocouples or TDLAS measurements located at one or more positions within the heater, including at locations on the process tubes 106).

[0084] At block 2028, the method 2000 determines if the cause of the discrepancy can be pinpointed. If yes, method 2000 proceeds with block 2030, else method 2000 proceeds with block 2032. In one example of block 2028, the air-flow discrepancy analyzer 1702 uses knowledge of the field of view, or scanning path, of the optical device used to generate the optical scan data 1734 thereby allowing the air-flow discrepancy analyzer 1702 to correlate the field of view, or scanning path, to a specific location within the heater 102 and therefore provide the remediation action 1704 accordingly. The optical scan data 1734 may indicate a process tube 106 leak if there are flames exiting one of the process tubes 106, shown in Figures 14 and 16. The optical scan data 1734 may indicate a blocked burner 104 if there is a dark spot over a burner 104 that should be firing, or a bright spot adjacent a burner 104 indicating a burning or hot piece of insulation or tile adjacent the burner, such as shown in Figure 12.

[0085] At block 2030, the method 2000 outputs a remediation action including the location of the air discrepancy

ancy. In one example of block 2028, the air-flow discrepancy analyzer 1702 outputs the remediation action 1704 including the location corresponding to the field of view, or scanning path, of the optical device used to generate the optical scan data 1734.

[0086] At block 2032, the method 2000 outputs a remediation action including identification of the oxygen sensor and/or an intake signal. In one example of block 2032, the air-flow discrepancy analyzer 1702 outputs the remediation action 1704 including (e.g., oxygen sensor 132) corresponding to the location at which the sensed oxygen level exceeded the expected oxygen level and/or an intake signal instructing the heater operator to manually inspect the air intake for birds' nests, bugs, or other obstructions. Identifying the oxygen sensor allows the operator to determine whether the oxygen sensor needs to be calibrated (or is otherwise "drifting" from appropriate readings).

[0087] At any time during method 2000, the method 2000 may execute block 2034 and determine if the sensed oxygen level(s) are at a dangerous condition. If so, method 2000 executes block 2006 and outputs a remediation action including a safety control signal. In one example of block 2034, the air-flow discrepancy analyzer 1702 determines if the sensed oxygen level 1708 is at dangerous levels, such as if there is insufficient airflow, or too much airflow, that could cause a stoichiometric unbalance resulting in a catastrophic failure. In one example of block 2036, the air-flow discrepancy analyzer 1702 outputs the remediation 1704 including control signal 1736.

Determination of Airflow Discrepancy in a Combustion System:

[0088] It should be appreciated that other discrepancies may be detected by the systems and methods described herein. For example, Figure 21 depicts an example of clogged fins on process tubes. These clogged fins will greatly impact the draft through the heater 102, and thus the sensed data will not be consistent with the expected data. As such, in embodiments, output remediation will indicate incorrect draft in the heater, and/or identify the location of the draft discrepancy, recommend maintenance thereon, and/or implement a control signal (e.g., control signal 1164) to automatically remedy the clog. If the clogged fins cause unsafe conditions, an alert (e.g., alarm 1166, or displayed operating condition 1168) 1250 may include a remediation action that shuts down the system for safety concerns.

[0089] Figure 22 depicts an example draft analyzer (e.g., draft analyzer 1152 of Figure 11), including draft discrepancy identifier 2202, in embodiments. Draft discrepancy identifier 2202 includes computer readable instructions that when executed by a processor (e.g., processor 1102), operate to generate one or more of remediation action 2204, which may include an alert 2206, control signal 2208, and/or displayed operating condition

2210, and any combination thereof. Alert 2206 is an example of alarm 1166 of Figure 11. Control signal 2208 is an example of control signal 1164 of Figure 11. Displayed operating condition 2210 is an example of displayed operating condition 1168 of Figure 11.

[0090] Figures 23-28 depict graphs indicating heater operation over time when the fins of process tubes become clogged due to harsh conditions in the heater, in an embodiment. Figure 29 depicts data table represented by the graphs of Figures 23-28. Conventionally, an operator is unaware of the clogging of process tube fins that results in an improper draft within the heater (e.g., heater 102). As previously illustrated, convection fouling is a build-up of debris on the tubes and extended surfaces in the convection. This causes an increase in thermal resistance reducing the heat transferred to the process and increased flue gas side pressure drop. Convection fouling causes a decrease in efficiency. Conventionally, the operator does not have enough insight into the heater operation to be fully aware of what is causing this decrease in efficiency. The operator is unable to visually see the fin clogging unless the is continuously viewing through a viewport of the heater 102, which is unrealistic. Because of this, the heater is typically controlled to fire at a higher rate forcing more duty to be absorbed in the radiant section. The overall absorbed duty / coil outlet temperature must be maintained to allow for proper process of the material in the process tubes. Increased thermal resistance can be seen as a decrease in coil cross-over temperature (if available), increase in firing rates, increase in bridgewall temperature, and an increase in stack temperature. Along with increased thermal resistance, this fouling forces the flue gas across a decreasing cross-sectional area along its flow path. This throttling effect increases the flue gas side pressure drop across the convection. This can be seen with an increase in open percentage of the stack damper to compensate and maintain the draft pressure at the bridge wall.

[0091] The analyzers discussed above, such as the draft discrepancy identifier 2202, may be configured to recognize discrepancies in the required draft throughout the heater 102. Draft discrepancy identifier 2202 utilizes a fired-systems model 2205 to calculate expected values of draft throughout the heater 102 at any given time. The fired-systems model 2205 is similar to the fired-systems model 1705 discussed above with respect to Figure 17. Comparison of these expected values defined by the fired systems model 2205 to real-time sensed data 2212 allows the draft discrepancy identifier 2202 to automatically detect and diagnose anomalies in the draft within the heater 102, such as convection fouling (e.g., clogging of the fins/heat sinks of process tubes 106). In Figures 23-29, it is seen that during time slot 1 (start of run "SOR"), the heater 102 is operating as expected, where the modeled convection section dP (e.g., expected draft within the heater 102 as defined by the fired-systems model 2205) matches the sensed convection section dP (e.g., sensed draft data 2212). However, as time passes, the

modeled convection section dP defined by the fired-systems model 2205 begins to deviate from the sensed convection section dP. At a certain point, the delta between the measured and modeled convection section dP may become greater than a predetermined discrepancy threshold 2214, at which the draft discrepancy identifier 2202 may generate the remediation action 2204. The modeled convection section dP may include a confidence region based on an uncertainty value as discussed above.

[0092] In certain embodiments, when the modeled convection section dP differs from the sensed convection section dP greater than the discrepancy threshold 2214, the draft discrepancy identifier 2202 may control a device (e.g., the TDLAS scanner 147, or an optical scanner) within the heater 102 to obtain optical scan data 2217 (similar to optical scan data 1734 discussed above) to further to pinpoint the cause of such discrepancy. Knowledge of the field of view, or scanning path, of the optical device used to generate the optical scan data 2217 allows the draft discrepancy analyzer 2202 to correlate the field of view, or scanning path, to a specific location within the heater 102 and therefore provide the remediation action 2204 accordingly. The optical scan data 2217 may indicate tube clogging at a specific height or other location within the heater 102 that causes certain of the process tubes 106 to operate in a different manner than others because the clogging of the fins on those tubes does not allow for designed convection at the location of those tubes. If, after analysis of the optical scan data 2217, there is no indication of process tube clogging, the remediation action 2204 may include the alert 2206, or displayed operating condition 2210, that instructs the operator to physically view the location of the draft discrepancy to check for other obstructions at the location of the draft (e.g., fallen refractory tiles at the process tubes 106 at the location of the draft discrepancy). In embodiments, instead of an optical scan, the draft discrepancy identifier 2202 analyzes one or more temperature sensors (e.g., thermocouples located on one or more of the process tubes 106) to correlate the location of a clogged fins on one or more process tube 106.

[0093] In embodiments, the remediation action 2204 includes a safety control signal 2208 that changes operation of the system 100 to prevent further dangerous or inefficient operating conditions within the heater 102. For example, the control signal 2208 may alter the air/fuel ratio being supplied to one or more burners 104 by controlling the fuel control valve(s) 162. As another example, the control signal 1736 may alter the air/fuel ratio being supplied to one or more of the burners 104 by controlling the stack fan 122, forced fan 124, the stack damper 118, the air register 120 (automatically if capable, or via an instruction to manually change the air-register setting), or a combination thereof.

[0094] In embodiments, the draft discrepancy identifier 2202 does not generate the remediation action 2204 unless the delta between modeled convection section dP

and the sensed convection section dP meets or exceeds the discrepancy threshold 2214. Controllability by the operator of the discrepancy threshold 2214 allows an operator to control the tolerance of the process tube 106 fin clogging within the system before the draft discrepancy identifier 2202 generates the remediation action 2204. Furthermore, there may be distinct discrepancy thresholds 2214 for a positive delta (indicating a higher sensed draft as compared to measured draft in the heater 102) and a negative delta (indicating lower sensed draft as compared to measured draft in the heater 102). Insufficient draft in the heater 102 may present a more dangerous condition or inefficient operation of the heater 102 to process the material within the process tubes 106, and thus the variable discrepancy threshold 2214 allows the operator to control efficiency thresholds for operating the system 100.

[0095] In embodiments, the draft discrepancy identifier 2202 is executed after the heater controller 128 verifies the fuel-side of the system 100. In other words, the heater controller 128 may execute computer readable instructions that analyze the fuel data 1110 sensed against expected fuel data to verify no inconsistencies within the system 100. If no (or nominal) fuel inconsistencies exist, and other aspects of the fuel-side of the system 100 are normal, but the sensed draft data 2212 are not as expected, as discussed above, this condition indicates that the output remediation action 2204 is associated with a draft discrepancy, even if the specific draft discrepancy cannot be pinpointed via the optical scan discussed above (or some other in-heater sensed condition).

[0096] Additionally, the characterized and expected emissions data (which may or may not include a confidence region based on an uncertainty value as discussed above) may be compared to the measured emissions data to provide further data necessary to point operators towards the likely root cause of the variation in draft.

[0097] Furthermore, additional troubleshooting may be performed to verify the root cause of the draft discrepancy. For example, historical data 2216 such as maintenance records may be utilized to identify potential areas fin clogging on the process tubes 106. As another example, the draft discrepancy identifier 2202 may compare other sensed data, such as one or more of: absorbed duty 2218 (defining the amount of duty absorbed by the process tubes 106); current firing rate 2220 (defining firing rate of all burners 104 in the system 100); heater efficiency 2222; bridge wall temperature 2224 (defining temperature as sensed by an optical scanner, thermocouple, or laser scanner); tube metal temperatures 2226 (defining temperatures of the process tubes 106); stack temperature 2228; air handling settings 2230 (defining positions of the burner dampers, stack dampers, and any other fans that control airflow within the heater 102; and process tube pressure drop 2232 (defining pressure in the process tubes 106)) to determine if those are in an expected range. Depending on which of these variables is within or out of expected range, the draft discrepancy

identifier 2202 is able to pinpoint the cause of the discrepancy.

[0098] The draft discrepancy identifier 2202 provides insight that operators conventionally previously did not have. Operators were typically unaware of what the convection section dP *should be*. Instead, operators had to manually visually inspect process tubes 106 to determine if the process tubes 106 were clogged. In contrast, the present system and methods are capable of flagging an anomaly when the heater's efficiency is lower than what it historically was (e.g., via monitoring the varying heater efficiency over time as shown in Figures 23-29) for the current process conditions (absorbed duty, inlet temperature, outlet temperature, etc.) and raise some questions. The present system is able to determine that the problem is not internal fouling (coking) occurring in the radiant tubes because the process pressure drop and tube metal temperatures are within the expected range. The present system is able to determine that the problem is convection fouling because, for the current firing rate there is an increase in bridge wall temperature, stack temperature, and the air handling settings is more open than expected as indicated by the fired-systems model 1204.

[0099] The above discussed anomaly detection may occur in either methods 2400 or 2600 during operation of the heater in blocks 2422 and 2618, respectively. Furthermore, the above discussed anomaly detection may be performed by other "analyzers" described herein, such as the fuel analyzer 1148, the draft analyzer 1152, the emissions analyzer 1154, and the process-side analyzer 1176. Each of these analyzers may operate to detect different anomalies, as well.

[0100] Furthermore, the above discussed discrepancy detection may be performed by other "analyzers" described herein, such as the fuel analyzer 1148, the draft analyzer 1152, the emissions analyzer 1154, and the process-side analyzer 1176. Each of these analyzers may operate to detect different discrepancies, as well.

[0101] Any portion of the heater controller 128, including the draft analyzer 2200 of Figure 22 may be implemented using an edge computing scheme. For example, the draft analyzer 2200 may be located at the external server 164, and data (such as the sensed draft data 2212, historical data 2216, absorbed duty 2218, current firing rate 2220, heater efficiency 2222; bridge wall temperature 2224, tube metal temperatures 2226, stack temperature 2228; air handling settings 2230, and process tube pressure drop 2232, or any combination thereof may be transmitted from the heater controller 128 (or another device) to the external server 164. This allows the fired-systems model 2205 to remain on the external server 164 for analysis thereon. The remediation action 2204 may then be transmitted from the external server 164 to the heater controller 128.

Determination of Burner / Fuel Discrepancy in a Combustion System

[0102] The present disclosure acknowledges that, as heaters operate over time, the burner tips begin to foul (plug up from debris or coking) and the fuel pressure going through that burner tip increases to maintain a constant fuel flow rate (firing rate) so that a cumulative desired process outlet temperature is maintained. As some burners gas tips begin to foul and gas pressure increases, the unfouled burner gas tips will also experience an increase in gas pressure and flow. This causes a maldistribution of fuel gas within the burner array, causing heat maldistribution within the firebox. This ultimately results in inefficiency caused by the non-uniform heat transfer to the process tubes. Additionally, non-uniform gas tip plugging will cause a maldistribution of air to fuel ratio per burner that can be a significant safety concern. When a burners gas tips get too plugged, the burner must be shut down for cleaning maintenance. In most cases, tip plugging is identified by visual observation. Because of this, the heater may be running for long periods of time with significant process heating maldistribution and inefficiency, costing the operator significant profit losses.

[0103] Figure 30 depicts two images of an array of burners installed into a heater with some burners that have plugged burner tips and all burners with clean burner tips. The image on the left depicts some burners that are plugged and thus not firing correctly. The wall of the heater has significant dark spots in various locations down the length of the heater causing inconsistent heating throughout the heater. The image on the right depicts burners operating after a cleaning process. It is apparent that the heater wall is being evenly heated, the combustion is occurring as designed, and that the process tubes have an improved uniformity in duty per burner.

[0104] Figure 31 depicts a burner having a burner tip that has completely failed, in an example. The burner tip has entirely burned off, and a large amount of gas flow is entering the furnace completely asymmetrically compared to the original design of the burner.

[0105] Figure 32 depicts a fuel analyzer 3200, which is an example of the fuel analyzer 1148, of Figure 11, in an embodiment. Fuel analyzer 3200 (or another one of the analyzers shown in Figure 11) includes a burner tip monitor 3202. Burner tip monitor 3202 includes computer readable instructions that when executed by a processor (e.g., processor 1102), operate to generate a burner tip health indication 3204.

[0106] The burner tip monitor 3202 executes a fired-systems model 3206 on the burner (e.g., burner 104) to determine a calculated burner heat release 3208 assuming clean burner tips. The fired-systems model 3206 model may be based on any one or more of combustion chemistry, combustion kinetics, air and fuel fluid dynamics, heat transfer, process side modeling, computational fluid dynamics modeling, and other various types of combustion modeling. For example, the fired-systems model

3206 may be based on a measured firing rate 3210, the fuel information 3212, and the burner geometry 3214. The measured firing rate 3210 indicates the rate at which all burners 104 is to be operated as controlled by the heater controller 128. The fuel information 3212 includes the fuel composition that is either sensed, or inferred as discussed above, and may also include other information such as expected fuel temperature and other data within fuel data 1110. The burner geometry 3214 includes the design characteristics (such as the burner tip orifice size, and the number of orifices on the burner tip) of the burner 104 that determine the fuel pressure drop through the burner.

[0107] In certain embodiments, the fired-systems model 3206 is based on additional information, such as one or more of the fuel supply line geometry 3216. Many process heaters do not include fuel control valves 162 at each individual burner. Instead, a single fuel control valve 162 may control the fuel flow to the entire heater, or multiple fuel control valves 162 may each control individual zones of the heater, each zone having a plurality of burners therein. Therefore, by analyzing the fuel supply line geometry 3216, the burner tip monitor 3202 performs modeling of the fuel flow through the fuel supply line(s) 160, and as a result accurately calculates the heat release for all burners based on a single fuel input. Without knowledge of the fuel supply line geometry 3216, the burner tip monitor 3202 may not have accurate prediction of fuel pressure at each burner due to pressure deviations occurring at directional changes in the supply line(s) 160, or at the fuel control valve(s) 162.

[0108] After determination of the calculated burner heat release 3208, the burner tip monitor 3202 may compare the calculated heat release 3208 against a real-time measured heat release 3218. To generate the real-time measured heat release 3218, the burner tip monitor 3202 may analyze real-time sensed fuel data 3220. In embodiments, the real-time sensed fuel data 3220 includes the fuel pressure data 1116. In embodiments, the real-time sensed fuel data 3220 additionally includes the fuel temperature data 1114.

[0109] Figure 33 depicts a comparison of a calculated heat release 3208 to a measured heat release 3218. The real-time measured heat release 3218 is significantly lower than the calculated heat release 3208. Figure 34 depicts an example burner tip health indication 3204 in the form of a graph 3400 depicting the ratio 3402 of the measured heat release 3218 to the calculated heat release 3208. In embodiments, the burner tip monitor 3202 may monitor this ratio of the burner tip health indication 3204 against a burner tip health threshold 3222. The burner tip health threshold 3222 may be a delta, or range of delta, of the ratio. For example, any ratio that is less than 1, within a delta of -0.03, may indicate some tip plugging or system plugging (pipe supply) is occurring. It could also mean one of the instruments used in these measurements or calculations is drifting as discussed in further detail below.

[0110] Moreover, the burner tip health threshold 3222 may alternatively or additionally include a threshold level that defines a burner tip burn-off (such as shown in Figure 31). If the ratio of measured heat release 3218 to the calculated heat release 3208, as defined in the burner tip health indication 3204, is above 1, it indicates that the burner is releasing more heat than expected and thus a burnt-off tip, or that there is a potential gas leak downstream of the measurement devices. For example, any ratio greater than one, within a delta of -0.03 may indicate a burnt-off tip or potential gas leak downstream of the measurement devices. The "ratio of measured heat release 3218 may be based on expected uncertainty that can be attributed to, for example, the manufacturers published measurement uncertainty of each measurement device, and tolerances of the burner geometry and then set based on the operational goals of the facility. Thus, the delta, although described herein as 0.03, may be a dynamic number that is definable so as to not alarm unless necessary.

[0111] Various burner alarms 3224 may be generated depending on which burner tip health threshold 3222 is breached by the burner tip health indication 3204, and each alarm may be an visual (e.g., displayed as displayed operating conditions 1168 of Figure 11, above), audio and/or tactile alarm (e.g., alarm 1166 of Figure 11, above).

[0112] Trends in this ratio may be used by the burner tip monitor 3202 to predict when maintenance on the burner tip is necessary and generate a burner tip maintenance schedule 3226. For example, historic statistical trends of the ratio 3402 may be analyzed by the burner tip monitor 3202 to determine the expected time at which the burner tip health indication 3204 will breach one or more of the burner tip health threshold 3222. The burner tip monitor 3202 may then output the maintenance schedule 3226 defining when the burner tip should be cleaned or replaced. This provides the advantage that the system operator may control when shutdowns occur and how long to space out maintenance shutdowns. Additionally, operators resort to "scheduled maintenance" for cleaning burner gas tips. When this is the case, they may spend countless hours cleaning perfectly well performing gas tips, and may accidentally cause premature enlarging of the gas tip holes by cleaning them too frequently. They are typically cleaned with high pressure steam or by mechanically running a drill bit of the correct diameter, by hand, in and out of the gas ports. So if the wrong drill bit diameter is used for cleaning, or if the person cleaning the tips uses a drill with the bit instead of cleaning the port by hand, it can bore the hole out beyond its intended tolerances.

[0113] In embodiments, prior to generating one or more burner alarms 3224, the burner tip monitor 3202 may verify the tip malfunction. There may be a variety of reasons besides burner tip plugging or burn-off that cause the ratio of the burner tip health indication 3204 to breach a burner tip threshold 3222. For example, the

pressure sensor obtaining the real-time sensed fuel data 3220 may be malfunctioning and thus the sensed data may deviate from actual conditions. Thus, the burner tip monitor 3202 may further analyze oxygen data 3228 from the oxygen sensor 132 to determine if the oxygen readings are as expected. If the fuel is not being injected to through the burner tip because of tip plugging, then the air/fuel ratio will be higher because not as much fuel is being injected into the heater as expected. Thus, the excess oxygen levels sensed by the oxygen sensor 132 will be greater because not all of the air being input into the heater is being consumed to produce the thermal energy 112. Further, if the burner tip monitor 3202 has verified that there is no additional tramp air (e.g., via the discussion of Figures 12-20, above), or has accounted for an estimated amount of tramp air, then the burner tip monitor 3202 is able to verify the ratio in the burner tip health indication 3204 utilizing the sensed excess oxygen data 3228.

[0114] While the most accurate method for monitoring real-time sensed fuel data 3220 at each given burner would be to include a fuel flow measurement sensor at each burner, this is simply not cost effective. Most process heaters do not include a fuel flow measurement sensor (e.g., mass flow sensor 154(3)) measuring pressure at that specific burner. Instead, often, a fuel flow sensor, such as only mass flow sensor 154(2), is included that measures fuel pressure to the entire heater. Thus, in embodiments, the burner tip monitor 3202 may further analyze in-heater data 3230 to determine the specific burner that is malfunctioning. For example, as discussed above, a plurality of TDLAS monitoring systems may be located within the heater 102. These may be used to detect the temperature of the heater at specific locations. Further, as shown in Figure 30, on the left image, the burner tip malfunction may cause inconsistent heating, where the dark spots indicate cooler areas of the heater than expected. Thus, the TDLAS systems may generate in-heater data 3230 that is able to identify these cool spots. Based on the cool spots, the burner tip monitor 3202 is able to specify which burner, or plurality of burners, have burner tips that are plugged. Other systems and sensors may generate the in-heater data 3230, such as imaging systems (visual and infrared), in-heater temperature sensors, etc. Where the burner tip monitor 3202 is able to identify the specific burner that is malfunctioning, the burner tip health indication 3204 may include an identification of said specific burner.

[0115] Some "cool spots" may be completely expected within the firebox even with complete clean burner gas tips due to the complex flue gas aerodynamics that occur within the firebox. In this case, a full computational fluid dynamics simulation (CFD), including the combustion process, can be executed on a connected and reoccurring basis. This CFD simulation may be a portion of the fired-systems model 3206 and can then be used to calculate what flue gas patterns and temperature profiles are expected to be present within the firebox based on

clean gas tips throughout. The burner tip monitor 3202 can then be configured to query the same or similar measurement path as configured with one of the TDLAS devices 147. The comparison of the calculated temperature, CO, or oxygen along the TDLAS measurement path can make even more accurate identification of a problem area within the heater, and effectively point operators towards the burners with plugged gas tips much more effectively.

[0116] Figure 35 depicts a method 3500 for generating a combustion system burner tip health indication, in embodiments. Method 3500 may be implemented using system 100 discussed above with respects to Figures 1-11, and 30-34, and, in some embodiments, within burner tip monitor 3202.

[0117] In block 3502, method 3500 calculates the burner heat release of a burner, or a plurality of burners assuming clean burner tips. In one example of block 3502, the burner tip monitor 3202 executes the fired-systems model 3206 on the burner (e.g., burner 104), or burners within the heater 102 to determine an expected burner heat release 3208. In embodiments of block 3502, the fired-systems model 3206 may be based on a controlled fire rate 3210, the fuel information 3212, and the burner geometry 3214. In certain embodiments of block 3502, the fired-systems model 3206 is based on additional information, such as the fuel supply line geometry 3216.

[0118] In block 3504, method 3500 determines a measured burner heat release. In one example of block 3504, the burner tip monitor 3202 analyzes the real-time sensed data to determine the real-time measured heat release 3218. In embodiments, the real-time sensed fuel data 3220 includes the fuel pressure data 1116. In embodiments, the real-time sensed fuel data 3220 additionally includes the fuel temperature data 1114.

[0119] In block 3506, method 3500 compares the expected burner heat release to the measured burner heat release to generate a burner tip health indication. In one example of block 3506, the burner tip monitor 3202 determines burner tip health indication 3204 including the ratio of the measured heat release 3218 to the calculated burner heat release 3208.

[0120] In block 3508, if included in method 3500, method 3500 determines if the burner tip health indication is at or below a burner tip threshold. In one example of block 3508 the burner tip monitor 3202 analyzes the ratio of the burner tip health indication 3204 against a burner tip health threshold 3222. The burner tip health threshold 3222 may be a delta, or range of delta, of the ratio. In an example of block 3508, the burner tip health threshold 3222 is 1 with a delta of 0.03 such that if the ratio defined in the burner tip health indication 3204 is below 0.97, then the burner tip is sufficiently plugged and requires maintenance. The "ratio of measured heat release may be based on expected uncertainty that can be attributed to, for example, the manufacturers published measurement uncertainty of each measurement device, and tolerances of the burner geometry and then set based on

the operational goals of the facility. Thus, the delta, although described herein as 0.03, may be a dynamic number that is definable so as to not alarm unless necessary.

[0121] If yes, method 3500 proceeds with block 3512, else method 3500 proceeds with block 3510 (if included) or loops back to block 3504.

[0122] In block 3510, if included in method 3500, method 3500 determines if the burner tip health indication is at or above a burner tip threshold. In one example of block 3510 the burner tip monitor 3202 analyzes the ratio of the burner tip health indication 3204 against a burner tip health threshold 3222 that defines a burner tip burn-off (such as shown in Figure 31). If the ratio of measured heat release 3218 to the calculated heat release 3208, as defined in the burner tip health indication 3204, is above 1, it indicates that the burner is releasing more heat than expected. Thus, the burner tip health threshold 3222 may be 1 with a delta of .03 such that if the ratio defined in the burner tip health indication 3204 is at or above 1.03, then the burner tip is likely burnt off and requires replacement. Any other delta may be used without departing from the scope hereof. If yes at block 3510, then method 3500 proceeds with block 3512, else method 3500 loops back to block 3504.

[0123] At block 3512, if included in method 3500, the method 3500 verifies the tip malfunction. In one example of block 3512, the burner tip monitor 3202 may further analyze oxygen data 3228 from the oxygen sensor 132 to determine if the oxygen readings are as expected. If the fuel is not being injected through the burner tip because of tip plugging, then the air/fuel ratio will be higher because not as much fuel is being injected into the heater as expected. Thus, the excess oxygen levels sensed by the oxygen sensor 132 will be greater because not all of the air being input into the heater is being consumed to produce the thermal energy 112. Further, in alternate or additional embodiments of block 3512, if the burner tip monitor 3202 has verified that there is no additional tramp air, or has accounted for an estimated amount of tramp air, then the burner tip monitor 3202 is able to verify the ratio in the burner tip health indication 3204 utilizing the sensed excess oxygen data 3228.

[0124] Figures 36 and 37 depict example data showing oxygen data used to verify that tip plugging was not occurring. Graph 3600 shows the measured heat release 3602 versus the calculated heat release 3604 based on clean gas ports with the known fuel composition and fuel pressure. This graph would seemingly illustrate that there is "tip plugging" occurring on the burners. However, graph 3700 shows that the calculated oxygen value 3704, which is an expected oxygen value calculated based on an assumption of clean burner tips and measured fuel pressure, matches very closely to the measured "ZoneO2" value 3706. However, when we look at the "Customer-FlowResults" expected O2 3702, which is based on real-time measured heat release based on fuel flow meter, it is seen to be much higher than the measured "ZoneO2"

3706. So, because of this analysis, the method could confidently conclude there is no tip plugging and output the maintenance schedule 3226 instructing to verify/calibrate the fuel flow meter.

[0125] At block 3514, if included in method 3500, the method 3500 verifies determines the specific burner tip having a malfunction. In one example of block 3514, the burner tip monitor 3202 may further analyze in-heater data 3230 to determine the specific burner that is malfunctioning. For example, as discussed above, a plurality of TDLAS monitoring systems may be located within the heater 102. Thus, the TDLAS systems may generate in-heater data 3230 that is able to identify these cool spots. Based on the cool spots, the burner tip monitor 3202 is able to specify which burner, or plurality of burners, have burner tips that are plugged. In additional or alternative embodiments, other systems and sensors may generate the in-heater data 3230, such as imaging systems (visual and infrared), in-heater temperature sensors, etc. Some "cool spots" may be completely expected within the firebox even with complete clean burner gas tips due to the complex flue gas aerodynamics that occur within the firebox. In this case, a full computational fluid dynamics simulation (CFD), including the combustion process, can be executed on a connected and reoccurring basis. This CFD simulation may be a portion of the fired-systems model 3206 and can then be used to calculate what flue gas patterns and temperature profiles are expected to be present within the firebox based on clean gas tips throughout. The burner tip monitor 3202 can then be configured to query the same or similar measurement path as configured with one of the TDLAS devices 147. The comparison of the calculated temperature, CO, or oxygen along the TDLAS measurement path can make even more accurate identification of a problem area within the heater, and effectively point operators towards the burners with plugged gas tips much more effectively.

[0126] In block 3516, the method 3500 outputs a burner tip health indication. In one example of block 3516, the burner tip monitor 3202 outputs the burner tip health indication 3204. Where the burner tip monitor 3202 is able to identify the specific burner or group of burners that is malfunctioning, the burner tip health indication 3204 may include an identification of said specific burner or group of burners. The burner tip monitor 3202 may be output to the heater controller 128 for display thereon. The burner tip health indication output in block 3516 may also include any of the above discussed burner tip alarms 3224, in embodiments.

[0127] In block 3518, if included in method 3500, the method 3500 determines and outputs a burner tip maintenance schedule. In one example of block 3518, the burner tip monitor 3202 analyzes trends in the ratio of the measured heat release 3218 to the expected burner heat release 3208 within the burner tip health indication 3204 to predict when maintenance on the burner tip is or will be necessary and generate the burner tip maintenance schedule 3226. The burner tip monitor 3202 may

then output the maintenance schedule 3226 to the heater controller 128 defining when the burner tip should be replaced.

[0128] Any portion of the heater controller 128, including the fuel analyzer 3200 of Figure 32 may be implemented using an edge computing scheme. For example, the fuel analyzer 3200 may be located at the external server 164, and data (such as the fuel information 3212, real-time sensed fuel data 3220, sensed oxygen data 3228, and/or in-heater data 3230) may be transmitted from the heater controller 128 to the external server 164. This allows the fired-systems model 3206 to remain on the external server 164 for analysis thereon. The burner tip health indication 3204, burner tip alarm 3224, and burner tip maintenance schedule 3226 may then be transmitted from the external server 164 to the heater controller 128.

[0129] Figure 38 depicts a method 3800 for determining discrepancy in a combustion system, in embodiments. Method 3800 is implemented in any one or more of the fuel analyzer 1148, the air analyzer 1150, the draft analyzer 1152, the emissions analyzer 1154, and the process-side analyzer 1176 discussed above, including the air analyzer 1700, the draft analyzer 2200, and the fuel analyzer 3200 discussed in Figures 17, 22, and 32 respectively. In certain embodiments, method 3800 is implemented after verification of the fuel-side of the system associated with the method.

[0130] In block 3802, the method 3800 senses real-time data inside the process heater. In one example of block 3802, any one or more of the fuel data 1110, air data 1118, heater data 1126, emissions data 1140, and process-side data 1170 is captured and stored in sensor database 130.

[0131] In block 3804, the method 3800 determines a fired-systems model. In certain embodiments, the fired-systems model is determined for the entire heater 102. In certain embodiments, the fired systems model is determined for a specific location correlating to a potential discrepancy location (e.g., at the process tubes 106, or at the location of a potential tramp-air leak). Fired-systems model 1705, and 2205, and 3206 are examples of the fired-systems model determined in block 3804.

[0132] In blocks 3806 and 3808, respectively, the method 3800 then determines if the real-time sensed data from block 3800 is greater than or less than the expected value defined by the fired-systems model determined in block 3804. In one example of block 3806, the draft discrepancy identifier 2202 determines if the sensed draft data 2212 is a value greater than the expected draft data defined by the fired-systems model 2205 (at a single location, or at a plurality of locations). In one example of block 3808, the draft discrepancy identifier 2202 determines if the sensed draft data 2212 is a value less than the expected draft data defined by the fired-systems model 2205 (at a single location, or at a plurality of locations). If, at block 3808, the sensed data is greater than the expected data, method 3800 proceeds with block

2010. Else, method 3800 repeats block 3802. In another embodiment, blocks 3508 and 3510 are an example of blocks 3806 and 3808.

[0133] At block 3810, the method 3800 displays an operating condition defining the difference between the expected and the sensed values from blocks 3804 and 3802, respectively. In an example, blocks 3516 and 3518 are examples of block 3810.

[0134] In certain embodiments, method 3800 includes blocks 3812 which is a decision in which method 3800 determines if the sensed value is above the expected value beyond a discrepancy threshold. In one example of block 3812, the draft discrepancy identifier 2202 determines if the sensed draft level 2212 is above the expected draft level defined by the fired-systems model 2205 by a delta that meets or exceeds a discrepancy threshold 2214.

[0135] In certain embodiments, the block 3810 includes sub-blocks that determine a location of the discrepancy. In block 3814 captures additional data corresponding to the potential discrepancy. In one example of block 3814, the draft discrepancy identifier 2202 may control a device (e.g., the TDLAS scanner 147, or an optical scanner) within the heater 102 to obtain optical scan data 2217 (similar to optical scan data 1734 discussed above, and/or the in-heater data 3230 discussed above) to further to pinpoint the cause of such discrepancy. Knowledge of the field of view, or scanning path, of the optical device used to generate the optical scan data 2217 allows the draft discrepancy analyzer 2202 to correlate the field of view, or scanning path, to a specific location within the heater 102 and therefore provide the remediation action 2204 accordingly. In embodiments of block 3814, instead of an optical scan, the draft discrepancy identifier 2202 analyzes one or more temperature sensors (e.g., thermocouples located on one or more of the process tubes 106) to correlate the location of a clogged fins on one or more process tube 106.

[0136] In sub-block 3816, the method 3800 determines if the additional data from sub-block 3814 matches the potential discrepancy. In one example of sub-block 3816, the optical scan data 2217 may indicate tube clogging at a specific height or other location within the heater 102 that causes certain of the process tubes 106 to operate in a different manner than others because the clogging of the fins on those tubes does not allow for designed convection at the location of those tubes. If yes at sub-block 3816, the method 3800 proceeds to sub-block 3818, else the method proceeds to sub-block 3812.

[0137] In sub-block 3818, the method 3800 outputs remediation action including location of the discrepancy. In one example of sub-block 3818, the draft discrepancy identifier 2202 outputs a remediation action 2204 defining the location of the draft discrepancy (e.g., location of the clogged fins of the process tubes 106).

[0138] In sub-block 3820 the method 3800 outputs remediation action indicating to visually inspect a specific location of the heater. In one example of sub-block 3820,

if, after analysis of the optical scan data 2217, there is no indication of process tube clogging, the remediation action 2204 may include the alert 2206, or displayed operating condition 2210, that instructs the operator to physically view the location of the draft discrepancy to check for other obstructions at the location of the draft (e.g., fallen refractory tiles at the process tubes 106 at the location of the draft discrepancy).

[0139] The blocks 3512-3518 are examples of sub-blocks 3814-3820. The sub-blocks 2014-2024 are examples of sub-blocks 3814-3820.

[0140] If, at block 3808, the sensed data is less than the expected oxygen data, method 3800 proceeds with block 3826. Else, method 3800 repeats block 3802.

[0141] Certain discrepancies are present when the sensed data is lower than the expected data, and certain discrepancies are present when the sensed data is greater than the expected data. Thus, blocks 3826, 3828, 3830, and 3832 are similar to blocks 3814, 3816, 3818, and 3820, respectively but are triggered when the sensed data from block 3002 is less than the expected data from block 3004.

[0142] At any time during method 3800, the method 3800 may execute block 3834 and determine if the sensed data are at a dangerous condition (e.g., above predefined threshold levels, a threshold level difference between expected and sensed, etc.). If so, method 3800 executes block 3836 and outputs a remediation action including a safety control signal. In one example of block 3836, the draft discrepancy identifier 2202 determines if the sensed draft level 2212 is at dangerous levels, such as if there is insufficient airflow, or too much airflow, that could cause a stoichiometric unbalance resulting in a catastrophic failure. In one example of block 3836, the draft discrepancy identifier 2202 outputs the remediation 2204 including control signal 2208.

Cloud computing embodiments:

[0143] In embodiments, a portion or all of the air-flow discrepancy analyzer 1702, draft discrepancy identifier 2202, burner tip monitor 3202 or other discrepancy detectors may be implemented remotely from the process controller 128, such as in the network-based "cloud", where the air-flow discrepancy analyzer and the process controller 128 are a portion of an edge computing scheme. For example, the air-flow discrepancy analyzer 1702, draft discrepancy identifier 2202, burner tip monitor 3202 or other discrepancy detectors may be stored and executed at the external server 164, such that after the remediation action 1704, the remediation action 2204, burner tip health indication 3204, burner tip health threshold 3222, burner tip alarm 3224, or burner tip maintenance schedule 3226, or any combination thereof is generated, said generated data then transmitted from the external server 164 to the process controller 128 for display on the display 1108 thereof or used automatic control of the hardware associated the system 100. The meas-

ured operating parameters used by one or more of the air-flow discrepancy analyzer 1702, draft discrepancy identifier 2202, burner tip monitor 3202 or other discrepancy detectors may be gathered at the process controller 128 (such as at the system DCS or PLC (plant control system) and transmitted to the external server 164 for analysis by the respective analyzer located on the external server 164. Alternatively, or additionally, one or more of the devices capturing the measured operating parameters may be an embedded device having data transmission capability that transfers its respective data directly to the external server 164 for analysis by the air-flow discrepancy analyzer 1702, draft discrepancy identifier 2202, burner tip monitor 3202 or other discrepancy detectors.

System component validation:

[0144] Continued understanding on the modeling side (by any of the above described "analyzers", or other physics-based modeling, or analytics discussed herein or in any of the provisional applications incorporated by reference as discussed above) allows for the process controller 128 to monitor and validate the measurement devices that populate the data within the sensor database 130. Because the modeling provides optimized control settings, the analyzers discussed herein are able to compare the measured data to the expected data generated via calculations. If the measured data varies with respect to the calculated data, the system is able to troubleshoot the particular reason for that discrepancy.

[0145] For example, a variation in a fuel-side calculation may indicate that the calculated heat release based on pressure with clean burner tips is higher than a given fuel mass flow measurement. In such situation, the fuel analyzer 1148 may implement the following troubleshooting: (i) identify that one or more of the burners are out of service, (ii) determine if one or more of the fuel valves are full-open (even though they are supposed to be at a specific setting), (iii) determine if the burner tips have additional fouling that is visually identifiable, (iv) determine if the burner tips have a different orifice diameter than expected, and (v) determine if the pressure transmitter or flow meter providing the measurements are in need of calibration.

[0146] As another example, a variation in a fuel-side calculation may indicate that the calculated heat release based on pressure with clean burner tips is lower than a given mass flow measurement. In such situation, the fuel analyzer 1148 may implement the following troubleshooting: (i) confirm quantity of out-of-service burners, (ii) verify that the out-of-service burners are truly out of service, (iii) determine if there are gas leaks within the combustion system (visually observed by small "candle flames" until the tip is plugged), (iv) determine if flame patterns match conditions indicating missing burner tips or burner tips that have ports that are eroded, (v) confirm burner tip orifice diameter, (vi) determine improper line

loss calculations, (vii) determine if the pressure transmitter or flow meter providing the measurements are in need of calibration.

[0147] As another example, a variation in an air-side calculation may indicate that the calculated oxygen is higher than a measured oxygen level. In such situation, the air-side analyzer 1150 (or the emissions analyzer 1154) may implement the following troubleshooting process: (i) confirm the number of burners out-of-service, (ii) confirm that the air register settings are accurate within the model, (iii) analyze the burners for blocked air passages, such as blocked air inlets, refractory fallen into burner throats, wall burner air-tip fouling, loose burner insulation, flashback or combustion back pressure within the burner, (iv) determine potential leaks within the process tubes (and shut down if so), (v) verify ambient air conditions, (vi) check wind speeds, (vii) calibrate air-side measurement devices such as the air-pressure and O₂ analyzer.

[0148] As another example, a variation in an air-side calculation may indicate that the calculated oxygen is lower than a measured oxygen level. In such situation, the air-side analyzer 1150 (or the emissions analyzer 1154) may implement the following troubleshooting process: (i) confirm the number of burners out-of-service, (ii) confirm that the air register settings are accurate within the model, (iii) analyze for tramp-air entering the system (such as via sight ports, lighting ports, gas tip riser mounting plates, etc.), (iv) determine potential leaks within the process tubes (and shut down if so), (v) verify ambient air conditions, (vi) check wind speeds, (vii) analyze for additional gas leakage into the system, (viii) calibrate air-side measurement devices such as the air-pressure and O₂ analyzer.

Definitions:

[0149] The disclosure herein may reference "physics-based models" and transforming, interpolating, or otherwise calculating certain data from other data inputs. Those of ordinary skill in the art should understand what physics-based models incorporate, and the calculations necessary to implement said transforming, interpolating, or otherwise calculating for a given situation. However, the present disclosure incorporates by reference chapter 9 of the "John Zink Hamworthy Combustion Handbook", which is incorporated by reference in its entirety (Baukal, Charles E. The John Zink Hamworthy Combustion Handbook. Fundamentals. 2nd ed., vol. 1 of 3, CRC Press, 2013) for further disclosure related to understanding of fluid dynamics physics-based modeling and other calculations. It should be appreciated, however, that "physics-based models" and transforming, interpolating, or otherwise calculating certain data from other data inputs is not limited to just those fluid dynamics calculations listed in chapter 9 of the John Zink Hamworthy Combustion Handbook.

[0150] Changes may be made in the above methods

and systems without departing from the scope hereof. It should thus be noted that the matter contained in the above description or shown in the accompanying drawings should be interpreted as illustrative and not in a limiting sense. The following claims are intended to cover all generic and specific features described herein, as well as all statements of the scope of the present method and system, which, as a matter of language, might be said to fall therebetween. Examples of combination of features are as follows:

(A1) In a first aspect, a method for determining discrepancy in air-flow of a process heater includes: sensing current oxygen level within a housing of the process heater; calculating a delta between the sensed current oxygen level and an expected oxygen level; comparing the delta to a predetermined threshold; and, outputting a remediation action in response to the delta breaching the predetermined threshold.

(A2) In an embodiment of (A1), the method further including, when the delta indicates unwanted excess air-flow: determining an amount of the unwanted excess air-flow in terms of leakage area within the housing based on the geometry of the housing, and an identified draft within the housing.

(A3) In an embodiment of any of (A2), the method further including comparing the leakage area to size of known components of the combustion system and outputting the remediation action with respect to one of the known components when the leakage area matches the size of the known component.

(A4) In an embodiment of any of (A2)-(A3), the known component being a viewing access panel.

(A5) In an embodiment of any of (A2)-(A4), the method further including displaying the leakage area at a process controller of the combustion system.

(A6) In an embodiment of any of (A1)-(A5), the method further including determining the predetermined threshold based on verified air-flow settings.

(A7) In an embodiment of any of (A6), the verified air-flow settings including burner damper settings, stack damper settings, stack fan settings, and/or forced fan settings.

(A8) In an embodiment of any of (A1)-(A7), the method further including sensing the oxygen level at a plurality of heights within the housing of the combustion system; the outputting a remediation action including identifying a height at which the delta breaches the predetermined threshold, and outputting a zone of the housing having likely tramp-air penetration based on the height.

(A9) In an embodiment of any of (A1)-(A8), the outputting a remedial action comprising performing an optical scan of inside the housing of the combustion system; identifying irregularity within the optical scan indicating tramp-air penetration; and, outputting a zone of the housing of the combustion system having

the irregularity.

(A10) In an embodiment of any of (A9), the optical scan including an infrared image.

(A11) In an embodiment of any of (A9)-(A10), the optical scan including a tunable diode laser absorption spectroscopy (TDLAS) scan. 5

(A12) In an embodiment of any of (A1)-(A11), when the delta indicates deficient air within the combustion system, the outputting a remedial action comprising performing an optical scan of a burner of the combustion system; identifying irregularity of a burner flame based on the optical scan; and, outputting a zone of the combustion system based on the irregularity. 10

(A13) In an embodiment of any of (A12), the optical scan including an infrared image. 15

(A14) In an embodiment of any of (A12)-(A13), the optical scan including a tunable diode laser absorption spectroscopy (TDLAS) scan.

(A15) In an embodiment of any of (A1)-(A4), the method further including, prior to outputting a remedial action, verifying fuel-flow rates within the combustion system. 20

(B1) In a second aspect, a system for determining operating discrepancy a process heater includes: a processor; and, memory storing computer readable instructions that, when executed by the processor, control the processor to: receive sensed current operating data within the process heater; calculate a delta between the sensed current operating data and an expected current operating data corresponding to the sensed current operating data; compare the delta to a predetermined threshold; and, output a remediation action in response to the delta breaching the predetermined threshold. 25 30

(B2) In an embodiment of (B1), the computer readable instructions including further instructions that, when executed by the processor, cause the processor to: solve a fired-systems model to determine the expected current operating data. 35 40

(B3) In an embodiment of any of (B1)-(B2), the computer readable instructions including further instructions that, when executed by the processor, cause the processor to: capture additional data when the delta breaches the predetermined threshold; determine the location of a discrepancy between the expected current operating data and the sensed current operating data based on the additional data. 45

(B4) In an embodiment of any of (B3), the additional data including optical scan data of a location of a potential discrepancy. 50

(B5) In an embodiment of any of (B1)-(B4), the sensed current operating data defining one or more of: absorbed duty, current firing rate, heater efficiency, bridge wall temperature, tube metal temperatures, stack temperature, damper positions, and process tube pressure drop; the remediation action identifying convection fouling when there is an in- 55

crease in bridge wall temperature, stack temperature, and air handling settings are more open than expected as defined by the expected current operating data.

(B6) In any embodiment of any of (B1)-(B5) the instructions implementing any of the features of (A1)-(A15).

(C1) In a third aspect, a combustion system having burner tip plugging indication, includes: a burner having a burner tip; a fuel pressure sensor generating fuel pressure data of a fuel source input into the burner; a processor; and, memory operatively coupled to the processor storing a burner tip monitor as computer readable instructions that when executed by the processor operate to: generate a calculated fuel heat release of the burner by executing a fired-systems model of the burner based on fuel information, a fuel pressure, and burner geometry, and compare the calculated fuel heat release of the burner to a measured heat release to generate a burner tip health indication of the burner tip.

(C2) In an embodiment of C1), the measured heat release being further based on fuel temperature data sensed by a fuel temperature sensor of the combustion system.

(C3) In an embodiment of any of (C1)-(C2), the burner tip health indication including a ratio of the measured heat release to the calculated fuel heat release.

(C4) In an embodiment of any of (C3), the computer readable instructions that when executed by the processor operate to compare including computer readable instructions that when executed by the processor operate to compare the ratio to a burner tip health threshold to identify a plugged burner tip.

(C5) In an embodiment of any of (C1)-(C4), the burner tip health threshold being a ratio less than 1.

(C6) In an embodiment of any of (C1)-(C5), the burner tip health threshold being a ratio determined based on expected uncertainty associated with the calculation.

(C7) In an embodiment of any of (C1)-(C6), the computer readable instructions that when executed by the processor operate to compare including computer readable instructions that when executed by the processor operate to compare the ratio to a burner tip health threshold to identify a burnt-off burner tip or other gas leakage.

(C8) In an embodiment of any of (C7), the burner tip health threshold being a ratio greater than 1.

(C9) In an embodiment of any of (C1)-(C8), the burner tip health threshold being a ratio determined expected uncertainty associated with the calculation.

(C10) In an embodiment of any of (C1)-(C9), the burner tip monitor including further computer readable instructions that when executed by the processor operate to: verify the burner tip health indication by analyzing oxygen data sensed by an oxygen sensor within the combustion system.

(C11) In an embodiment of any of (C1)-(C10), the burner including a plurality of burners; the burner tip monitor including further computer readable instructions that when executed by the processor operate to: identify a specific burner or group of burners having a tip malfunction identified in the burner tip health indication based on in-heater data.

(C12) In an embodiment of any of (C11), the in-heater data including data captured by one or more tunable diode laser absorption spectroscopy (TDLAS) systems within the combustion system.

(C13) In an embodiment of any of (C11)-(C12), the in-heater data including data captured by one or more image sensors within the combustion system.

(C14) In an embodiment of any of (C1)-(C13), the burner tip monitor including further computer readable instructions that when executed by the processor operate to: analyze historical data within the burner tip health indication to identify trends of the burner tip health indication, and generate a burner tip maintenance schedule predicting when the burner tip will need replacement.

(C15) In an embodiment of any of (C1)-(C14), the burner tip monitor being located remotely from a heater controller in an edge computing configuration, and the burner tip monitor configured to transmit the burner tip health indication to the heater controller.

(C16) In any embodiment of any of (C1)-(C15) the instructions implementing any of the features of (A1)-(A15), and/or (B1)-(B6).

(D1) In a fourth aspect, a method for generating a burner tip health indication, comprising: calculating a fuel heat release of a burner by executing a fired-systems model of the burner based on fuel information, a fuel pressure measurement, and burner geometry, and comparing the calculated fuel heat release of the burner to a measured real-time heat release to generate a burner tip health indication of a burner tip of the burner.

(D2) In any embodiment of any of (D1) the method further including any of the features of (A1)-(A15), (B1)-(B6), and/or (C1)-(C16).

Claims

1. A combustion system having burner tip plugging indication, comprising:

a burner having a burner tip;
a fuel pressure sensor generating fuel pressure data of a fuel source input into the burner;
a processor; and,
memory operatively coupled to the processor storing a burner tip monitor as computer readable instructions that when executed by the processor operate to:

generate a calculated fuel heat release of the burner by executing a fired-systems model of the burner based on fuel information, a fuel pressure, and burner geometry, and

compare the calculated fuel heat release of the burner to a measured heat release to generate a burner tip health indication of the burner tip.

2. The combustion system of claim 1, the measured heat release being further based on fuel temperature data sensed by a fuel temperature sensor of the combustion system.

3. The combustion system of claim 1 or 2, the burner tip health indication including a ratio of the measured heat release to the calculated fuel heat release.

4. The combustion system of claim 3, the computer readable instructions that when executed by the processor operate to compare including computer readable instructions that when executed by the processor operate to compare the ratio to a burner tip health threshold to identify a plugged burner tip.

5. The combustion system of claim 4, the burner tip health threshold being a ratio less than 1.

6. The combustion system of claim 4 or 5, the burner tip health threshold being a ratio determined based on expected uncertainty associated with the calculation.

7. The combustion system of claim 3, the computer readable instructions that when executed by the processor operate to compare including computer readable instructions that when executed by the processor operate to compare the ratio to a burner tip health threshold to identify a burnt-off burner tip or other gas leakage.

8. The combustion system of claim 7, the burner tip health threshold being a ratio greater than 1.

9. The combustion system of claim 7 or 8, the burner tip health threshold being a ratio determined expected uncertainty associated with the calculation.

10. The combustion system of any one of claims 1 to 9, the burner tip monitor including further computer readable instructions that when executed by the processor operate to:
verify the burner tip health indication by analyzing oxygen data sensed by an oxygen sensor within the combustion system.

11. The combustion system of any one of claims 1 to 10,

the burner including a plurality of burners;
the burner tip monitor including further computer
readable instructions that when executed by the
processor operate to:

identify a specific burner or group of burners having
a tip malfunction identified in the burner tip health
indication based on in-heater data. 5

12. The combustion system of claim 11, the in-heater
data including data captured by one or more tunable
diode laser absorption spectroscopy (TDLAS) sys-
tems within the combustion system. 10

13. The combustion system of claim 11 or 12, the in-
heater data including data captured by one or more
image sensors within the combustion system. 15

14. The combustion system of any one of claims 1 to 13,
the burner tip monitor including further computer
readable instructions that when executed by the
processor operate to: 20

analyze historical data within the burner tip
health indication to identify trends of the burner
tip health indication, and 25

generate a burner tip maintenance schedule
predicting when the burner tip will need replace-
ment,
and/or

wherein the burner tip monitor is located remote-
ly from a heater controller in an edge computing
configuration, and the burner tip monitor is con-
figured to transmit the burner tip health indica-
tion to the heater controller. 30

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15. A method for generating a burner tip health indica-
tion, comprising:

calculating a fuel heat release of a burner by
executing a fired-systems model of the burner
based on fuel information, a fuel pressure meas-
urement, and burner geometry, and 40

comparing the calculated fuel heat release of
the burner to a measured real-time heat release
to generate a burner tip health indication of a
burner tip of the burner. 45

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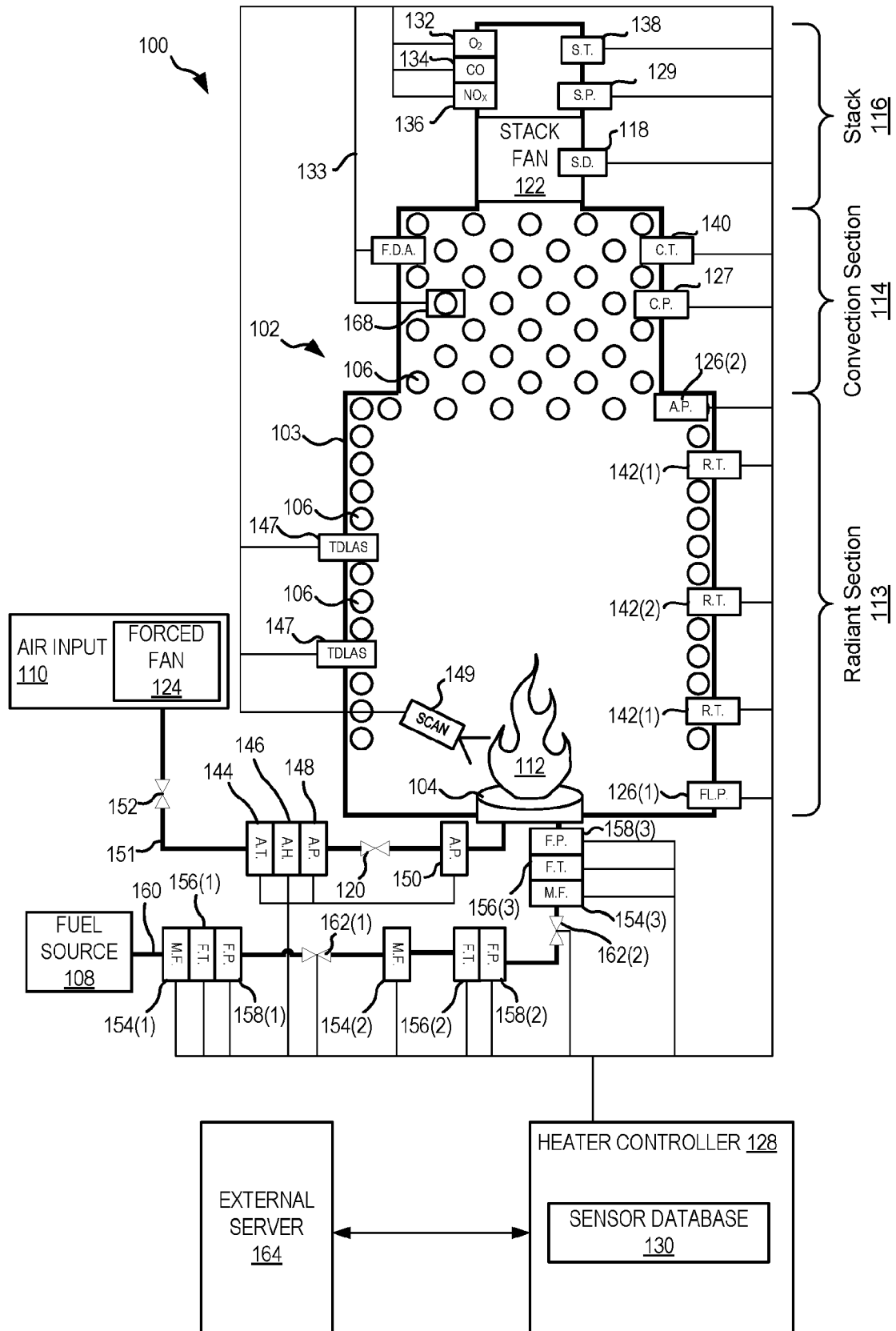


FIG. 1

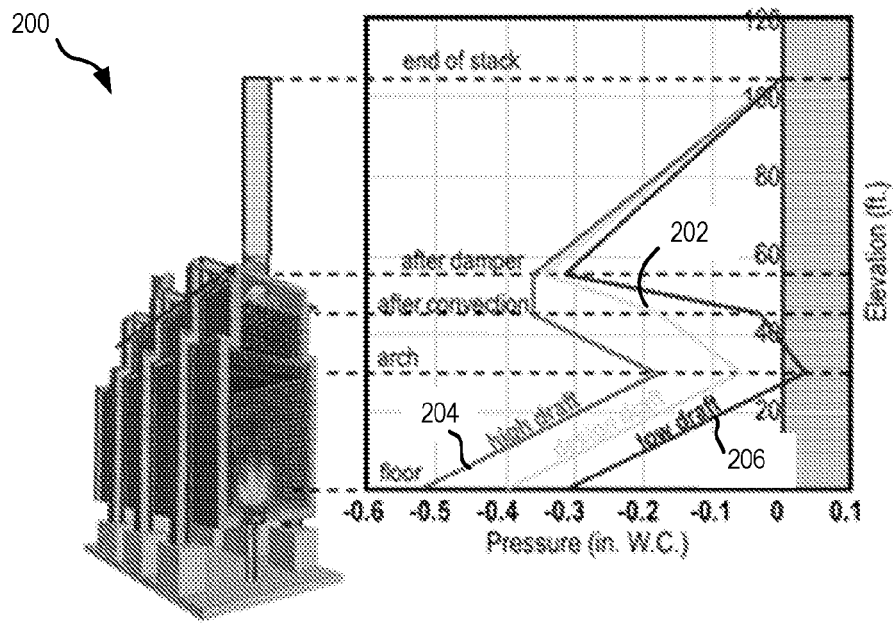
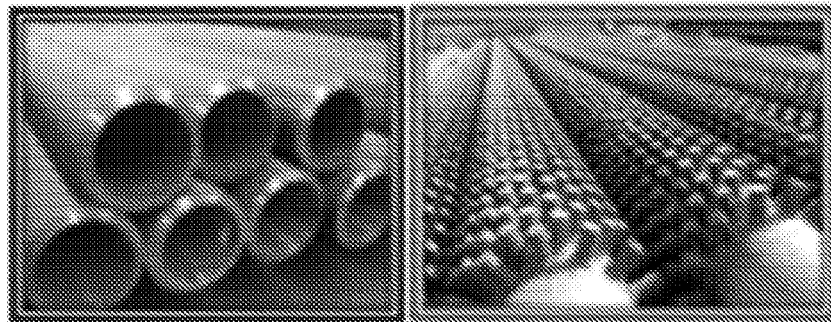
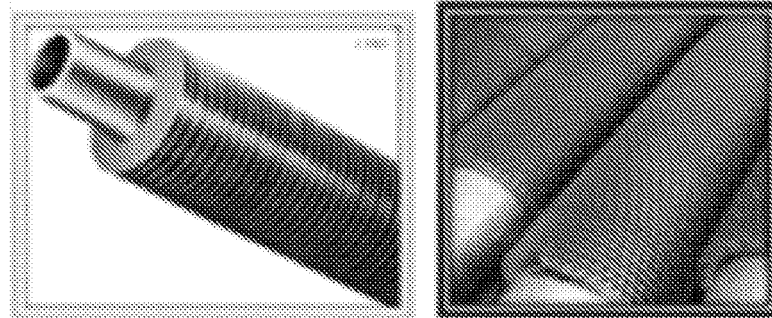


FIG. 2



Bare tubes

Studded tubes



Fins

Segmented fins

FIG. 3

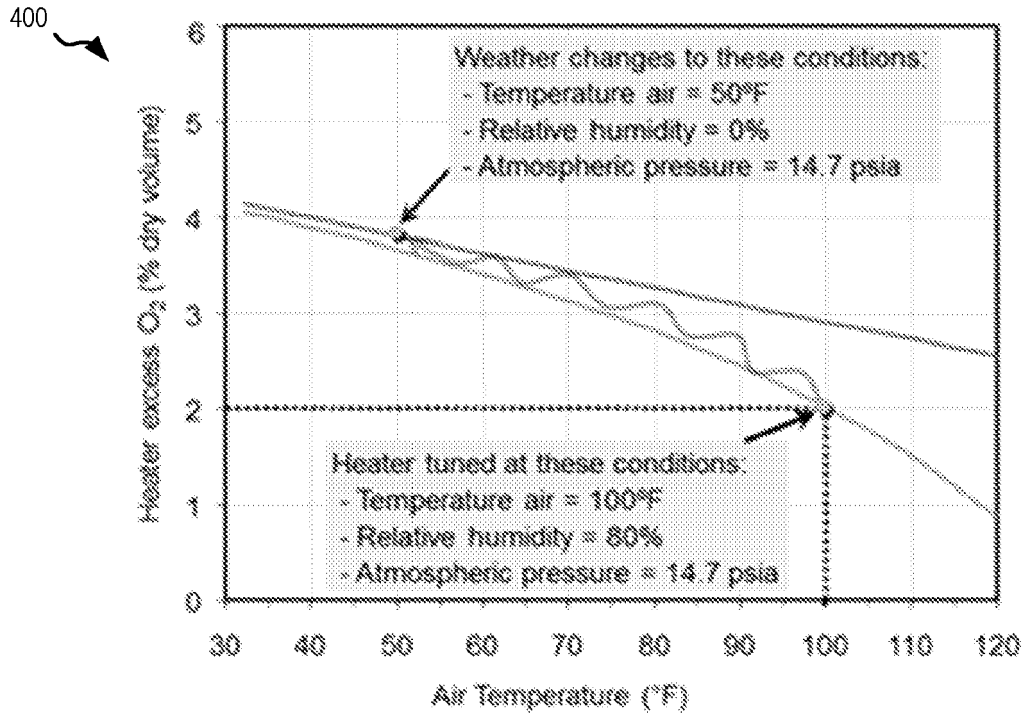


FIG. 4

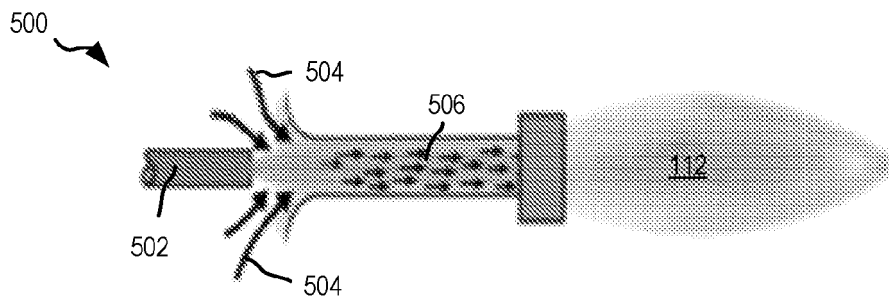


FIG. 5

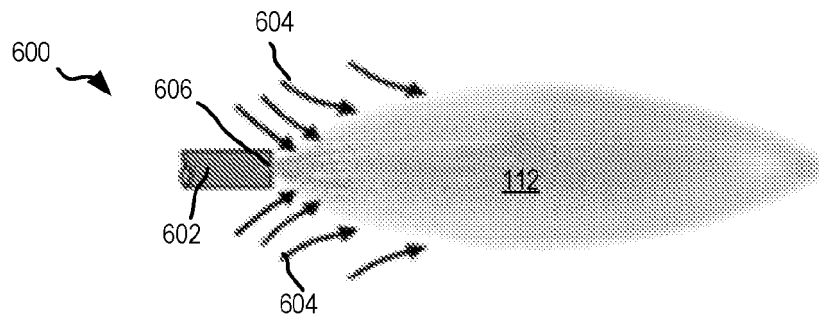


FIG. 6

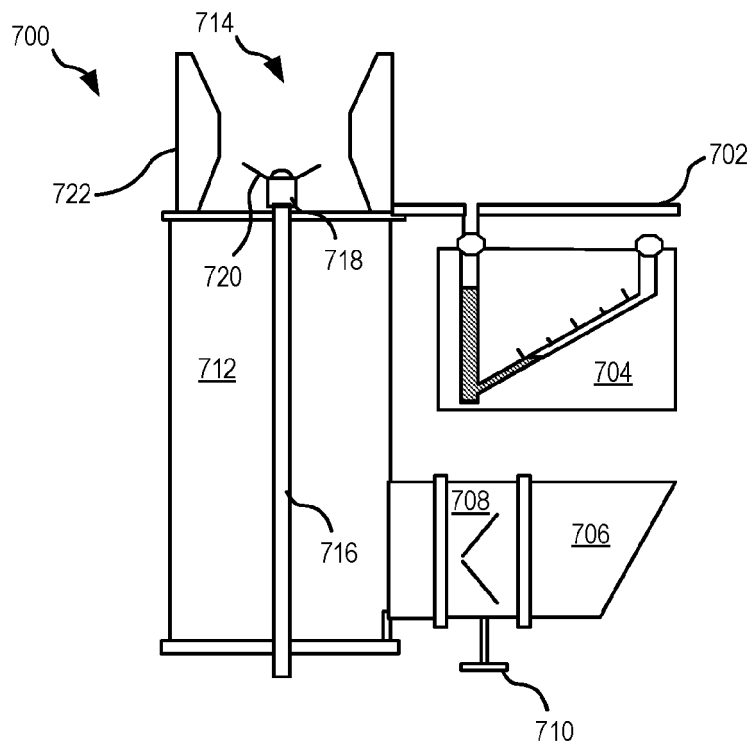


FIG. 7

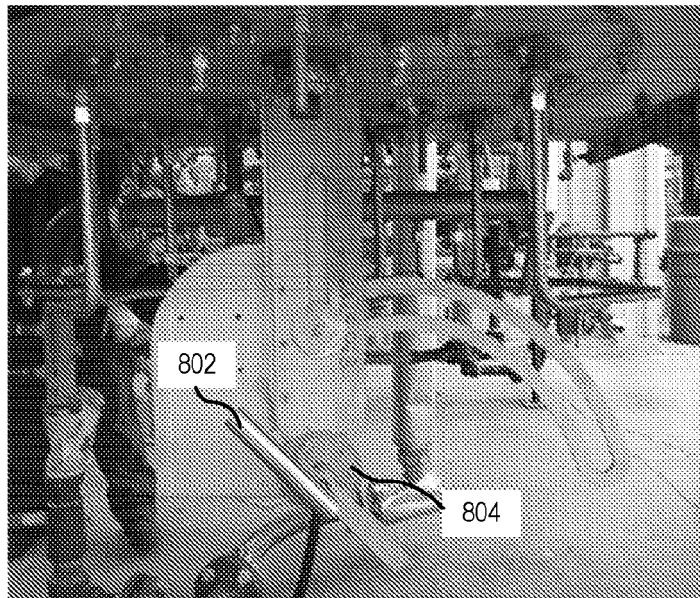


FIG. 8

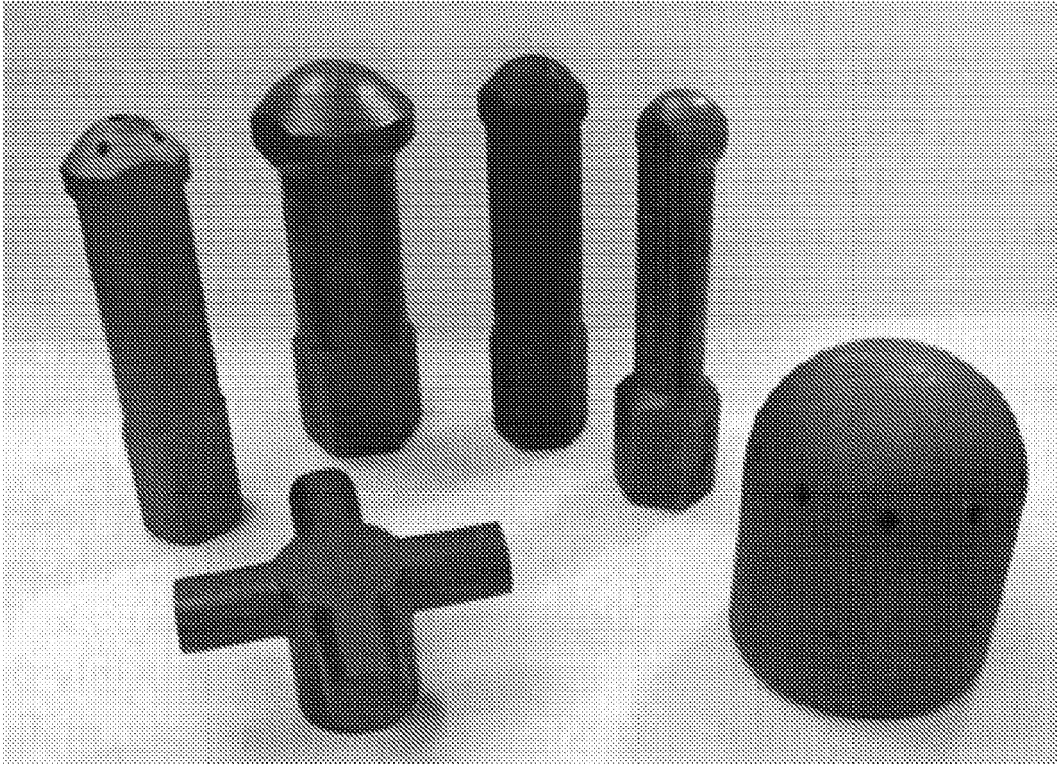


FIG. 9

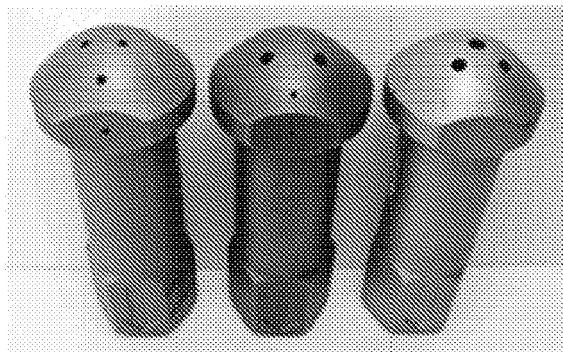
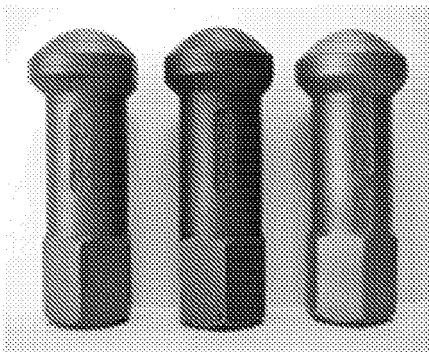


FIG. 10

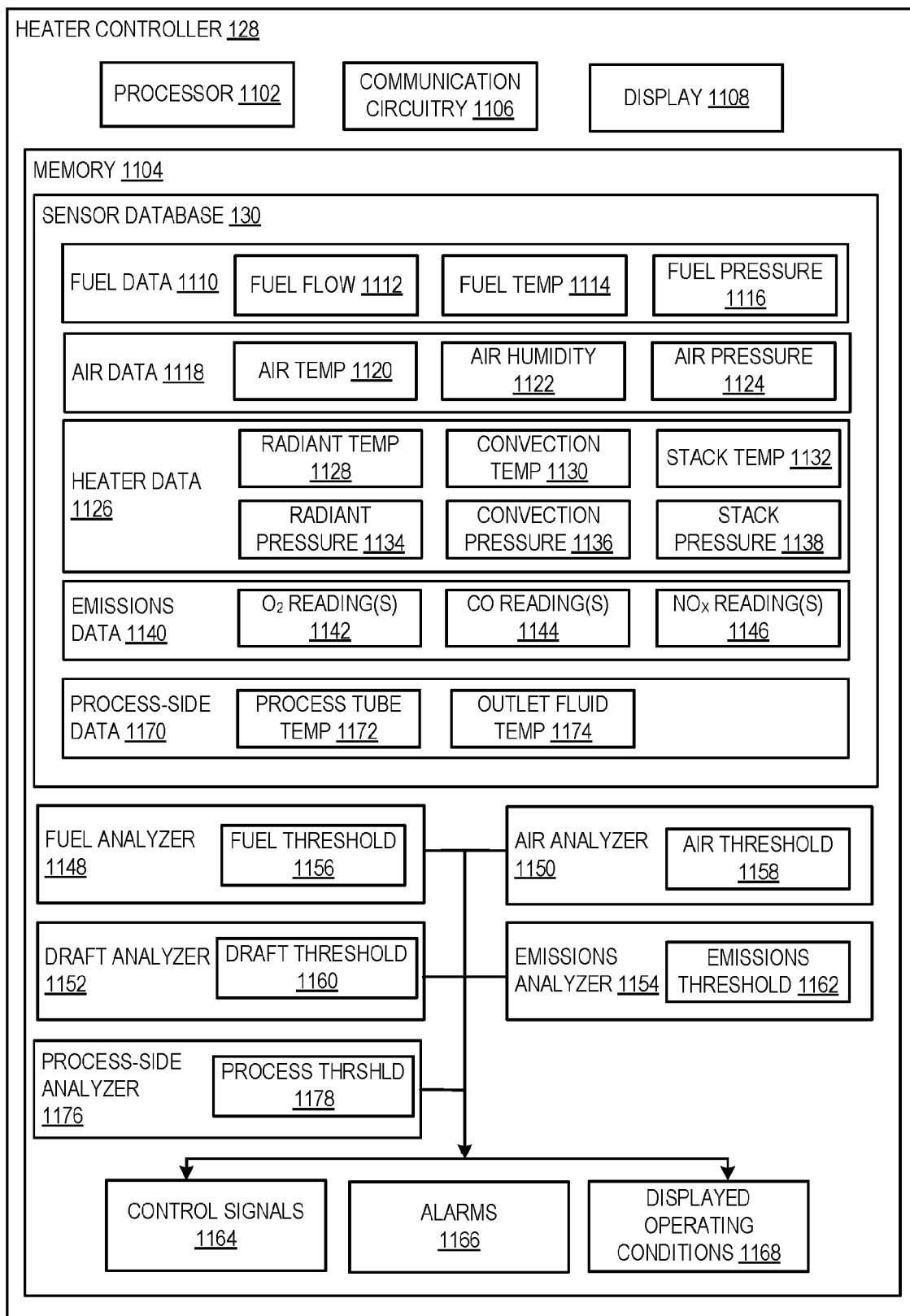


FIG. 11

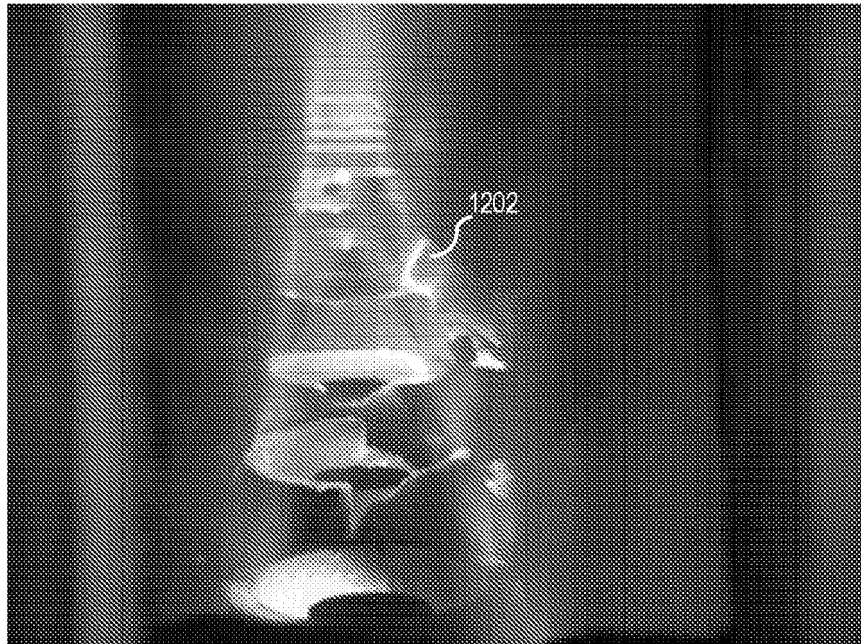


FIG. 12

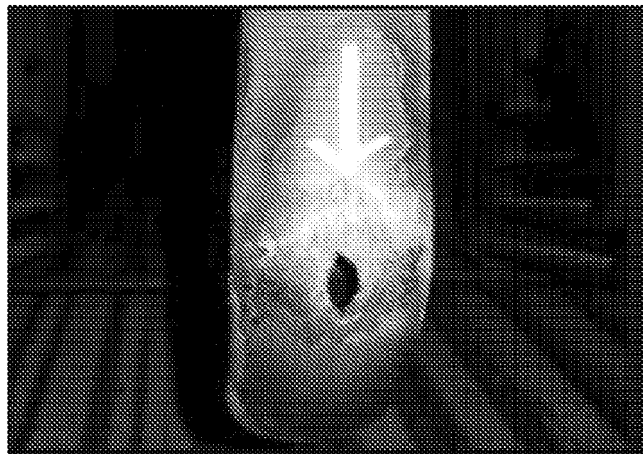


FIG. 13

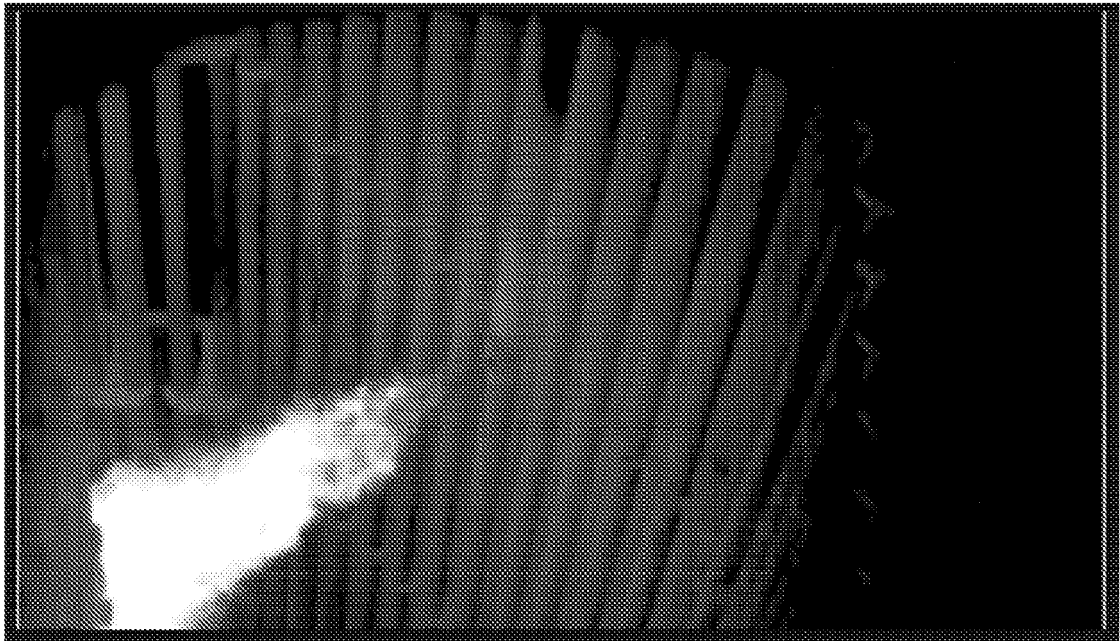


FIG. 14

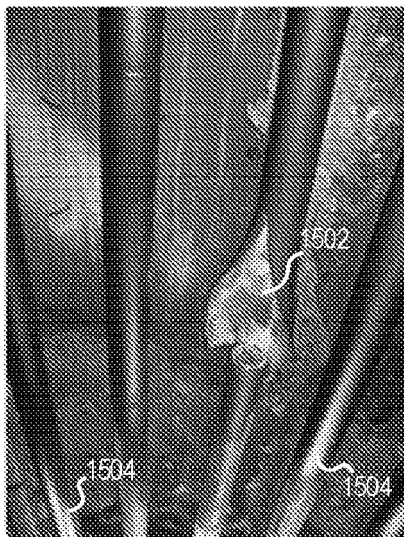


FIG. 15



FIG. 16

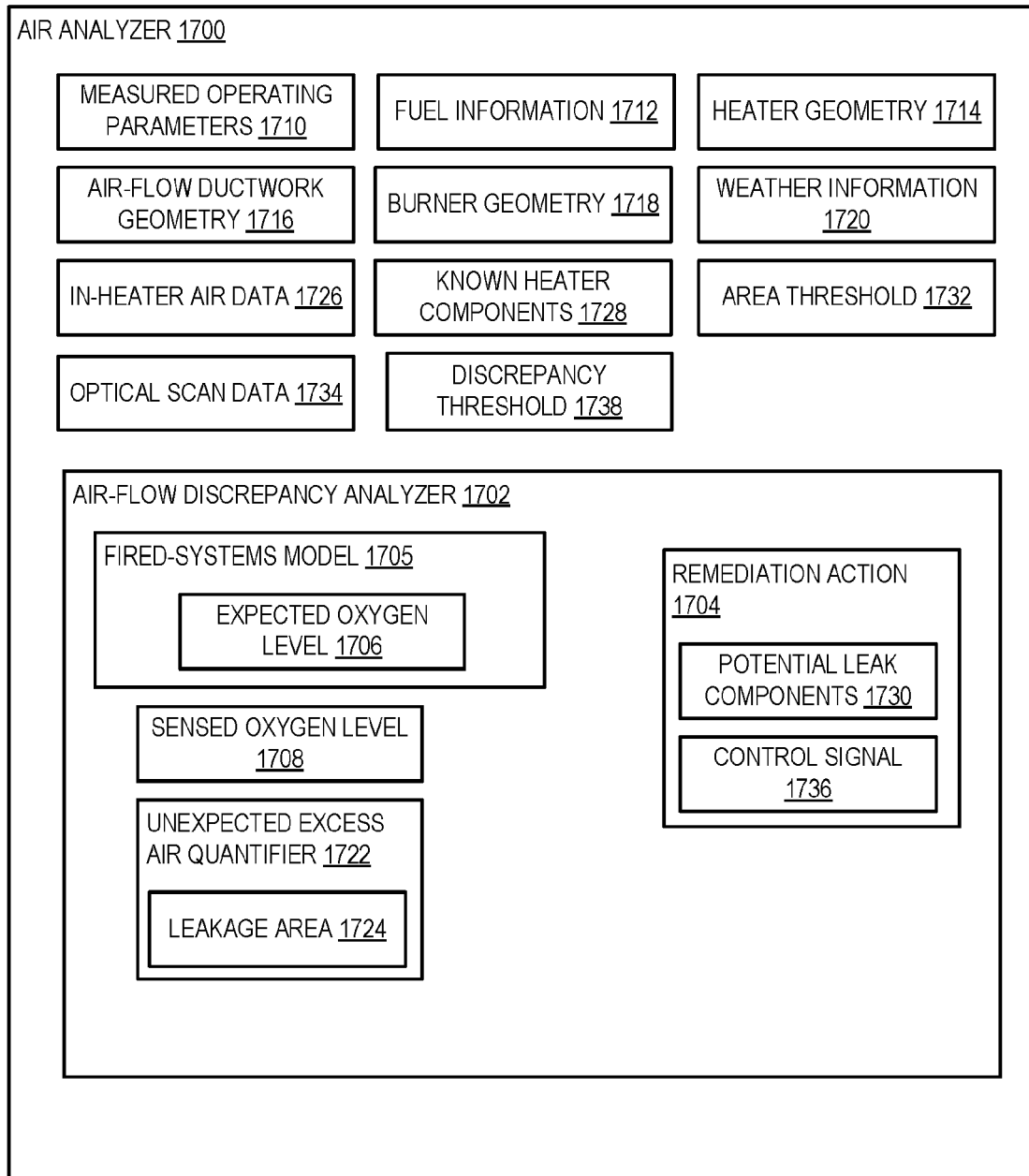


FIG. 17

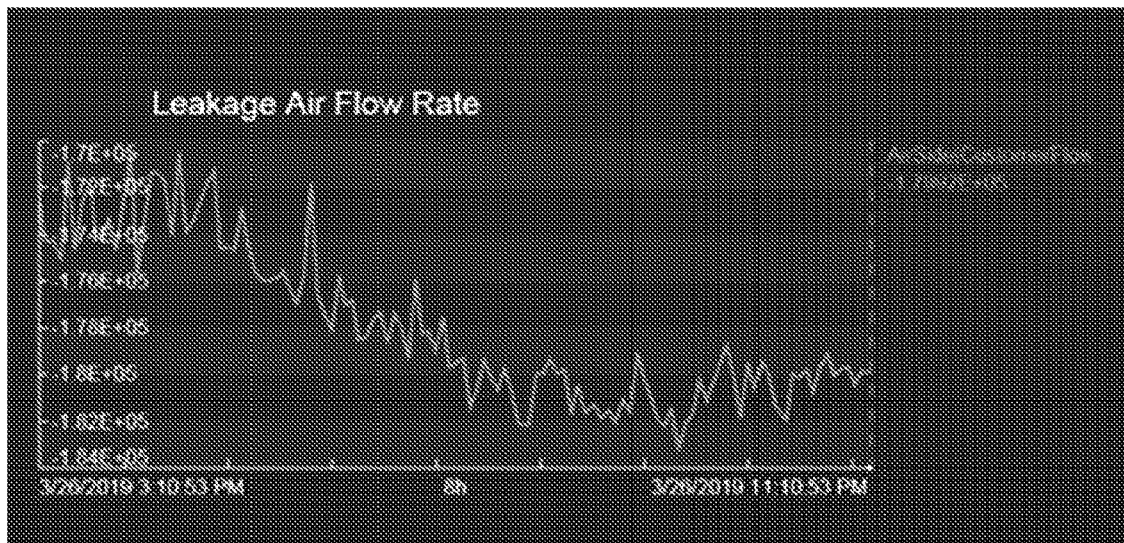


FIG. 18

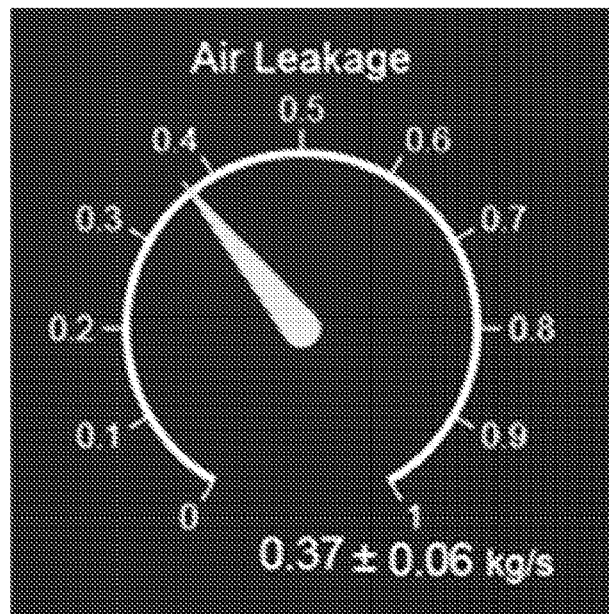


FIG. 19

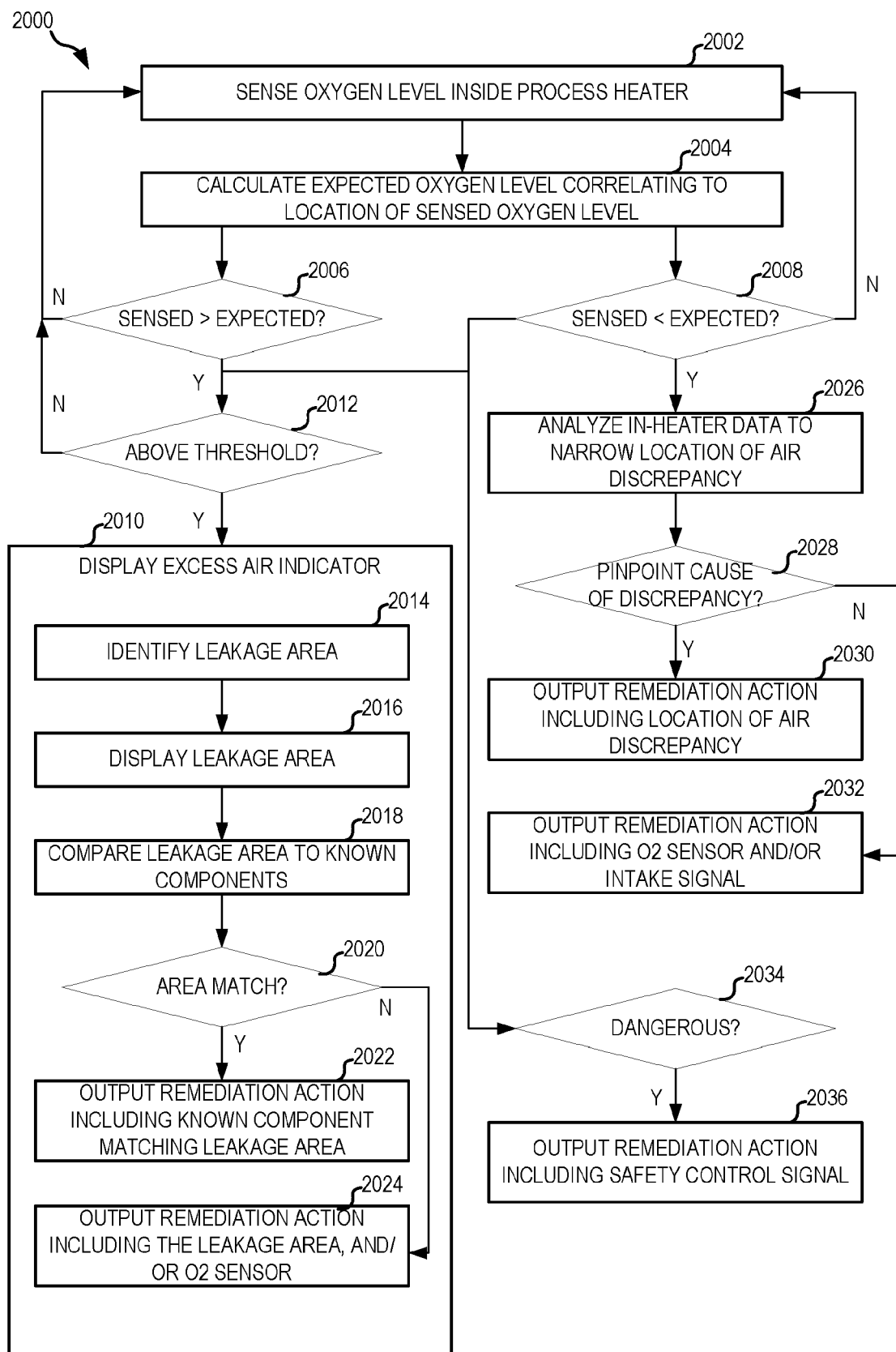


FIG. 20

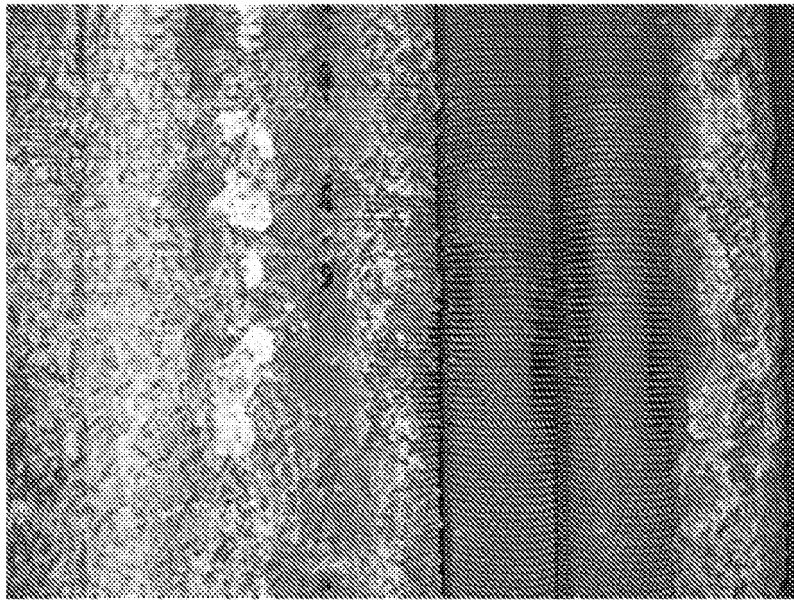


FIG. 21

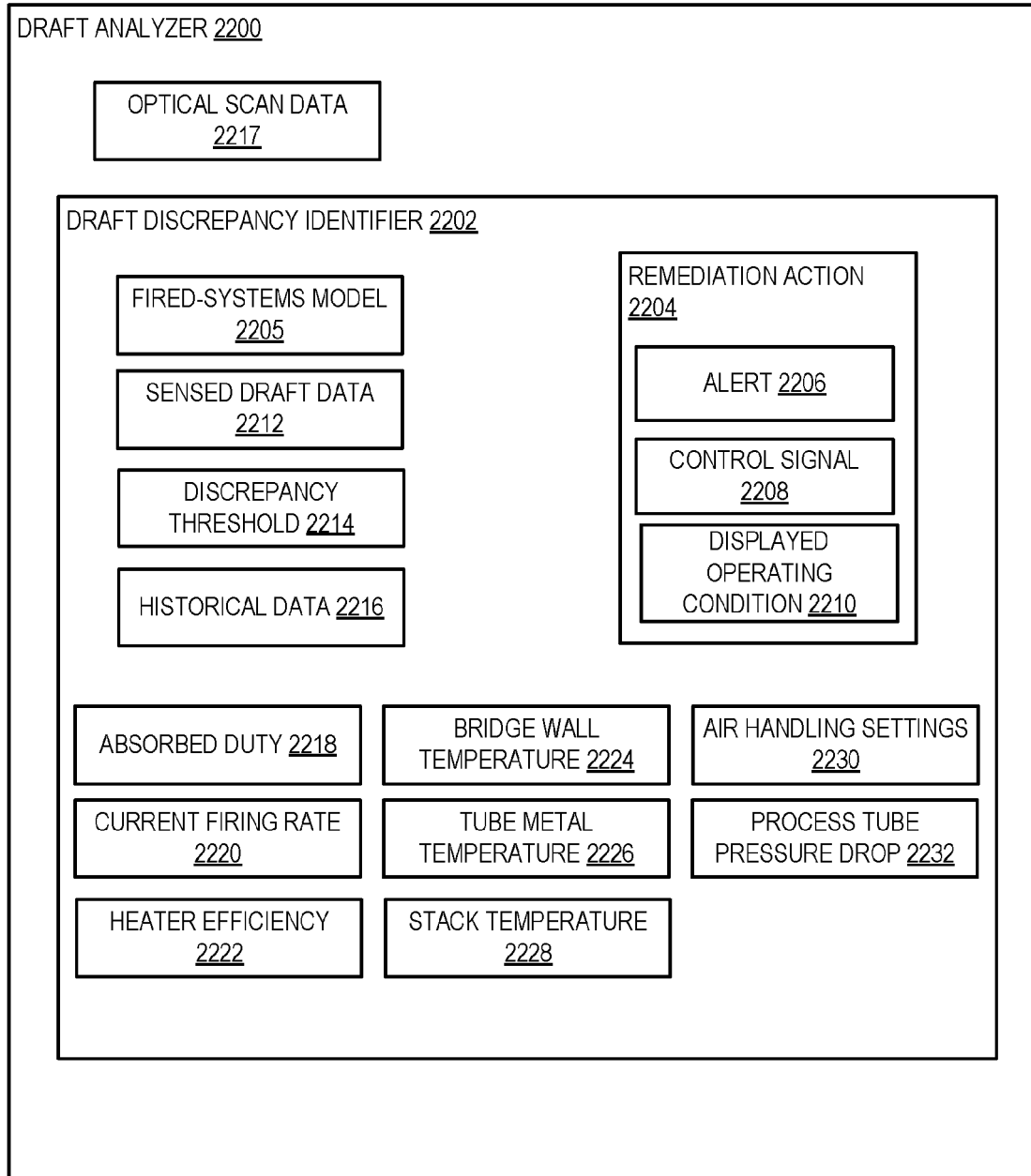


FIG. 22

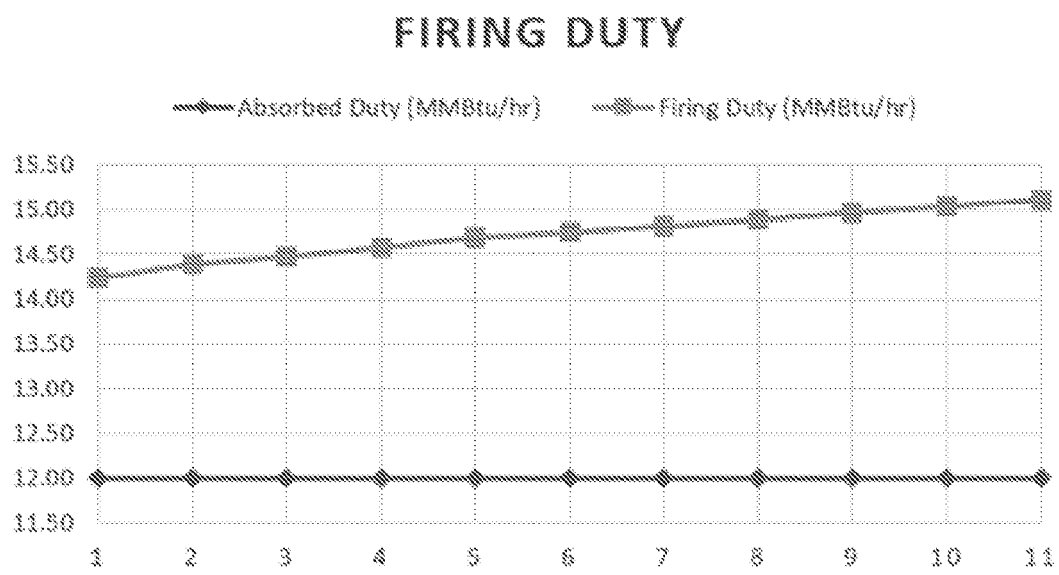


FIG. 23

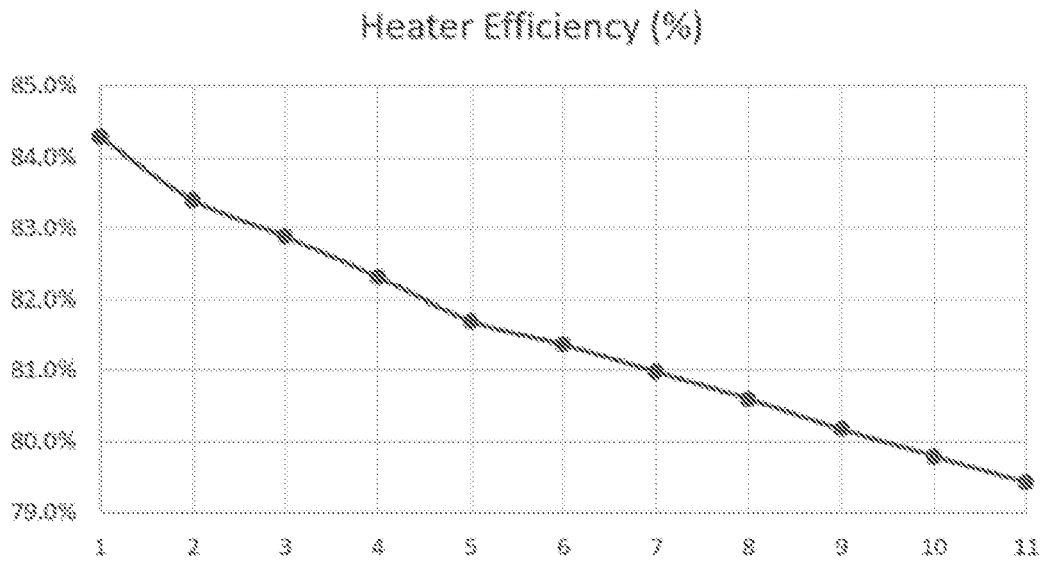


FIG. 24

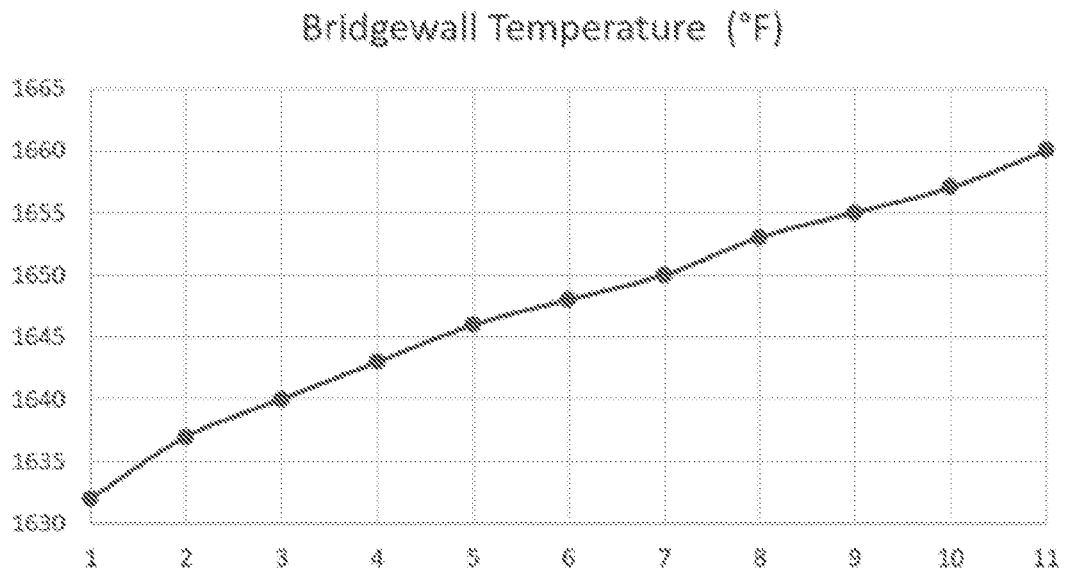


FIG. 25

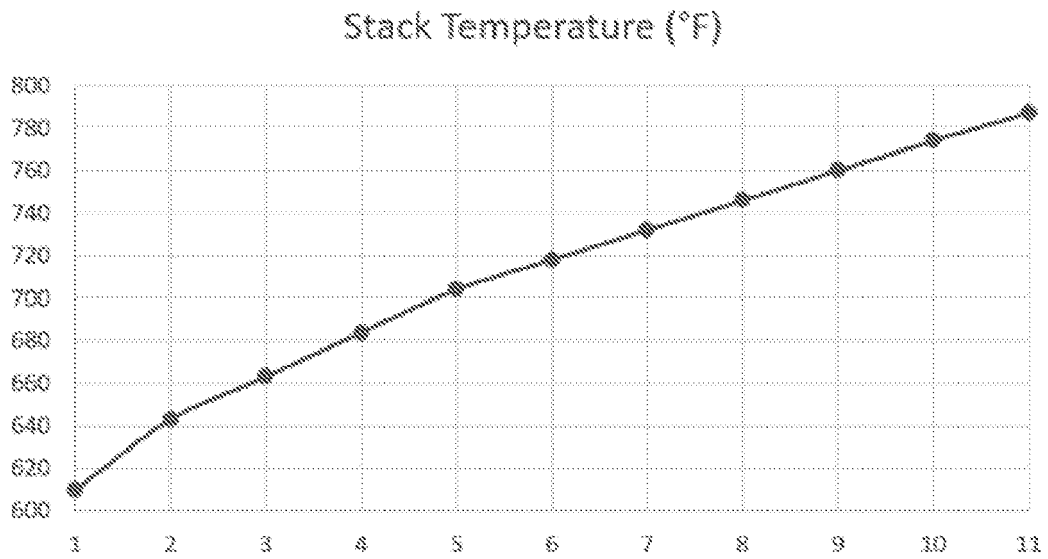


FIG. 26

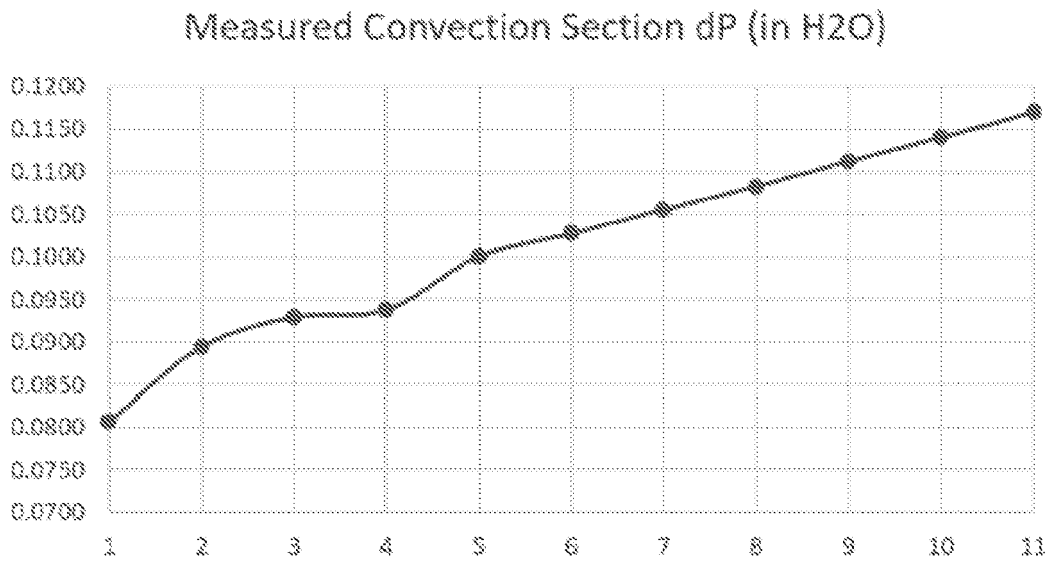


FIG. 27

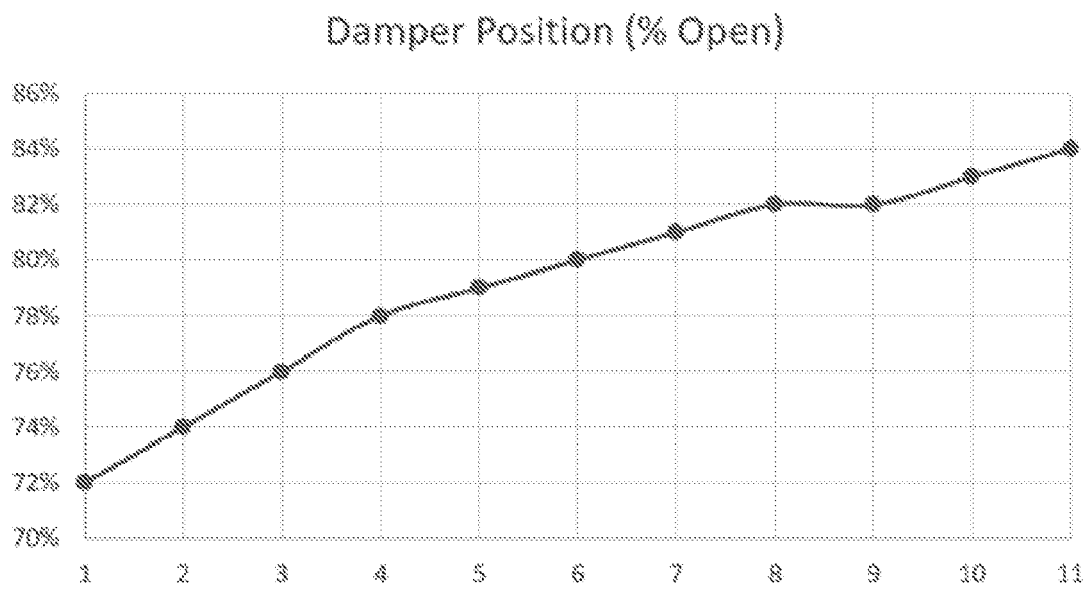


FIG. 28



Cases	Absorbed Duty (MMBtu/hr)	Firing Duty (MMBtu/hr)	Heater Efficiency (%)	Bridgwall Temperature (°F)	Maximum TMT (°F)	Stack Temperature (°F)	Convection Section dP (in H ₂ O)	Damper Position (% Open)	Modeled Convection Section dP (inH ₂ O)
SOR	12	14.24	84.30%	1632	661	610	0.0806	72%	0.08
2	12	14.39	83.40%	1637	662	643	0.0894	74%	0.08
3	12	14.48	82.90%	1640	662	663	0.0929	76%	0.08
4	12	14.58	82.30%	1643	662	684	0.0937	78%	0.08
5	12	14.69	81.70%	1646	663	704	0.1	79%	0.08
6	12	14.75	81.40%	1648	663	718	0.1027	80%	0.08
7	12	14.82	81.00%	1650	663	732	0.1055	81%	0.08
8	12	14.89	80.60%	1653	663	746	0.1082	82%	0.08
9	12	14.97	80.20%	1655	664	760	0.1112	82%	0.08
10	12	15.04	79.80%	1657	664	774	0.114	83%	0.09
11	12	15.11	79.40%	1660	664	787	0.117	84%	0.09

FIG. 29



FIG. 30





FIG. 31

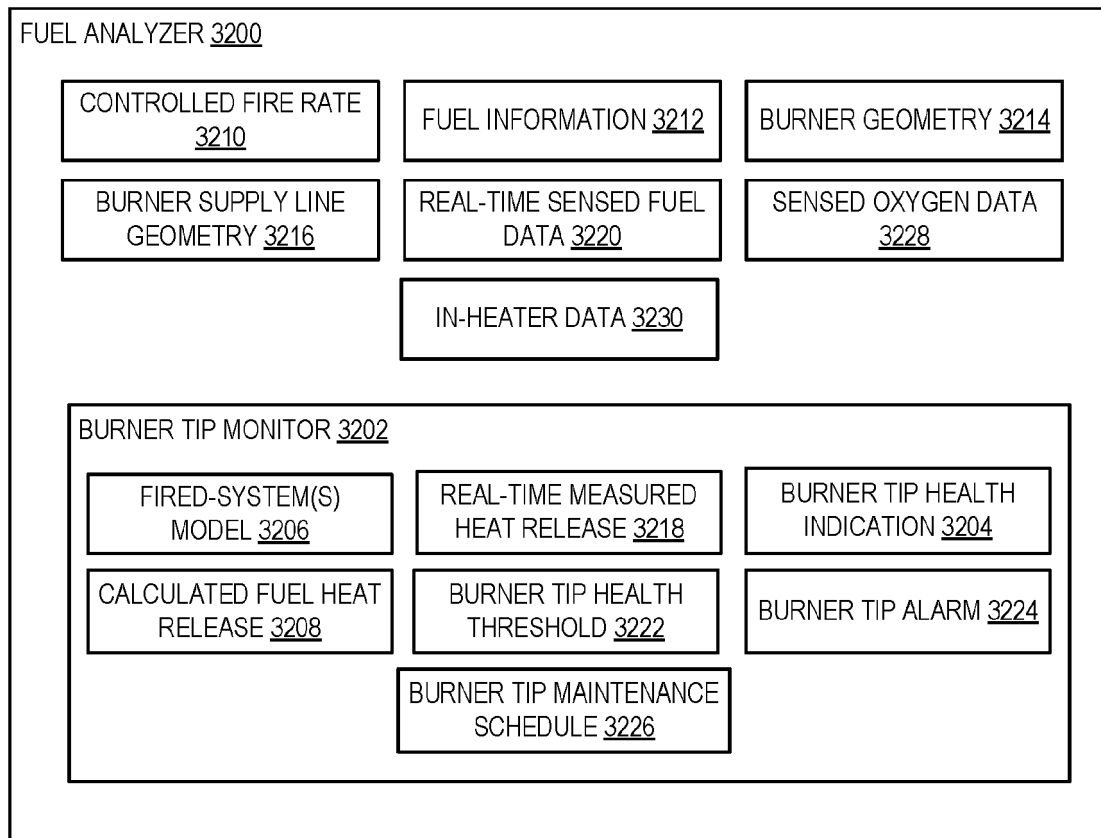


FIG. 32

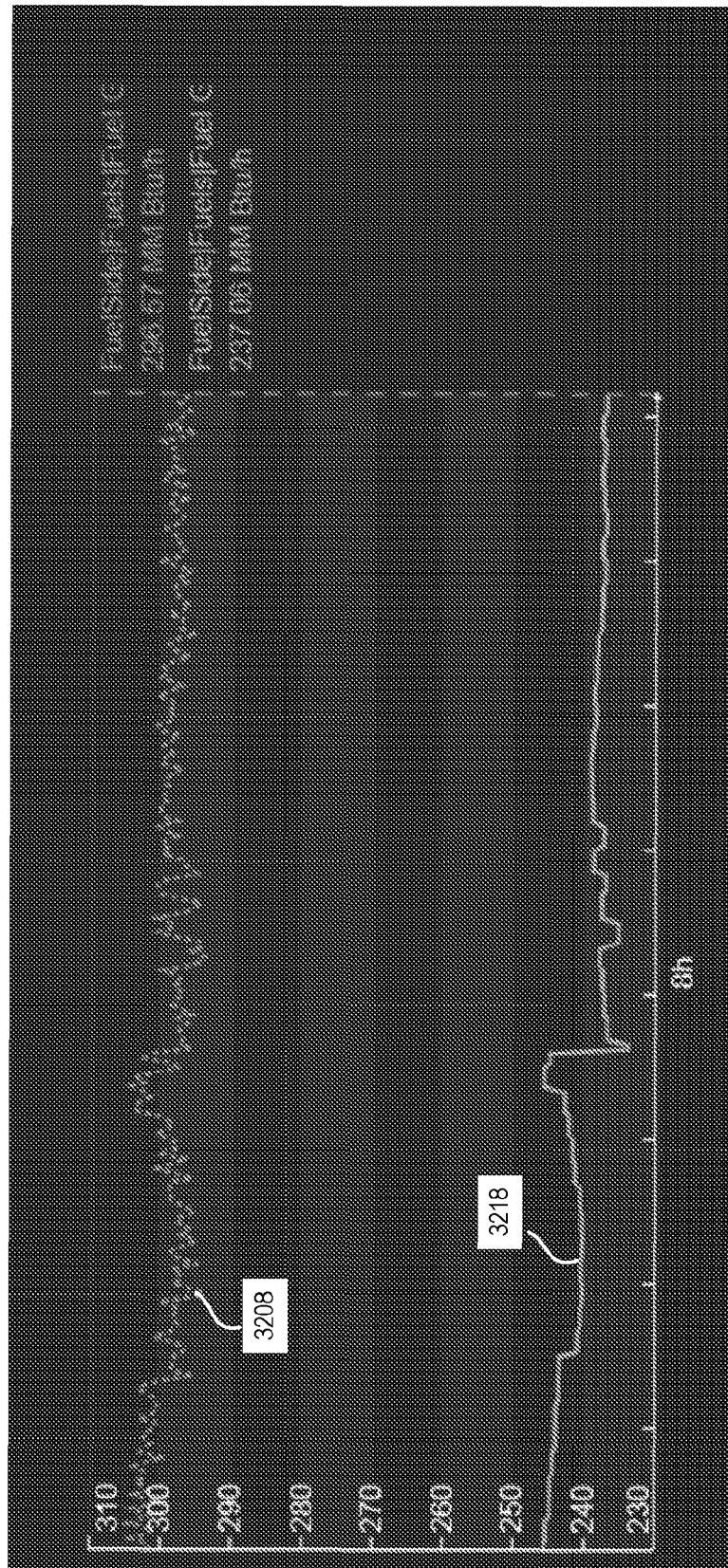


FIG. 33

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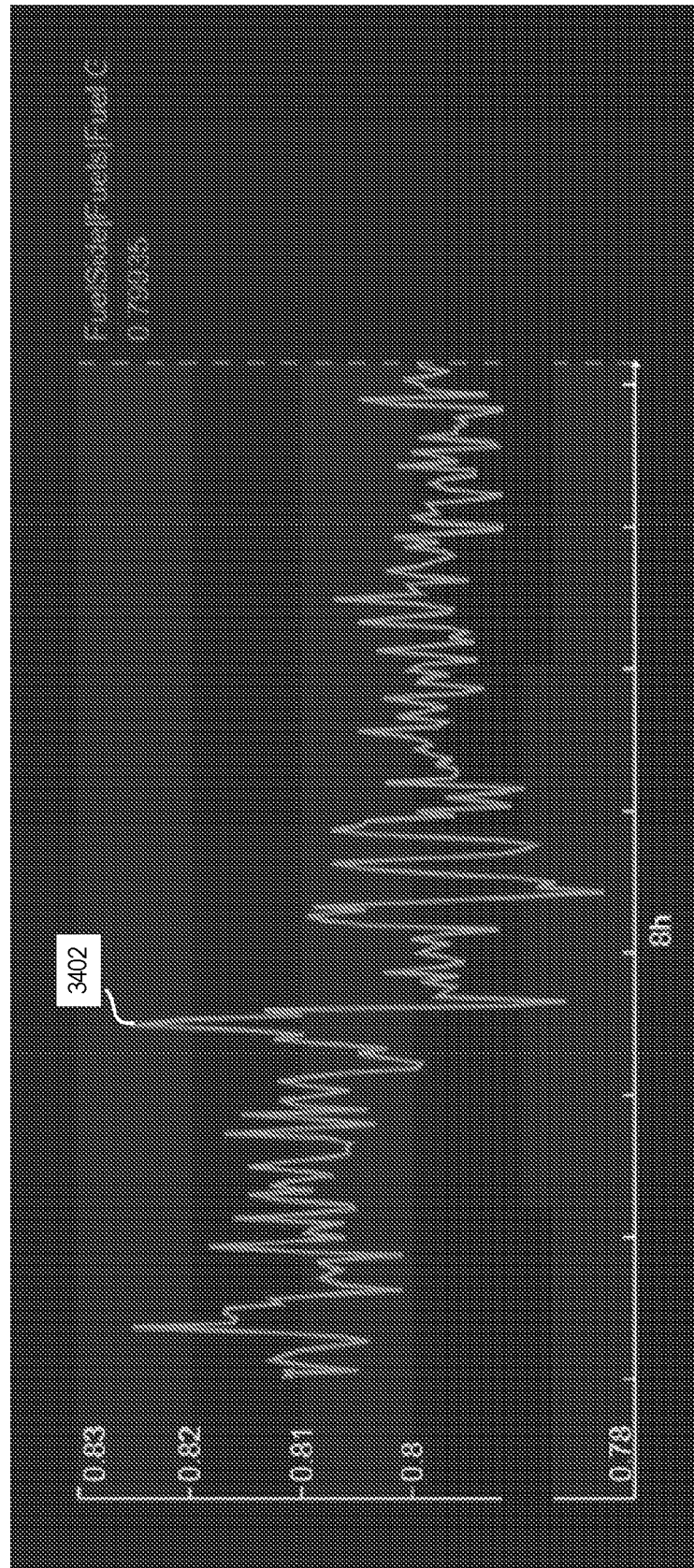


FIG. 34

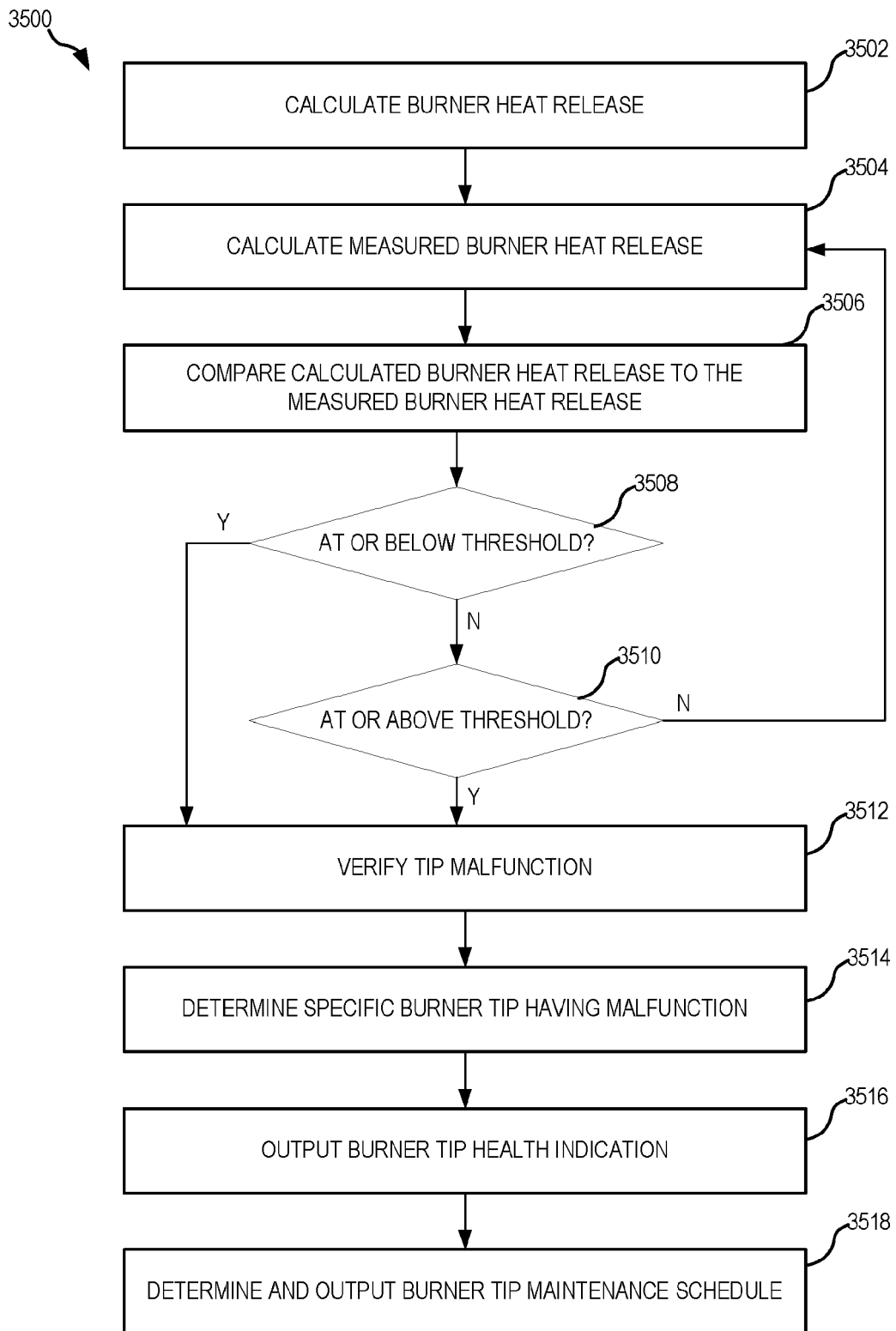


FIG. 35

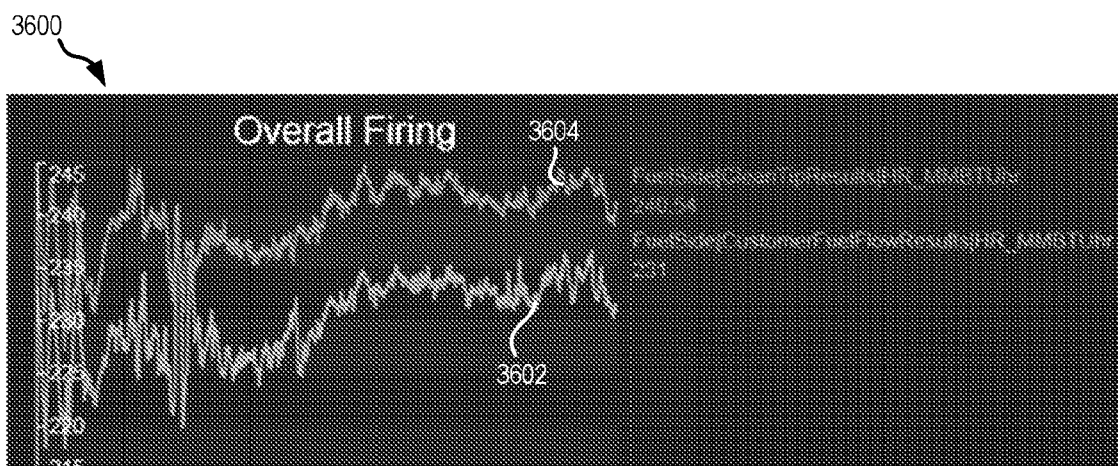


FIG. 36

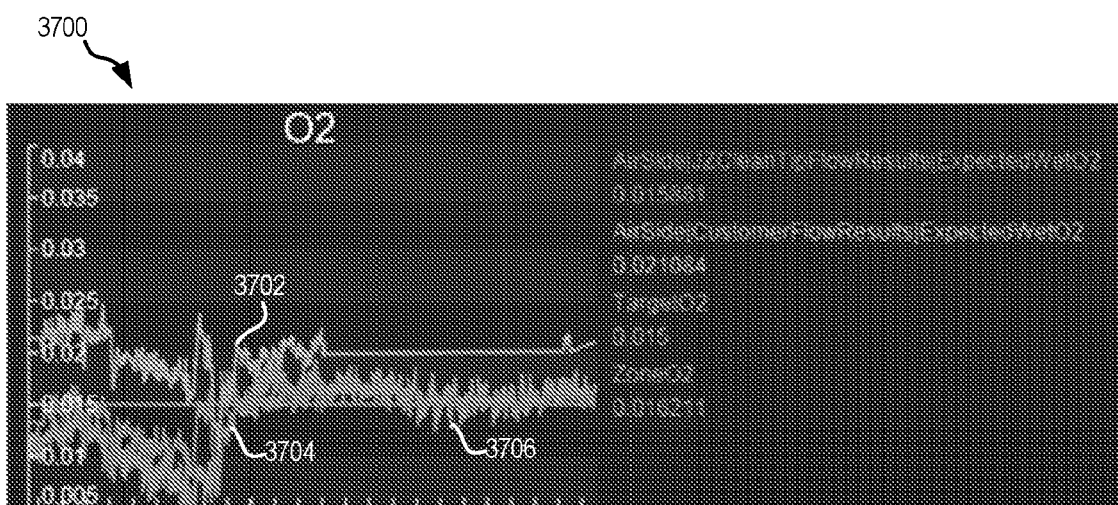


FIG. 37

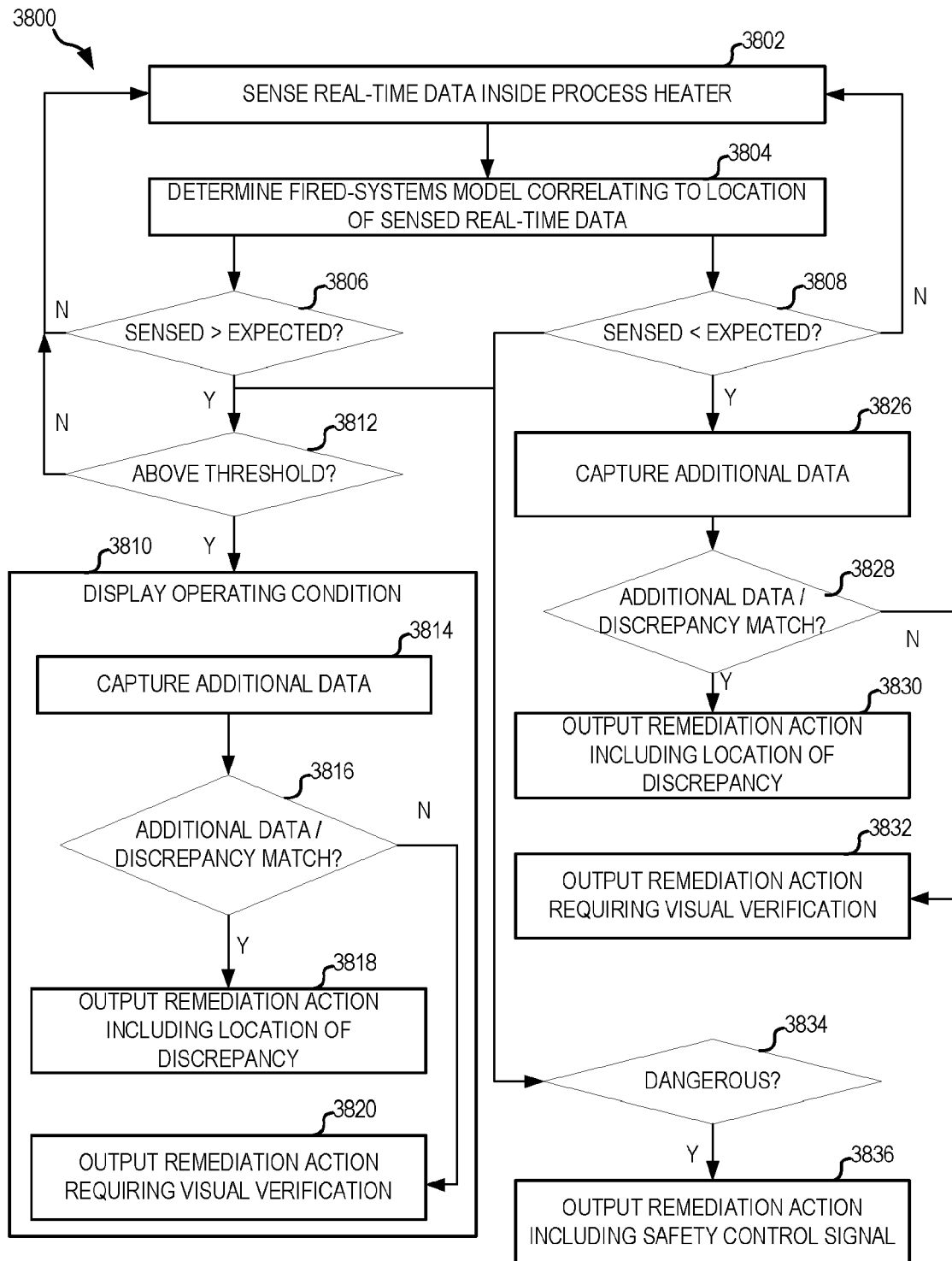


FIG. 38



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			F23L F23N F23D
The present search report has been drawn up for all claims			
Place of search Munich		Date of completion of the search 11 March 2022	Examiner Hauck, Gunther
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