US 20210190311A1

(19) United States

(12) Patent Application Publication (10) Pub. No.: US 2021/0190311 A1

Lee et al. (43) Pub. Date: Jun. 24, 2021

(54) **SYSTEM AND METHOD FOR BIOMASS COMBUSTION**

(71) Applicant: **Morgan State University**, Baltimore, MD (US)

(72) Inventors: **Seong W. Lee**, Baltimore, MD (US); **Xuejun Qian**, Baltimore, MD (US); **Yulai Yang**, Baltimore, MD (US); **Raghul Kumar Chandrasekaran**, Baltimore, MD (US); **Oludayo Alamu**, Baltimore, MD (US); **Blaise Kalmia**, Baltimore, MD (US)

(21) Appl. No.: **17/195,790**

(22) Filed: **Mar. 9, 2021**

Related U.S. Application Data

(63) Continuation-in-part of application No. 16/378,986, filed on Apr. 9, 2019, now abandoned, which is a continuation of application No. 15/056,179, filed on Feb. 29, 2016, now Pat. No. 10,253,974.

(60) Provisional application No. 62/121,843, filed on Feb. 27, 2015, provisional application No. 63/089,760, filed on Oct. 9, 2020, provisional application No. 63/112,717, filed on Nov. 12, 2020, provisional application No. 63/117,744, filed on Nov. 24, 2020, provisional application No. 63/117,732, filed on Nov. 24, 2020.

Publication Classification

(51) **Int. Cl.**

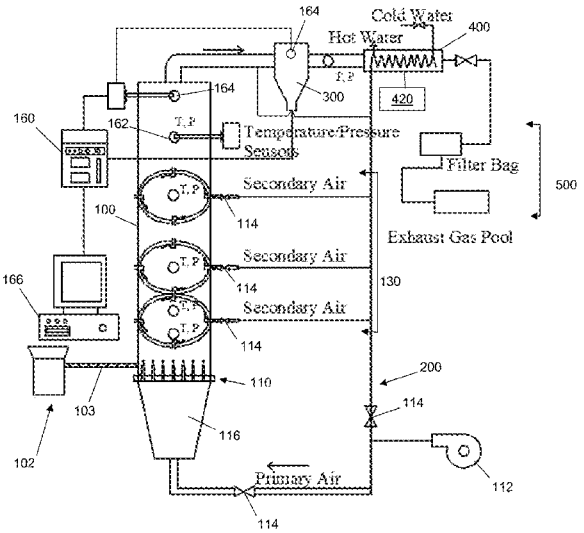
F23C 10/20	(2006.01)
F23G 5/30	(2006.01)
F23G 5/44	(2006.01)
F23G 5/50	(2006.01)
F23G 5/46	(2006.01)
F23C 10/12	(2006.01)
F23G 5/14	(2006.01)

(52) **U.S. Cl.**

CPC ***F23C 10/20*** (2013.01); *F23G 2200/00* (2013.01); ***F23G 5/444*** (2013.01); ***F23G 5/50*** (2013.01); ***F23G 5/46*** (2013.01); ***F23C 10/12*** (2013.01); ***F23G 5/14*** (2013.01); *F23G 2203/50* (2013.01); *F23G 2202/10* (2013.01); *F23G 2207/102* (2013.01); *F23G 2206/10* (2013.01); *F23G 2207/101* (2013.01); *F23G 2209/262* (2013.01); *F23G 2207/30* (2013.01); ***F23G 5/30*** (2013.01)

(57) **ABSTRACT**

Disclosed is a system and method for the combustion of biomass material employing a swirling fluidized bed combustion (SFBC) chamber, and preferably a second stage combustion carried out in a cyclone separator. In the combustion chamber, primary air is introduced from a bottom air box that fluidizes the bed material and fuel, and staged secondary air is introduced in the tangential direction and at varied vertical positions in the combustion chamber so as to cause the materials in the combustion chamber (i.e., the mixture of air and particles) to swirl. The secondary air injection can have a significant effect on the air-fuel particle flow in the combustion chamber, and more particularly strengthens the swirling flow, promotes axial recirculation, increases particle mass fluxes in the combustion chamber, and retains more fuel particles in the combustion chamber. This process increases the residence time of the particle flow. The turbulent flow of the fuel particles and air is well mixed and mostly burned in the combustion chamber, with any unburned waste and particles being directed to the cyclone separator, where such unburned waste and particles are burned completely, and flying ash is divided and collected in a container connected to the cyclone separator, while dioxin production is significantly minimized if not altogether eliminated. A Stirling engine along with cooling system and engine control box is integrated with the SFBC chamber to produce electricity from the waste combustion process. Residual heat in the flue gas may be captured after the combustion chamber and directed to a fuel feeder to first dry the biomass. System exhaust is directed to a twisted tube-based shell and tube heat exchanger (STHE) and may produce hot water for space heating.



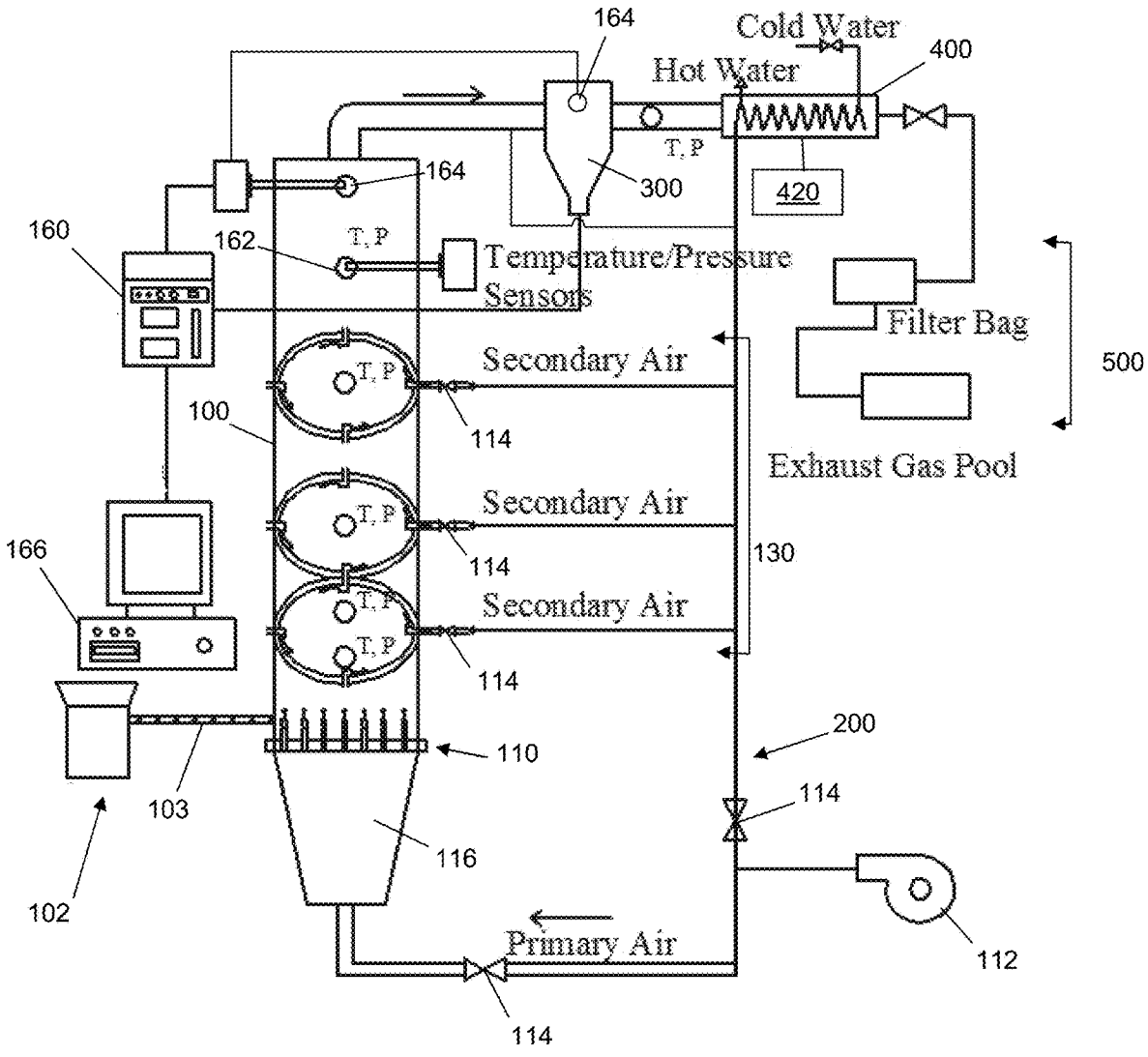

164
Cold Water
400
Hot Water
T, P
164
300
420
160
162
T, P
Temperature/Pressure
Sensors
Filter Bag
500
Secondary Air
T, P
100
114
Exhaust Gas Pool
Secondary Air
T, P
166
114
130
Secondary Air
T, P
T, P
114
200
110
114
103
116
102
Primary Air
112
114

FIGURE 1

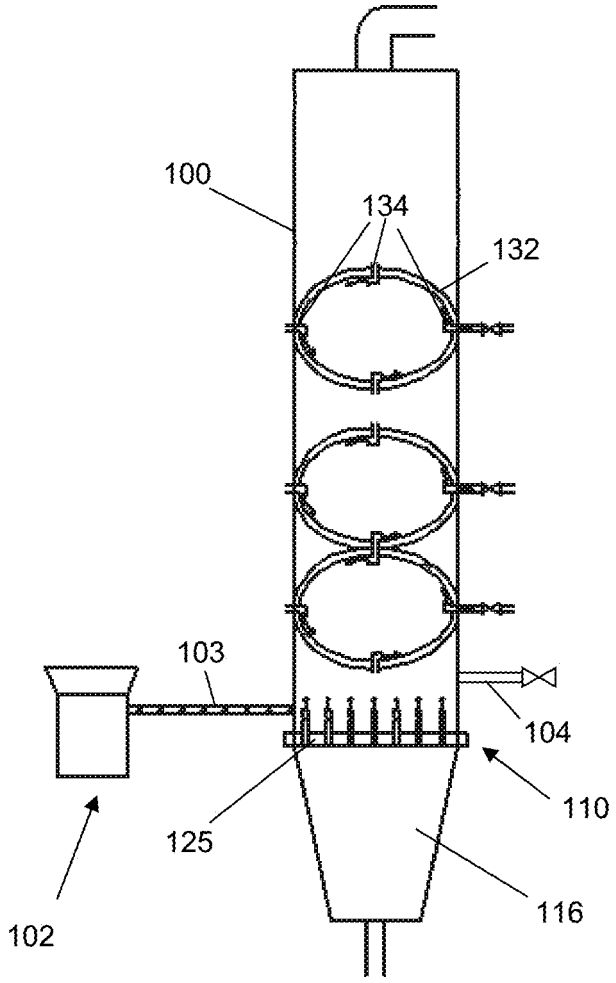


FIGURE 2

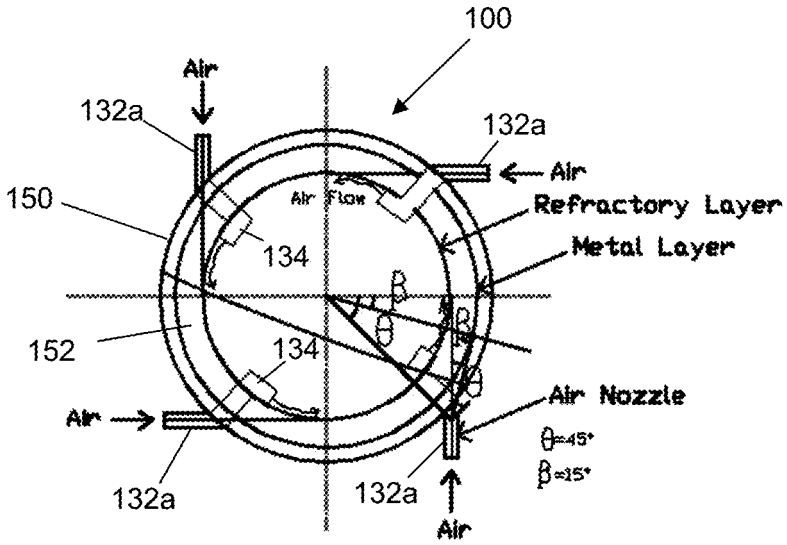


FIGURE 3

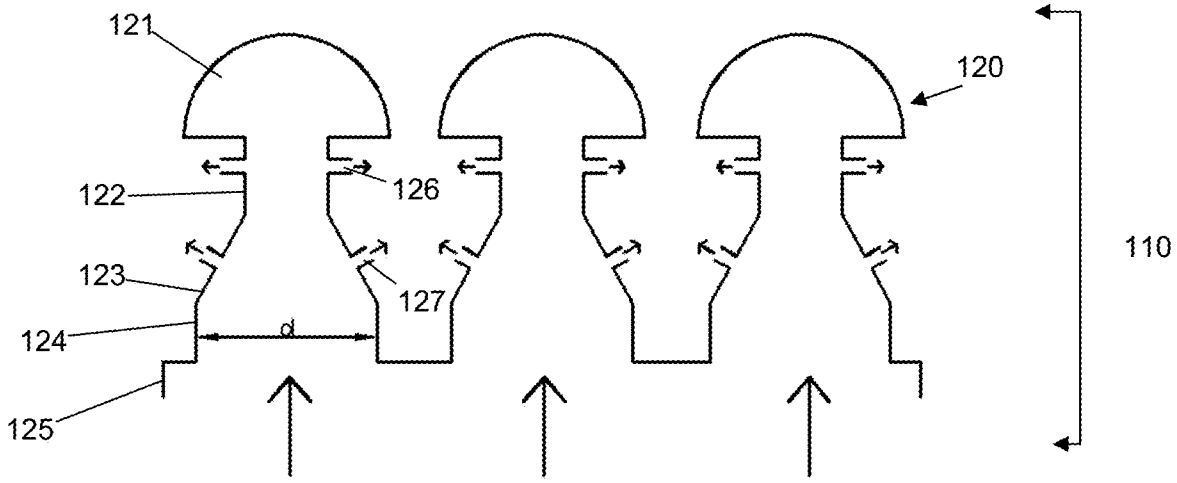


Diagram of the Bubble-Cap Primary Air Distributor

FIGURE 4

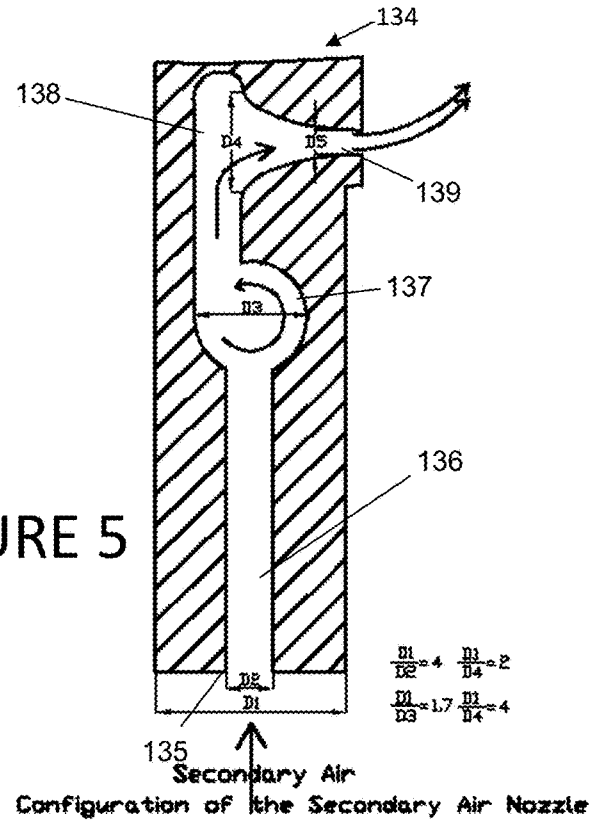


FIGURE 5

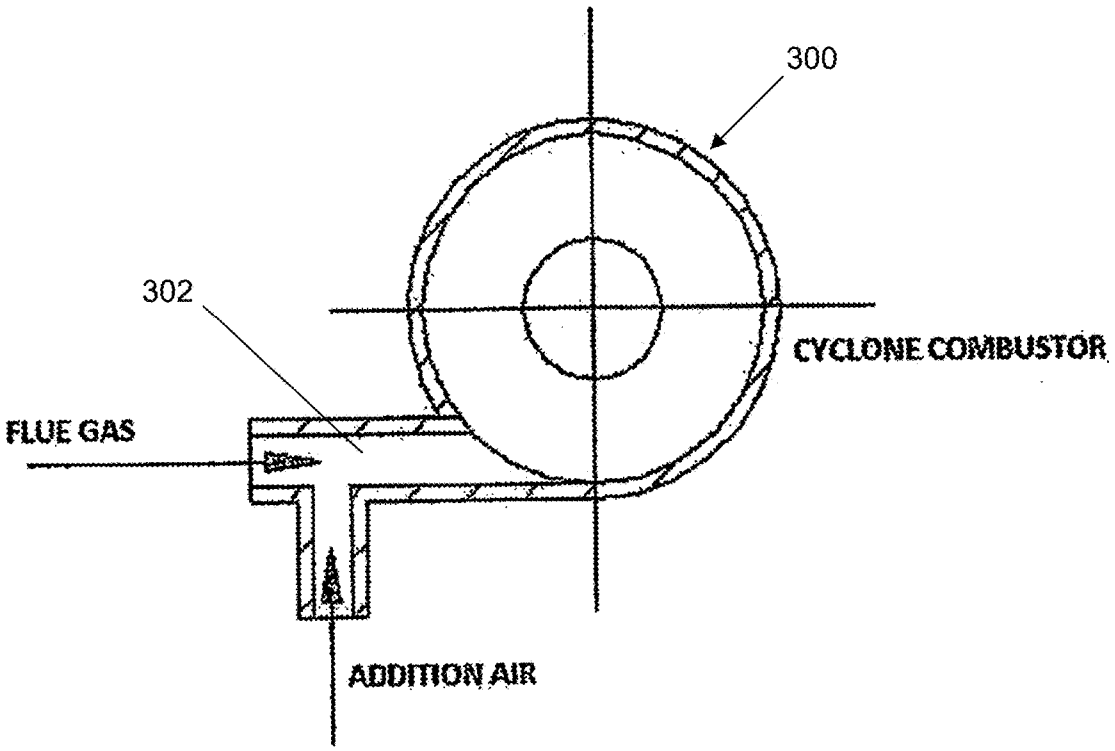


FIGURE 6

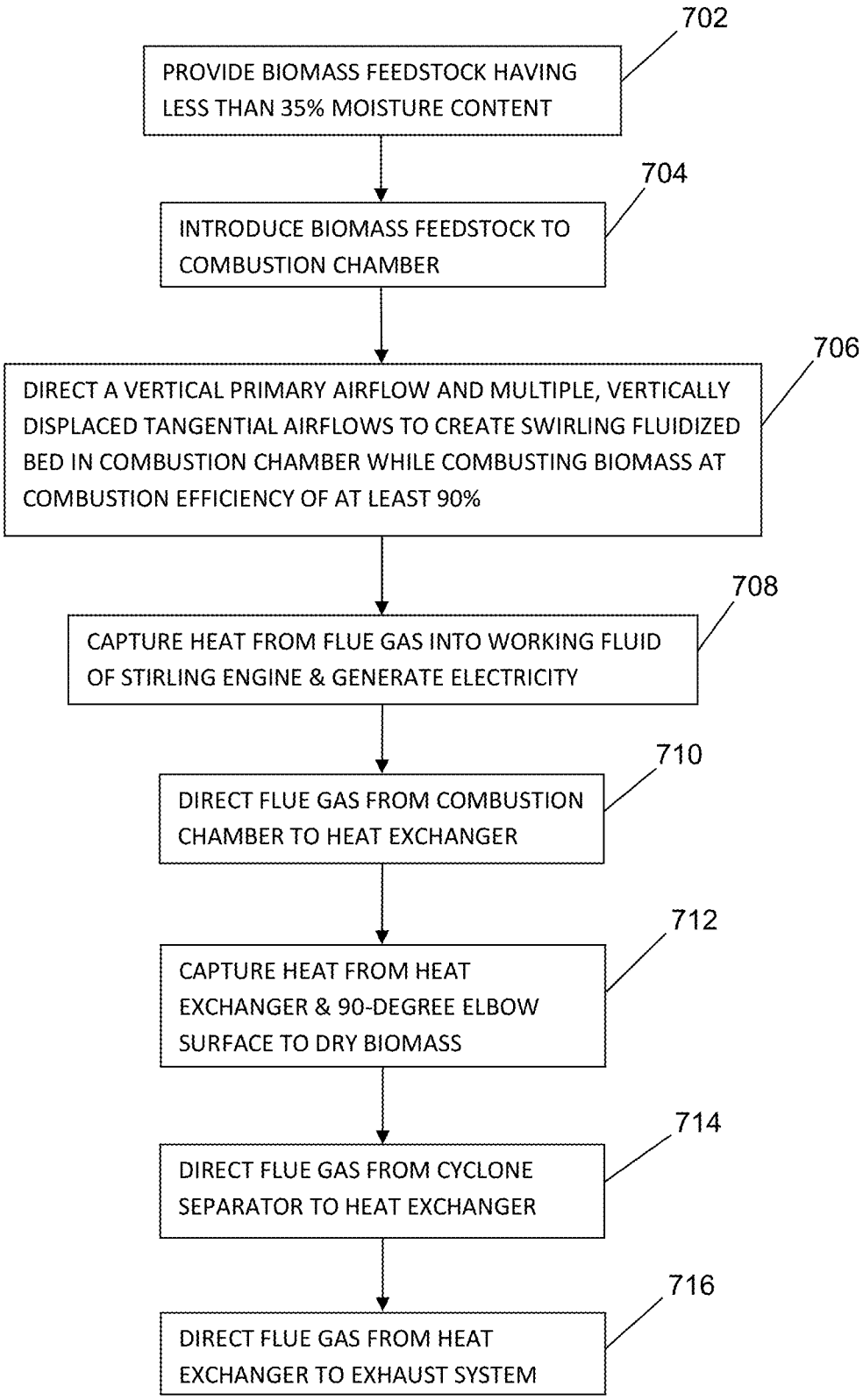

702
PROVIDE BIOMASS FEEDSTOCK HAVING LESS THAN 35% MOISTURE CONTENT
704
INTRODUCE BIOMASS FEEDSTOCK TO COMBUSTION CHAMBER
706
DIRECT A VERTICAL PRIMARY AIRFLOW AND MULTIPLE, VERTICALLY DISPLACED TANGENTIAL AIRFLOWS TO CREATE SWIRLING FLUIDIZED BED IN COMBUSTION CHAMBER WHILE COMBUSTING BIOMASS AT COMBUSTION EFFICIENCY OF AT LEAST 90%
708
CAPTURE HEAT FROM FLUE GAS INTO WORKING FLUID OF STIRLING ENGINE & GENERATE ELECTRICITY
710
DIRECT FLUE GAS FROM COMBUSTION CHAMBER TO HEAT EXCHANGER
712
CAPTURE HEAT FROM HEAT EXCHANGER & 90-DEGREE ELBOW SURFACE TO DRY BIOMASS
714
DIRECT FLUE GAS FROM CYCLONE SEPARATOR TO HEAT EXCHANGER
716
DIRECT FLUE GAS FROM HEAT EXCHANGER TO EXHAUST SYSTEM

FIGURE 7

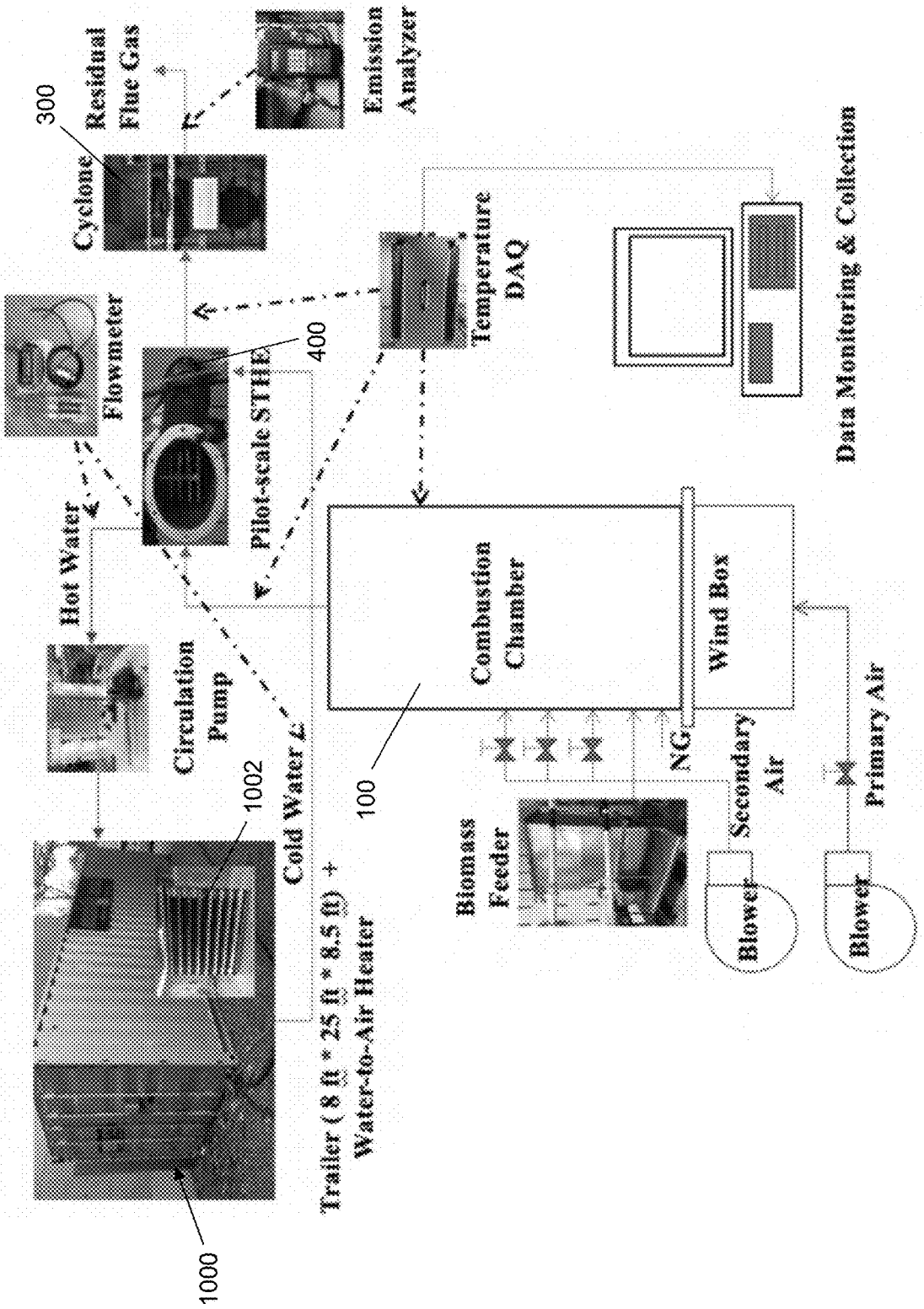

1000
1002
Trailer (8 ft * 25 ft * 8.5 ft) +
Water-to-Air Heater
Cold Water
Hot Water
Circulation Pump
Flowmeter
Pilot-scale STHE
400
300
Cyclone
Residual Flue Gas
Emission Analyzer
Temperature DAQ
Data Monitoring & Collection
100
Combustion Chamber
Wind Box
NG
Secondary Air
Primary Air
Blower
Blower
Biomass Feeder

FIG. 8

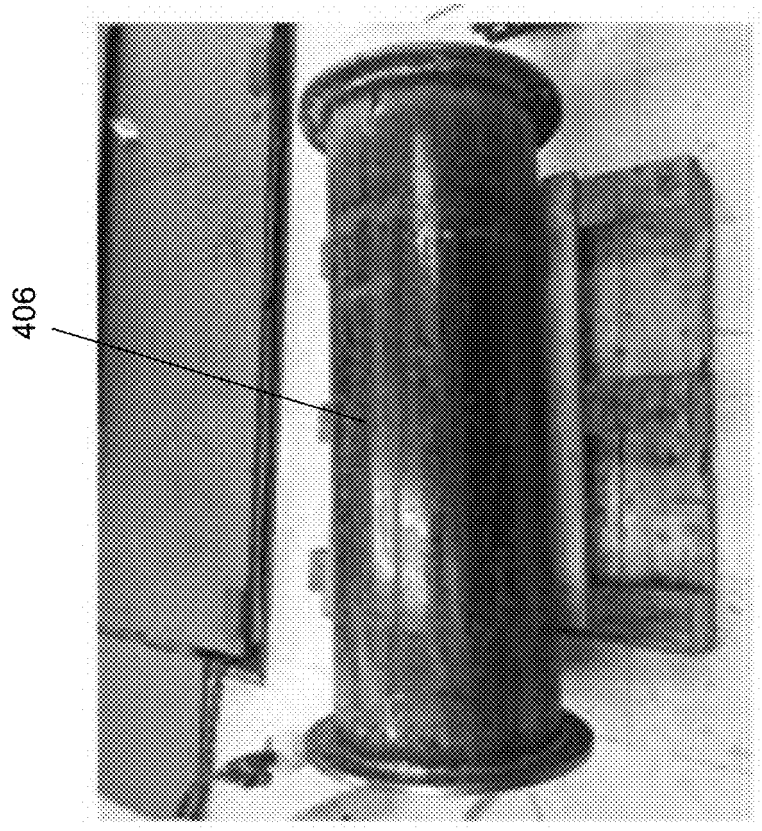


FIG. 9(b)

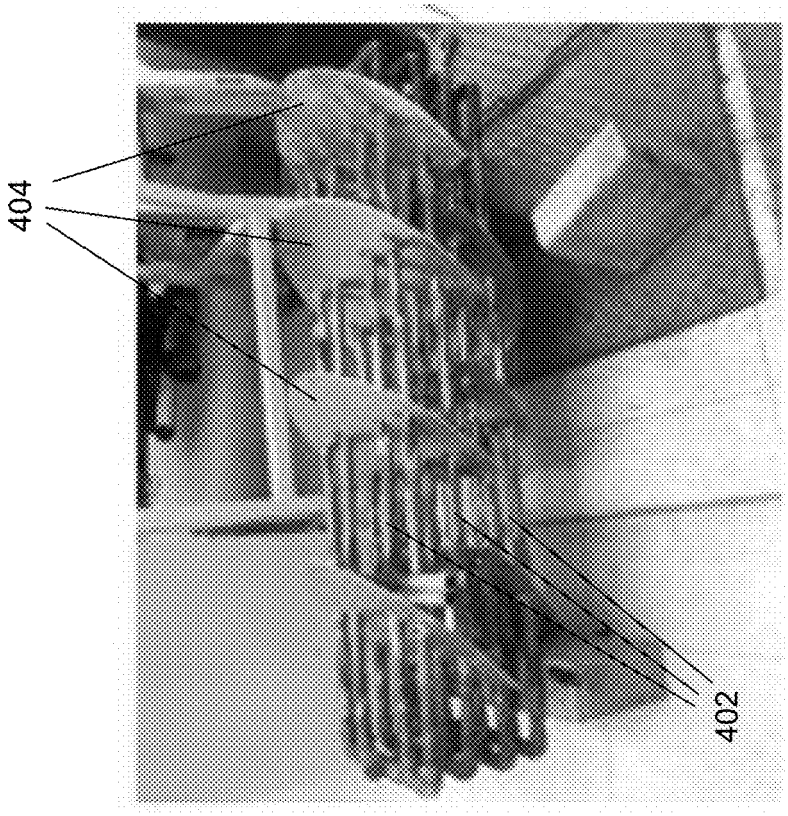


FIG. 9(a)

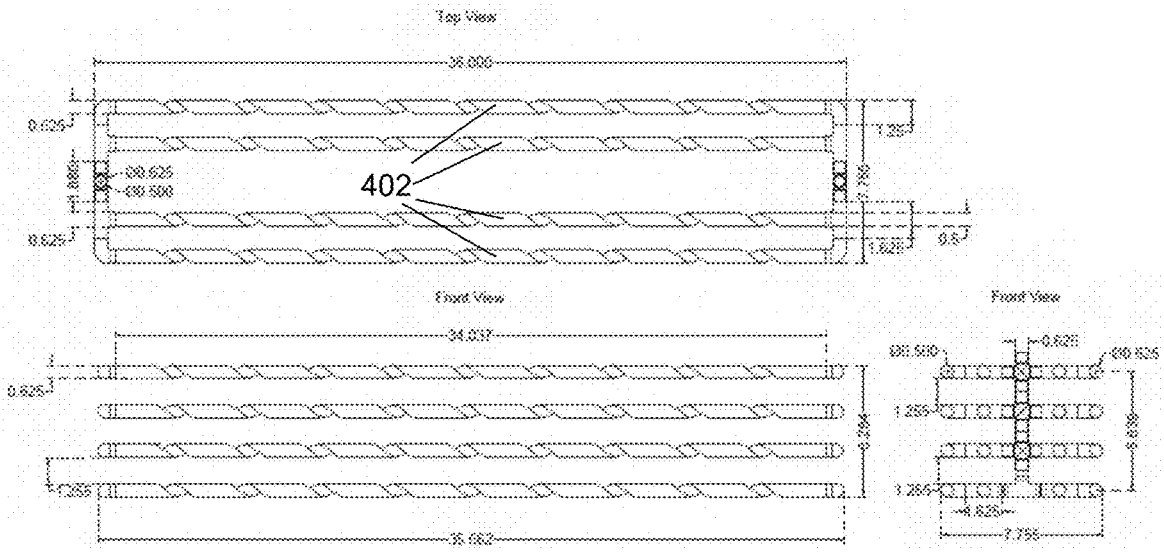


FIG. 10

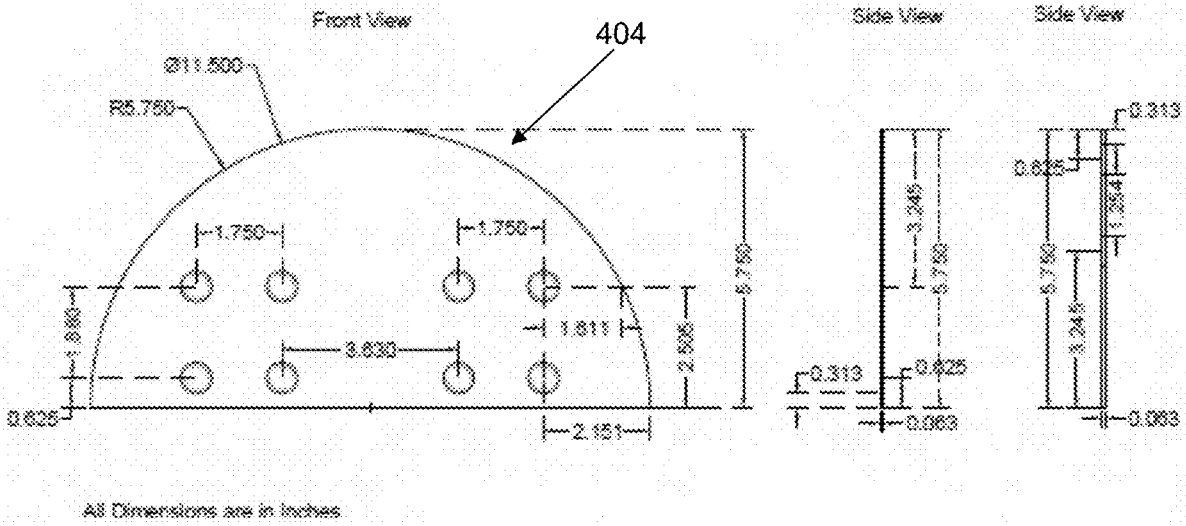


FIG. 11(a)

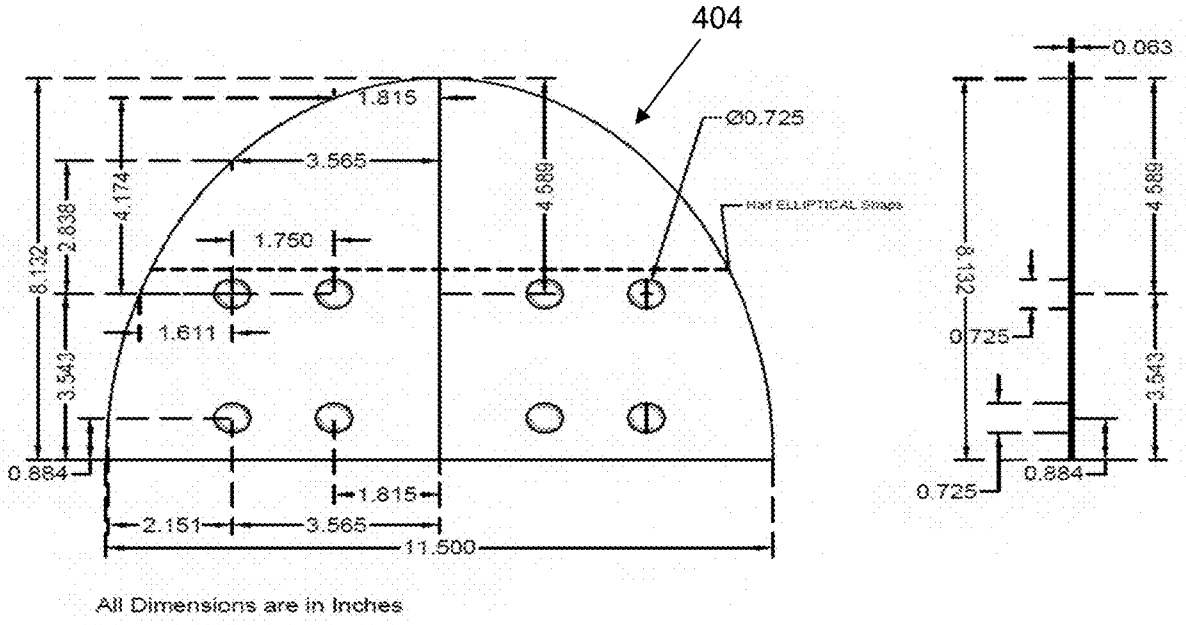


FIG. 11(b)

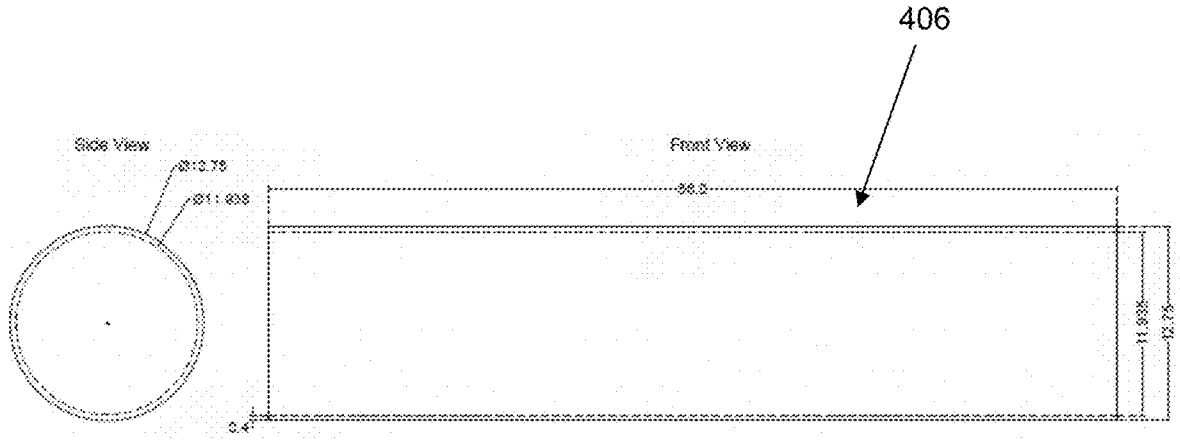


FIG. 12

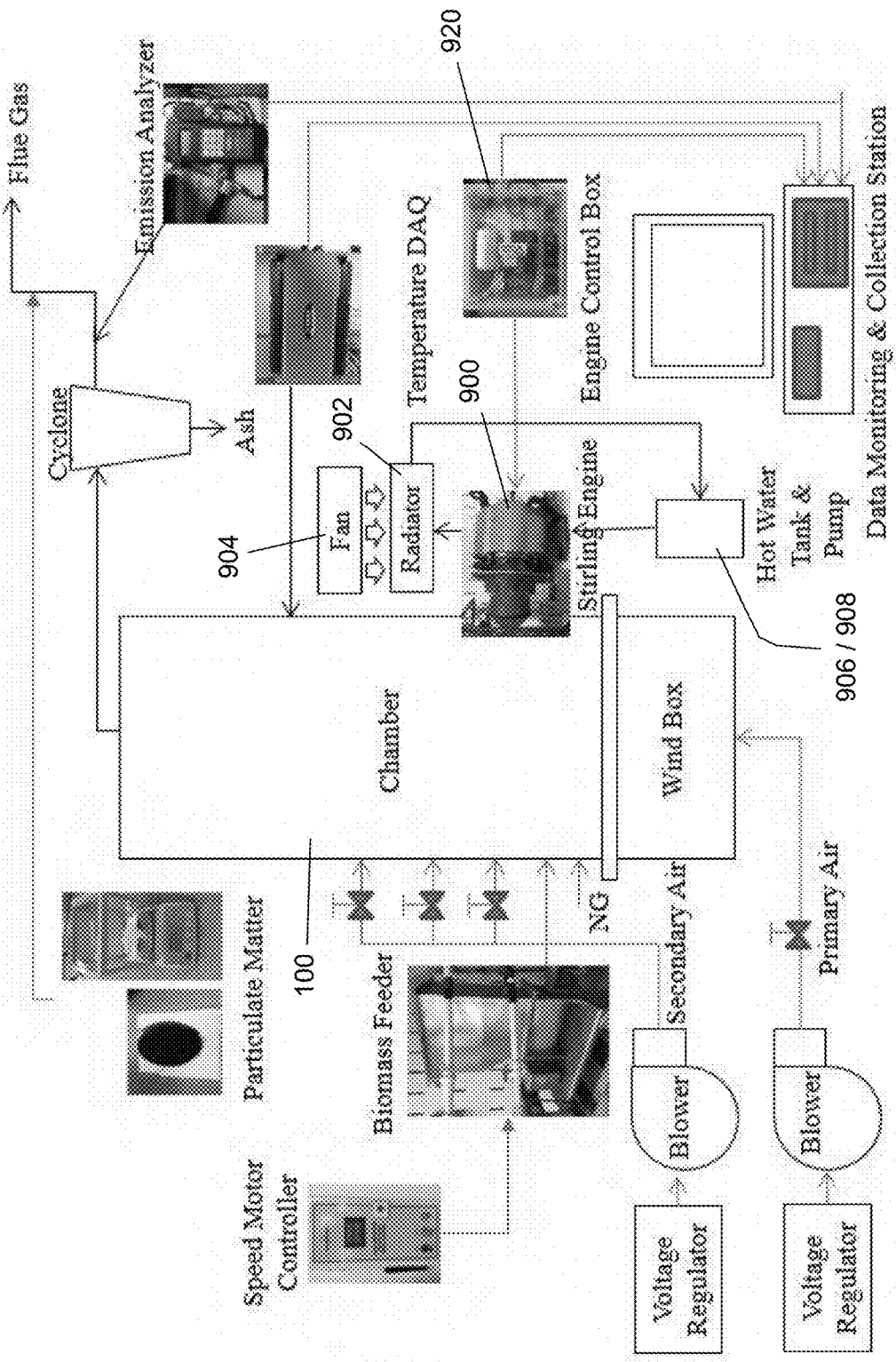

Flue Gas
Emission Analyzer
920
Temperature DAQ
Engine Control Box
Data Monitoring & Collection Station
Cyclone
Ash
902
900
904
Fan
Radiator
Sterling Engine
Hot Water Tank & Pump
906 / 908
Chamber
Wind Box
Particulate Matter
100
Biomass Feeder
NG
Secondary Air
Primary Air
Speed Motor Controller
Blower
Blower
Voltage Regulator
Voltage Regulator

FIG. 13(a)

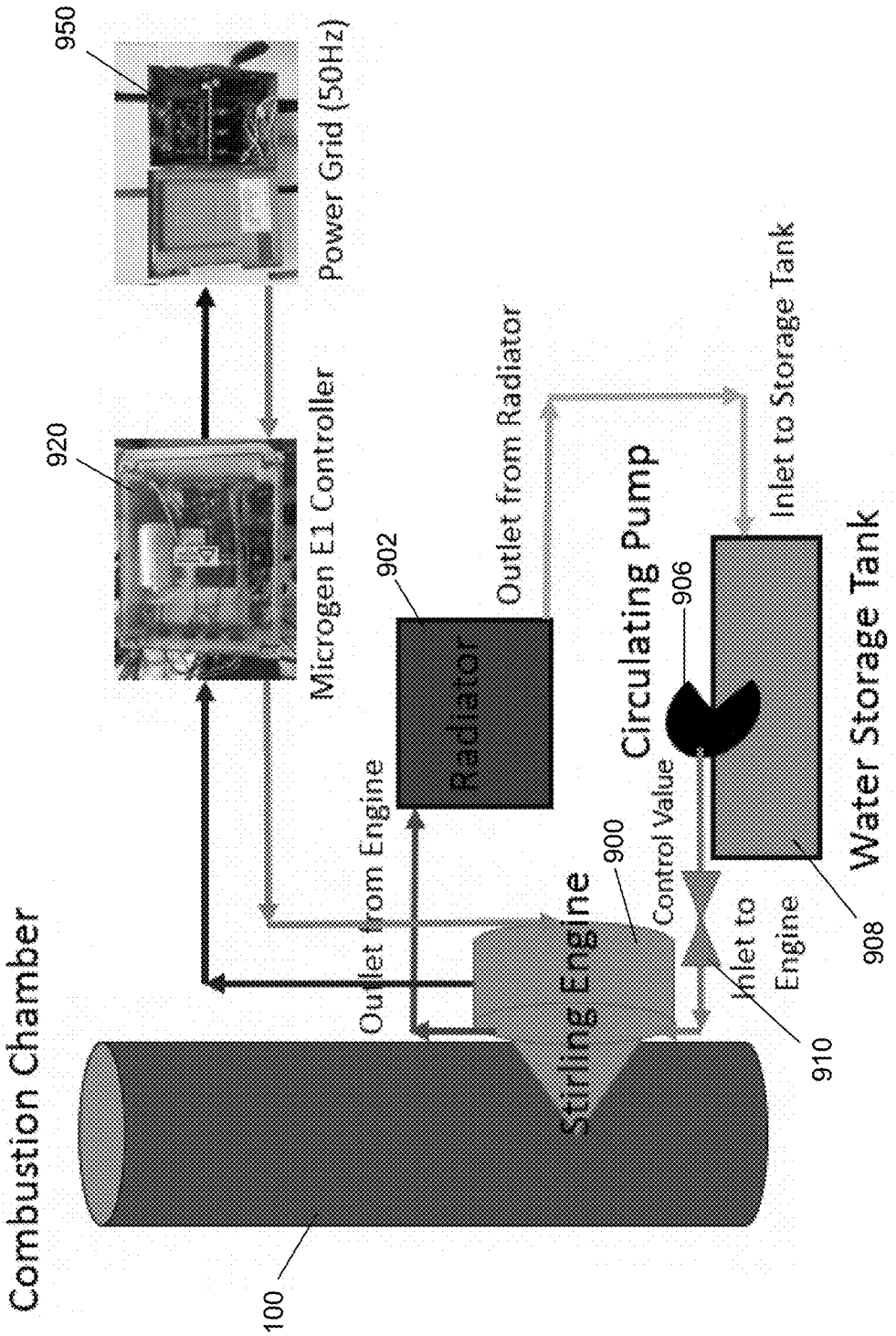

950
Power Grid (50Hz)
920
Microgen E1 Controller
902
Radiator
Outlet from Radiator
Inlet to Storage Tank
906
Circulating Pump
Water Storage Tank
Outlet from Engine
900
Control Value
Stirling Engine
Inlet to Engine
908
910
Combustion Chamber
100

FIG. 13(b)

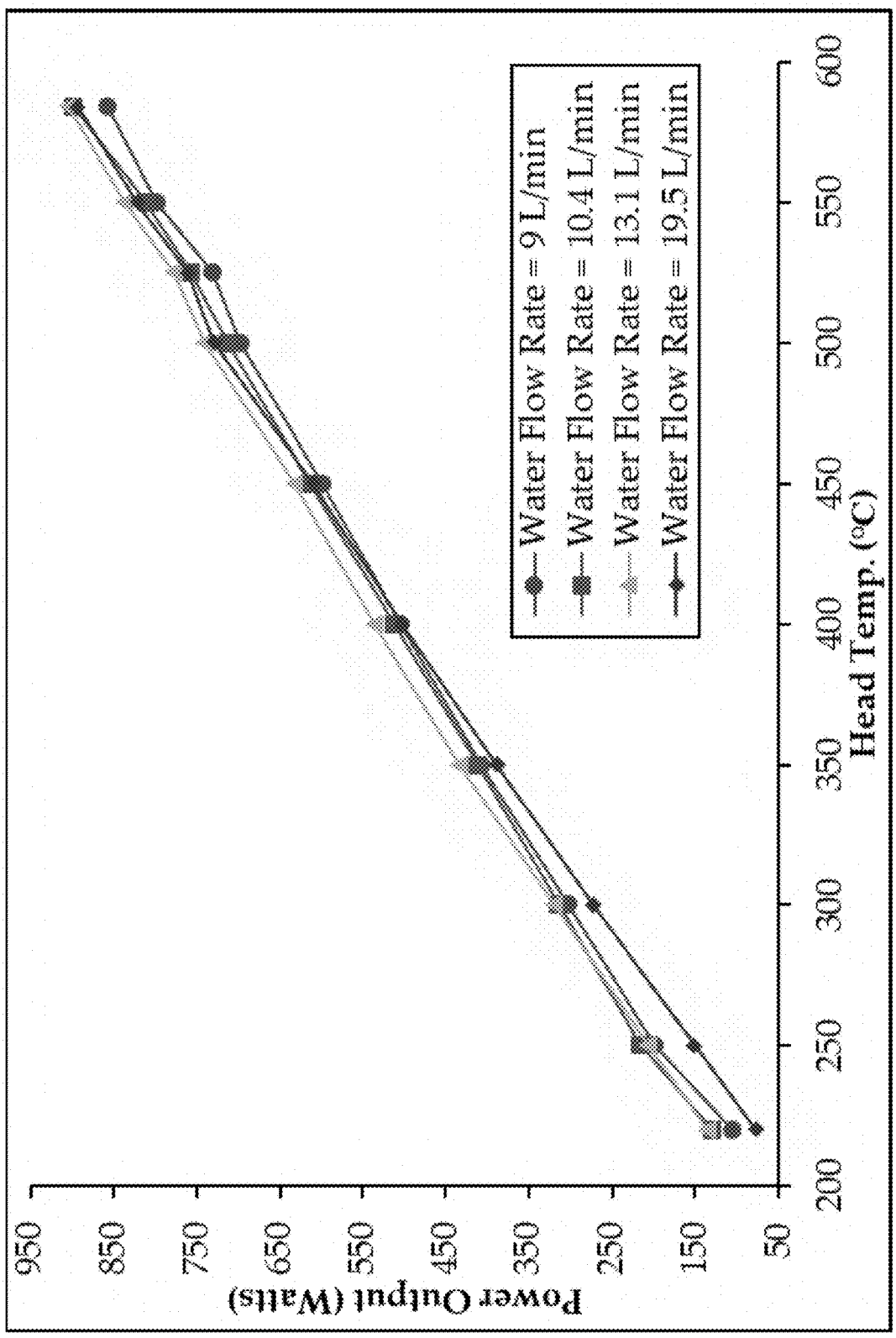

Power Output (Watts)
950
850
750
650
550
450
350
250
150
50
200
250
300
350
400
450
500
550
600
Head Temp. (°C)
Water Flow Rate = 9 L/min
Water Flow Rate = 10.4 L/min
Water Flow Rate = 13.1 L/min
Water Flow Rate = 19.5 L/min

FIG. 14

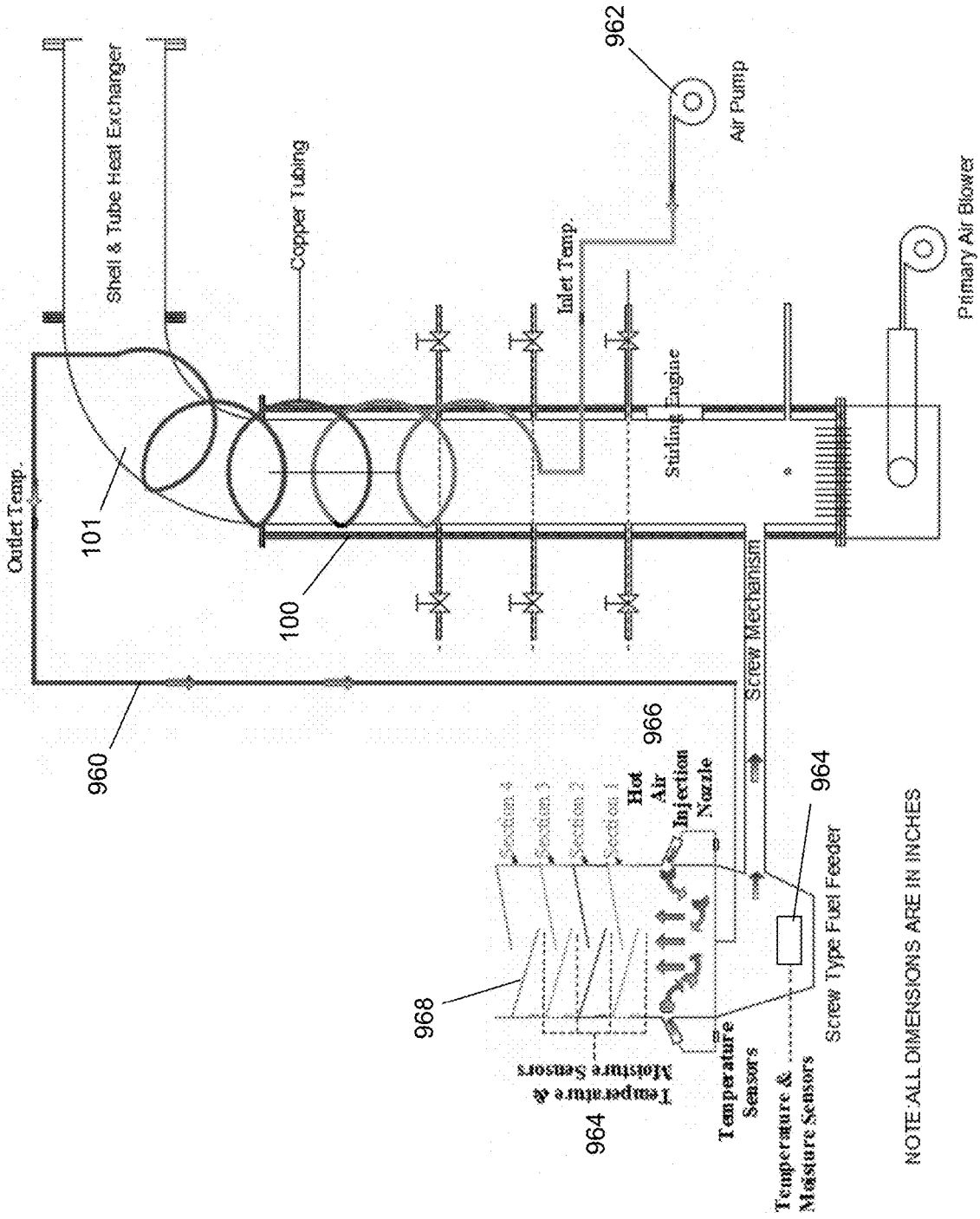

Outlet Temp.
Shell & Tube Heat Exchanger
Copper Tubing
962
Air Pump
Inlet Temp.
Stirling Engine
Primary Air Blower
101
100
960
Screw Mechanism
966
Hot Air Injection Nozzle
964
Section 4
Section 3
Section 2
Section 1
968
Temperature & Moisture Sensors
964
Temperature Sensors
Temperature & Moisture Sensors
Screw Type Fuel Feeder
NOTE: ALL DIMENSIONS ARE IN INCHES

FIG. 15

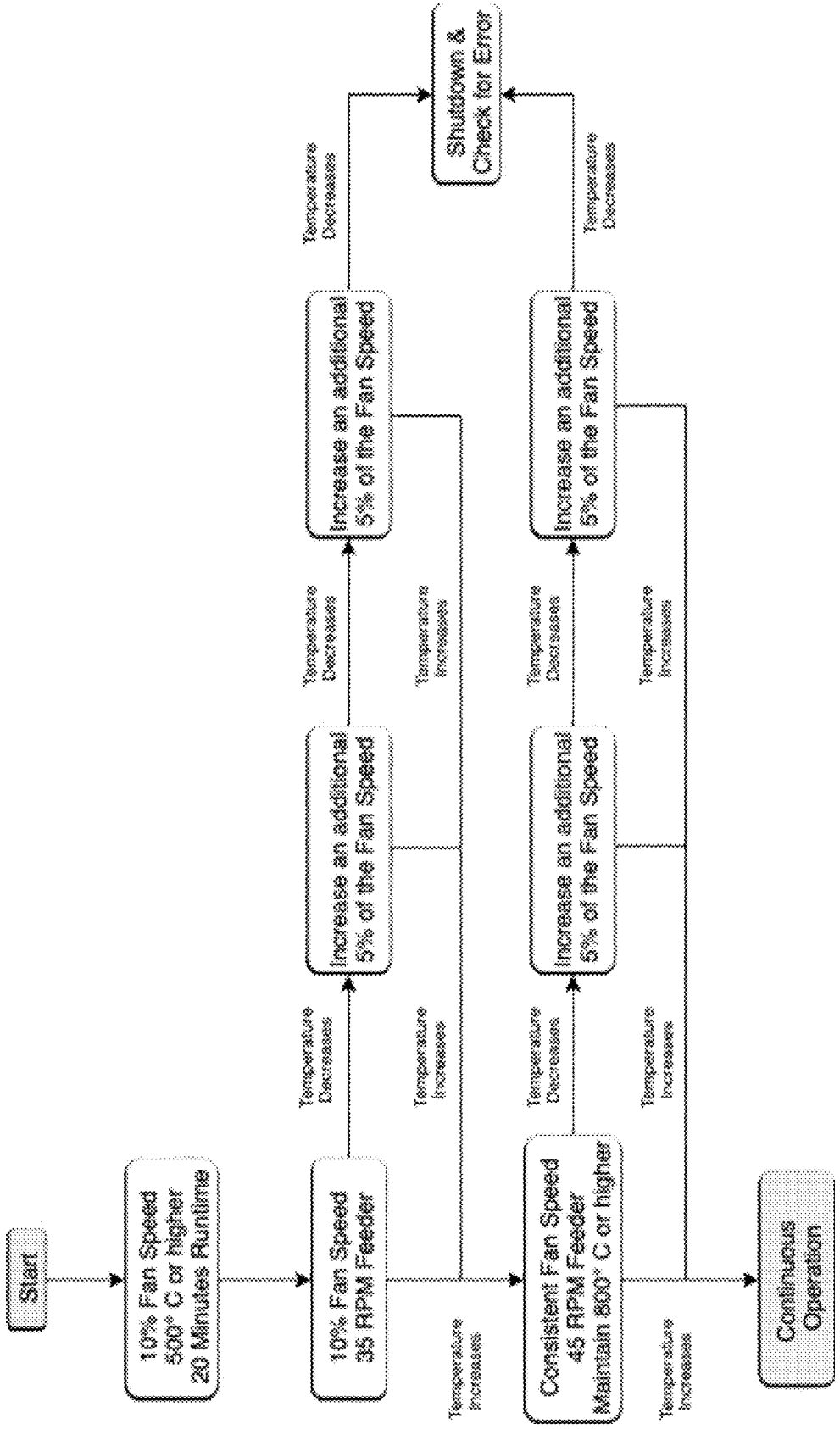

Start
10% Fan Speed
500° C or higher
20 Minutes Runtime
10% Fan Speed
35 RPM Feeder
Consistent Fan Speed
45 RPM Feeder
Maintain 800° C or higher
Continuous
Operation
Increase an additional
5% of the Fan Speed
Increase an additional
5% of the Fan Speed
Shutdown &
Check for Error
Temperature
Decreases
Temperature
Increases

FIG. 16

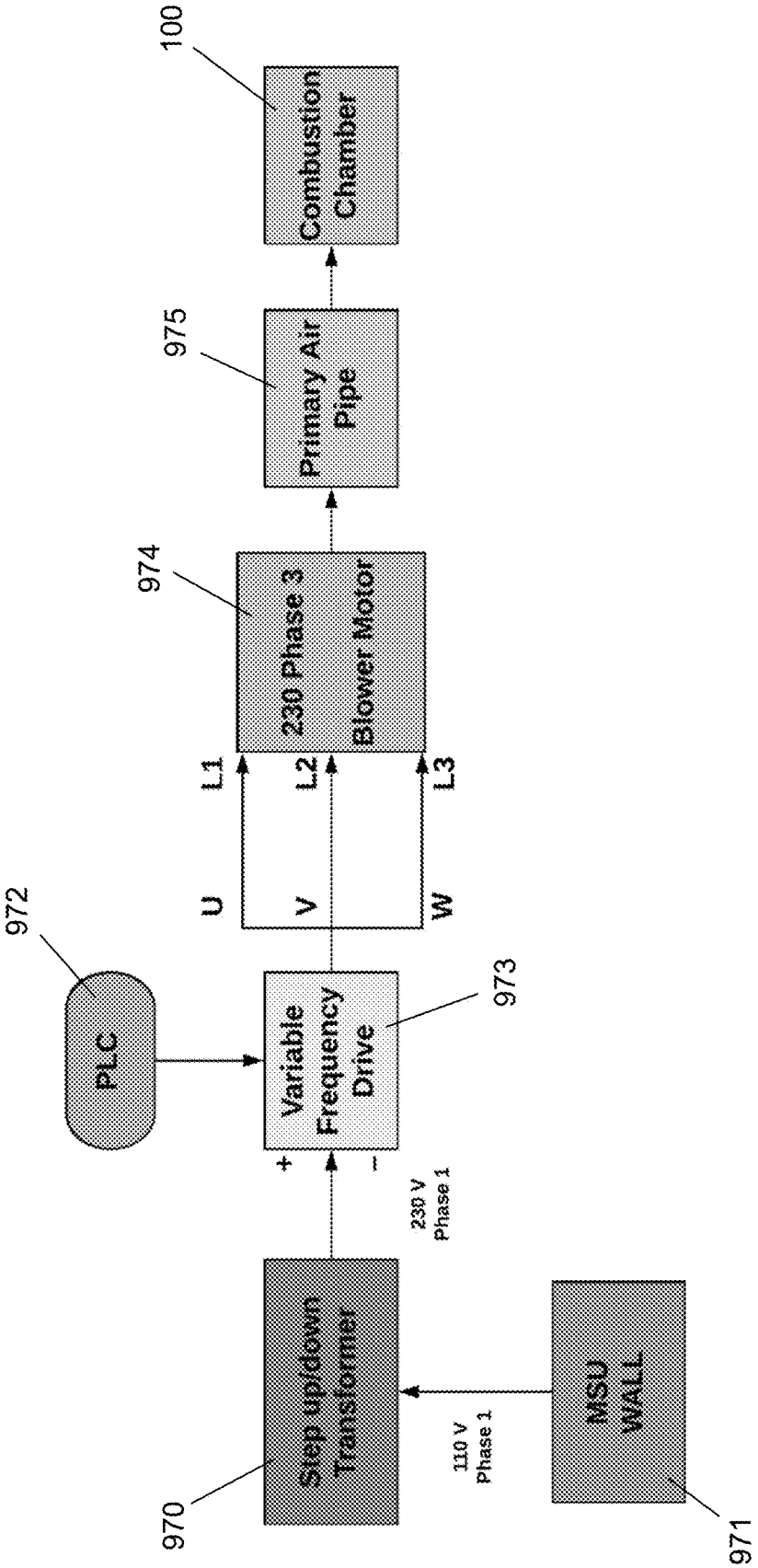

100
Combustion Chamber
975
Primary Air Pipe
974
230 Phase 3 Blower Motor
L1
L2
L3
U
V
W
972
PLC
Variable Frequency Drive
973
+
–
230 V Phase 1
Step up/down Transformer
970
110 V Phase 1
MSU WALL
971

FIG. 17

SYSTEM AND METHOD FOR BIOMASS COMBUSTION

CROSS REFERENCE TO RELATED APPLICATION

[0001] This application is a continuation-in-part of copending U.S. patent application Ser. No. 16/378,986 entitled "SYSTEM AND METHOD FOR BIOMASS COMBUSTION" filed with the U.S. Patent and Trademark Office on Apr. 9, 2019, which application is a continuation of U.S. patent application Ser. No. 15/056,179 entitled "SYSTEM AND METHOD FOR BIOMASS COMBUSTION" filed with the U.S. Patent and Trademark Office on Feb. 29, 2016, now U.S. Pat. No. 10,253,974 issued on Apr. 9, 2019, which is based upon and claims benefit of copending U.S. Provisional Patent Application Ser. No. 62/121,843 entitled "Method and Design of the Ultra-Clean Mobile Combustor for Waste Biomass and Poultry Litter Disposal," filed with the U.S. Patent and Trademark Office on Feb. 27, 2015 by the inventor herein. This application is also based upon and claims benefit of copending U.S. Provisional Patent Application Ser. No. 63/089,760 entitled "Efficient and Innovative Drying Process of Poultry Litter," filed with the U.S. Patent and Trademark Office on Oct. 9, 2020; U.S. Provisional Patent Application Ser. No. 63/112,717 entitled "Shell and Twisted Tube-Based Heat Exchanger System," filed with the U.S. Patent and Trademark Office on Nov. 12, 2020; U.S. Provisional Patent Application Ser. No. 63/117,744 entitled "Space Heating Method for a Poultry Farm," filed with the U.S. Patent and Trademark Office on Nov. 24, 2020; and U.S. Provisional Patent Application Ser. No. 63/117,732 entitled "Electricity and Thermal Energy Generation Method Using the Combustor and the Stirling Engine," filed with the U.S. Patent and Trademark Office on Nov. 24, 2020. The specifications of each of the foregoing applications are incorporated herein by reference in their entireties.

FIELD OF THE INVENTION

[0002] This invention relates to systems and methods for fluidized bed combustion, and more particularly to a fluidized bed combustion system and method optimized for burning biomass wastes and poultry litter in an environmentally-friendly manner, wherein such system is used to produce electricity using a Stirling engine, to produce hot water using a shell and tube heat exchanger, to dry biomass fuel, and more particularly poultry litter, and to provide space heating particularly for poultry farms that may be used as the source of the biomass processed by the fluidized bed combustion system and method.

BACKGROUND OF THE INVENTION

[0003] The consolidation and industrialization of the poultry industry over the last 50 years has resulted in highly concentrated regional poultry operations. Traditionally, farmers managed the manure or litter associated with poultry production by spreading it on cropland fields. However, as the industry consolidated, operations became highly regionally concentrated, and cropland diminished, this waste disposal method became less viable. For example, in the Maryland-Delaware region, 523 million chickens are now produced annually, generating approximately 42 million cubic feet of chicken waste each year, such that chickens outnumber people in the region by as much as 400 to 1. With the assumption of 1.1 to 1.4 tons per 1,000 birds, U.S. poultry waste production increased from 8.4. billion (in 2012) to 8.9 billion (in 2017). This high concentration of waste causes eutrophication (e.g., runoff of nitrogen, phosphorus, and potassium), particularly along the shores of the Chesapeake Bay, the largest estuary system in the United States, creating an urgent need for efficient, clean, environmentally friendly chicken waste disposal approaches and systems.

[0004] The United Nations and the U.S. Federal Government have identified agriculture as the biggest user of water and a major polluter of water. In fact, agriculture has been identified as the single largest source of pollutants for rivers, lakes, and estuaries in the U.S. The industrialization of agriculture has resulted in such high concentrations of animal waste such that conventional disposal methods are no longer adequate or viable (i.e., spreading on fields). Thus, there is an urgent need for environmentally safe and economically viable approaches to disposing of agricultural waste (i.e., animal waste). This need, in combination with global demand for clean, low-cost, renewable energy, has fueled interest in biomass-to-energy conversion technologies, including for use in disposing of high concentrations of animal waste, which becomes even more appealing given recently implemented regulations that restrict the use of chicken litter as fertilizer on significant acreage. Chicken litter is one type of animal waste and biomass and includes a large portion of the bedding materials (e.g., rice husk, sawdust) in the manure and spilled waste feed. However, due to the relatively low energy density of biomass, the economics of biomass-to-energy conversion technologies have been challenging (e.g., fuel collection and transportation costs can be high relative to energy density; high moisture content adds to transportation costs and reduces burn efficiencies). Thus, there remains a need for sustainable solutions that can reduce the cost of converting biomass into energy and/or increase the efficiency of the combustion process.

[0005] Fluidized bed combustion systems are often used for burning biomass fuel. Most of the existing fluidized bed combustion apparatus known to the inventor have only a single level secondary injection of air in the fixed tangential direction to facilitate a turbulent or swirling flow, as shown in U.S. Pat. No. 5,105,917 to Harada et al., and in U.S. Pat. No. 8,161,917 to Yang et al., the specifications of which are incorporated herein by reference in their entireties. Certain systems disclose multiple secondary air supply ports, such as the system shown in European Patent Publication No. 0 458 967 A1. Still other systems disclose methods for incinerating waste using a two-level swirling flow fluidized bed without tangential flow for suppressing re-synthesis of dioxins produced during incineration and the removal of a suspended particulate material, such as the system disclosed in International PCT Publication No. WO/2010/010630. The specifications of each of the foregoing references are incorporated herein by reference in their entireties. However, widespread commercial acceptance of such prior systems has been lacking, due to an inability to reach sufficiently high combustion efficiencies and minimization of noxious emissions. Thus, there remains a need in the art for fluidized bed combustion systems and methods capable of efficiently and cleanly disposing of biomass materials.

SUMMARY OF THE INVENTION

[0006] Disclosed is a system and method for ultra-clean and preferably mobile combustion, particularly configured for burning biomass and poultry litter in an environmentally friendly manner (i.e., so as to reduce emissions of pollutants), which system and method provides high combustion efficiency using equipment of compact design and that is easy to operate.

[0007] In accordance with certain aspects of an embodiment of the invention, the system carries out preferably a two-step combustion process, namely, a first stage combustion carried out in an advanced swirling fluidized bed combustion (SFBC) chamber, and a second stage combustion carried out in a cyclone separator. In the combustion chamber, primary air is introduced from a bottom air box that fluidizes the bed material and fuel, and staged secondary air is introduced in the tangential direction and at varied vertical positions in the combustion chamber so as to cause the materials in the combustion chamber (i.e., the mixture of air and particles) to swirl. The secondary air increases the residence time of the particle flow. The turbulent flow of the fuel particles and air is well mixed and mostly burned in the combustion chamber. Any waste and particles that remain unburned in the combustion chamber are directed to the cyclone separator, where such unburned waste and particles are burned completely, and flying ash is divided and collected in a container connected to the cyclone separator, while dioxin production is significantly minimized if not altogether eliminated. The collected ash and char may optionally be used as fertilizer. The system exhaust, in the form of high temperature flue gas, is directed to a pollutant control unit and heat exchanger, where the captured heat may be put to useful work, such as by generating steam for delivery to a turbine, powering a Stirling engine, or such other energy generation devices as may be apparent to those skilled in the art, or for direct heating of process materials, such as water, feed stock (for drying the same), or the like, or such other direct heat application processes as may be apparent to those skilled in the art.

[0008] The system and method set forth herein have the potential to significantly improve the economics of biomass-to-energy operations, by dramatically improving the efficiency of the combustion process while reducing capital and operating costs. The single chamber design in comparison to the classic combustor system with multiple chambers contributes to lower capital costs. This novel system yields a more efficient burn rate and less solid and gaseous waste than conventional systems for biomass waste disposal.

[0009] Relative to other biomass combustion systems, the system and method disclosed herein is expected to have a higher electrical output, lower capital cost, lower maintenance costs, and greater flexibility regarding fuel sources and conditions. Thus, the system and method set forth herein has the potential to significantly improve the economics of biomass-to-energy operations. In a particularly preferred embodiment, a system and method operating in accordance with the disclosure herein would have a commercial electrical power rating of 50 MWe, would carry a capital cost of $3,000-$3,200 per kW, and would carry operating and maintenance costs of $15-$20/ton of feed, thus offering a clean, high efficiency, and affordable method to dispose of biomass and poultry litter while generating energy.

[0010] Moreover, fossil fuel depletion, environmental damages, strict regulations and policies have shifted energy production goals from fossil fuels towards use of a variety of renewable energy resources, such as biomass. Biomass combustion plays a major contribution towards energy generation because biomass has a CO_2 neutral effect during the photosynthesis and combustion process. Poultry litter is one type of biomass and animal waste occurring during the poultry farming process. Capture of the heat generated during those processes to put that heat to useful work as described herein (e.g., for power generation through a Stirling engine, through heat transfer to radiators for heating occupied spaces, etc.) furthers these goals as well.

[0011] In accordance with certain aspects of an embodiment of the invention, a system for fluidized bed combustion is disclosed comprising a combustion chamber, the combustion chamber further comprising a primary air distribution and delivery system configured to provide vertical airflow through the combustion chamber, and a secondary air distribution and delivery system configured to provide a plurality of vertically displaced, horizontally aligned, tangential airflows in the combustion chamber; a biomass feeder in communication with an interior of the combustion chamber and positioned to deliver biomass material to the interior of the combustion chamber at a location above the primary air distribution and delivery system and below the secondary air distribution and delivery system; and a shell tube and heat exchanger comprising a plurality of twisted tubes, a plurality of baffles, and a cylindrical shell around the twisted tubes and the baffles, wherein the shell tube and heat exchanger receives flue gas from the combustion chamber and is configured to collect heat from the flue gas as it flows through the cylindrical shell.

[0012] In accordance with further aspects of an embodiment of the invention, a system for fluidized bed combustion is disclosed comprising a combustion chamber, the combustion chamber further comprising a primary air distribution and delivery system configured to provide vertical airflow through the combustion chamber, and a secondary air distribution and delivery system configured to provide a plurality of vertically displaced, horizontally aligned, tangential airflows in the combustion chamber; a biomass feeder in communication with an interior of the combustion chamber and positioned to deliver biomass material to the interior of the combustion chamber at a location above the primary air distribution and delivery system and below the secondary air distribution and delivery system; and a heat engine in thermal contact with the combustion chamber and configured to generate electrical power and heat energy from heat generated inside of the combustion chamber.

[0013] In accordance with still further aspects of an embodiment of the invention, a system for fluidized bed combustion is disclosed comprising a combustion chamber, the combustion chamber further comprising a primary air distribution and delivery system configured to provide vertical airflow through the combustion chamber, and a secondary air distribution and delivery system configured to provide a plurality of vertically displaced, horizontally aligned, tangential airflows in the combustion chamber; a biomass feeder in communication with an interior of the combustion chamber and positioned to deliver biomass material to the interior of the combustion chamber at a location above the primary air distribution and delivery system and below the secondary air distribution and delivery system; and a fuel drying system, the fuel drying system further comprising an air conduit wrapping around and in

thermal contact with the combustion chamber and a blower at an inlet of the air conduit, the air conduit having a plurality of outlets with an air injection nozzle at each outlet and positioned to direct heat from the combustion chamber to biomass prior to entry of the biomass into the combustion chamber.

BRIEF DESCRIPTION OF THE DRAWINGS

[0014] The numerous advantages of the present invention may be better understood by those skilled in the art by reference to the accompanying drawings in which:

[0015] FIG. **1** is a schematic view of a system for burning biomass in accordance with certain aspects of an embodiment of the invention.

[0016] FIG. **2** is a close-up, cross-sectional view of a combustion chamber used in the system of FIG. **1**.

[0017] FIG. **3** is a top, cross-sectional view of the combustion chamber of FIG. **2**.

[0018] FIG. **4** is a side view of primary airflow nozzles for use in the combustion chamber of FIG. **2**.

[0019] FIG. **5** is a cross-sectional view of a secondary airflow nozzle for use in the combustion chamber of FIG. **2**.

[0020] FIG. **6** is a top, cross-sectional view of a cyclone separator used in the system of FIG. **1**.

[0021] FIG. **7** is a flowchart depicting a method for burning biomass in accordance with certain aspects of an embodiment of the invention.

[0022] FIG. **8** is a schematic view of the system of FIG. **1** and including a twisted tube-based shell tube and heat exchanger (STHE) system.

[0023] FIG. **9**(*a*) is a close-up view of an internal twisted tube assembly for use in the shell tube and heat exchanger system of FIG. **8**.

[0024] FIG. **9**(*b*) is a close-up view of a cylindrical shell for use in the shell tube and heat exchanger system of FIG. **8**.

[0025] FIG. **10** provides top, front, and end views of the internal twisted tube assembly of FIG. **9**(*a*).

[0026] FIG. **11**(*a*) provides front and side views of a baffle for use with the internal twisted tube assembly of FIG. **9**(*a*).

[0027] FIG. **11**(*b*) provides front and side views of another baffle for use with the internal twisted tube assembly of FIG. **9**(*a*).

[0028] FIG. **12** Provide cross-sectional side and end views of the cylindrical shell of FIG. **9**(*b*).

[0029] FIG. **13**(*a*) is a schematic view of the system of FIG. **1** and including a Sterling engine.

[0030] FIG. **13**(*b*) is a schematic view of the system of FIG. **13**(*b*) with certain elements omitted for clarity.

[0031] FIG. **14** is a chart showing power output as a function of heat engine temperature varying flow rates in the system of FIG. **12**.

[0032] FIG. **15** is a schematic view of the system of FIG. **1** and including a system for heating biomass fuel prior to its delivery to the combustion chamber.

[0033] FIG. **16** is a flowchart depicting the logical program flow of a programmable logic controller (PLC) in a control system for use in the system of FIG. **1**.

[0034] FIG. **17** is a flowchart depicting the direction of control signals from a PLC in a control system for use in the system of FIG. **1**.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

[0035] The following description is of a particular embodiment of the invention, set out to enable one to practice an implementation of the invention, and is not intended to limit the preferred embodiment, but to serve as a particular example thereof. Those skilled in the art should appreciate that they may readily use the conception and specific embodiments disclosed as a basis for modifying or designing other methods and systems for carrying out the same purposes of the present invention. Those skilled in the art should also realize that such equivalent assemblies do not depart from the spirit and scope of the invention in its broadest form.

[0036] FIG. **1** shows a schematic view of a system for burning biomass in accordance with certain aspects of an embodiment of the invention, including a combustion chamber **100**, air delivery system (shown generally at **200**), a cyclone separator **300**, a heat exchanger **400**, and exhaust system **500**. Optionally, the entire system may be housed on a mobile chassis (not shown) so that the system may be moved from site to site for processing of biomass at the site of production or collection of the biomass.

[0037] Combustion chamber **100** includes a generally cylindrical housing having preferably a metal exterior and a refractory layer on an interior surface of the metal exterior. A primary air distribution and delivery system **110** is provided in the bottom of the combustion chamber **100** and receives high pressure air from air delivery system **200**, in turn directing that air toward the top of the combustion chamber in order to vertically distribute the biomass/fuel and diffuse particles throughout the column in the combustion chamber **100**. Moreover, secondary air distribution and delivery system **130** includes multiple, vertically displaced rows of nozzles, discussed in greater detail below, which nozzles are configured to provide controllable, multi-angle air-injection at multiple, distinct vertical levels within combustion chamber **100** to provide a swirling flow in the column, which in turn maximizes combustion throughout the combustion chamber **100**.

[0038] A fuel feeder (shown generally at **102**) is provided adjacent combustion chamber **100**, and may be provided, by way of non-limiting example, a hopper for receiving biomass, poultry litter, and other materials that might be used for fuel in the combustion chamber **100**, and a delivery mechanism **103**, such as a feed screw, configured to deliver such biomass/fuel from fuel feeder **102** to combustion chamber **100**. Such biomass/fuel is delivered into combustion chamber **100** at a point above primary air distribution and delivery system **110**, and below secondary air distribution and delivery system **130**. The solid biomass/fuel is supplied tangentially into the combustion chamber **100**, such that no bed material is required. The airflow from the primary air distribution and delivery system **110** and from the secondary air distribution and delivery system **130** act as both particle fluidizers and combustion oxidizers. The multiple levels of nozzles of secondary air distribution and delivery system **130** provide extended swirl flow along with additional air (e.g., oxygen supply). This configuration retains particles in the combustion zone, reducing unburned particles and thus minimizing residual material. The extended swirling flow generated by the system results in

vigorous particle-to-wall collisions, which increases the residence time and combustion efficiency of fuel particles in the combustion zone.

[0039] A natural gas feed **104** is preferably positioned to feed natural gas into combustion chamber **100** above primary air distribution and delivery system **110**. Natural gas is preferably used only to initiate the burn at startup in order to achieve the initial biomass ignition. Further, monitoring and control subsystem **160** is provided, which preferably includes temperature and pressure sensors **162** within combustion chamber **100**, one or more particulate matter (PM) meters and emissions probes **164** capable of monitoring both levels of particulates and gaseous emissions (including NOx, SOx, CO, and CO_2), which sensors and probes are readily commercially available such that their specific configuration is not addressed further here. Likewise, those skilled in the art will recognize that additional process control accessories may be provided as may be suitable for a particular installation. Monitoring control subsystem **160** is also in electrical communication with, and thus is configured to provide control signals to, delivery mechanism **103** from fuel feeder **102** (e.g., by controlling a motor driving a feed screw of delivery mechanism **103**) to control the amount of biomass/fuel delivered to combustion chamber **100**, to a blower **112** to control the amount of air delivered through primary air distribution and delivery system **110** and through secondary air distribution and delivery system **130**, and preferably to valves **114** to allow independent control of the amount of air delivered through such systems **110** and **130** with respect to one another. Alarm levels may be established for monitored data, which alarm levels are preferably set by a person using data processing equipment **166** responsible for configuring the system. As an alarm relay is activated, the monitoring and control subsystem **160** is configured to decrease the fuel feeding rate through preferably a variable speed controller, reducing such feed rate to a point necessary to have the particulate matter levels below the set alarm relay levels. Likewise, monitoring and control subsystem **160** controls the amount of air delivered through primary air distribution and delivery system **110** and through secondary air distribution and delivery system **130** (through control of blower **112** and valves **114** in air delivery system **200**) so as to control the burn rate in combustion chamber **100**. All of these factors may be controlled so as to maintain the safest possible burn rate so as to maintain emissions within a desired range and so as to ensure a maximum efficiency in biomass combustion is maintained.

[0040] With continued reference to FIG. **1**, exhaust from combustion chamber **100** is directed to a cyclone separator **300**. As will be discussed in further detail below, any waste and particles that remain unburned in combustion chamber **100** are directed to the cyclone separator **300**, where such unburned waste and particles are burned, and flying ash is divided and collected in a container connected to the cyclone separator, while dioxin production is significantly minimized if not altogether eliminated. The collected ash and char may optionally be used as fertilizer. The system exhaust, in the form of high temperature flue gas, is directed from cyclone separator **300** to a heat exchanger **400** and an exhaust system **500** including a pollutant control unit. Heat captured by heat exchanger **400** may be put to useful work through use of any thermal energy conversion device **420** as may be deemed appropriate for a given installation by persons of ordinary skill in the art, such as by way of non-limiting example by generating steam for delivery to a turbine, powering a Stirling engine, or such other energy generation devices as may be apparent to those skilled in the art, or for direct heating of process materials, such as water, feed stock (for drying the same), or the like, or such other direct heat application processes as may be apparent to those skilled in the art.

[0041] FIG. **2** provides a front, cross-sectional view of combustion chamber **100**, while FIG. **3** provides a top, cross-sectional view of combustion chamber **100**. As shown in FIGS. **1-3**, combustion chamber **100** includes a primary air box **116** that receives primary air from blower **112** and directs such primary air to primary air distribution and delivery system **110**. Primary air distribution and delivery system **110** directs primary air into combustion chamber **100**, where such primary air receives natural gas through natural gas feed **104** and biomass/fuel from delivery mechanism **103**, both igniting the biomass as it enters combustion chamber **100** and causing it to flow upward in combustion chamber **100**. As such biomass flows upward through combustion chamber **100**, it encounters secondary air distribution and delivery system **130**, which in turn comprises two or more airflow manifolds **132**, each of which receives air from air delivery system **200**. Each airflow manifold **132** directs secondary air to a plurality of secondary air injection nozzles **134** positioned around an interior circumference of combustion chamber **100**. In a particularly preferred embodiment, four air injection nozzles **134** are provided at a common height on the interior of combustion chamber **100** and are spaced evenly along the interior circumference of combustion chamber **100** at that common height. The secondary air injection nozzles **134** control the direction of the injected secondary air into combustion chamber **100**, injecting such secondary air at various angles so as to cause the particles and air in combustion chamber **100** to achieve a swirling effect so as to increase combustion of the biomass in combustion chamber **100**.

[0042] As best shown in the top, cross-sectional view of FIG. **3**, air nozzles **132***a* may be provided along an exterior of combustion chamber **100** that receive secondary air from airflow manifolds **132** and deliver such secondary air to each secondary air injection nozzle **134**. Each secondary air injection nozzle **134** has a first branch that extends radially through both an exterior metal layer **150** of combustion chamber **100** and an internal refractory layer **152** lining an interior of combustion chamber **100**. An interior branch of each air injection nozzle **134** is arranged at approximately 90° to each respective first branch so as to position the outlet of secondary air injection nozzle **134** to direct secondary air tangentially along the interior of refractory layer **152** of combustion chamber **100**, in turn creating a swirling effect on the interior of combustion chamber **100**.

[0043] As shown in the side view of primary air distribution and delivery system **110** of FIG. **4**, the primary air distribution and delivery system **110** includes a plurality of primary nozzles **120**, which nozzles **120** are particularly configured to maximize air distribution at the bottom of combustion chamber **100**. Each nozzle **120** has a rounded, semi-circular head **121**, a cylindrical branch **122** extending downward from head **121**, and an outwardly extending lower branch **123** that has a widening diameter as it extends from cylindrical branch **122** to base portion **124**, which base portion **124** comprises the widest diameter d for each nozzle

120. Base portion **124** receives air directly from primary air distribution and delivery manifold **125**, which extends horizontally along the bottom portion of combustion chamber **100**, receiving air from primary air box **116**. In certain configurations, a plurality of manifolds **125** may extend horizontally across the bottom of combustion chamber **100** so as to provide even distribution of nozzles **120** across the full width of combustion chamber **100**.

[0044] With continued reference to FIG. **4**, horizontally extended outlets **126** are positioned on each cylindrical branch **122**, and upwardly angled outlets **127** are positioned on each lower branch **123**, for feeding air from primary air distribution and delivery system **100** into combustion chamber **100**. In a particularly preferred embodiment, each primary nozzle **120** includes four horizontally extended outlets **126** and four upwardly angled outlets **127**. In a prototype construction implementing the system and methods described herein (described in greater detail below), a total of 24 outlets **126** were provided, each having a diameter d of ⅛ inch. In an embodiment of the invention, openings formed by horizontally extended outlets **126** and upwardly angled outlets **127** comprise 2% of the overall surface area of the primary air distributor.

[0045] Similarly, and with reference to the cross-sectional view of secondary air injection nozzles **134** of FIG. **5**, both the shape and axial position of secondary air nozzles **134** are important to providing proper air and material flow within combustion chamber **100**. More particularly, secondary air injection nozzles **134** function to change the direction of the supplied secondary air so as to cause a swirling flow condition inside of combustion chamber **100**. As mentioned above, sets of preferably four, evenly circumferentially spaced secondary air injection nozzles **134** are provided at at least two, and preferably three, distinct heights on the interior of combustion chamber **100**. In the prototype construction described above, the bottom-most set of secondary air injection nozzles **134** were positioned 34 inches from the bottom of the combustion chamber and primary air distribution manifold **125**, with the subsequent higher sets of secondary air injection nozzles **134** each evenly spaced 10-11 inches above the next-lowest set. In any configuration, the position and number of secondary air injection nozzles will generally be determined by the height of the combustion chamber **100** above air box **116**, with horizontally aligned sets of secondary air injection nozzles **134** being positioned equidistant to one another. It has been found that at least three horizontal sets of secondary air injection nozzles **134** are most preferred in order to ensure that an optimal biomass material residence time is maintained for the biomass particles undergoing combustion. The higher the number of second air injection nozzles **134**, the higher the oxygen supply into the combustion chamber **100**, which in turn increases the swirling effect on the fluidized bed and a resulting high combustion efficiency above 90%.

[0046] Each secondary air injection nozzle **134** includes inlet **135** that receives secondary air from an airflow manifold **132**. Inlet **135** opens into inlet channel **136**, which in turn directs secondary air into a centrally located, circular chamber **137**. An interior flow channel **138** extends from chamber **137**, and at a distal end directs the airflow through nozzle outlet **139**, which outlet **139** extends at generally 90° to a flow axis of both inlet channel **136** and interior flow channel **138**, in turn introducing air into combustion chamber **100** in a tangential direction so as to cause swirling air flow. This configuration has been found to provide a swirling air flow from the secondary air injection into combustion chamber **100**, which in turn forms the particle suspension layer and dilution zone within combustion chamber **100**. Through adjustment of the secondary air injection through secondary air injection nozzles **134** configured in this manner, the axial position of the particle suspension layer within combustion chamber **100** can be closely controlled.

[0047] The resulting strong swirling air flow field in combustion chamber **100**, in combination with the interaction of centrifugal forces and gravity on the particles in combustion chamber **100**, cause larger particles to be kept in combustion chamber **100** for a significant amount of time, in turn contributing to high combustion efficiency and extremely low emissions. The swirling particle flow in combustion chamber **100** can be described by stochastic trajectory modeling (STM), and the diffusion-kinetics model can be used for predicting fuel materials depletion during the combustion process to describe the residence time of particles in combustion chamber **100**, which modelling techniques are known to those of ordinary skill in the art. These techniques may, in turn, be used to control biomass feed rate and airflow through primary air distribution and delivery system **110** and secondary air distribution and delivery system **130** to effect residence time and the overall combustion process in combustion chamber **100**. By way of non-limiting example, in the exemplary prototype construction described below, biomass material residence time in combustion chamber **100** would preferably be in the range of 2-5 seconds with combustion temperatures of 1400-1700° F.

[0048] FIG. **6** is a top, cross-sectional view of the cyclone combustor **300**, having an air inlet **302** that receives flue gas from combustion chamber **100** and fresh air from air delivery system **200**. The high temperature flue gas directed to cyclone combustor **300** may contain unburned carbon particles. As shown in FIG. **6**, fresh air is added into the flue gas before it enters the cyclone combustor **300**. In this configuration, the unburned carbon particles and oxygen in the fresh air will burn again in the cyclone combustor **300**. In addition to re-burning the unburned carbon, the cyclone combustor **300** functions as a particle separator in which the coarse particles will fall down to a particle collector. The flue gas is therefore preliminarily cleaned through the cyclone, before it is passed on to heat exchanger **400** and exhaust system **500**. After heat exchanger **400**, the flue gas may thus be directed to exhaust system **500**, which may include (by way of non-limiting example) a filter bag or other filter housing, and an exhaust stack or exhaust gas pool of standard configuration.

[0049] As mentioned above, heat exchanger **400** may be employed to capture heat from the flue gas from combustion chamber **100** to generate useful energy. Residual heat from combustion chamber **100** may be used for producing electricity, direct heating of water, for drying of materials (including drying of biomass material that is to be processed through combustion chamber **100** before its introduction into combustion chamber **100**), or for heating of spaces for workers, consumers, livestock, or the like.

[0050] For example, in certain configurations, and as shown in the schematic view of FIG. **8**, heat exchanger **400** may comprise a shell tube and heat exchanger (STHE) system positioned between combustion chamber **100** and cyclone separator **300** to allow for heating of a fluid, such as

water, and transporting that fluid to a trailer **1000**, space or equipment that is to be heated, such as a closed room, such as a housing unit, and particularly a housing unit configured for housing chickens that produce animal waste (i.e., poultry litter) that is burned in combustion chamber **100**. By way of summary and as discussed in greater detail below, the STHE **400** in such a system may comprise a plurality of twisted tubes (e.g., copper tubes), baffles, flanges, and a cylindrical shell in which heat generated from the combustion of biomass in combustion chamber **100** heats fluid in the tubes, which heated fluid (e.g., water) is transported to another location, such as a house or trailer **1000** as may be used for holding chickens, in order to provide that space heating with radiated heat.

[0051] In the configuration of FIG. **8**, combustion chamber **100** burns material, such as biomass (which as above may comprise poultry litter), and in that process generates hot flue gas as the biomass is combusted into ash. As part of the combustion process, the hot flue gas and ash also travels through series of tubes (to, as described above, be processed by cyclone separator **300** and further through the system), which heats up the surface of the tubes to hundreds of degrees. From those heated tubes, a portion of radiated heat may be used for a variety of purposes, including space heating and drying processes.

[0052] As shown in FIGS. **9**(*a*) through **12** (all dimensions being exemplary only), an efficient and cost-effective, compact twisted tube-based STHE system **400** includes a plurality of twisted tubes **402** and segmented baffles **404**, and a cylindrical shell **406** holding the foregoing assembly, which cylindrical shell **406** may in certain configurations be composed of carbon steel pipe. In certain test configurations of STHE **400**, six twisted tubes **402** and five segmented baffles **404** have been employed. In other configurations 16 twisted tubes **402** have been employed, although more or fewer twisted tubes **402** and segmented baffles **404** may be used for particular installations without departing from the spirit and scope of the invention. In each case, twisted tubes **402** may be interconnected at their ends using appropriate joints, such as 90° elbows, T-joints and 4-way cast copper crosses.

[0053] In exemplary configurations, a single twisted tube **402** may have at least four sets of twists, and multiple tubes extend in parallel with one another, each having one input end and one output end.

[0054] Segmented baffles **404** support the bundle of twisted tubes **402** inside cylindrical shell **406** and maintain the desired velocity of hot flue gas through STHE **400**. As best viewed in FIG. **9**(*a*), baffles **404** are preferably alternatively positioned on upper and lower sets of twisted tubes **402**. Such arrangement of baffles **404** creates turbulence and resists vibrations, in turn enhancing the fluid flow to increase the heat transfer coefficient of STHE **400**. More particularly, the segmented baffle forces the flue gas inside of shell **406** to travel through in a zigzag manner, thus improving heat transfer with acceptable pressure drops. Further, the baffle inclination angle may play an important role in controlling flow velocity and influence the transfer coefficient. A 90° inclination angle may cause a dead zone to form behind baffles and may lead to an increase of fouling resistance, which ultimately decreases the heat transfer rate. Thus, baffles **404** as used herein are preferably positioned with respect to twisted tubes **402** so that they have 20°-50° inclination angle, and more preferably a 40° inclination angle.

[0055] In an exemplary configuration, cylindrical shell **406** (FIG. **9**(*b*)) may include flanges **408** at opposite ends and configured for sealed connection to the rest of the combustion system between 90-degree elbow section **101** and cyclone separator **300**.

[0056] During the combustion process, biomass such as poultry litter is fed into combustion chamber **100** by feeder **102**. In addition, the primary and secondary blowers supply combustion air into combustion chamber **100** as detailed above. After the combustion process generates a hot flue gas, it is directed into shell **406** and passes through the series of segmented baffles **404** to heat the water in twisted tubes **402**. The processed hot water from the STHE **400** may then be supplied into radiators **1002** to heat space **1000**, and thereafter returned as cold water into the STHE **400**. In a particularly preferred configuration, space **1000** is provided two radiators **1002** arranged in parallel flow, which was found to have significantly higher heating capability than two radiators **1002** arranged in serial flow.

[0057] Swirl flow in twisted tubes **400** increases residence time and produces inertial mass forces, which generates a secondary flow and enhances the tube side mixing of fluid to increase convective heat transfer coefficients inside of tubes **402**. In the meantime, a steady velocity profile of flow in the shell **406** is also interrupted by constant direction change on the twisted tube surface, which maintains turbulent flow and achieves good transverse mixing to increase the heat transfer rate.

[0058] As shown in FIG. **8**, in order to measure results in an exemplary prototype configuration, a data acquisition system, water flow-rate sensors, and thermocouples were carefully installed to monitor and record inlet/outlet water flow rate and hot/cold flue temperature changes. Results indicated that countercurrent flow with an optimized location of three pumps in the space heating module provided hot water (around 149° F.-150° F., from 68° F.-69° F.) and can provide space heating for poultry houses (from 57° F.-63° F. to 90° F.-95° F.) within 180 minutes of the start of the heating process (outside temperature 57° F.-64° F.). Hot water circulation pumps were particularly placed with two positioned between the space **1000** and STHE **400** in series and pumping water to STHE **400**, with a source of fresh water being supplied between the two pumps, and a third pump positioned between STHE **400** and space **1000** and pumping newly heated water to space **1000**, allowing a maximum control of water flow rate through STHE **400** and the resultant heat transfer between the hot flue gas in shell **406** and the water inside of twisted tubes **402**. Alternatively, in certain configurations, a single large capacity water circulation pump may be employed to assist in increasing water flow rate and velocity through tubes **402**, such as between the STHE **400** and space **1000** that is to be heated.

[0059] The foregoing showed that the configuration of twisted tubes **402** provided better performance than a straight tube based STHE system. Analysis and calculations found that the prototype twisted tube based STHE system had a conversion efficiency between 34.3% and 41.1% in transferring heat energy from the hot flue gas resulting from the poultry litter combustion process into the cold water inside of twisted tubes **402**. Notably, however, use of a system as described herein comprising 16 twisted tubes **402** with baffles **404** situated at a 40° inclination angle yielded a 47.7%-60.1% efficiency in transferring heat energy from the

hot flue gas resulting from the poultry litter combustion process into the water inside of twisted tubes **402**.

[0060] Total heat energy from the biomass combustion process entering the pilot-scale heat exchanger **400** (Q_{in}) is equal to the energy that leaves the heat exchanger **400** through radiation from the pipe to the room air (Q_{air}), the energy transferred to the water (Q_{water}), and the energy that exits the exchanger as flue gas ($Q_{exhaust}$). This can be expressed as: $Q_{in}=Q_{air}+Q_{water}+Q_{exhaust}$ The energy content of hot flue gas (Q_{in}) and exhaust flue gas (Q_{out}) were calculated by following equation:

$$Q\dot{m}*C_p*dT$$

where $\dot{m}$ is the total mass flow rate of fuels (i.e., poultry litter), air and natural gas, C_p is the specific heat of the hot flue gas (assumed to be close to 0.24 Btu/lb.° F.), and dT refers to the temperature changes of flue gas before entering and exiting the heat exchanger **400**. Energy transferred to the water (Q_{water}) was calculated by using water flow rates, water density, specific heat of water and water temperature changes between water inlet and water outlet. Then, the efficiency was calculated by dividing the Q_{water} to Q_{in}. As shown in Table 1, approximately 34.3% to 41.1% of the energy entering the heat exchanger **400** was transferred to the water.

TABLE 1

Summary of the Operating Factors and Performance Parameters of the Prototype STHE System

PL %	NG 1 & 2 SCFH		PA %	SA %	Gas In F	Gas Out F	Water in F	Flow Rate GPM	Water Out F	Q_{in} BTU	Q_{water} BTU	Eff. %
45	20	20	20	5	1055.66	580.82	75	0.8	106	31,799	13,070	41.1
55	20	20	25	5	1191.2	662.36	82	0.86	122	38,230	15,411	40.3
55	20	20	25	5	1168.34	718.7	94	0.84	133	45,385	15,883	35.0
55	20	20	25	5	1212.98	731.3	100	0.84	142	46,415	16,800	36.2
60	0	20	30	5	1171.76	778.42	105	0.82	146	48,991	16,808	34.3
60	0	70	30	5	1201.87	730.76	110	0.92	146	47,296	17,197	36.4

The exemplary prototype configuration discussed above also exhibited improved heat transfer efficiency where the fluid in twisted tubes **402** ran in a direction countercurrent to flue gas in shell **406**. With such countercurrent configuration, the prototype system processed hot water (heating close to 146° F., up from the inlet temperature of 87° F.) at a flow rate of 0.46-0.64 gallons per minute (GPM) while the hot gas inlet temperature is 1150° F. and the hot gas outlet temperature is 861° F. (as compared to heating only to 126° F. under a concurrent or parallel flow configuration).

[0061] In further configurations, heat generated by combustion chamber **100** may be applied to the generation of electrical and thermal energy, such as through use of a heat engine, such as by way of non-limiting example a Stirling engine. FIG. **13**(*a*) is a schematic view of the combustion system including a Stirling engine **900**, and FIG. **13**(*b*) shows a more simplified schematic view of such system with certain elements removed for clarity. Such removed elements may likewise optionally include the heat exchanger **400** and space heating system discussed above with respect to FIGS. **8-12**.

[0062] A Stirling engine, also known as a heat engine, is an external heat engine that converts heat energy into mechanical work via a closed regenerative thermodynamic cycle that has same theoretical thermal efficiency as the Carnot cycle. The engine experiences periodical compression and expansion of working fluid at different temperature levels to convert thermal energy into mechanical energy. The heat engine consists of a displacement piston that pushes a working fluid (i.e., helium) through the regenerator from the head to the cooler. The spring on the opposite casing at the bottom pushes the piston back upwards. The helium is alternately heated and cooled, and as a result it expands and contracts again to create a pressure wave. This process repeats as the cycle begins again. The working piston is moved up and down by the pressure waves. The working piston is surrounded by a fixed magnetic tape and interacts with copper coils in order to generate alternating current. This cycle may be repeated, for example, 50 times per second to generate AC power at 50 Hz. In an exemplary prototype configuration implementing certain aspects of the invention, the Stirling engine used in testing was manufactured by Microgen Engine Corporation, although other Stirling engines are commercially available and could likewise be used.

[0063] In accordance with certain aspects of an embodiment of the invention, and with particular reference to FIGS. **13**(*a*) and **13**(*b*), Stirling engine **900** is combined with combustion chamber **100**, preferably at a position that will absorb maximum heat and simultaneously produce both power and hot water during the combustion process. In an exemplary prototype configuration, six (6) K-type thermocouples were installed in the biomass combustion chamber **100** at varied chamber heights to monitor the temperature changes. From previous testing and temperature results, the engine heat head was placed at an optimal height of 406.4 mm above the primary air distributor. The temperature of the engine head inside of combustion chamber **100** was higher (about 2500° F. or 1371° C.) at this position.

[0064] The external heat source from the biomass combustion system is absorbed by the engine head surface and is transferred to the helium in the engine head. Then, helium expands and functions as a piston inside of the Stirling engine to generate alternating current as discussed above. The engine head temperature should not exceed 1076° F. (or 580° C.) to protect overheating of the engine. Once the engine head temperature reaches an optimal temperature (e.g., between 977° F. or 525° C. and 1076° F. or 580° C.), external heat and engine head temperature should be maintained to get full power (e.g., 1 kw) from the Stirling engine.

[0065] During the processes of electrical generation and hot water generation, the working fluid and engine head are

cooled to avoid overheating. To prevent overheating, a cooling system is provided for the Stirling engine. The cooling system consists of a radiator **902**, fan **904**, circulating pump **906**, water storage tank **908**, and control value **910** configured to reject heat generated on the working fluid during the power generation process. The radiator **902** (e.g., aluminum core, plastic tank) can be used as a heat exchanger to reject heat from the hot coolant into the surrounding space and return as cold coolant with the help of a 12-volt or 115-volt fan **904**. The pump **906** with a water storage tank **908** (e.g., DAYTON 1XLK9 ⅛ HP 115-volt Pump/tank) is preferably used to store and circulate the coolant, comprising a mixture of 50% water & 50% antifreeze coolant, between the engine **900** and the radiator **902**. The control valve **910** controls the flow rate of coolant to the engine **900**.

[0066] A coolant flow sensor from the Stirling engine may be provided between water storage tank **908** and Stirling engine **900** to measure the water inlet flow rate and temperature. The performance of Stirling engine **900** may be measured and monitored with an engine control box **920** along with a Microgen Test Rig Data Viewer. The Microgen Test Rig Data Viewer can also monitor the coolant flow rate. To run the engine in the exemplary prototype configuration without error, the coolant flow was set at a minimum of 7 liters per minute (L/min) while the maximum was set at 25 L/min. The control valve **906** was used to set the coolant flow at 10 L/min. It was observed that higher coolant flow (more than 15 L/min) rejected too much heat from Stirling engine **900** and took a longer time to harvest enough heat from the combustion chamber **100** to generate alternating current (AC) and electricity. The hot coolant from the engine outlet can be connected to the radiator **902** to convert hot coolant flow into cold coolant flow with the help of fan **904**. The cooled coolant from the outlet of the radiator **902** can be returned directly to the storage tank **908** and supplied to the Stirling engine **900**. This system is a closed loop cooling system to cool the engine from overheating.

[0067] The alternating current can be passed through the engine controller system **920**. A controller system **920** is used to transfer the alternating current through the regular three-phase grid **950**. The engine controller **920** may be used to monitor engine performance and to ensure safe operation of the engine against outside (electrical) damaging events. It also contains the start/stop procedures and provides the connections to other controls, such as the application control and power-related functions. It will automatically shut down the engine if the engine head temperature reaches the maximum temperature of 580° C.

[0068] Stirling Engine **900** is connected to and disconnected from the low-voltage electricity distribution network by a grid interface connection **950**. The grid interface connection **950** comprises a 50 Hz, 230-volts connection box. The Microgen E1 controller box requires the power to start/stop the engine in ideal conditions and initial power can be taken from the grid to run all of the sensors, data monitoring and log software. In order to start the engine control box, the initial engine head temperature must be less than the grid connection enable temperature (e.g., lower than 338° F. or 170° C.). During the combustion process, alternative power is generated when the engine head temperature reaches 410° F. or 210° C. The alternative power can return to the same grid because the alternative power is also at 50 Hz, 230 volts. A circuit breaker box was built to change 50 Hz, 230 volts into 60 Hz, 110 volts for U.S. usage. The grid disconnection will normally occur when the engine head temperature falls below the grid disconnection temperature (lower than 270° F. or 150° C.) or when there is no power (0 watt) generation at the beginning. As soon as grid disconnection has occurred, the control system moves into an overrun state. In the overrun state, a fan **904** is used to cool the engine head until the engine head temperature falls below the grid connection enable temperature. For emergency grid disconnection, the grid switch can be manually turned off at any time.

[0069] A dedicated data monitoring and logging system can be constructed for the Microgen E1 Controller **920**. As an example, in the exemplary prototype configuration discussed above, data was continuously transmitted via the RS-485 interface (J9). This data can be readily decoded and used to monitor real-time operation and/or to log test data. Performance data is captured and carried out on a desktop by using the serial port. An RS-485 to RS-232 converter is used to perform the signal conversion and transferred into the Test Rig Data View, which allows one to monitor data that may include the engine head temperatures, coolant flow rate, coolant inlet and outlet temperature, back-end temperature, ambient temperature, voltage, current, power and energy output, etc.

[0070] Table 2 below shows the running condition of Stirling engine **900**, wherein the head of Stirling engine **900** was placed inside of combustion chamber **100**, and a temperature sensor was placed near the engine head to measure the temperature and calculate amount of heat near the engine head. During the biomass (i.e., poultry litter) combustion process, the engine head absorbs the heat and starts running at an engine head temperature of 428° F. or 220° C., while the chamber temperature will be around 1562° F. or 850° C. At the engine running condition, the coolant flow rate will be maintained at 10.0 L/min, and it starts generating power of approximately 180 watts initially. If the engine head temperature ranges from 977° F. (or 525° C.) to 1076° F. (or 580° C.), it is expected to generate full power (about 1 kW) from the engine. However, if the outlet coolant temperature exceeds 131° F. (or 55° C.), the control valve **906** should be changed to increase the water flow rate from 10.0 L/min to 15.0 L/min for maximum power output. Accumulated total (or thermal) energy for the Stirling engine may also be recorded. At an engine head temperature of 1076° F. (or 580° C.) and chamber temperature of 2390° F. (or 1310° C.), 880 watts of electricity and 9.12 kWh of total energy (about 0.88 kWh electricity) was generated at a water flow rate of 10.1 L/min.

[0071] During the combustion process, the engine head absorbs heat and starts running at the engine head temperature of 220° C. while the chamber temperature is around 850° C. As the Stirling engine **900** is running, coolant flow rate is maintained at 10.0 L/min, and the Stirling engine **900** starts generating power initially of about 180 watts. If the engine head temperature is maintained around 525° C. to 580° C., full power (e.g., 1 kW) is expected to be produced from the engine. However, if the outlet coolant temperature exceeds 55° C., the control valve should be changed to increase the water flow rate between 10.0 L/min to 15.0 L/min. During the time that the engine head temperature is 580° C. and the chamber temperature is 1310° C., 880 watts of power may be produced and results in 9.12 kWh of total energy. Accumulated total or thermal energy for the Stirling engine can also be recorded.

TABLE 2

Stirling Engine Generating Power Under Different Operating Conditions (note: temperature unit conversion from ° C. to ° F. may be determined by ° F. = 1.8* ° C. + 32)

No	Engine Head Temp (° C.)	Biomass Chamber Temperature Channel 2 (° C.)	Power (Electricity) (Watts)	Engine Coolant Flow Rate (liters/min)	Inlet Coolant Temp (° C.)	Outlet Coolant Temp (° C.)	Total or Thermal Energy (kWh)
1	220	850	180	10	21.7	21.9	7.68
2	250	896	238	10	77.8	73.4	7.69
3	300	916	348	10	24.8	25.3	7.72
4	350	963	449	10	28.1	29	7.78
5	400	995	553	10	32	33.4	7.87
6	450	1000	642	10.1	32.5	36.1	7.98
7	500	1022	703	10.1	32.7	36.8	8.24
8	525	1062	739	10.1	33.7	37.6	8.56
9	530	1090	758	10.1	34	37.9	8.77
10	530	1109	767	10.1	34.1	37.9	8.79
11	535	1154	772	10.1	34.2	38.2	8.82
12	540	1186	782	10.1	36	40.4	8.88
13	550	1201	808	10.1	34.9	43.8	8.92
14	560	1237	875	10.1	33.9	47.1	8.98
15	570	1282	855	10.1	33.7	49.8	9.02
16	580	1310	880	10.1	31.5	53.3	9.12

[0072] Electricity outputs of the Stirling engine were determined by the difference between heat absorption of working fluid (i.e., helium) from the biomass (i.e., poultry litter) combustion process and heat rejection through the cooling process of coolant. Based on preliminary tests and findings, head control temperatures and water flow rates of Stirling engine **900** were determined to be important indicators of the heat absorption during the biomass combustion and heat rejection during the cooling process. As shown in FIG. **14**, electricity outputs were measured at water flow rates of 9.1, 10.4, 13.1 and 19.4 L/min, along with various engine head temperatures from 428° F. or 220° C. to 1083° F. or 584° C. to further evaluate the performance of Stirling engine **900**. Experimental results indicated that the electricity output linearly increased with engine head control temperature of the Stirling engine **900**, while the head temperature was increased by increasing surrounding chamber temperature at a height of 15 in. (about 381.0 mm) above the primary air distributor. When the Stirling head control temperature was lower than 662° F. or 350° C., the minimum threshold of electricity output was found at a water flow rate of 19.5 L/min. This confirmed that heat rejection at a water flow rate of 19.5 L/min was more than the required cooling of the working gas during electricity production. However, when the Stirling engine head control temperature increased to 752° F. or 400° C., the minimum threshold of electricity output was found to be at a water flow rate of 9.0 L/min. A possible reason may be that the water flow rate of 9.0 L/min was too low to provide enough cooling of the working fluid at Stirling engine **900**. These results infer that either high (19.5 L/min) or low (9.0 L/min) water flow rate was not appropriate to provide sufficient cooling of the working fluid on Stirling engine **900** and provide optimal electricity output during the poultry litter and natural gas co-combustion process. Based on test and evaluation process, it was found that the lab-scale biomass conversion system requires an optimal water flow rate of 13.1 L/min to effectively cool the Stirling engine **900** within the acceptable cooling temperature to prevent melting of engine parts and produce relatively high electricity output, and thereby improve the overall efficiency of system performance. At a water flow rate of 13.1 L/min, the electricity output reached a maximum value of 905 watts at a Stirling engine head control temperature of 1083° F. or 584° C.

[0073] Optionally, residual heat from combustion chamber **100** that is produced during the combustion process may be applied to drying of the biomass (i.e., poultry litter) before being processed in the system itself, thus reducing the existing moisture content and contributing to improved combustion efficiency. As shown in the schematic view of the combustion system of FIG. **15** and in accordance with further aspects of an embodiment of the invention, the system may include a direct drying process that precedes the combustion chamber **100**, which direct drying process may be used to pre-dry the biomass (e.g., poultry litter) in the fuel feeder **102** using hot air from combustion chamber **100** to reduce the moisture content of the biomass/fuel and improve its combustion efficiency. Such direct drying process may be monitored and controlled so as to increase its efficiency and reduce gas emissions.

[0074] The direct drying process is generally comprised of copper tubes **960**, an air pump **962**, a moisture detection sensor **964**, and thermocouples. Copper tube **960** is wrapped around combustion chamber **100** and the 90-degree elbow section **101** to absorb heat from the outer surface of combustion chamber **100** and 90-degree elbow section **101** into copper tube **960**. The 90-degree elbow section **101** is particularly included as a heat transfer source for the system as a higher quantity of heat is radiated from its outer surface, due to the fact that such 90-degree elbow section **101** need not include a ceramic layer on the inner wall, as would typically be the case in combustion chamber **100**.

[0075] Air pump **962** supplies cold air that travels through copper tube **960** to absorb heat and become hot air. The end of copper tube **960** is connected to preferably four individual hot air injection nozzles **966**, with one such nozzle **966**

positioned on each side of fuel feeder **102**. Each individual hot air injection nozzle **966** includes several holes to effectively supply air into the fuel feeder **102**. Thus, hot air is transported from copper tube **960** and split into four lines, causing hot air to be circulated in feeder **102**. Additionally, copper tube **960** may optionally include insulation so as to avoid heat loss. Inlet and outlet air temperatures and air velocity in copper tube **960** may be measured and monitored to monitor the amount of heat absorption.

[0076] A preferably rectangular, clear, and plastic hopper with a sieve may be provided on top of fuel feeder **102** to remove any stray materials (e.g., rocks and the like) and to feed the poultry litter into fuel feeder **102**. A plurality of inclined boards **968** may be provided in the plastic hopper to feed poultry litter slowly and to reduce vertical weight and pressure during the feed operation. A biomass moisture sensor and thermocouple **964** measures the initial moisture content and temperature of the poultry litter as it enters the plastic hopper. Both the poultry litter and the hot air move counter-current (i.e., hot air flowing in an upward direction while the fuel flows downward) to maximize heat transfer rate. Upon contact, the hot air works to reduce and remove moisture present in the poultry litter. Using another similarly configured thermocouple and moisture sensor **964**, temperature and moisture content may likewise be measured after the drying process using weight changes. The resulting difference in temperature and moisture content then establishes the effectiveness of the drying process and may be used to adjust the process to achieve a desired level of drying of the poultry litter.

[0077] An experimental prototype drying system was first evaluated via computer simulation using Simprosys software, a WINDOWS-based software package available from Simprotek Corporation. That simulation software provides an integrated, powerful, yet highly user-friendly and contemporary tool for the design and simulation of dryer flow sheet and drying systems.

[0078] For a continuous convective dryer, the material and heat balance equations are as follows:

$$Wg(Yo - Yi) = Ws(Xi - Xo)$$

$$dQ = \frac{\text{dm_hot_gas}}{dt} * \text{Cp_hot gas} * (Ti - To)$$

The drying process efficiency was measured using the Thermal Efficiency and the Specific Heat consumption (or thermal energy) of the simulated dryer with governing equations contained in the simulation software. The drying process was simulated for moisture content reduction from 22 wt. % to 15 wt. % using the following factors specified in Table 3:

TABLE 3

Simulation Factors

Poultry Litter	Hot Air
Feed moisture content = 0.22 kg/kg wb	Inlet Temperature (Dry Bulb) = 60-90° C.
Feed Temperature = 20° C.	Inlet Pressure = 101.3 kPa
Product Temperature = 50° C.	Initial absolute humidity = 0.009 kg/kg
Mass Flow Rate = 10 kg/h	Air Velocity = 0.5-1.0 m/s

Table 3: Simulation Factors

[0079] Then, emission results, combustion efficiency, and temperature distribution during the poultry litter combustion process were monitored and recorded under the proposed drying process. Experimental results were gathered from the poultry litter sample that did not go through the drying process. These results were compared with previous test results to identify the benefit of the drying process for the system performance.

[0080] Because of the high moisture content of poultry litter, there was some uncertainty as to whether steady and complete combustion of poultry litter alone could be maintained. Co-firing of poultry litter with fossil fuels (i.e., coal) is considered as a feasible means to address the energy supply issues and aid in the solution of air pollution control problems. But there is a large amount of increasing poultry litter production and challenges of transporting poultry litter to the existing coal power plants, such as lower energy density, decentralized farms, and high transportation costs. There is thus a need for reducing moisture content and burning poultry litter alone on the poultry farm sites.

[0081] In an experimental implementation, a ⅛ inch diameter spiral copper tube was used to absorb heat from hot water, with cold air blown from one end of the tube, such that the air gained heat in the pipe from the hot water to mimic the flue gas during the poultry litter combustion process. Then, the processed hot air was transferred into poultry litter material held in a container. This was a form of forced convective heat transfer. In the experimental setup, hot water was placed in an aluminum plate and lost its temperature to the surrounding environment, such that the hot air temperature could not be controlled. Thus, the team designed a calorimeter using a Styrofoam box to reduce heat loss. This helped to maintain a relatively constant hot water temperature. The experiment carried out is summarized in Table 4.

TABLE 4

Experimental Results fof Drying Process

	Drying Time = 5 mins, Air Velocity = 1.7 m/s, Air Pump Pressure = 15 psi		
Parameters	Test 1	Test 2	Test 3
Initial weight of Sample (Poultry Litter)	50 g	50 g	50 g
Amount of water added	7.33 g	6.38 g	6.27 g
Total sample weight with water	57.33 g	56.38 g	56.27 g
Heating material	Aluminum Plate	Styrofoam box	Styrofoam box
Initial Feed temp	82° F.	85° F.	88° F.
Initial Water Temp	187° F.	184° F.	162° F.
Final Water Temp	149° F.	167° F.	148° F.
Final Feed Temp	88° F.	95° F.	104° F.
Air Temp in drying material	104° F.	113° F.	122° F.
Final weight of sample with water	57.13 g	55.46 g	54.55 g

The foregoing results show the feasibility of using heat transferred from a source, such as combustion chamber **100** (obviously operating at much higher temperatures than those in the above experiment) to cold forced air through a copper

tube, and delivered hot forced air to moist poultry litter in order to reduce moisture to, in turn, improve combustion efficiency in combustion chamber **100**.

[0082] As discussed above, monitoring and control system **160** may control the amount of biomass fuels delivered to combustion chamber **100** (e.g., control the feeder's rate (in RPM) with a Programmable Logic Controller (PLC)), to a blower **112** to control the amount of air delivered through primary air distribution and delivery system **110** and through secondary air distribution and delivery system **130** (e.g., through fan control with the PLC), and preferably to valves **114** to allow independent control of the amount of air delivered through such systems **110** and **130** with respect to one another.

[0083] FIG. **16** is a flowchart showing the logical control of the combustion process using a PLC. The goal of such process is to continue adjusting the fan speed every time the temperature drops than desired combustion temperature, as well as the feeder's rate under a steady increase in temperature inside of combustion chamber **100**. However, if the temperature is able to reach the desired temperature, e.g., 800° C. or higher, then the operation will run continuously for 20 minutes or more. In general, the PLC may be used to control the feed rate of biomass fuel from the feeder **102** and air flow based on temperature changes detected by thermocouple sensors. FIG. **17** is a schematic view of the PLC control circuit, in which a step up/down transformer **970** may be provided to step up the regular power supply from a wall power outlet **971**. Once the temperature is detected by the temperature sensor, the control system computer sends program codes to a communication module. Then, the PLC CPU **972** transfers the signal to an analog I/O module, which in turn transfers the signal to a variable frequency drive (VFD) **973** for the air blower **974** to control the air flow rate. In an exemplary configuration, a 230V 3-phase blower **974** is connected to VFD **973**, which receives 230V single phase from transformer **970**. Blower **974** may have 9 lines encrypted as T1-T9 for lead connection depending on input voltage, whether 230V (low voltage) or 460V (high voltage). Likewise, PLC CPU **972** sends another analog signal to the analog I/O module and fuel feeder **102** for controlling the fuel feeding rate.

[0084] The foregoing system may be used to process a wide variety of biomass materials, including (by way of non-limiting example) poultry litter, municipal solid waste, agricultural waste, algae waste, biomedical hazard waste, and the like. Moreover, sawdust, wood chips, wood pellets, switch grass, dried leaves, corn husks, rice shells, and such other biomass materials as may be selected by those skilled in the art may similarly be processed by the foregoing system to produce high heat and energy.

[0085] The foregoing system may be particularly well suited to processing of poultry litter. While total poultry litter production on a given poultry farm will determine feed rate of materials to combustion chamber **100**, in a particularly preferred configuration, poultry litter may be directed to combustion chamber **100** at a feed rate of 40-60 lb/hr to process a single poultry farm's waste (about 300 tons/year with 3 poultry houses). Operating at a schedule of 20 hours/day, 6 days/week, and 52 weeks/year, such a feed rate can process approximately 300,000 pounds of poultry litter each year. In processing such poultry litter (as well as other biomass materials), it will be important to monitor and regulate moisture of the feedstock to ensure proper combustion in combustion chamber **100**. Particularly for poultry litter, a desired practical moisture level is between 15% and 35%, and above this range, pre-drying will be required for combustion to proceed efficiently in combustion chamber **100**. Of course, feedstock may certainly have a lower moisture content and achieve proper combustion in combustion chamber **100**, such that an overall operational target is for moisture content of any biomass material to be generally below 35%.

[0086] In accordance with certain aspects of the invention, a method for processing biomass material may comprise the steps shown in FIG. **7**. At step **702**, biomass feedstock is provided having a moisture content that is general less than 35%. In the event that such biomass has a moisture content higher than 35%, predrying of such biomass material should be carried out to reduce the moisture content. Next, at step **704**, such biomass material is introduced into a combustion chamber **100** of a biomass combustion system configured as detailed above. As the biomass material is being introduced into combustion chamber **100**, as noted at step **706**, a vertical primary airflow is directed into combustion chamber **100**, while multiple, vertically displaced tangential airflows are introduced into combustion chamber **100**, so as to create a swirling fluidized bed of the biomass particles in combustion chamber **100**, with the biomass particles being combusted at a combustion efficiency of at least 90%. At step **708**, heat generated from the biomass combustion process is carried in the form of flue gas and a portion of heat may be transferred into the working fluid of a Stirling engine to generate electricity and hot water. Then, the flue gas enters 90-degree elbow section **101** and at step **710** is directed toward heat exchanger **400** from combustion chamber **100**. At step **712**, heat may be captured from the surface of heat exchanger **400** and 90-degree elbow section **101** to perform the process of pre-drying of biomass. At step **714**, flue gas from the heat exchanger **400** is directed to a cyclone separator configured as above, where any unburned waste and particles that were unburned in the combustion chamber are burned completely, and flying ash is divided and collected in a container connected to the cyclone separator, while dioxin production is significantly minimized if not altogether eliminated. The collected ash and char may thereafter optionally be used as fertilizer. Next, at step **716**, the system exhaust (in the form of high temperature flue gas) is directed to the exhaust system with significantly reduced noxious emissions, and more particularly having NO_x of less than 80 ppm, SO_x of less than 20 ppm, CO_2 of less than 2%, and particulate matter content of less than 3 lb/MM Btu.

[0087] In accordance with the foregoing method, heat captured from the flue gas is thus put to useful energy, such as by generating steam for delivery to a turbine, powering a Stirling engine, or other such other energy generation devices as may be apparent to those skilled in the art, or for direct heating of process materials, such as water, feed stock (for drying the same), or the like, or such other direct heat application processes as may be apparent to those skilled in the art.

EXAMPLE 1

[0088] A lab-scale prototype of the system described above was designed and built by the Lee Research Group at The Center for Advanced Energy Systems and Environmental Control Technologies (CAESECT) at Morgan State University in Baltimore, Md. The lab prototype system can

process 11-24 lb/hr of pre-dried poultry litter with high combustion efficiency (over 96%) without bed materials. The poultry litter was burned in a well-controlled environment at a temperature low enough (1,400-2,100° F.) to avoid formation of nitrogen oxides, but high enough to avoid agglomeration and slagging in the ash. Milestones for efficiency, ultra-clean emissions, and particular matter were set as follows: NO_x (30-80 ppm), SO_x (15-20 ppm), CO_2 (1.5-2.0%), and particulate matter (2.0-2.5 lb/MM Btu). The residual fly ash (i.e., phosphate P_2O_5 and potassium, K_2O) is a high value fertilizer. The results produced from the prototype configuration indicate improved performance characteristics over other combustion technologies, as shown in Table 5 below.

TABLE 5

Comparison of System with Other Combustion Technologies

	Stoker*	BFBC*	CFBC*	System According to Aspects of the Invention
Firing Capacity	Small/ Medium	Small/ Medium	Medium/ Large	Small/ Medium
Combustion Efficiency (%)	=80%	80-90%	85-94%	Above 95%
SO_x Removal in combustor	None	Sorbent in bed	Sorbent in bed/freeboard	Optional
NO_x Emissions	High	Low	Very low	Very low
Ash Form	Bottom ash	Bottom ash	Bottom ash	Fly ash
Combustion Temperature (° C.)	1,300	850-950	850-1000	850-1,250
Primary Air Fraction (%)	100	100	>80	10-50
Mean Gas-Particle Slip Velocity (m/s)	None	0.2	0.5-1.0	1-5
Turbulence in Combustor	None	Good	Excellent	Excellent

*Stoker-Fired Combustor, BFBC-Bubbling Fluidized Bed Combustor (FBC), CFBC-Circulating FBC, SFBC

[0089] In order to achieve the foregoing benefits, the prototype system was configured as detailed in Table 6 below:

Combustor Dimensions

	Component Description	Units (in)	Units (cm)
1	Combustor Outer Diameter (d_{cod})	15.12	38.4048
2	Combustor Internal Diameter (d_{cid})	13.72	34.8488
3	Refractory Material Thickness (t_r)	0.7	1.778
4	Fuel Feeder Diameter (d_f)	2.9	7.366
5	Primary Air Inlet Diameter (d_p)	3.5	8.89
6	Secondary Air Inlet Diameter (d_s)	0.46	1.1684
7	Total Combustor Height (H)	74	187.96
8	Air Box Height (H_a)	13	33.02
9	Combustion Chamber Height (H_c)	61	154.94

The prototype configuration was provided one primary port and 12 secondary ports. The primary air was injected from the bottom of the chamber. The heights of secondary air nozzles were 34, 45 and 55.5 inches from the primary air distributor, respectively. The feeding rate for the prototype configuration was 11-24 lb/hr. The air flow rate for primary air was 49-110 cubic feet per minute (cfm), and for secondary air was 6-16 cfm. The temperature during poultry litter combustion was between 1,400-2,100° F., which achieved up to 97% combustion efficiency. The measured emissions from the combustion chamber were 0-23 ppm NO_x, 0-19 ppm SO_x, 0-1.7% CO_2, and particular matter of 0.45-1.19 lb/MM Btu, achieving a combustion efficiency of up to 97%.

[0090] A system and method implemented in accordance with the above disclosure provides significant opportunity for the clean disposal of biomass with the added advantage of power and hot water generation. The total number of farms in the U.S. producing poultry products, including broilers, breeders and egg layers is estimated at 99,700. Of this total, approximately 30,000 broiler farms account for 95% of broiler production in the U.S., with 6%-7% of broiler production generated in the Delaware-Maryland-Virginia region, with 2,700 broiler farms. The U.S. accounts for 20% of the world's broiler production, while European Union countries account for 12% (60% of U.S.). The current projections for both the small-scale farm unit and a large-scale regional unit configured as described above would generate energy to the grid that is currently estimated to be able to pay back the capital cost in 3.5 years. This does not include any environmental credits/funding, or the value of cost for bio-waste disposal.

[0091] Longer-term markets would include any agricultural industry where biomass is generated and must be disposed of in a clean, cost-efficient manner (including, by way of non-limiting example, pork and meat production industries, rice straw, rice husk, wheat straw, corn stalk, and post algal processed (oil-extracted) biomass). In addition, algae is an interesting source of bio-energy for its concentration of oil. Currently, after oil extraction, the remaining algal biomass can be dried, pelletized, and used as fuel that is burned in industrial boilers and other power generation systems. The system and method described herein may be suitable to decrease costs of generating energy from the remaining algal biomass, increasing the market potential for the technology.

[0092] Moreover, the system and method described herein are believed to provide significant improvement over conventional direct combustion technologies. For example, for bubbling fluidized bed combustion, high pressure air is fed through the bottom of the boiler with lower fluidization velocity which causes a bubbling effect and allows most of the bed material to be retained in the lower furnace. For circulating fluidized bed combustion, high-pressure air suspends the bed material and fuel particles, which can rise up the chamber into the cyclone. Heavy particles will fall into the cyclone hopper and be returned to the furnace to be used again. For conventional swirling fluidized bed combustion, secondary air ports provide a swirling flow environment for combustion in an effort to increase the particle residence time and reduce unburned particles. However, the system and method described herein and employed in accordance with the invention provides multiple levels of secondary air injection nozzles, with optimized configurations for both primary air injection nozzles and secondary air injection nozzles, which features optimize the ability to control the combustion process and achieve higher combustion efficiencies (with resulting lower noxious emissions) than such previously known systems. As demonstrated in the initial test results (above), the system and method disclosed herein also 1) provides efficient burning at controlled temperatures which reduces NO_x and particulate emissions, 2) supplies

sufficient secondary air and extended swirling air to burn fuels in the upper part of combustion chamber with high efficiency, 3) mixes fuel and combustion air quickly and uniformly, and 4) provides large gas-particle slip motion which prolongs particle residence time and allows a reduction in chamber size and thus the cost of the system.

[0093] Having now fully set forth the preferred embodiments and certain modifications of the concept underlying the present invention, various other embodiments as well as certain variations and modifications of the embodiments herein shown and described will obviously occur to those skilled in the art upon becoming familiar with said underlying concept. It should be understood, therefore, that the invention may be practiced otherwise than as specifically set forth herein.

1. A system for fluidized bed combustion, comprising:
- a combustion chamber, said combustion chamber further comprising:
  - a primary air distribution and delivery system configured to provide vertical airflow through said combustion chamber; and
  - a secondary air distribution and delivery system configured to provide a plurality of vertically displaced, horizontally aligned, tangential airflows in said combustion chamber;
- a biomass feeder in communication with an interior of said combustion chamber and positioned to deliver biomass material to said interior of said combustion chamber at a location above said primary air distribution and delivery system and below said secondary air distribution and delivery system; and
- a shell tube and heat exchanger comprising a plurality of twisted tubes, a plurality of baffles, and a cylindrical shell around said twisted tubes and said baffles, wherein said shell tube and heat exchanger receives flue gas from said combustion chamber and is configured to collect heat from said flue gas as it flows through said cylindrical shell.

2. The system of claim **1**, wherein said baffles are positioned at an inclined angle with respect to said twisted tubes.

3. The system of claim **2**, wherein said inclined angle is 40°.

4. The system of claim **1**, wherein each baffle has at least one and fewer than all tubes of said plurality of twisted tubes extending therethrough.

5. The system of claim **1**, wherein said baffles in said shell define a non-linear flow path of said flue gas as it travels through said cylindrical shell.

6. The system of claim **1**, further comprising a closed space having at least one radiator in fluid communication with said shell tube and heat exchanger.

7. The system of claim **6**, wherein said at least one radiator further comprises a plurality of radiators arranged in parallel in a closed fluid system including said plurality of radiators and said shell tube and heat exchanger.

8. The system of claim **6**, wherein said closed space further comprises a housing space housing a source of biofuel processed by said system.

9. The system of claim **1**, further comprising a heat engine in thermal contact with said combustion chamber and configured to generate electrical power and heat energy from heat generated inside of said combustion chamber.

10. The system of claim **1**, further comprising a fuel drying system, said fuel drying system further comprising:
- an air conduit wrapping around and in thermal contact with said combustion chamber and a blower at an inlet of said air conduit, said air conduit having a plurality of outlets with an air injection nozzle at each said outlet and positioned to transfer heat from said combustion chamber to biomass prior to entry of said biomass into said combustion chamber.

11. The system of claim **1**, further comprising a control system configured to, in response to temperature levels detected in said system, control an airflow of said primary air and said secondary air, and control a rate of delivery of biomass to said combustion chamber.

12. A system for fluidized bed combustion, comprising:
- a combustion chamber, said combustion chamber further comprising:
  - a primary air distribution and delivery system configured to provide vertical airflow through said combustion chamber; and
  - a secondary air distribution and delivery system configured to provide a plurality of vertically displaced, horizontally aligned, tangential airflows in said combustion chamber;
- a biomass feeder in communication with an interior of said combustion chamber and positioned to deliver biomass material to said interior of said combustion chamber at a location above said primary air distribution and delivery system and below said secondary air distribution and delivery system; and
- a heat engine in thermal contact with said combustion chamber and configured to generate electrical power and heat energy from heat generated inside of said combustion chamber.

13. The system of claim **12**, said heat engine having an outlet directing heated water to a radiator.

14. The system of claim **13**, said radiator having a radiator outlet directing water to a storage tank.

15. The system of claim **14**, further comprising a circulating pump positioned to pump water from said storage tank back to said heat engine, and a control valve positioned between said circulating pump and said heat engine.

16. The system of claim **12**, wherein said heat engine is a Stirling engine.

17. A system for fluidized bed combustion, comprising:
- a combustion chamber, said combustion chamber further comprising:
  - a primary air distribution and delivery system configured to provide vertical airflow through said combustion chamber; and
  - a secondary air distribution and delivery system configured to provide a plurality of vertically displaced, horizontally aligned, tangential airflows in said combustion chamber;
- a biomass feeder in communication with an interior of said combustion chamber and positioned to deliver biomass material to said interior of said combustion chamber at a location above said primary air distribution and delivery system and below said secondary air distribution and delivery system; and
- a fuel drying system, said fuel drying system further comprising:
  - an air conduit wrapping around and in thermal contact with said combustion chamber and a blower at an inlet of said air conduit, said air conduit having a plurality of outlets with an air injection nozzle at

each said outlet and positioned to direct heat from said combustion chamber to biomass prior to entry of said biomass into said combustion chamber.

18. The system of claim **17**, wherein said air conduit further wraps around an elbow conduit above said combustion chamber and that transfers flue gas downstream in said system, wherein said elbow conduit exhibits a higher level of heat transfer from an interior of said elbow conduit to an exterior of said elbow conduit than said combustion chamber transfers heat from an interior of said combustion chamber to an exterior of said combustion chamber.

19. The system of claim **17**, further comprising a hopper positioned above said biomass feeder and positioned to direct moist biomass into said fuel feeder.

20. The system of claim **19**, wherein said air injection nozzles are positioned with respect to said hopper to expose moist biomass in said hopper to heated air so as to reduce moisture in said moist biomass.

* * * * *