

Sept. 8, 1959

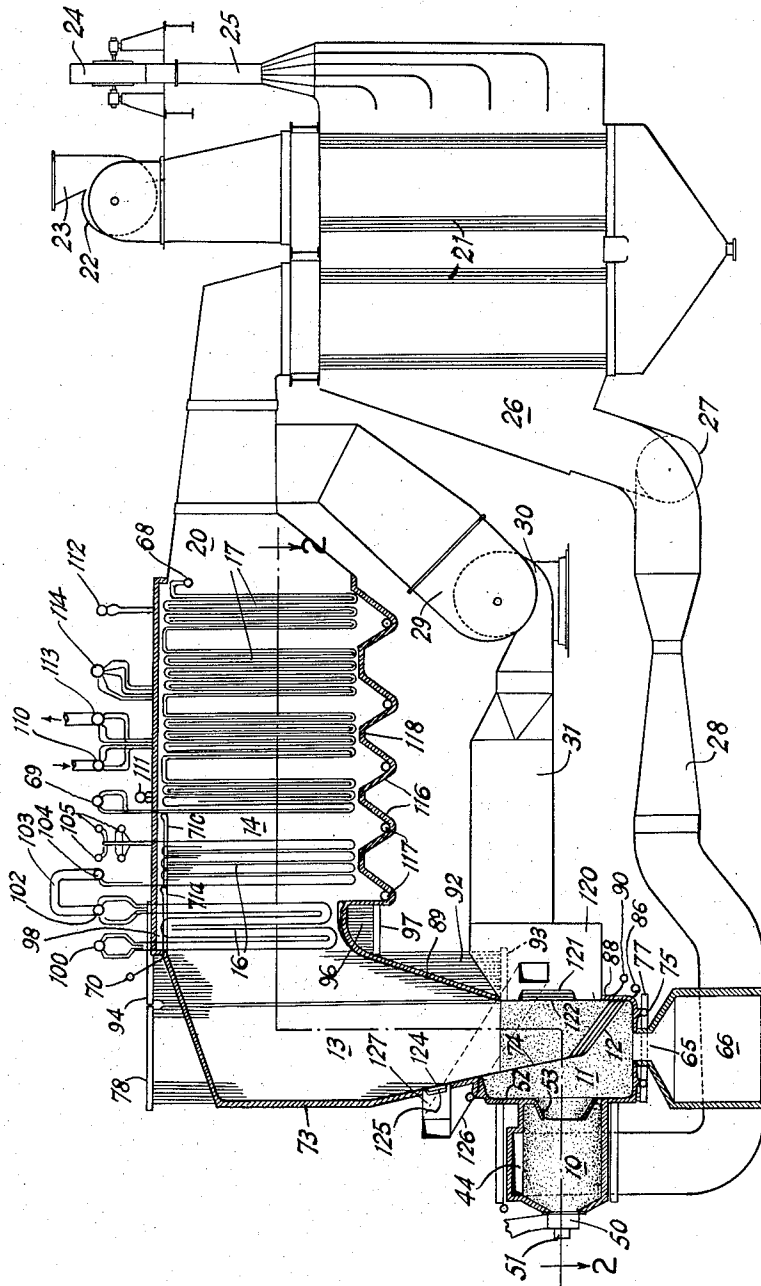
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2,902,982

FORCED CIRCULATION VAPOR GENERATING UNITS

Filed June 26, 1953

6 Sheets-Sheet 1



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6 Sheets-Sheet 2

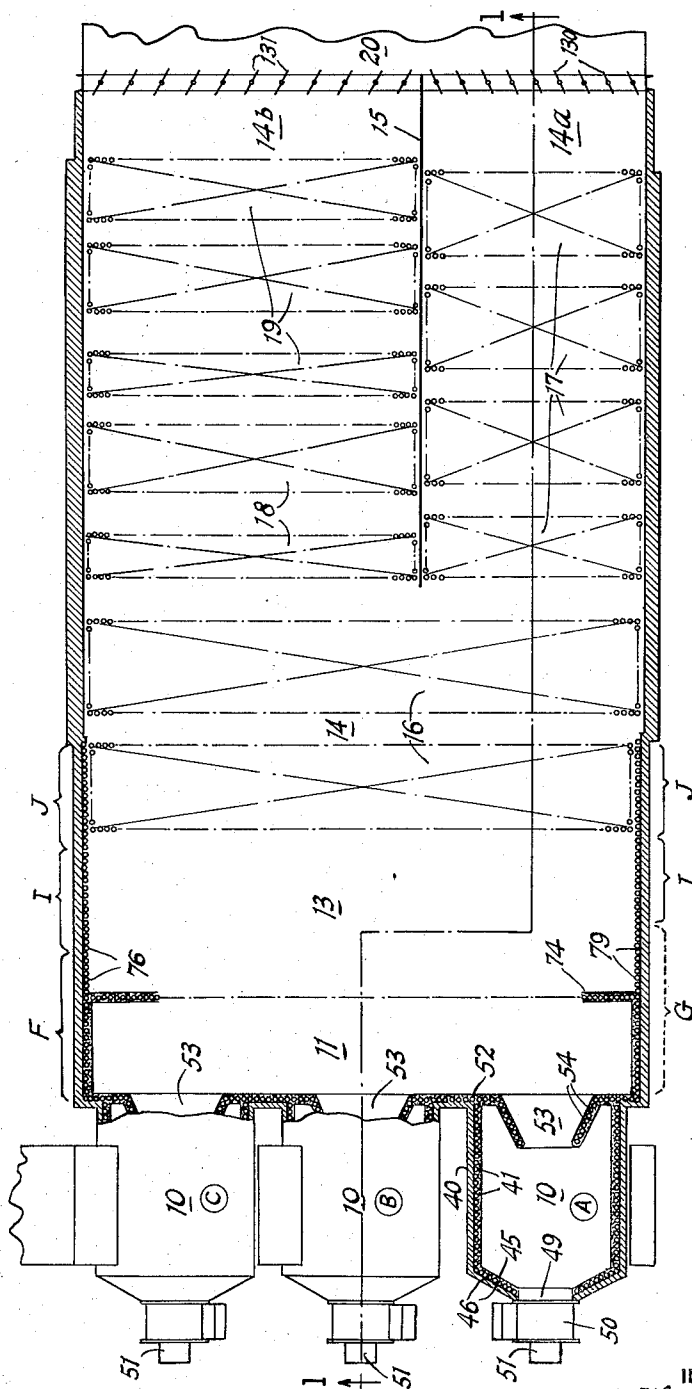


FIG. 2

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6 Sheets-Sheet 3

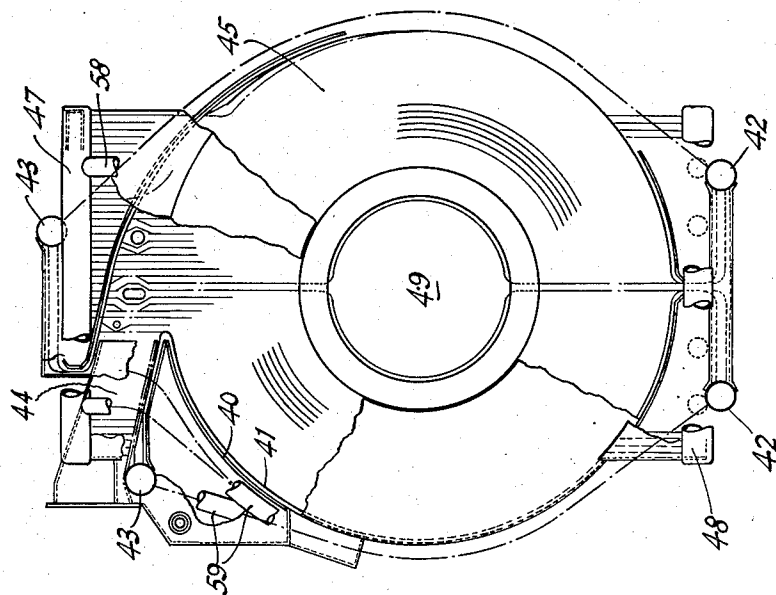


FIG. 3

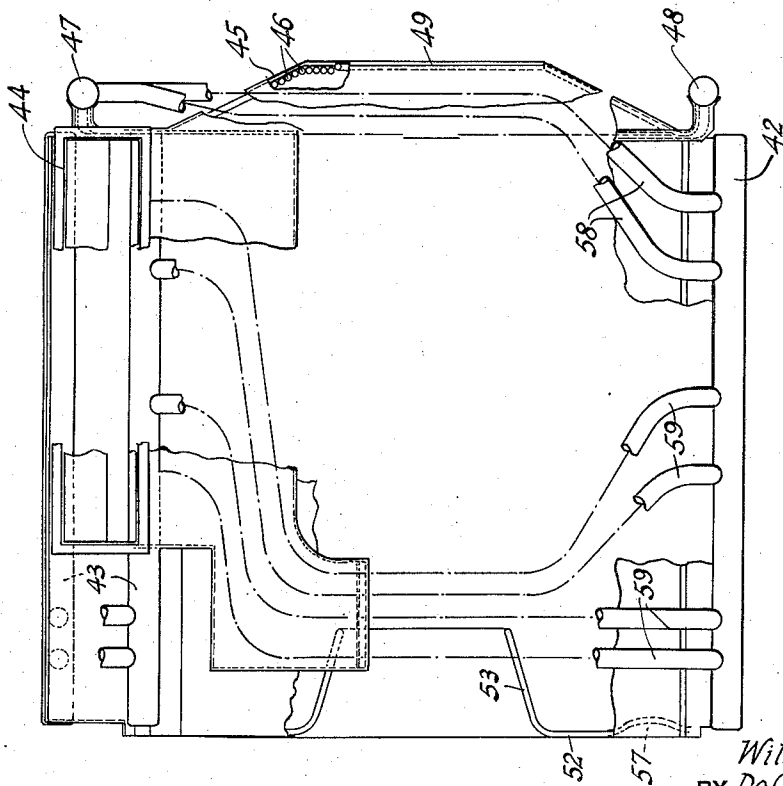


FIG. 4

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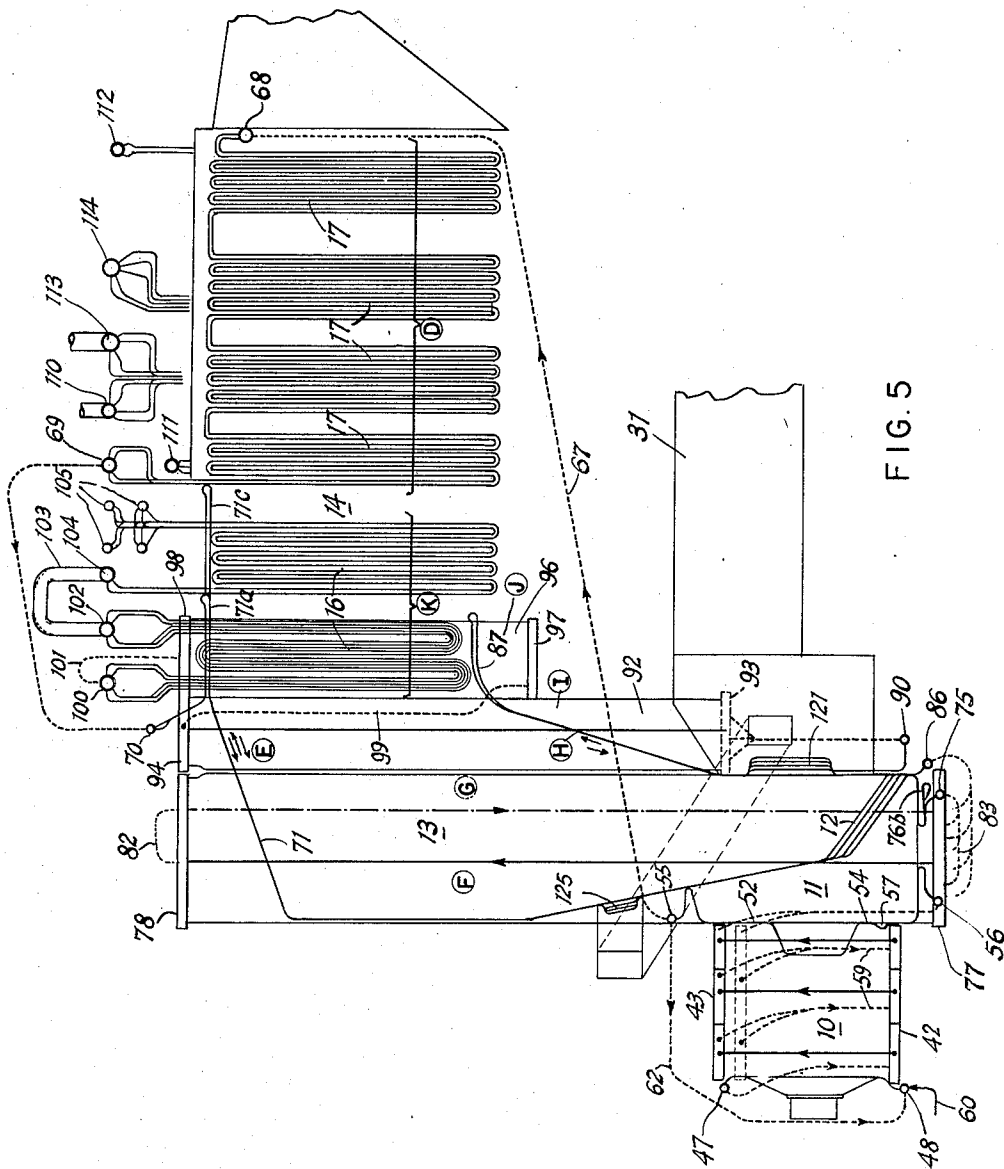
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FORCED CIRCULATION VAPOR GENERATING UNITS

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6 Sheets-Sheet 4



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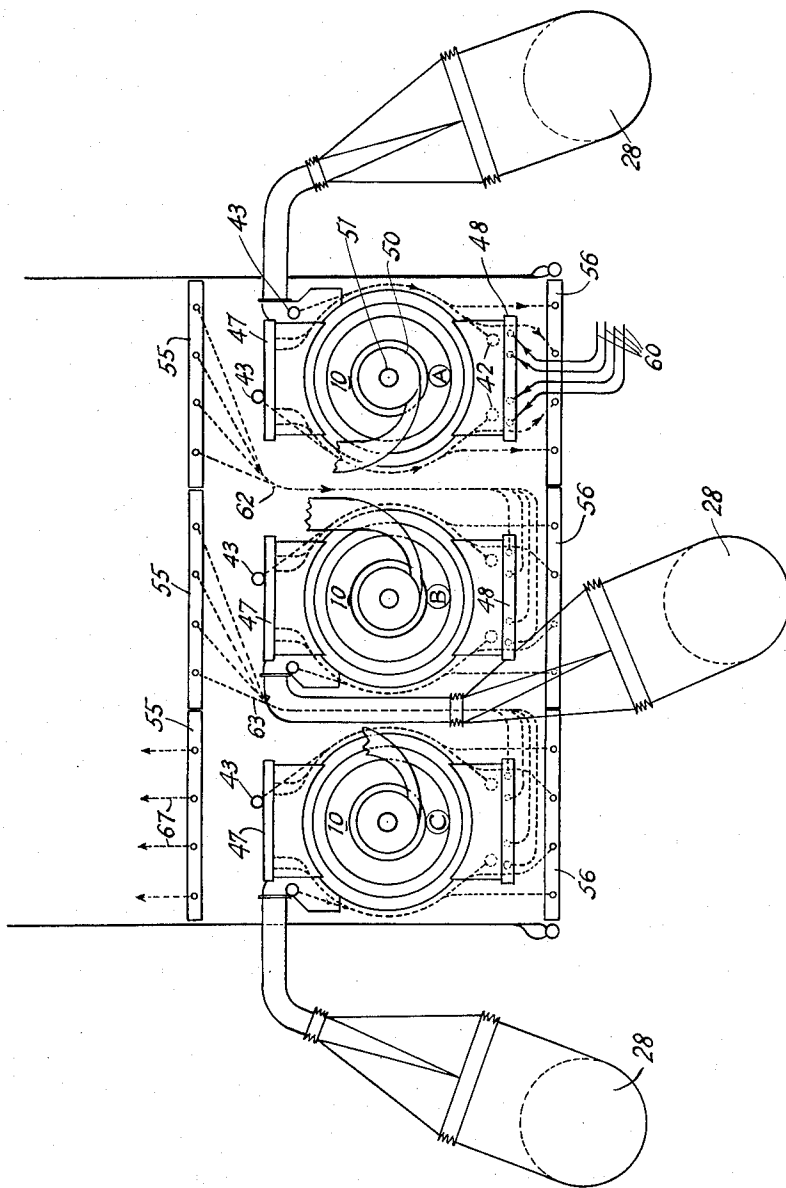
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FORCED CIRCULATION VAPOR GENERATING UNITS

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6 Sheets-Sheet 5



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6 Sheets-Sheet 6

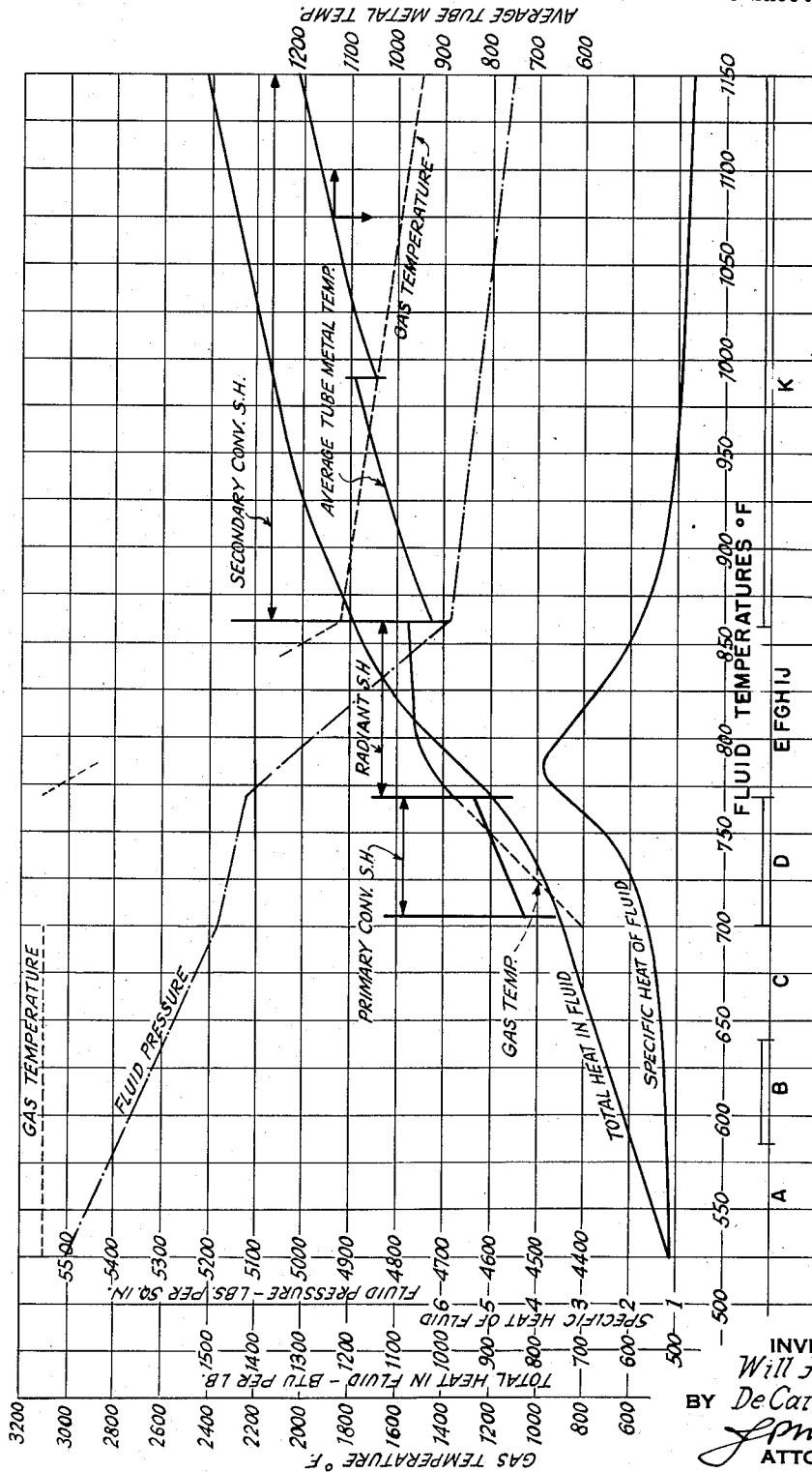


FIG. 7

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FORCED CIRCULATION VAPOR GENERATING UNITS

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Application June 26, 1953, Serial No. 364,378

11 Claims. (Cl. 122—478)

The present invention relates in general to the construction and operation of forced circulation vapor generators, and more particularly, to the construction and operation of forced flow once-through steam generating units especially adapted and particularly designed for the production of superheated steam at pressures and temperatures in excess of the critical pressure of 3206 p.s.i. and the critical temperature of 705° F.

While the high thermal efficiencies attainable in a steam power plant through the use of a forced circulation once-through steam generating unit producing superheated steam at pressures and temperatures in excess of the critical values have been known for many years (e.g. British Patents 201,304, 206,559 and 398,413), the design, construction and operating problems of such units have been such as to restrict the few such units actually built to small experimental installations of relatively low steam generating capacity. For substantially the same reasons the only commercial size forced circulation once-through steam generating units have been designed and constructed for operation at pressures below the critical pressure. Such sub-critical pressure operation has the additional problem of solid deposition and/or corrosive oxidation of metal in the transition zone in which the contained fluid is changed with a change in density from a liquid to a vapor state.

The general object of the present invention is the provision of a commercial size forced circulation once-through vapor generating unit and a method of operating the same to produce superheated vapor from a vaporizable liquid over a wide range of high pressures and temperatures above and below the critical pressure value, and characterized by its adaptability for use at capacities commensurate with that of the prime mover served; operability with available commercial fuels, including coal, at high combustion efficiencies; utilization of feed liquid supplied from a regenerative feed liquid heating system of the prime mover at relatively high temperature levels, the simultaneous reheating of lower pressure vapor in one or more stages, and without requiring the use of expensive materials or construction arrangements.

A further and more specific object of the invention is the provision of a steam generating unit of the general character described designed and constructed for operation at pressures substantially above critical pressure which is constructed and arranged with a general arrangement requiring a minimum of expensive structural supporting members; an arrangement of the heat absorbing fluid heating surface of the unit providing an optimum relation of fluid velocity within the tubes to heat input into the tube walls to effect adequate cooling of the tube wall to a safe temperature without imposing an excessive pressure drop in the fluid flow path; a division of the fluid heating surface between the radiant and convection heated sections of the unit whereby the water heating surface is mainly confined to the boundary walls of the furnace chamber or chambers and the furnace chamber volume and boundary wall area are proportioned in

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amount to heat the water in the chamber wall tubes under designed maximum load conditions of the unit to a temperature less than the critical temperature; a division of the fuel burning capacity of the unit between a plurality of independently operable water cooled furnace chambers in which the chamber wall cooling is effected by a serial flow of water through the wall tubes of successive furnace chamber units; solid fuel firing means in the form of a plurality of independently operable coal fired cyclone furnaces discharging the gaseous products of combustion into a common chamber at temperatures above the fuel ash fusion temperature, permitting the disposal of the separated incombustible ash residue as a molten slag; provisions for recirculating relatively cool heating gases to temper the high temperature gases to maintain the tube metal in the radiant and convection heating sections at a safe operating level and solidify any molten slag particles in suspension in the heating gases before passing to the convection heating section of the unit; and the arrangement of one or more convection heated steam reheating sections in a portion of the unit in which the amount of heating gases passing thereto can be effectively controlled for control of the reheated steam temperature or temperatures.

The objects of the invention also include the provision of a forced circulation once-through steam generating unit of the character described with a method of operation comprising the economic operation of the unit at high steaming capacities and a high thermal efficiency at operating pressures and steam temperatures substantially higher than the critical values; increasing or decreasing the superheated steam temperature by rendering ineffective or effective a substantial portion of the water heating surface of the unit during partial load operation; and control of reheated steam temperature over a relatively wide load range of proportioning the amount of heating gases in heat transfer contact therewith.

The various features of novelty which characterize the invention are pointed out with particularity in the claims annexed to and forming a part of this specification. For a better understanding of the invention, its operating advantages and specific objects attained by its use, reference should be had to the accompanying drawings and descriptive matter in which we have illustrated and described a preferred embodiment of the invention.

Of the drawings:

Fig. 1 is a partly diagrammatic sectional elevation taken on the line 1—1 of Fig. 2 of a forced circulation once-through steam generating unit designed for operation at super-critical pressures and constructed and operable in accordance with the present invention;

Fig. 2 is a partly diagrammatic plan section taken on the line 2—2 of Fig. 1;

Fig. 3 is an end view, partly broken away, of one of the cyclone furnaces;

Fig. 4 is a side view of the cyclone furnace shown in Fig. 3;

Fig. 5 is a schematic view showing the fluid flow through the apparatus illustrated in Figs. 1—4;

Fig. 6 is an end view showing the fluid flow through the cyclone furnaces; and

Fig. 7 is a curve sheet showing operating conditions in different portions of the unit.

In the drawings we have illustrated the invention as embodied in a forced flow once-through steam generating unit intended for central station use. The particular unit illustrated is designed for a maximum continuous steam output of 675,000 lbs. of steam per hr. at a pressure of 4550 p.s.i.g. and a total temperature of 1150° F. at the superheater outlet, based on feed water being supplied at a pressure of 5500 p.s.i.g. and a temperature of 525° F. and coal firing. The unit includes two steam

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reheaters, one to raise the temperature of 655,000 lbs. of steam per hr. entering at a pressure of 1225 p.s.i.g. from 800° F. to 1050° F. and the second to raise 520,000 lbs. of steam per hr. entering at a pressure of 150 p.s.i.g. from 630° F. to 1000° F.

The main portions of the unit illustrated include a fuel firing section consisting of a plurality of independently operable furnace chambers 10 of relatively small volume and boundary wall area arranged to burn a solid fuel at high rates of heat release and separately discharging high temperature gaseous products of combustion and separated ash residue as a molten slag into a primary furnace chamber 11. The heating gases with a small amount of molten ash in suspension are directed downwardly adjacent the slag discharge points and then pass upwardly through a slag collecting screen 12 into a vertically elongated radiation and gas mixing chamber 13 of rectangular horizontal cross-section. The heating gases from the chamber 13 leave the upper rear side thereof and flow horizontally through a horizontally elongated convection heating chamber 14 of rectangular vertical cross-section, the rear portion of which is divided into parallel heating gas passes 14^a and 14^b by a vertical baffle 15. The furnace end of the gas pass 14 is occupied by a convection secondary steam superheater 16, the gas pass 14^a by a convection primary steam superheater 17, and the gas pass 14^b by convection steam reheaters 18 and 19 arranged in series with respect to gas flow. The heating gases from the gas passes 14^a and 14^b flow into a common outlet duct 20 leading to the tubes of a two-section tubular air heater 21 from which the gases are withdrawn by an induced draft fan 22 having a stack gas outlet 23. Air for combustion is supplied at a positive pressure sufficient to overcome the gas flow resistance through the unit to the furnace chambers 10 by a forced draft fan 24 and a conduit 25 leading to the air heater 21. The entering air flows across the tubes of the air heater 21 and through an outlet flue 26 to a main supply duct 27 from which it passes through ducts 28 at opposite sides of the steam generating unit to the furnace chambers 10. A portion of the relatively cool heating gases flowing through the gas outlet duct 20 is withdrawn therefrom through a conduit 29 leading to a gas recirculating fan 30 from which it discharges through a duct 31 into the radiation and gas mixing chamber 13 at vertically spaced points therein.

In accordance with our invention the solid fuel burning furnaces 10 are advantageously in the form of a plurality of horizontally arranged cyclone type furnaces independently fired by crushed or granulated coal and of the general character disclosed in U.S. Patent No. 2,357,301. As shown in Figs. 1-4, each furnace chamber 10 is of substantially cylindrical cross-section with its curved peripheral wall 40 defined by oppositely arranged groups of refractory covered closely spaced studded curved tubes 41 extending between pairs of horizontal subdivided lower headers 42 and upper headers 43. The upper and lower ends of each tube 41 are reversely bent, and opposite tubes at the top of the chamber spaced apart to form a tangentially arranged secondary combustion air inlet 44 extending over a major portion of the length of the furnace chamber and connected to one of the air supply ducts 28. The front or outer end of each furnace chamber is closed by a frusto-conical wall section 45 defined by refractory covered closely spaced studded tubes 46 extending between horizontally arranged top and bottom headers 47 and 48 respectively, and with their intermediate portions curved to define a circular fuel inlet port 49. A fuel inlet casing 50 of logarithmically curved peripheral formation registers with the port 49 and is arranged to discharge a whirling stream of primary combustion air and coal which has been crushed or granulated to a relatively coarse mixture in suitable crushing apparatus (not shown) through the port 49. An inlet 51 for tertiary

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combustion air is positioned to discharge axially of the fuel inlet casing 50.

The opposite end of each furnace chamber is formed by a vertical water cooled wall 52 having a flaring re-entrant throat 53, the wall and throat being defined by refractory covered closely spaced studded tubes 54 extending between upper and lower headers 55 and 56 respectively with intermediate portions of certain tubes bent to define the throat and an opening 57 in the wall 52 adjacent the bottom of the furnace chamber for the discharge of molten slag from the furnace chamber into the primary furnace chamber 11.

As indicated in Fig. 5, the furnace wall tube headers 42 and 43 are sub-divided by transverse internal diaphragms to group the wall tubes 41 into similar adjoining tube panels, with the upper header of one tube panel being connected to the lower header of the next tube panel by external downcomer tubes 59. A series of feed water supply pipes 60 are connected to the header 48 of the front wall of one end cyclone furnace for supplying feed water thereto at a supercritical pressure of, for example, 5500 p.s.i.g. from a suitable high pressure pump (not shown). The upper front wall header 47 is connected to the lower header sections for the outermost furnace wall tube panels by downcomer tubes 58, and the upper header sections for the rearmost wall tube panels are connected to the end wall lower header 56. The end wall headers 55 and 56 extend across the width of the unit and are also subdivided lengthwise by internal diaphragms into separate end-to-end sections. The lower end portions of the end wall tubes 54 are reversely bent to form a plurality of transversely spaced slag discharge openings 65 in the floor of the primary furnace chamber 11 leading to a subjacent slag collecting chamber 66. Tubes 62 connect the upper header 55 to the lower front wall header 48 of the second cyclone furnace and tubes 63 connect the upper header section 55 above the second cyclone furnace to the lower front wall header 48 of the third cyclone furnace. Discharge tubes 67 extend from the upper header section 55 of the third cyclone and connect to an inlet header 68 of the primary steam superheater 17. The primary superheater (hereinafter referred to as the convection section D) consists of four groups of pendantly supported nested multi-looped tubes arranged in laterally spaced panels with corresponding panels serially connected to define parallel flow paths for fluid flow between the header 68 and a transverse external outlet header 69 above the front end of the gas pass 14^a.

The header 69 is connected to a header 70 from which tubes 71 having reversely looped portions 71^a extending along the roof of the gas pass 14, and thence along the inclined roof 72 of the radiation and gas mixing chamber 13. The tubes 71 extend downwardly along the front wall 73 of the chamber 13 and along an inclined target wall or partition 74 partly separating the primary furnace chamber 11 from the chamber 13. The partition tubes are bent to form the slag screen 12 and then reversely bent to cooperate with the tubes 54 in forming the slag discharge openings 65. The lower end of each tube 71 has a reversely looped portion 71^b, from which a second parallel upflow tube leg returns along the partition front wall and roof, with its upper end again reversely looped at 71^c to form a third parallel downflow leg which terminates in the header 75. The tubes 71 thus form a radiant tube panel E in which the fluid has a high velocity flow through two downflow legs and one upflow leg of each tube.

One side wall of the radiation and gas mixing chamber 13 is defined by tubes 76 forming a radiant steam superheater tube panel F extending between lower and upper headers 77 and 78 respectively, while the opposite side wall is defined by tubes 79 forming a second radiant steam superheater panel G extending between corresponding lower and upper headers (not shown).

The upper side wall headers are connected by tubular connectors 82. The lower header 77 receives partly superheated steam from the header 75 through tubes 83, so that in operation steam will flow upwardly through the radiant tube panel F and then downwardly through the radiant tube panel G.

The lower header of the tube panel G is connected by tubes 85 to a cross-header 86, from which a series of inverted U-shaped steam superheater tubes 87 extend upwardly to define the vertical rear wall 88 of the chamber 13 and a rearwardly inclined extension 89 of the wall forming the bottom of the entrance portion of the gas pass 14. The opposite ends of the tubes 87 terminate in a header 90 adjacent the header 86. The tubes 87 thus define a vertical superheater tube panel H.

The remaining portion of each side wall of the chamber 13 is defined by a tube panel I formed by vertical tubes 92 extending between lower and upper heads 93 and 94 respectively. Tubular connectors 95 extend from the header 90 to each of the lower wall headers 93 providing an upflow of fluid through the tube panels I.

Similar tube panels J formed by tubes 96 extending between lower and upper headers 97 and 98 respectively, are arranged in opposite side walls at the entrance to the gas pass 14. External tubes 99 connect the upper side wall headers 94 to the lower headers 97 to provide an upflow of steam through the tube panels J. The tube panels E, F, G, H, I and J are thus serially arranged with respect to fluid flow and constitute the radiant superheating section of the unit which receives superheated steam from the primary superheater section and is arranged to discharge the steam with additional superheat to the secondary superheater section 16. As shown in Figs. 1 and 2, the secondary superheater section 16 consists of two groups of pendant multiple-looped nested tubes arranged in longitudinal and transverse rows extending the full width of the unit. The superheated steam is delivered to an inlet header 100 by the tube connections 101 from the upper side wall headers 98. The secondary superheater section is arranged for steam flow parallel to the gas flow through the gas pass 14, with the steam from the header 100 passing through the first tube group 16 and being discharged to an outlet mixing header 102, from which it passes through conductors 103 to an inlet header 104 of the second superheater tube group. The steam receives its final superheating in this group of tubes and is discharged to outlet headers 105 from which it passes to a point of use, such as a turbo-generator set designed for operation at supercritical pressures and temperatures.

As shown in Figs. 1 and 2, the gas passes 14a and 14b are occupied respectively by the primary superheater section 17, and a plurality of steam reheating sections 18 and 19, the reheater 18 being a high pressure unit and the reheater 19 being a low pressure unit. The reheaters are formed by vertically arranged multiple-looped pendants supported nested tubes substantially similar to the tubes of the primary superheater 17, the reheater 18 consisting of two serially connected groups at the gas entrance end of the gas pass 14b arranged in contraflow relation with the heating gases and having their ends connected to an inlet header 110 and an outlet header 111. The low pressure reheater 19 consists of three contraflow groups of tubes serially connected for steam flow between an inlet header 112 and an outlet header 113, with an intermediate header 114 positioned between the second and third tube groups. As shown in Fig. 1, the bottoms of the gas passes 14, 14a and 14b are defined by a series of V-shaped troughs 116 having screw conveyors 117 positioned in the bottom thereof for the collection and removal of fly ash separating out in these gas passes. The upper ends of adjacent ash collecting troughs are formed by plateau sections 118 adjacent the looped lower ends of the superheater and reheater tubes to avoid gas by-passing of those tube banks.

The cyclone furnaces 10 are designed in normal operation to burn fuel at heat release rates sufficient to cause the discharge of streams of heating gases at temperatures above the fuel ash fusion temperature through the discharge throats 53 against the target wall formed by the partition 74, which together with the slag collecting screen 12 tends to separate a large portion of the slag particles remaining in suspension in the heating gases. As indicated in Fig. 6, the fuel and air inlets are arranged in angular directions of entry to provide gas whirls in the end cyclone chambers in opposite rotational directions, the right end cyclone in Fig. 6 providing a counter-clockwise gas whirling movement, and the left end cyclone a clockwise movement. The intermediate cyclone can be in either direction, but is shown as having a clockwise gas whirl. This arrangement tends to effect a discharge from each end cyclone in a direction away from the adjacent side wall of the primary furnace chamber 11, and to equalize the static pressure conditions in that chamber. As indicated in Fig. 1, the tubes lining the walls of the cyclone furnaces 10, the primary furnace 11 and the lower part of the radiant and gas mixing chamber 13 and the partition 74 therebetween are of the "fully studded" type and covered with refractory to withstand the high temperature conditions in those sections.

In accordance with the invention, the temperature of the heating gas stream flowing upwardly through the radiant and gas mixing chamber 13 is regulated to insure a gas temperature at the entrance of the secondary superheater section 16 which will insure any slag particles in suspension in the gases being in a solidified or "dry" condition, avoid over-heating of the tubes in the radiant and secondary superheater sections, and yet provide a heat content of the heating gases sufficient to attain the desired final superheat temperatures. For this purpose, the flue gases withdrawn by the recirculating fan 30 are passed from the conduit 31 to a chamber 120 extending along the lower rear wall of the chamber 13. The tubes 87 lining that wall are bent outwardly as indicated at 121 to form a series of vertically elongated transversely spaced recirculated gas inlet ports 122 in the rear wall. The recirculated gases enter at sufficient velocity to insure an intimate mixing with the fresh combustion gases passing upwardly through the slag screen 12. Similar recirculated gas inlet ports 124 are formed in the front wall 73 of the chamber 13 by bending some of the tubes 71 lining that wall as indicated at 125. The recirculated gas supply to the ports 124 is provided by a branch duct 126 leading from the chamber 120 to a chamber 127 enclosing the ports 124. The total amount of gases introduced by the ports 122 and 124, and the division of the gases between the ports, is regulable by suitable dampers in the ducts leading to the ports.

In the normal operation of the steam generating unit described at pressures and temperatures above the critical values, a relatively coarse crushed solid fuel is supplied to the cyclone chambers from independently controllable sources, such as separate crushers, and the fuel burned in the cyclone furnace chambers at high rates of heat release sufficient to maintain a normal mean temperature therein above the fuel ash fusion temperature. The secondary combustion air is supplied at a substantial positive pressure sufficient to overcome the gas flow resistance through the unit and in quantities insuring substantially complete combustion of the fuel in the cyclone furnaces. The ash separates as a molten slag which flows along the bottom of each cyclone furnace chamber into the primary furnace chamber 11, and is discharged through the floor slag openings 65 therein. The collection of slag particles in suspension is aided by the arrangement of the partition 74 and slag screen 12. The stream of gaseous products of combustion sweeping adjacent the slag discharge openings 65 aid in maintaining the same clear,

and on passing upwardly into the chamber 13 is intimately mixed with the relatively low temperature recirculated flue gases entering through the ports 122 and 124. The gas temperature leaving the chamber 13 is controlled by variation of the rate of fuel firing and variation of the speed of the recirculating fan 30 to control the amount of recirculated gases. The tempered heating gases at the desired temperature flow horizontally through the gas pass 14 in contact with the tubes of the secondary superheater section 16, and are then divided by the partition 15 between the gas passes 14^a and 14^b, the proportioning of the gas flow therebetween being controlled by the sets of dampers 130 and 131 to control the final temperature of the steam reheated in the low and high pressure reheaters. The gas streams then merge in the outlet duct 20 and, except for whatever portion may be recirculated, flow successively through the tube banks of the air heater 21 to the induced draft fan 22 from which they are discharged through the outlet duct 23.

As indicated in Figs. 5 and 6, the feed water is normally supplied at a high temperature level to the header 48 of the right end cyclone furnace, passing upwardly through the front end wall of the cyclone, and serially through the pairs of tube panels A, B and C at each side of the cyclone, then upwardly through the throat end wall tubes 54 to the corresponding header 55 from which the water is directed to the lower header 48 of the next cyclone and the flow repeated through corresponding tube elements. The second cyclone furnace is similarly constructed and after flowing through the side and end walls thereof, the water is discharged to the header 48 of the left end cyclone furnace and the flow circuit repeated. The upflow arrangement of all of the heated tubes in the water heating section is especially useful when the unit is operated at subcritical pressures. The header 55 for the third cyclone is connected by the tubes 67 to the header 68 at the rear end of the primary superheater section 17. The cyclone furnaces 10 have their water heating tubular surface proportioned and serially arranged to heat the contained water under maximum load conditions to a temperature approaching, but still below, the critical temperature before the water reaches the header 68. With this arrangement the portion of the heated fluid circuit in which the transition of the water from a liquid to a vapor condition occurs will always be located in the relatively low temperature primary superheater section 17 throughout the operating range. The steam flow through the tubes of the primary superheater section is counter to the gas flow and is discharged from the outlet header 69 to the tubes 71 forming the radiant superheater panel E. The tubes 71 forming the panel E are lesser in number but multi-looped to form a high steam velocity radiant section. The radiant superheating of the steam continues in the upflow tube panel F, downflow tube panel G, up and downflow tube panel H, upflow tube panel I, and upflow tube panel J. The final superheating of the steam is effected in the secondary superheater section 16 and steam at the desired temperature and pressure is discharged from the headers 105.

The designed operation of the unit at supercritical pressures and temperatures under a high capacity load and with gas recirculation is diagrammatically illustrated in the graphs of Fig. 7. The gas temperatures through the various sections of the unit are shown by the graphs entitled "Gas Temperature" and "Gas Temp.," the temperature being substantially constant through the water heating zones associated with the cyclones A, B and C, and the drops rapidly in an unknown manner in the zones of the radiant tube panels E, F, G, H, I and J, and gradually decreases through the secondary superheater section K and primary superheater section D. The fluid pressure progressively decreases through the unit with the maximum rate of drop through the radiant tube panels E, F, G, H, I and J where higher velocity conditions of the contained fluid occur.

It has been found that the specific heat of the fluid as shown by the graph illustrating the same in Fig. 7 has a substantial humped portion in the supercritical pressure range indicated. In accordance with the invention the fluid flow path is so designed that the higher specific heat range will substantially correspond to the section of the unit in heat transfer association with the radiant panels E, F, G, H, I and J. This relationship is of particular advantage in obtaining the proper correlation of heat input into the outside of the tube walls in these sections and the transfer of that heat from the inner faces of the tube walls to the contained fluid streams in attaining an economic construction with adequate consideration to desirable tube metal temperatures. The graph figure also illustrates the increasing amount of total heat in the fluid during its progress through the unit, as well as the average tube metal temperature in the primary convection superheater, radiant superheater, and secondary convection superheater sections.

In accordance with the invention the final steam superheat temperature is controlled primarily by controlling the firing rate of the independently operable cyclone furnaces 10 to vary the quantity of high temperature heating gases to which the radiant and convection superheater sections are subjected. A further control is provided, particularly suitable for operation at partial loads, to increase the final superheat temperature, this supplementary control being to vary the number of cyclone furnaces in use, and thereby render inoperative the portion of the water heating surface otherwise heated by the inactive cyclone furnace or furnaces. This is possible with the described series flow arrangement of the water heating furnace wall cooling tubes through the successive cyclone furnaces without involving undesirable temperature differentials in the fluid streams. The length of the water heating portion of the fluid flow path remains the same, but the heating effect in the portions associated with the inactive cyclones is substantially reduced, whereby the amount of heat absorbed by the water heating section of the unit is reduced and the heat available in the heating gases flowing to the radiant and convection superheating zones is correspondingly increased.

Recirculated gases will be introduced at top operating loads and regulated in part from a determination of a heating gas temperature related to the gas temperature leaving the radiant and gas mixing chamber 13 and entering the secondary convection superheater 16. By such recirculated gas introduction the temperature of the gases leaving chamber 13 will be sufficiently low to avoid slagging of the tubes but also will be of a mass adequate to effect the desired absorption in the convection superheater to obtain the optimum temperature of the steam from the headers 105.

As the load is reduced and the quantity of heating gases developed by fuel combustion is correspondingly reduced, the gases discharged from the cyclone furnaces will undergo some reduction in temperature but the temperature will not fall off as much as would occur with a large water cooled fuel burning furnace. It is contemplated that the amount of gas recirculated will be correspondingly adjusted downwardly in accordance with a correlation of furnace exit gas temperature and an indication of delivered superheated steam temperature.

Through the ability to operate the unit with either one, two or three cyclone furnaces, it is possible to deliver combustion gases to the chamber 13 which will not vary substantially in temperature irrespective of the rate of fuel burning, the rate of fuel burning in one, two or three furnaces being correlated with the load on the unit, of which the rate of feed water supply is a close indication of the rate of superheated steam delivery from the unit.

It is to be noted that the gas temperature at the zone of entrance to the parallel gas passes 14^a, 14^b is of the order of 1325° F. The steam leaving the primary super-

heater 17 will be of the order of 770° F. at this position, while the temperature of the steam leaving the outlet of the high pressure reheater 18 in a corresponding gas temperature zone is to be at 1050° F. The low pressure reheater 19, located downstream of the high pressure reheater in the same gas pass 14^b, receives gases from which some heat has been extracted by the high pressure reheater. The amount of heat absorbed by the reheaters and thereby the temperature of the superheated steam streams delivered therefrom will be controlled by the regulation of the gas flow by means of adjustment of the dampers 130 and/or dampers 131 at the outlet ends of the gas passes 14^a and 14^b, respectively. With a given mass flow of heating gases from the secondary superheater 16 the degree of high pressure or low pressure reheat superheating will be regulated by dividing the gas flow between passes 14^a and 14^b in accordance with reheat temperature indications. As it is essential that neither the high pressure reheated steam or the low pressure reheated steam temperature exceed a predetermined temperature, as a protective measure in connection with the steam turbine receiving the respective steam flows, the dampers controlling the division of gas flow will be regulated in accordance with either the steam outlet temperature from the high pressure reheater or the steam temperature from the low pressure reheater, whichever is the higher with respect to its optimum value.

Summarizing, the fundamental operation of this unit will be in accordance with the following. The rate of feed water introduction will be regulated to maintain the desired pressure of the delivered superheated steam. The rate of fuel introduction and burning will be regulated from indications of high pressure superheated steam delivery. The recirculated gas introduction will be adjusted in accordance with a gas temperature indication related to the gas temperature at the entrance to the convection superheater and the reheater heat absorption will be controlled by adjustment of heating gas flow therefor in accordance with the tendency of either the high pressure or the low pressure reheated steam temperature to depart from an optimum value.

The forced flow once-through high pressure high temperature vapor generating unit constructed and operated as above described meets the steam generating requirements of modern central stations as regards apparatus to supply large quantities of high-pressure high-temperature steam with the heat therefor generated by customarily available fuels, yet operable through a wide range of steam delivery rate with reliability. The arrangement of the unit is also such that construction and maintenance costs will not be excessive.

While in accordance with the provisions of the statutes we have illustrated and described herein a specific form of the invention now known to us, those skilled in the art will understand that changes may be made in the form of the apparatus disclosed without departing from the spirit of the invention covered by our claims, and that certain features of the invention may sometimes be used to advantage without a corresponding use of other features.

What is claimed is:

1. A forced circulation steam generator comprising a plurality of furnace chambers each having a relatively small volume and boundary wall area, independently operable means for burning fuel at high rates of heat release in said furnace chambers, a heating gas pass arranged to receive high temperature heating gases from said furnace chambers, water heating tubes defining at least one boundary wall of each of said furnace chambers, a bank of convection steam superheating tubes in said gas pass, means for supplying water to said water heating tubes under a substantial pressure, and means for interconnecting said water heating and steam superheating tubes to provide a serial flow of fluid through the wall tubes of successive furnace chambers and thence through said convection steam superheating tubes.

2. A forced circulation steam generator comprising a plurality of cyclone furnace chambers each having a relatively small volume and boundary wall area, independently operable means for burning fuel at high rates of heat release in said furnace chambers, a heating gas pass arranged to receive high temperature heating gases from said cyclone furnace chambers, water heating tubes defining at least one boundary wall of each of said cyclone furnace chambers, a bank of convection steam superheating tubes in said gas pass, means for supplying water to said water heating tubes under a substantial pressure, and means for interconnecting said water heating and steam superheating tubes to provide a serial flow of fluid through the wall tubes of successive cyclone furnace chambers and thence through said convection steam superheating tubes.

3. A forced flow steam generator comprising a plurality of separate furnace chambers, means for independently burning fuel in each of said furnace chambers, a gas pass arranged to receive high temperature heating gases from said furnace chambers, water heating tubes defining at least one boundary wall of each of said furnace chambers, the total water heating surface in said boundary walls being proportioned in amount to heat the contained water when flowing serially through the boundary wall tubes of successive furnace chambers under maximum load conditions to a temperature less than the saturated temperature, a bank of convection steam superheating tubes in said gas pass, means for supplying water to said water heating tubes under a substantial pressure, and means for interconnecting said water heating and steam superheating tubes to provide a serial flow of fluid through said furnace boundary wall tubes of said separate furnace chambers and convection steam superheating tubes.

4. A forced flow steam generator comprising a plurality of separate furnace chambers each having a relatively small volume and boundary wall area, means for independently burning fuel in each of said furnace chambers, a gas pass arranged to receive high temperature heating gases from said furnace chambers, water heating tubes defining at least one boundary wall of each of said furnace chambers, the total water heating surface in said boundary walls being proportioned in amount to heat the contained water when flowing serially through the boundary wall tubes of successive furnace chambers under maximum load conditions to a temperature less than the saturated temperature, a bank of convection steam superheating tubes in said gas pass, means for supplying water to said water heating tubes under a substantial pressure, means for interconnecting said water heating and steam superheating tubes to provide a serial flow of fluid through said furnace wall tubes of said separate furnace chambers and convection steam superheating tubes, and means for withdrawing relatively cool heating gases after passing over said steam superheating tubes and introducing the withdrawn gases in gas mixing relationship with the heating gases leaving said furnace chambers.

5. A forced circulation steam generator comprising a plurality of cyclone furnace chambers each having a relatively small volume and boundary wall area, independently operable means for burning fuel at high rates of heat release in said furnace chambers, a radiation and gas mixing chamber arranged to receive high temperature heating gases from said cyclone furnace chambers, a gas pass serially connected to said radiation and gas mixing chamber for heating gas flow therethrough, water heating tubes defining at least one boundary wall of each of said cyclone furnace chambers, radiantly heated steam superheating tubes defining one or more walls of said radiation and gas mixing chamber, a bank of convection steam superheating tubes in said gas pass, means for supplying water to said water heating tubes under a substantial pressure, means for interconnecting said water heat-

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ing and steam superheating tubes to provide a serial flow of fluid through the wall tubes of successive cyclone furnace chambers, and thence through said radiant steam superheating tubes and said convection steam superheating tubes, and means for withdrawing relatively cool heating gases after passing over said convection steam superheating tubes and introducing the withdrawn gases in gas mixing relationship with the heating gases in said radiation and gas mixing chamber.

6. A forced circulation once-through super-critical pressure steam generator comprising a plurality of furnace chambers each having a relatively small volume and boundary wall area, independently operable means for burning fuel at high rates of heat release in said furnace chambers, a radiation chamber arranged to receive high temperature heating gases from said furnace chambers, a gas pass serially connected to said radiation chamber for heating gas flow therethrough, water heating tubes defining at least one boundary wall of each of said furnace chambers, radiantly heated steam superheating tubes defining one or more walls of said radiation chamber, a bank of convection steam superheating tubes in said gas pass, means for supplying water to said water heating tubes under a pressure substantially above the critical pressure, and means for interconnecting said water heating and steam superheating tubes to provide a serial flow of fluid through the wall tubes of successive furnace chambers, and thence through said radiant steam superheating tubes and said convection steam superheating tubes.

7. A forced circulation once-through supercritical pressure steam generator comprising a plurality of cyclone furnace chambers each having a relatively small volume and boundary wall area, independently operable means for burning fuel at high rates of heat release in said furnace chambers, a radiation and gas mixing chamber arranged to receive high temperature heating gases from said cyclone furnace chambers, a gas pass serially connected to said radiation and gas mixing chamber for heating gas flow therethrough, water heating tubes defining at least one boundary wall of each of said cyclone furnace chambers, radiantly heated steam superheating tubes defining one or more walls of said radiation and gas mixing chamber, a bank of convection steam superheating tubes in said gas pass, means for supplying water to said water heating tubes under a pressure substantially above the critical pressure, and means for interconnecting said water heating and steam superheating tubes to provide a serial flow of fluid through the wall tubes of successive cyclone furnace chambers, and thence through said radiant steam superheating tubes and said convection steam superheating tubes, and means for withdrawing relatively cool heating gases after passing over said convection steam superheating tubes and introducing the withdrawn gases in gas mixing relationship with the heating gases in said radiation and gas mixing chamber.

8. A forced flow once-through vapor generator comprising walls defining a furnace chamber, means for burning fuel in said furnace chamber, a radiation and gas mixing chamber arranged to receive high temperature heating gases from said furnace chamber, a gas pass serially connected to said radiation and gas mixing chamber for heating gas flow therethrough, heat absorbing surface for a vaporizable liquid comprising liquid heating tubes defining a wall of said furnace chamber, radiant heat absorbing vapor superheating tubes defining one or more walls of said radiation chamber, a bank of secondary vapor superheating tubes in said gas pass, means for dividing said gas pass downstream of said secondary vapor superheating tubes into a plurality of sections, a bank of primary vapor superheating tubes in one of said gas pass sections, a vapor reheater in another of said gas pass sections arranged to receive vapor superheated in said superheating tubes after a reduction in the pressure and temperature thereof, damper means

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arranged to proportion the heating gas flow through said gas pass sections, means for supplying a vaporizable liquid to said liquid heating tubes under a substantial pressure, means for interconnecting said liquid heating and vapor superheating tubes to provide a serial flow of fluid successively through said furnace wall tubes, primary vapor superheating tubes, radiant superheating tubes, and secondary vapor superheating tubes, and means for withdrawing relatively cool heating gases after passing over said primary vapor superheating tubes and introducing them in gas mixing relationship with the heating gases in said radiation and gas mixing chamber.

9. A forced flow steam generator comprising a furnace chamber, means for burning fuel at high rates of heat release in said furnace chamber, a heating gas pass arranged to receive high temperature heating gases from said furnace chamber, water heating tubes defining at least one boundary wall of said furnace chamber, a bank of secondary steam superheating tubes in the gas entrance end of said gas pass, means for dividing said gas pass into parallel sections, a bank of primary steam superheating tubes in one of said gas pass sections, a plurality of independent steam reheaters in the other gas pass section arranged to receive steam superheated in said secondary superheater tubes after a reduction in the pressure and temperature thereof, means for supplying water to said water heating tubes under a substantial pressure, means for interconnecting said water heating and steam superheating tubes to provide a serial flow of fluid through said furnace wall tubes, primary steam superheating tubes, and secondary steam superheating tubes, and means for proportioning the heating gas flow between said gas pass sections in response to variations in final steam temperature in one of said steam reheaters to increase the heating gas flow over said steam reheaters on a decrease in said final steam temperature and vice versa.

10. A forced circulation steam generator comprising a plurality of furnace chambers each having a relatively small volume and boundary wall area, means for burning fuel at high rates of heat release in said furnace chambers, a heating gas pass arranged to receive high temperature heating gases from said furnace chambers, water heating tubes defining at least one boundary wall of each of said furnace chambers, a bank of convection steam superheating tubes in said gas pass, means for supplying water to said water heating tubes under a substantial pressure, means for interconnecting said water heating and steam superheating tubes to provide a serial flow of fluid through the wall tubes of successive furnace chambers and thence through said convection steam superheating tubes, and said fuel burning means being operable, as the operating load decreases, to decrease the ratio of heat absorbed by said water heating tubes to the heat absorbed by said steam superheating tubes by rendering inactive the fuel burning means for one or more of said furnace chambers to eliminate the heating effect of said fuel burning means on the water heating tubes in the boundary wall of the inactive furnace chamber or chambers and thereby increase the heating of said convection superheating tubes.

11. A forced circulation steam generator comprising a plurality of furnace chambers each having a relatively small volume and boundary wall area, means for burning fuel at high rates of heat release in said furnace chambers, a radiation and gas mixing chamber arranged to receive high temperature heating gases from said furnace chambers, a heating gas pass serially connected to said radiation and gas mixing chamber for heating gas flow therethrough, water heating tubes defining at least one boundary wall of each of said furnace chambers, radiantly heated steam superheating tubes defining one or more walls of said radiation and gas mixing chamber, a bank of convection steam superheating tubes in said gas pass, means for supplying water to said water heating tubes under a

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substantial pressure, means for interconnecting said water heating and steam superheating tubes to provide a serial flow of fluid through the wall tubes of successive furnace chambers and thence through said radiant steam superheating tubes and said convection steam superheating tubes, and said fuel burning means being operable, as the operating load decreases, to decrease the ratio of heat absorbed by said water heating tubes to the heat absorbed by said steam superheating tubes by rendering inactive the fuel burning means for one or more of said furnace chambers to eliminate the heating effect of said fuel burning means on the water heating tubes in the boundary wall of the inactive furnace chamber or chambers and thereby increase the heating of said convection superheating tubes, and means for withdrawing relatively cool heating gases after passing over said convection steam generating tubes and introducing the withdrawn gases in gas mixing relationship with the heating gases in said radiation and gas mixing chamber.

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tionship with the heating gases in said radiation and gas mixing chamber.

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