June 17, 1952 A. J. NERAD 2,601,000

COMBUSTOR FOR THERMAL POWER PLANTS HAVING TOROIDAL FLOW PATH IN PRIMARY MIXING ZONE

Filed May 23, 1947 4 Sheets-Sheet 1

Fig. 1.

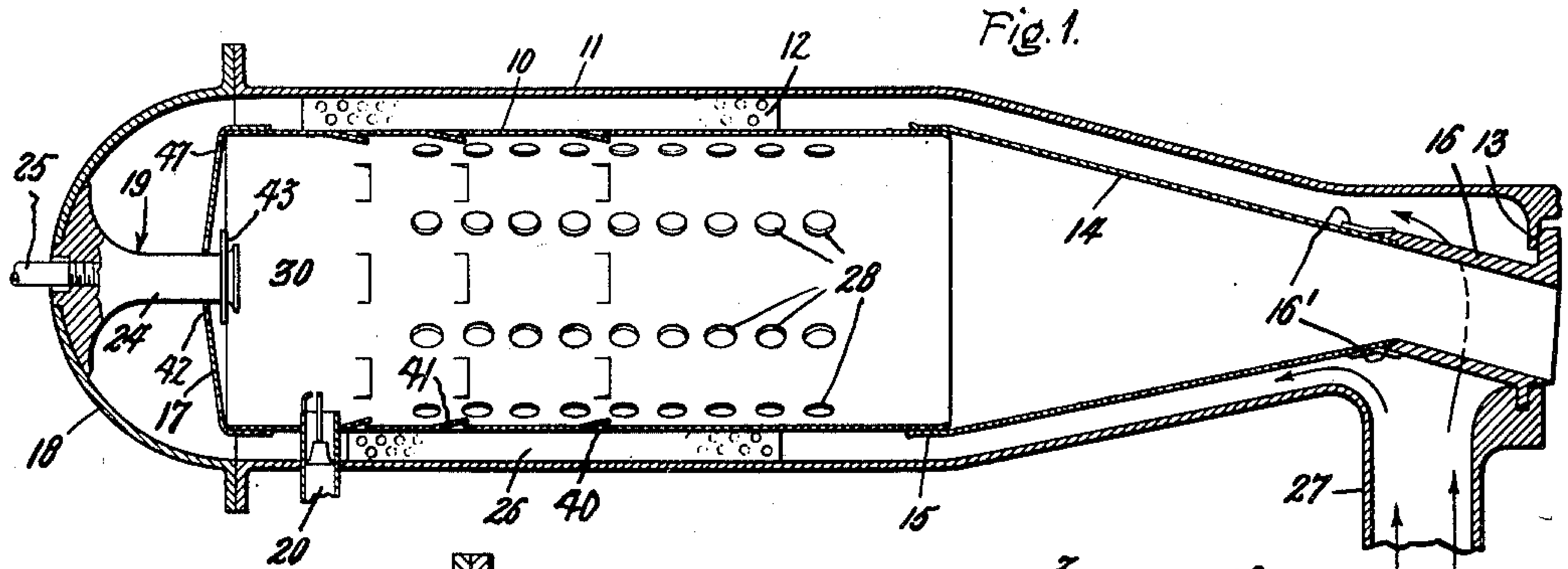

Fig. 2.

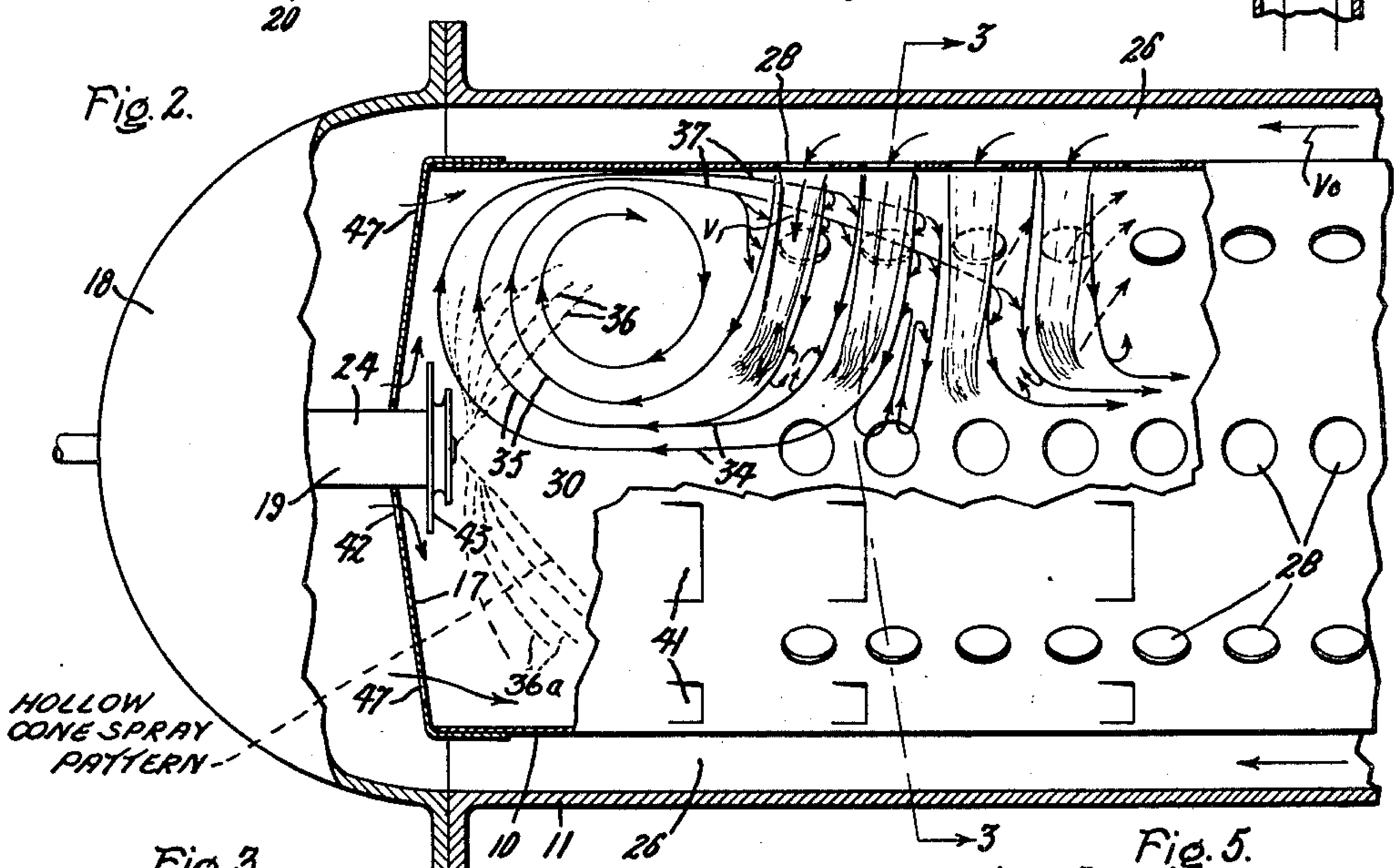


Fig. 3.

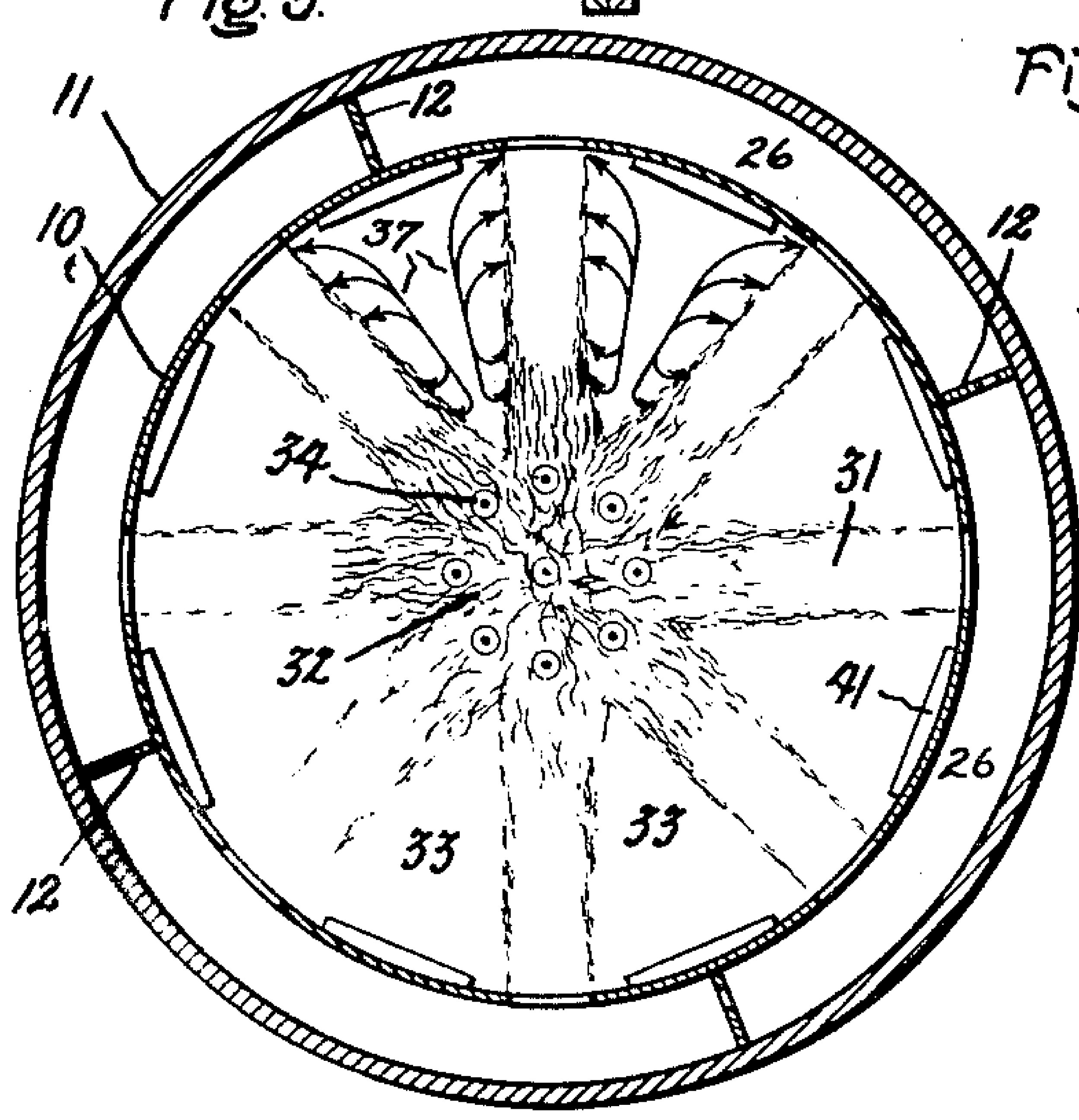

Fig. 4.

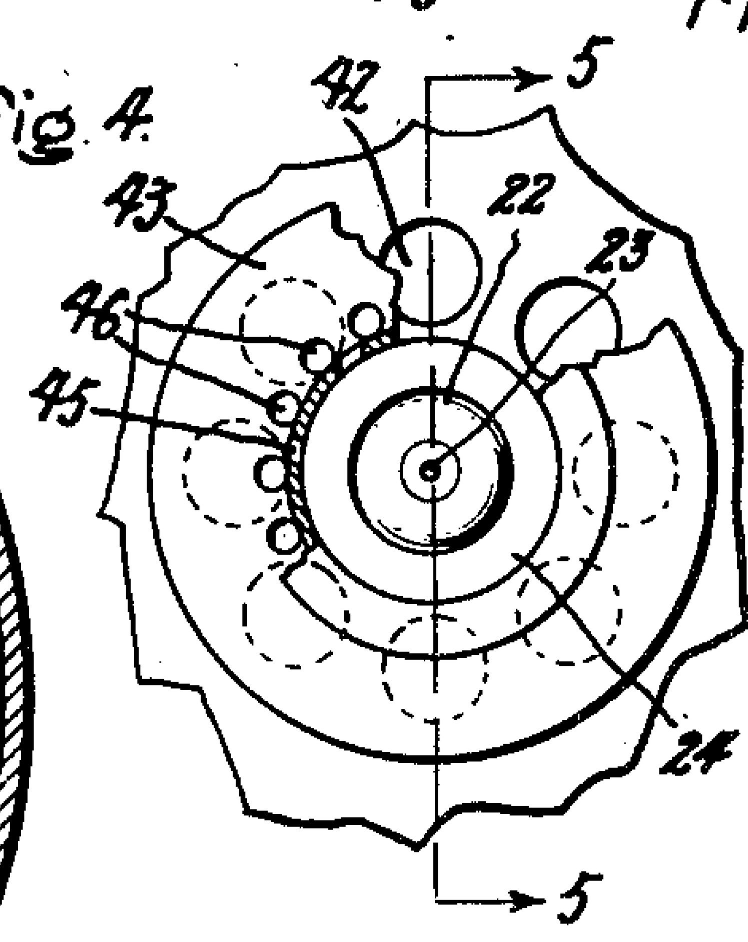

Fig. 5.

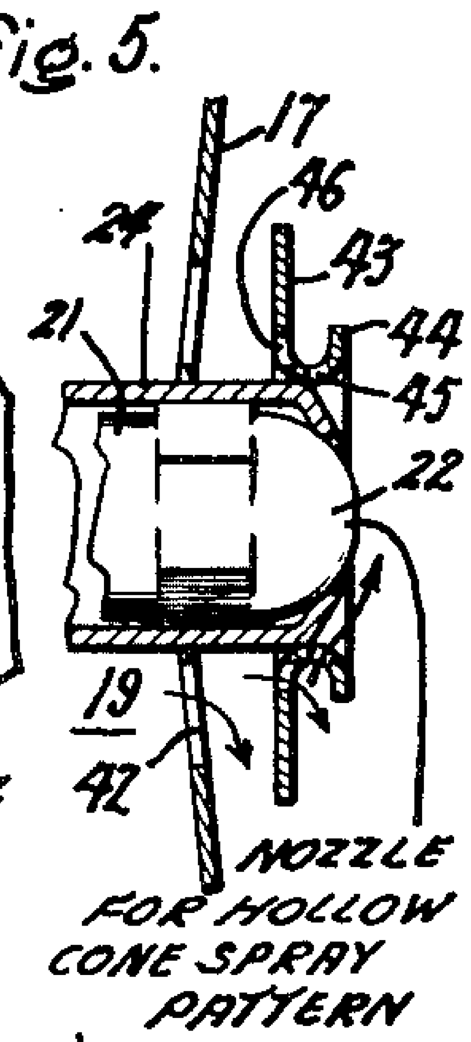


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Fig. 6.

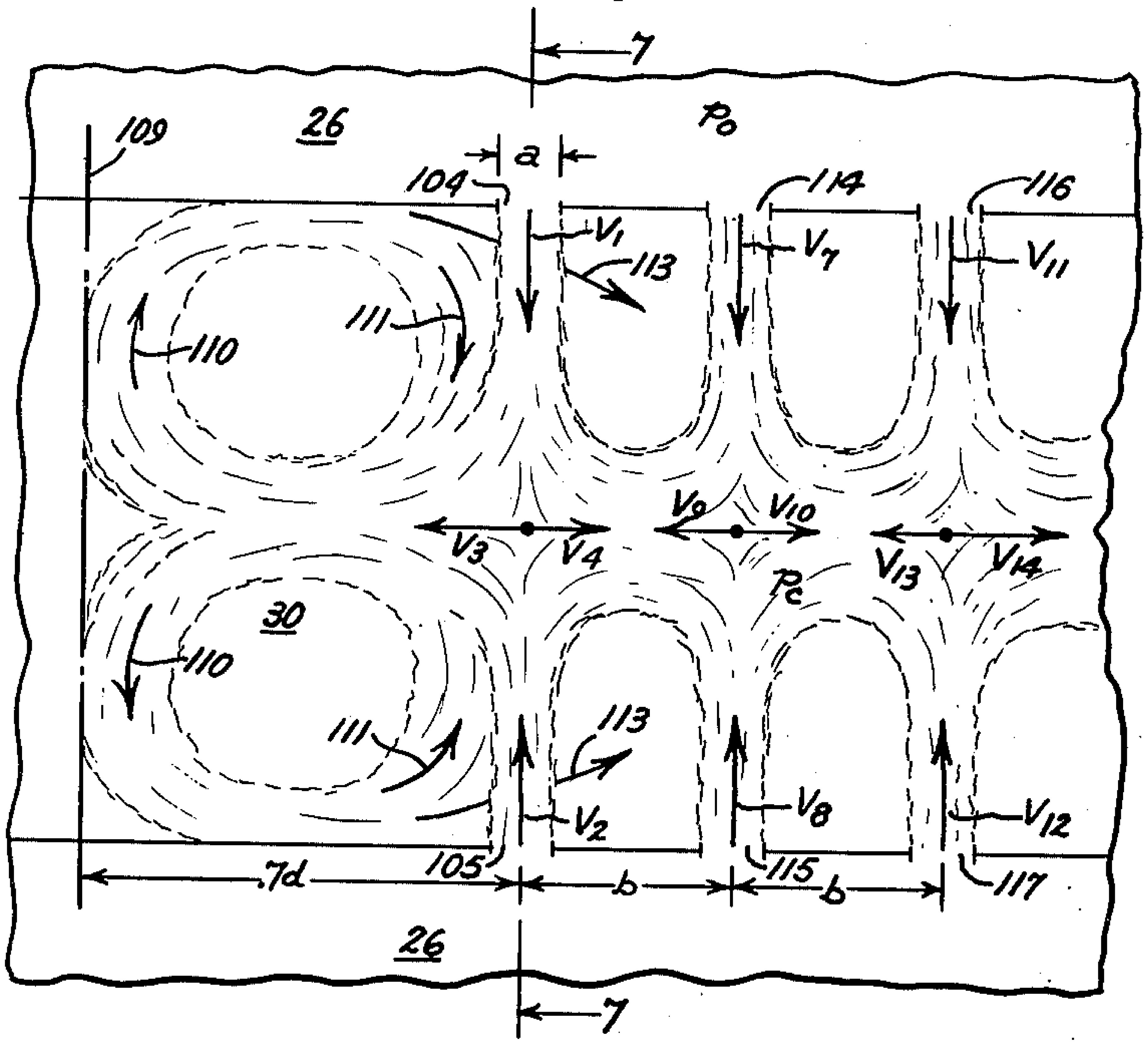



Fig. 7.

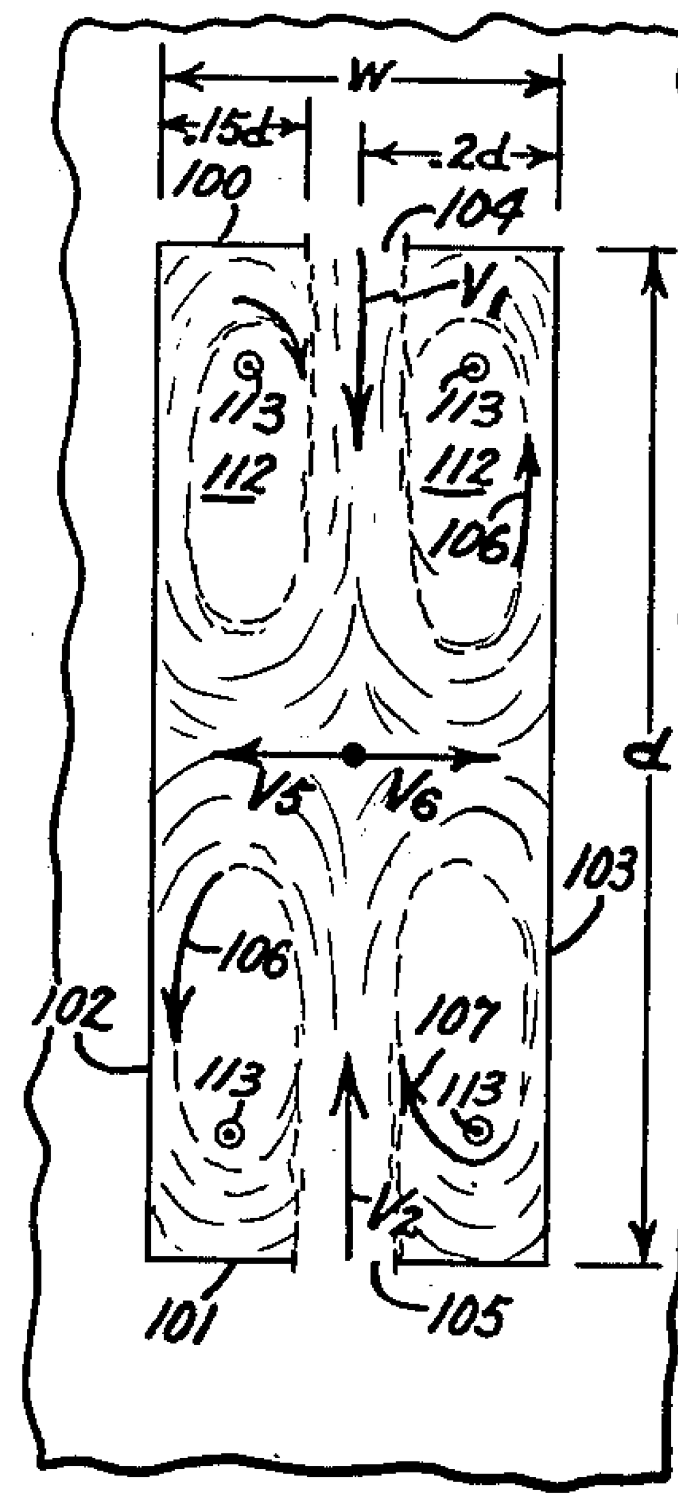



Fig. 8

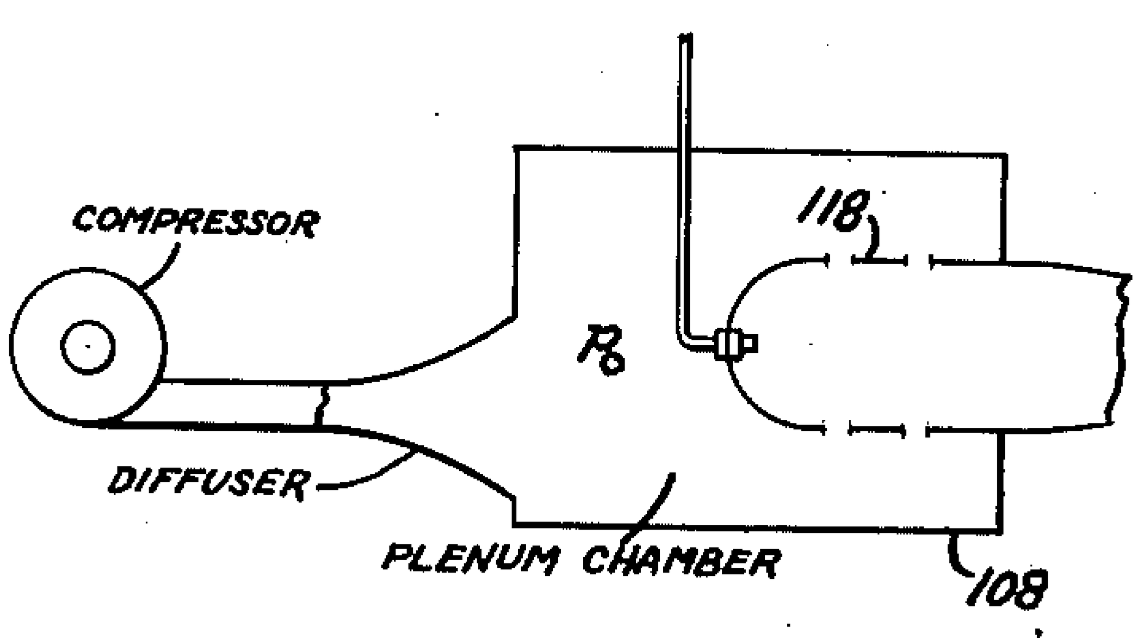



Fig. 9.

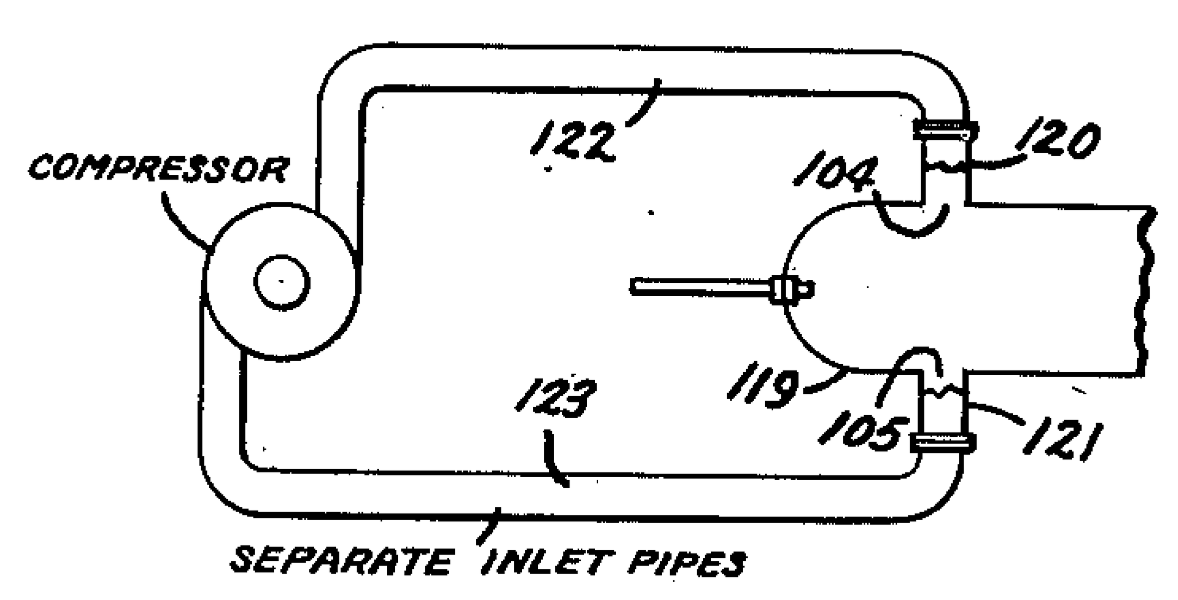
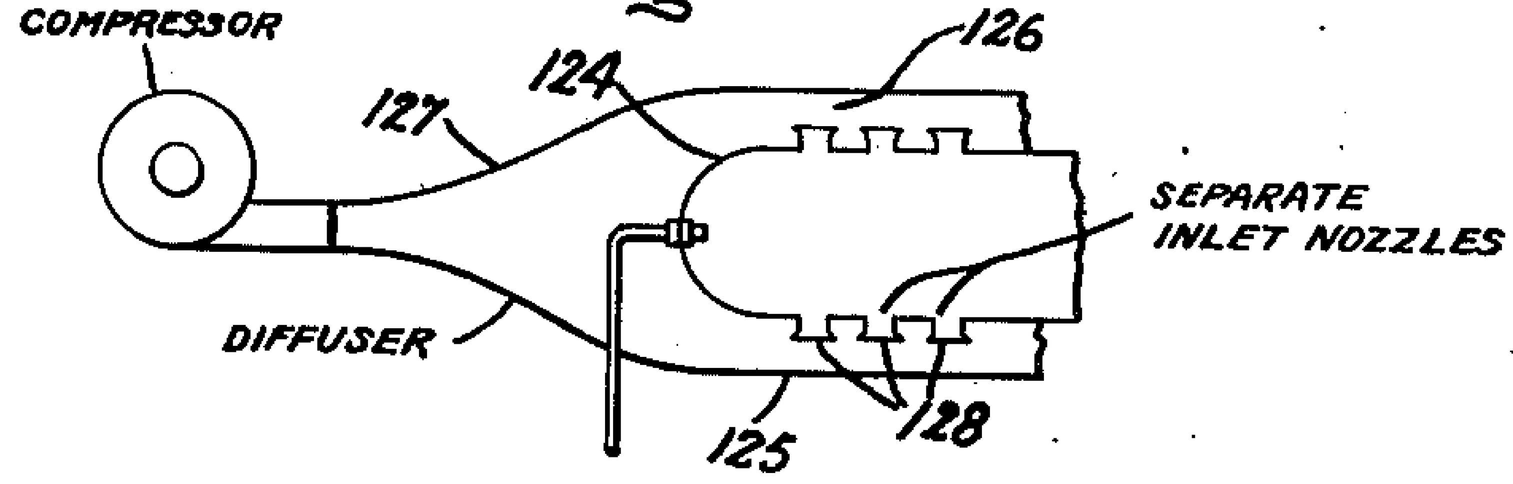



Fig. 10.

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COMBUSTOR FOR THERMAL POWER PLANTS HAVING TOROIDAL FLOW PATH IN PRIMARY MIXING ZONE

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Fig.11.

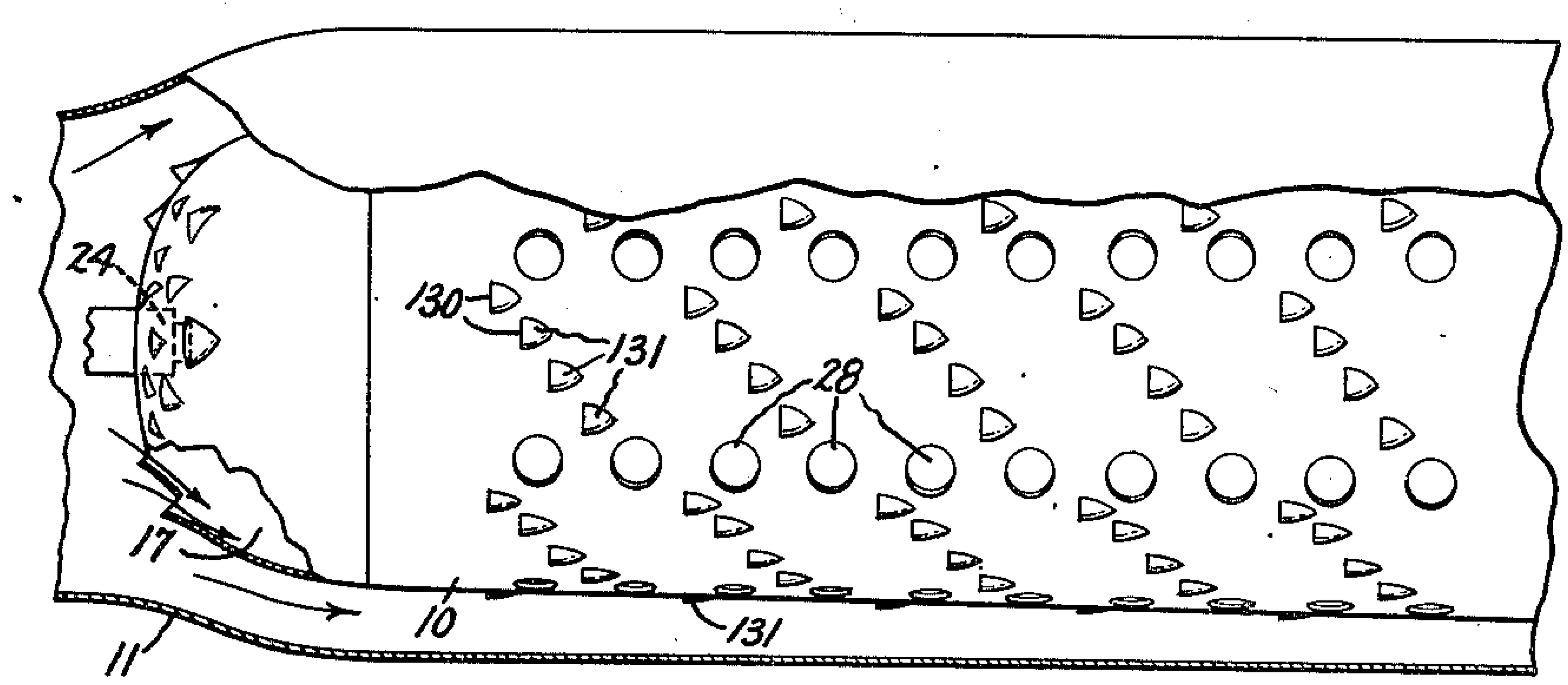
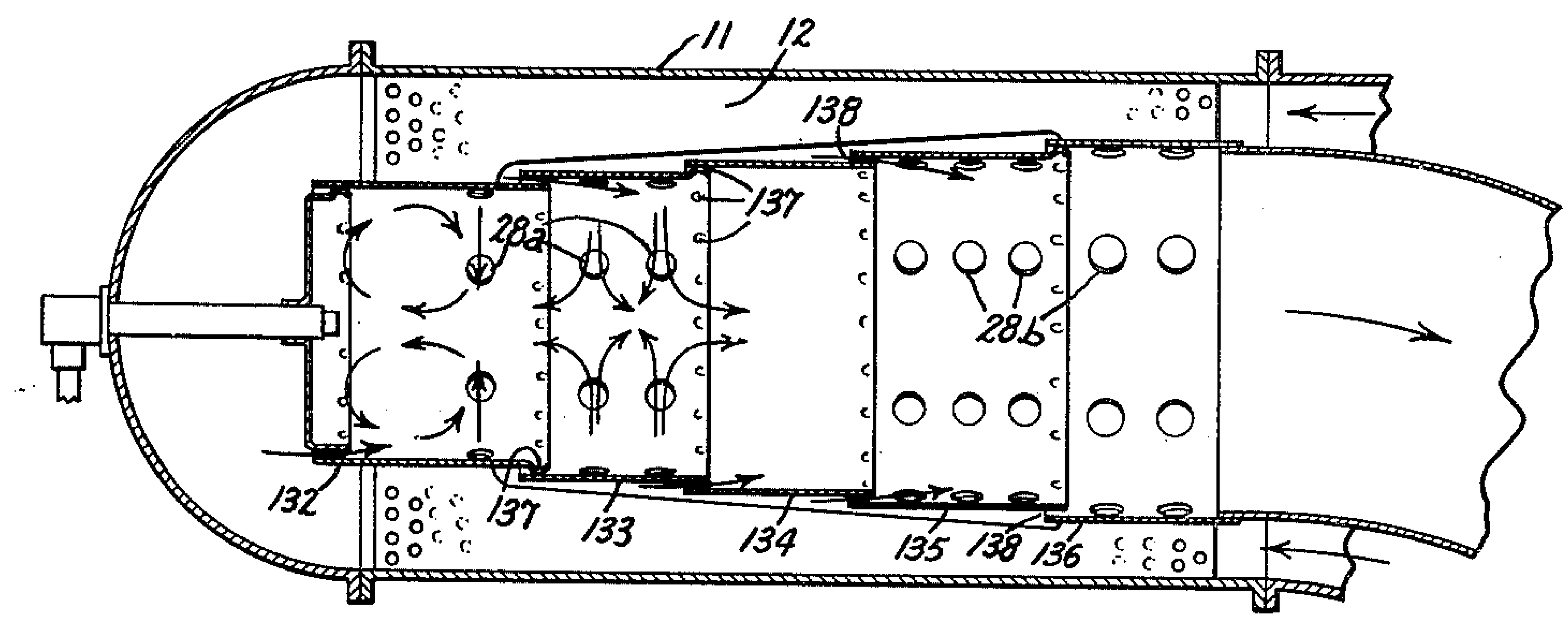



Fig.12.

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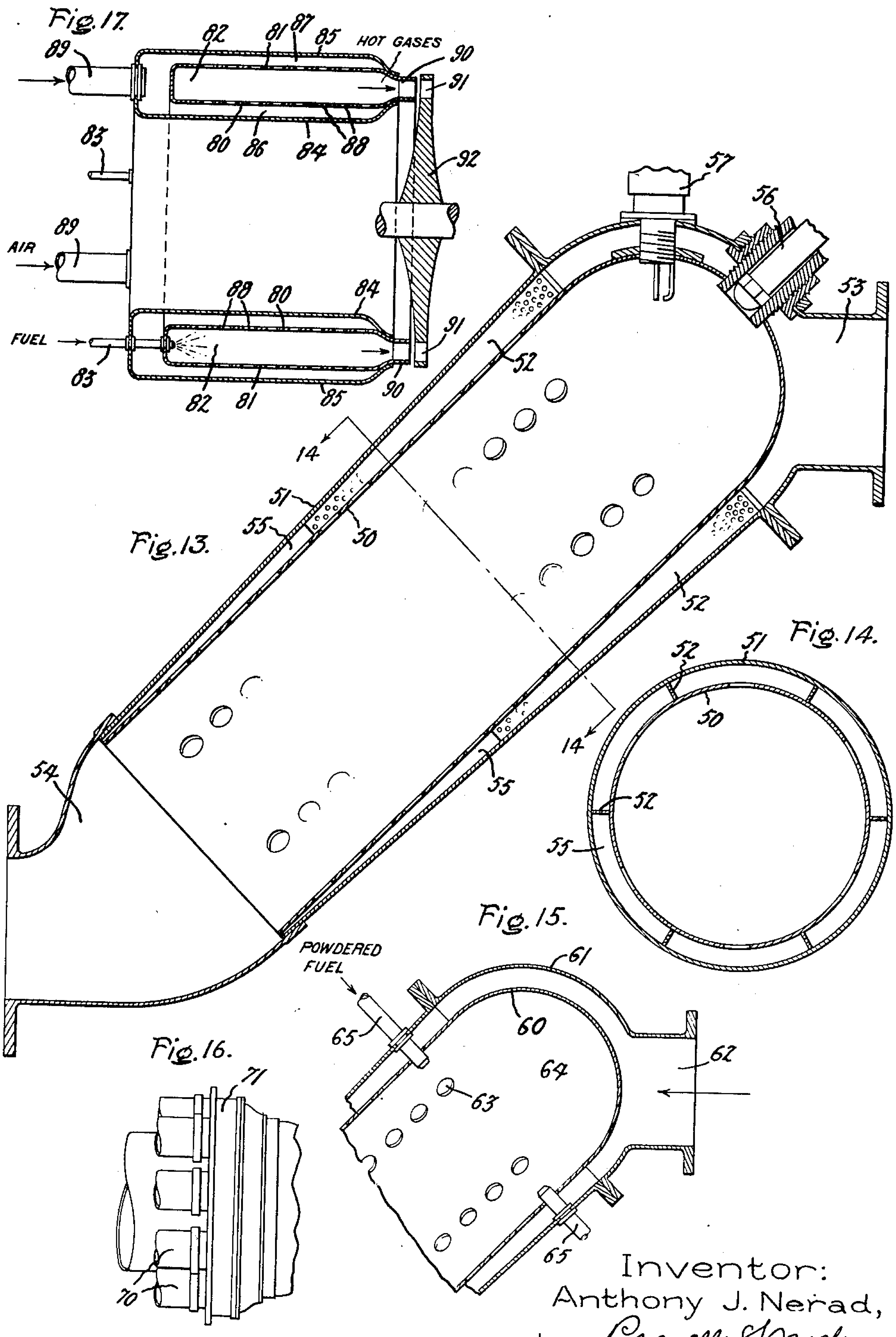
Filed May 23, 1947 4 Sheets-Sheet 4

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Patented June 17, 1952 2,601,000

# UNITED STATES PATENT OFFICE

2,601,000

## COMBUSTOR FOR THERMAL POWER PLANTS HAVING TOROIDAL FLOW PATH IN PRIMARY MIXING ZONE

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Application May 23, 1947, Serial No. 750,015

18 Claims. (Cl. 60—39.65)

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This invention relates to apparatus for effecting heat releasing reactions between two fluid reactants. It has found particular utility as a device for the combustion of fluid fuels in air, for instance as a combustor in a gas turbine powerplant, and is particularly well suited for small, high capacity, light weight combustors for aircraft powerplants. This application is a continuation-in-part of my application Serial No. 501,106, filed September 3, 1943, and now abandoned.

An object of the invention is to provide a fluid reaction device having a new method of operation which gives greatly improved performance characteristics when used as a combustor for fluid fuels.

Another object is to provide a combustor for fluid fuels capable of effecting efficient mixing, ignition, and combustion under exceptionally difficult conditions, and under an extremely wide range of heat release rates, up to a maximum many times that though feasible with the most advanced combustion equipment known to the prior art, while employing apparatus which is simple and inexpensive to fabricate, small in size and light in weight, and capable of giving excellent performance with a reasonable life expectancy.

Another object is to provide a liner arrangement for a reaction device of the type described having means for forming cooling and insulating fluid strata over the interior surfaces exposed to the reaction products, which serves to prolong the liner life, reduce to a minimum the deposition of carbonized particles when used as a combustor for fluid fuels, while permitting operation with extremely high combustion temperatures.

Still another object is to provide an improved combustor capable of very rapid changes in the rate of heat release without serious disturbance to the combustion process.

A further object is to provide a fluid fuel combustor arrangement which facilitates the initiation of combustion at high rates of air flow by means of an electric sparking device.

A further object is to provide a combustor capable of effecting ready ignition and efficient combustion over a very wide range of combustion space pressures, as is required in thermal powerplants for high altitude aircraft.

The invention is particularly well suited for the combustion of a wide variety of liquid fuels, and may also be used with pulverized solid fuels entrained in a suitable fluid or with various other types of fluid reactants, such as those used with rocket or reaction motors.

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Other objects and advantages will be apparent from the following description taken in connection with the accompanying drawings, in which Fig. 1 is a longitudinal sectional view of a combustor embodying my invention; Fig. 2 is a view on a larger scale of one end of the structure shown in Fig. 1; Fig. 3 is a sectional view taken on the plane 3—3 of Fig. 2; Fig. 4 is an end view of the fuel nozzle and adjacent chamber walls of the structure of Figs. 1 and 2; Fig. 5 is a sectional view taken on the plane 5—5 of Fig. 4; Fig. 6 is a diagrammatic view illustrating the basic theory of operation of the invention; Fig. 7 is a sectional view taken on the plane 7—7 of Fig. 6; Fig. 8, Fig. 9, and Fig. 10 are diagrammatic representations of alternate methods of supplying a fluid uniformly to the reaction space; Fig. 11 and Fig. 12 are views of combustors illustrating alternate arrangements for forming the cooling and insulating fluid strata on the interior surfaces of the reaction chamber; Fig. 13 is a sectional view of a still further modified form of the invention; Fig. 14 is a sectional view on the plane 14—14 in Fig. 13; Fig. 15 is a view of a modification arranged to burn pulverized solid fuels; Fig. 16 illustrates diagrammatically how a plurality of combustors embodying the invention may be arranged in a thermal powerplant such as a gas turbine; and Fig. 17 illustrates the invention applied to an annular reaction chamber used as a combustor for a gas turbine powerplant.

Referring first to the embodiment of the invention shown in Figs. 1–5 inclusive, the combustion unit comprises two coaxial walls, an inner wall or liner 10 and an outer wall 11 held in spaced relation to each other by a number of circumferentially spaced axially extending fins 12 which may be welded or otherwise fixed to either one or both of walls 10 and 11. The right hand portions of the unit walls 10 and 11 are tapered and are connected together as is indicated at 13. In the present instance, the tapered discharge portion of inner wall 10 is formed as a separate member 14 which telescopes over the main portion of the wall 10 as is indicated at 15 and its end is in the form of a discharge nozzle 16 which telescopes over and is loosely attached to member 14 by circumferentially spaced clips 16′ which may be welded to member 14 and engage over the end of nozzle 16. This arrangement permits the parts to expand and contract readily relatively to each other. Discharge nozzle 16 may supply gases to any desired point of consumption such as to the buckets of a gas turbine wheel.

The forward or admission end of inner wall 10 is closed by a head 17. The forward or admission end of outer wall 11 is closed by a head or dome 18. Supported centrally in heads 17 and 18 is a fuel spray nozzle 19. At 20 is a suitable spark plug for igniting the fuel-air mixture.

The fuel supplying means comprises a tubular nozzle 21 (Figs. 4 and 5) having a rounded spray tip 22 in which is a small discharge orifice 23. Nozzle 21 is supported in an outer casing 24 which at its one end projects through an opening in head 17 and its other end is provided with a boss which fits in an opening in dome 18. Thus the nozzle casing is firmly supported in the two heads. At 25 is a supply pipe through which fluid fuel is supplied to the nozzle at a suitable pressure by a pump or other means (not shown).

The space between walls 10 and 11 and between heads 17 and 18 forms a plenum chamber 26 to which air is supplied by a conduit 27 from any suitable source, such as an air compressor (not shown). In the case of a gas turbine power-plant, it may be an air compressor driven by a turbine operated by hot gases from the combustion unit.

In inner wall or liner 10 are a plurality of circumferentially spaced axially extending rows of holes 28 through which combustion air passes from plenum chamber 26 to the axially elongated reaction space defined by inner wall 10. In the present instance, eight longitudinal rows of holes are shown equally spaced circumferentially. However, a somewhat greater or lesser number may be utilized, as noted more specifically hereinafter.

The longitudinal rows of holes 28 terminate short of head 17 (or, otherwise stated, the first circumferential row of holes is spaced from head 17) to define what may be termed an initial mixing and ignition chamber 30 to which no air is directly discharged through the combustion air inlet holes 28.

It will be seen that the axial rows of holes 28 are arranged so that corresponding holes in the respective rows are in a common plane normal to the axis of the chamber. The fuel nozzle discharges fuel in a spray into chamber 30, the arrangement being such that the fuel is distributed in the form of a substantially hollow cone as shown at 36 in Fig. 2. To this end, a "wide angle" spray nozzle, that is, one giving a spray angle on the order of 80°, is employed. It should be understood that nozzles of other angles may be used; and for various modifications of combustor design, nozzles having spray angles in the range from 50° to 90° have been found appropriate. The first ring of holes 28 is spaced from head 17 a distance such that fuel discharged from the spray nozzle does not reach them, so that drops of liquid fuel are not discharged directly into the comparatively cool entering air jets from the holes 28. To this end, the first ring of holes is spaced from the head 17 a distance of the order of .7 the diameter of the cylinder formed by wall 10, i. e., .7 the mean diameter of the combustion space, but of course this spacing required would vary somewhat with the spray angle of the nozzle used.

The fuel nozzle 21 has as its primary object the even distribution of atomized fuel particles about the axis of the chamber and must be amenable to accurate flow rate control, preferably by means of varying the supply pressure. Uniform distribution of fuel over a wide range of fuel flow rates is important, especially where uniform temperatures are desired across the exit of the combustion unit. Another desideratum for optimum results is that the fuel be given a low forward or axial component of velocity. This avoids hurling large droplets of fuel axially down the combustion space at such high velocity as to give insufficient chance for mixing and burning.

In operation, fuel is supplied to chamber 30 by nozzle 21 and air is supplied through holes 28 to the combustion chamber.

The action which takes place is illustrated in Figs. 2 and 3 and will be described more particularly in connection with Figs. 6 and 7. Air entering through each circumferential ring of holes flows in substantially radial jets toward each other, meeting at the center of the combustion chamber. This is illustrated in Fig. 3 where 31 indicates outlines of the air streams flowing through a ring of holes 28 and impinging into each other near the center of the combustion chamber, as is indicated at 32. Between the entering streams of air 31 are triangular shaped spaces 33. From the center of the combustion chamber, the air turns and flows axially. From the first two or three rings of holes next adjacent the mixing chamber 30 air flows axially toward end closure head 17 as indicated by the arrows 34, the flow toward the head being confined to the central portion of the chamber. This axial flow is aided somewhat by the low pressure area created at the axis of the liner adjacent the nozzle by entrainment of air with the fluid fuel spray discharged from the nozzle. In Fig. 3, the heads of the approaching arrows are indicated by dots surrounded by circles. As the air approaches the head, it spirals radially outward as is indicated by the curved arrows 35. The fuel oil spray is indicated at 36. The air flows transversely across this spray pattern picking up fuel particles, and this air with fuel particles mixed therewith flows axially as indicated by arrows 37, the flow being initially through the comparatively unobstructed axial spaces 33. Air from the remaining rings of holes 28, after impinging at the central portion of the combustion chamber, flows axially toward the discharge end of the combustion chamber. The fuel air mixture flowing axially from chamber 30, as indicated by arrows 37, becomes commingled with the air from such remaining rings of holes, the final result being a complete and thorough mixing of the fuel with the air and burning of the fuel.

The air from the initial openings 28 which flows axially towards the nozzle as indicated by arrows 34, 35 in Fig. 2 corresponds to what is ordinarily called "primary air" in the combustion art, while that entering from successive openings and flowing axially toward the open discharge end of the liner 10 corresponds to the "secondary air."

The discrete jets of primary air are somewhat heated by radiation and conduction from, as well as some intermingling with, the burning gases flowing in the direction of the arrows 37 from the mixing and ignition chamber through the spaces 33 between the entering jets of primary air. This preheating effect on the entering primary air has an important effect on the ignition characteristics, ease of starting, and ability to maintain combustion under adverse conditions and over a wide range of air and fuel flow.

The air flow represented by arrows 34, 35 decribes a symmetrical opposed spiral or "toroidal" path in the space between the end plate 17 and the first circle of holes 28. This toroidal flow will herein be referred to as the "tore."

The chamber **30** defines adjacent to the fuel nozzle a zone of highly turbulent flow relatively independent of the load on the combustion unit, which serves to maintain combustion, thoroughly entraining and mixing the fresh cool fuel from the nozzle. Once burning has been established in this ignition space, the flame will not be extinguished by material or rapid changes in fuel and air flow rates. As demonstrative of this fact, in such a chamber there has been burned fuel at varying rates of flow in the ratio of 1 to 100 without extinction of the flame and with high efficiency.

This arrangement accomplishes another important result. Ignition is readily initiated by means of an electric spark due to the good vaporization of the fuel entrained in the air coming in jets through the first ring of holes due to the preheating effect noted above. This fuel and air mixture forming the tore is readily ignited by the spark and this is accomplished over the full range of air flows and under very difficult operating conditions.

My improved construction results in the creation of the above-described "mixing tore" and avoids the disadvantageous condition present in many prior art devices wherein jets of cool incoming air get behind the incipient flames and blow them entirely or partly out. If blown out, combustion ceases; if blown partly out, noisy and irregular or partially completed combustion results. The provision of the tore chamber **30**, without any holes **28**, has the additional advantage that any large drops of fuel thrown from the nozzle are not projected directly through the air inlet holes **28**, since the fuel nozzle is selected with a spray angle such that the spray cone **36** intersects wall **10** between the head **17** and the first circumferential row of holes **28**.

This provision of an initial mixing chamber to which no air is directly discharged through holes **28** is a very important feature of my invention. It forms a cul-de-sac into which the fuel oil is sprayed and into which air flows in a definite symmetrical path to effectively pick up the fuel particles, mix with and vaporize the fuel and initiate burning. It is important that the holes **28** be so sized and spaced that in operation the air forms a stable ignition tore, and that thorough mixing of fresh fuel, air, and burning combustion gases take place with a relatively small loss in total fluid head.

The precise arrangement, location, size and number of the holes determines the "strength" of the tore, and thereby determines the quality and efficiency of the combustion as well as the capacity. The holes **28** are spaced apart axially and circumferentially by distances such that discrete jets are formed, as shown in Fig. 3, by the air from the annular space about the inner wall **10** flowing through these holes. The very effective action of a free jet in mixing with and entraining ambient fluid is well known to those familiar with fluid flow phenomena, and the mixing is of great rapidity. I have determined that the holes **28** should have diameters of the order of .1 the diameter of the combustion space formed by wall **10**, i. e., the inner diameter of the liner, and they should be spaced apart circumferentially between centers by distances of the order of ⅛ to ⅙ of the circumference of such cylinder. The holes may be spaced axially a distance of the order of 1⅔ hole diameters between centers or a distance of the order of ⅙ the diameter of the combustion chamber between centers. Such an arrangement gives the necessary mixing space adjacent each free jet and at the same time avoids excessive length of liner **10**. Excess length of inner wall **10**, it has been found, results in higher liner wall temperatures.

To prevent deposit of carbon on the inner walls of the combustion chamber, I provide means whereby these surfaces of the walls are swept over continuously by thin sheets of cooling and insulating air. To this end, I provide slots **40** in wall **10** between the rows of holes **28** with which are associated deflecting plates **41** for directing air flowing through the slots in an axial direction along the inner surfaces of wall **10** between the axial rows of holes **28**. The slots and deflecting plates may be formed by making U-shaped cuts in the wall and bending the "tongues" so formed slightly inwardly, as shown particularly in Fig. 1. A sufficient number of slots **40** are provided, and they are made of such a width, that there flows over the inner surface of wall **10** an envelope of air in volume and extent sufficient to prevent deposits of carbon from forming on the inner surface of the wall. This envelope of cool air also serves to cool the liner wall.

To prevent deposits of carbon on the inner surface of end closure head **17**, I provide air admission openings **42** in head **17** around wall **24** and, in front of the openings, a deflecting plate **43** attached to the inner end of wall **24** by welding or other suitable means. Air flowing through openings **42** strikes deflecting plate **43** and is fanned out to flow radially outward across the inner surface of head **17** to cool it and prevent carbon deposits from forming thereon.

To likewise prevent formation of carbon deposits on the end of the fuel nozzle tip **22**, a second deflecting plate **44** is located in front of deflecting plate **43** and provided with openings **45** located to direct streams of air across the face of the fuel nozzle, deflecting plate **43** being provided with openings **46** for flow of air into contact with deflecting plate **44**. Deflecting plate **44** is of lesser diameter than deflecting plate **43** and may be formed integral with it as shown particularly in Fig. 5. It serves also to direct air across the adjacent surface of deflecting plate **43** to prevent carbon from depositing thereon. A series of openings **47** adjacent the outer circumference of head **17** effects flow of air in the direction of the arrows in Fig. 2 over that portion of the surface of liner **10** which defines the mixing tore chamber **30**, thus keeping it clear of carbon deposits.

With the foregoing arrangement, there is provided a protective envelope of air which flows over the inner surfaces of head **17** and wall **10** and over the exposed surfaces of the fuel nozzle to prevent formation of carbon deposits on such surfaces. This envelope is thin relative to the diameter of the combustion chamber, thus avoiding any material effect on the temperature of the outflowing gases. For example, the slots **40** may be of a radial width such that the air envelope has a thickness of the order of 1% of the diameter of the combustion chamber.

It should be noted that the quantity of carbon-preventing air entering through slots **40**, holes **42**, **46**, and **47** is small compared with the combustion air which enters through the holes **28**. The function of the air "envelope" is not primarily to furnish air for combustion but to provide a fluid shield for preventing unburned or partly burned fuel particles from contacting the comparatively cool metal walls of liner 10 and other interior surfaces and carbonizing thereon. It will also be observed that the air entering the carbon-preventing openings 42, 46, 47 does so in a direction to complement and augment the tore in chamber 30. By arranging these auxiliary air inlets properly, an appreciable "strengthening" of the tore is obtained.

It is necessary to operate my combustion chamber with an air supply to the plenum chamber defined by walls 10 and 11 which is very uniformly distributed, not rotating about the axis of the chamber or having vigorous eddies. In a gas turbine application, such ideal conditions are not always met. In order to rectify such conditions, a number of perforated metal strips 12 may be provided which in width extend from wall 10 to wall 11 and in length are approximately two-thirds of the length of inner liner 10. The result of the use of such means for rectifying the flow in the annulus is to improve the uniformity of air supply to holes 28, markedly, noticeably shortening the flame, increasing the capacity, widening the useful range of operation and extending the ignition range. In other words, the function of the perforated baffles 12 is to smooth out the flow and make completely uniform the flow of air in the annulus.

With this arrangement for insuring a uniform supply of air to the holes 28, the jets from a given circumferential row of holes 28 will meet exactly in the center of the chamber, as shown in Fig. 3, and then travel axially as represented by the arrows in Fig. 2.

The design of reaction chambers employing the new principles of my invention may be rationalized as follows:

The most elemental form of the invention is represented in Figs. 6 and 7, which show two pairs of parallel, flat, opposed wall members 100, 101, and 102, 103, respectively, defining an elongated combustion space having a rectangular cross-section of width $w$ and a height $d$, as indicated in Fig. 7. Let the opposed walls 100, 101 each be provided with a single combustion air inlet port 104 and 105, respectively, which may be considered to be round holes. Assume now that air is supplied by a suitable compressor to the space 26 surrounding the walls 100, 101, 102, 103. Air will begin to flow through the ports 104, 105 as soon as a pressure difference is established between the space 26 and the combustion space defined within the walls. The supply of pressure fluid to the space 26 is assumed to be such that it diffuses uniformly around the combustor walls at a common static pressure $p_0$, the fluid velocity in the space 26 being so small that the velocity head is negligible. Let it be assumed also that the combustion space is at a uniform static pressure $p_c$ substantially equal to ambient atmospheric pressure.

For small values of the pressure ratio $p_0/p_c$, the "spouting velocity" of the opposed jets formed by the orifices 104, 105, represented by the vectors $V_1$ and $V_2$, will be small. Because of the well-known "entraining" action of a free jet, the spouting velocity is soon dispersed. In other words, the discrete opposed jets $V_1$ and $V_2$ extend only a short distance from the walls 100, 101 into the combustion space. If now the pressure ratio $p_0/p_c$ is increased, the magnitude of the spouting velocities $V_1$, $V_2$, increases, and the length of the free jets also increases until they meet at the center of the combustion space. Because the fluid is supplied to the space 26 at a uniform pressure $p_0$ with substantially zero "velocity of approach" to the nozzles 104, 105 the jets represented by the vectors $V_1$, $V_2$ will be exactly normal to the walls 100, 101 and therefore they will be coaxial, so as to meet at the center of the combustion space.

It may be noted that as the pressure ratio across a simple sharp-edge orifice increases, the length of the free jet produced also increases, as described above, until a certain maximum length is attained, whereupon further increase in the pressure ratio will produce no further increase in the length of the jet. This maximum length of jet is also a function of the diameter of the orifice, indicated as $a$ in Fig. 6. In practicing my invention, the distance $d$ between the opposed orifices 104, 105 should be so related to the orifice diameter $a$ that the discrete jets produced by the orifices are sufficiently long that the jets $V_1$ and $V_2$ actually meet at the center of the combustion space with an appreciable residual velocity. When this happens the fluid "fans out" laterally, as indicated by the stream-lines in Figs. 6 and 7. Thus the spouting velocities $V_1$, $V_2$ are converted into transverse velocity components $V_3$, $V_4$, $V_5$, $V_6$, as represented by the vector arrows projecting radially from the point of intersection of the jets $V_1$, $V_2$. Since the velocities $V_1$ and $V_2$ were equal in magnitude and exactly opposed in direction, the velocities $V_3$, $V_4$, $V_5$, $V_6$, will likewise tend to be equal to each other in magnitude and radiating uniformly from, and normal to, the common axis of the jets $V_1$, $V_2$.

From a consideration of Fig. 7 it will be seen that the fluid represented by the velocities $V_5$, $V_6$ will directly impinge on the side walls 102, 103 and will again fan out transversely as indicated by the flow lines. The magnitude of the velocities $V_3$, $V_4$, $V_5$, $V_6$, depends upon the magnitude of the spouting velocities $V_1$, $V_2$, and the efficiency with which these velocities are converted into the transverse velocity components. If the velocities $V_5$, $V_6$ are of sufficient magnitude, the fluid may flow along the walls 102, 103 as represented by the flow lines and arrows 106, and may actually recirculate and be partially entrained by the jets $V_1$, $V_2$, as indicated by the arrows 107.

Now let one end of the combustion space be closed by means of a transverse plate inserted at the location of the plane 109 in Fig. 6. The fluid flow represented by the axial velocity $V_3$ will now impinge at the center of the end closure plate 109 and fan out as indicated by arrows 110. With suitable velocities, this fluid will likewise recirculate as indicated by the flow lines, some of it being entrained with the jets $V_1$, $V_2$ as indicated by the arrows 111. That fluid which is not so entrained will flow in a generally axial direction past the jets $V_1$, $V_2$ through the comparatively unobstructed spaces 112 defined between the jets $V_1$, $V_2$ and the side walls 102, 103 as represented by the arrows 113.

The resemblance between this basic flow path produced by the orifices 104, 105 in Fig. 5 to that described in connection with Fig. 2 above will now be seen. The reverse axial flow represented by the vector $V_3$ establishes a double opposed spiral flow path in the zone 30, which may be considered to be two oppositely rotating vortices. Fluid is continually fed to these vortices from the entering jets $V_1$, $V_2$, a corresponding amount of fluid leaving each vortex as represented by the arrows 113.

If now liquid fuel particles are injected by suitable means into the opposed vortices represented by arrows 110, 111, the fuel will be vaporized or further broken up and mixed by reason of the high velocity in the vortices. After combustion is initiated, the burning mixture serves to preheat the comparatively cool incoming jets $V_1$, $V_2$ by radiation, by conduction, and by partial entrainment with the fluid represented by the arrows 111, 113.

It has been found that in order to produce discrete jets which meet at the axis of the chamber so as to create a strong reverse axial velocity $V_3$, the distance $d$ between the opposed nozzles 104, 105 should be on the order of ten times the diameter of the nozzles, when the nozzles are round in shape. It should be understood, however, that the nozzles need not be exactly round but may be rectangular or other elongated or elliptical shapes. Orifices of such other shapes should preferably have the same "hydraulic diameter" as an equivalent round orifice. The hydraulic diameter may be defined as equal to four times the "hydraulic radius." As is well known, the hydraulic radius is equal to the cross-section area of the orifice divided by its "wetted perimeter." It follows that for orifices of shapes other than circular, the following relation should be approximately adhered to:

$$.1d=4\times\frac{A}{P}$$

where

$d$=distance between opposed orifices, as in Fig. 7.
A=cross-section area of the orifice used.
P=wetted perimeter of the orifice used.

It has been found that the hole size may be made smaller than indicated by the above relation. However, smaller holes require that larger pressure ratios be employed to obtain the velocities necessary for the establishment of a strong vortex flow pattern. For instance, tests have shown that the diameter of round orifices may be one-half that determined by the above relation, at the expense of perhaps 4% total pressure drop across the system.

It has also been found that to provide sufficient space adjacent the entering jets $V_1$, $V_2$, in order to secure efficient entraining action, the side walls 102, 103 should be spaced from the axis of the jets by a distance approximately $.2d$. With round orifices, this means that the spacing from the side wall to the edge of the orifice should be at least $.15d$. In cylindrical combustors, as in Figs. 1, 11, 12, 13, etc., good transverse spacing between jets will be obtained if the holes are arranged at ⅙ to ⅛ the circumference, measured between centers. It is however entirely feasible to use only two opposed orifices, as in Figs. 6 and 7, or four holes; but six or more have been found preferable.

I have also ascertained that the optimum spacing of the initial air inlet ports 104, 105 from the plane of the end closure 109 is on the order of $.7d$. This axial spacing of the initial jets $V_1$, $V_2$ from the closed end furnishes sufficient volume for the establishment of the double spiral opposed vortices. While greater spacing of the initial jets from the closed end may be used, this requires also a higher pressure drop in order to obtain a velocity component $V_3$, which will be strong enough to persist all the way to the end closure 109 and then produce the transverse opposed velocities 110. A further consideration



affecting the minimum spacing of the first nozzles from the end closure 109 is that a sufficient time interval must be provided for the fuel particles to mix with the air and begin burning. If the axial spacing of the initial jets from the closed end is too small, then the combustion process will not be sufficiently well established by the time the fuel-air mixture reaches the jets $V_1$, $V_2$ and the comparatively cool incoming jets will tend to "blow out" the burning mixture. It appears that a space of the order of $.7d$ is the optimum required to effect efficient ignition and combustion with a minimum overall pressure drop.

So far, in the above discussion relating to Figs. 6 and 7, it has been considered that there were only two opposed orifices, 104, 105. Assume now that a second set of opposed orifices 114, 115 be added, as indicated in Fig. 6. These orifices are arranged similarly to 104, 105, but are spaced axially downstream by a distance $b$, measured center to center. This second set of opposed orifices will produce jets represented by the vectors $V_7$, $V_8$ which are equal in magnitude to $V_1$, $V_2$ and are likewise exactly normal to the axis of the reaction space. These jets will meet at the axis and tend to separate and flow axially in opposite directions as represented by the vectors $V_9$, $V_{10}$. It will be apparent from Fig. 6 that the vector $V_9$ is in direct opposition to the vector $V_4$, so that the effect of the former is to decrease the latter. The result is that the vector $V_3$ is increased, which means that more air from the first set of orifices 104, 105 is caused to flow axially to the left. If now still another set of openings 116, 117 is added, the jets $V_{11}$, $V_{12}$, will produce axial velocities $V_{13}$, $V_{14}$. The vector $V_{13}$ will likewise react with vector $V_{10}$ so as to cause more air from the initial set of nozzles to flow to the left into the opposed vortices in chamber 30. It will thus be seen that adding additional axially spaced sets of nozzles has the effect of increasing the flow of fluid into the vortex chamber 30.

A certain minimum spacing, $b$ in Fig. 6, is required in an axial direction between the orifices. This minimum depends upon the space required to produce effective entraining action of the free jets with the surrounding fluid. The axial spacing required between orifices is considerably less than the transverse or circumferential spacing (Fig. 3), by reason of the fact that the transverse spacing must also be great enough to form the comparatively unobstructed longitudinal flow passages, represented at 33 in Fig. 3 and at 112 in Fig. 7, to permit the flow of burning mixture from the chamber 30 to the exit of the combustor with a minimum pressure drop. It has been found that when round orifices are used, a desirable axial spacing is in the neighborhood of 1⅔ times the hole diameter measured between centers, which gives a spacing between jets of ⅔ times the hole diameter. The maximum axial spacing between orifices is determined by the desirability of keeping the overall length of the combustor to a minimum in order to conserve space. It has also been found that too great an axial spacing makes the liner more difficult to cool.

The total number of holes depends upon the aggregate orifice area necessary to pass that quantity of primary and secondary air, without exceeding the allowable pressure loss, which is required to complete the combustion process and then reduce the average temperature of the reaction products to a value which the structure of the combustor exit and other parts associated therewith may safely be subjected to. It will be appreciated by those skilled in the art that in modern gas turbine powerplants its is necessary to introduce a certain quantity of air in excess of that required for good combustion in order to dilute the combustion products to a temperature which the turbine wheel will withstand. As described more particularly hereinafter, a rule of thumb which may be used to determine the aggregate orifice area is that the total hole area should be that required to make the overall pressure drop through the combustor roughly equivalent to 1% of the total head of the fluid supplied to the combustor. It has been found that combustors meeting this requirement give good combustion efficiency with a minimum cost in terms of loss of pressure energy.

Tests of an actual combustor with a plurality of axially spaced nozzles show that substantially all of the air from the first set of nozzles flows axially into the vortex chamebr **30**. Likewise some, or perhaps all, of the fluid entering from the second set of nozzles **114**, **115** will flow to the left into the vortex chamber. However, at some axial location there will be noted a division, fluid entering through nozzles to the left of this location going into the vortex chamber **30**, while jets at the right of this location flow to the right. This division point is shown quite clearly in Fig. 2 as located between the second and third sets of orifices. As noted hereinbefore, that fluid which flows leftward into the vortex chamber **30** is what is ordinarily known in the combustion art as the "primary air," while that which flows to the right corresponds to the "secondary air."

Attention is directed to the fact that Figs. 6 and 7 represent diagrammatically the nature of the flow path. The stream lines and the vector arrows representing fluid velocities have not been drawn with mathematical exactness to represent actual magnitudes, but are merely illustrative.

It will now be seen that the fluid velocities in the opposed vortices in the initial mixing chamber **30** depend upon the magnitude of the initial spouting velocity $V_1$, $V_2$, the efficiency with which this initial velocity is converted into the axial component $V_3$, and the effect of subsequent jets $V_7$, $V_8$, $V_{11}$, $V_{12}$, etc., as described above. On the other hand, the shape or symmetry of the vortices depends upon the direction of the jets $V_1$, $V_2$, $V_7$, $V_8$, etc., the direction of the first set of jets $V_1$, $V_2$ being particularly important. In order to form a uniform symmetrical vortex flow pattern, it is necessary that the axial velocity component $V_3$ be parallel to the axis of the reaction space in order that the fluid will approach the end closure member **109** in a direction perpendicular thereto, so as to divide evenly and produce the transverse oppositely directed velocities **110**. To produce this uniform symmetrical flow pattern, the supply of air to the orifices **104**, **105**, etc. must be entirely uniform, both with respect to the static pressure $p_0$ at which the fluid is supplied to the orifice, and with respect to the velocity of approach to the orifices. If the air supply is not uniform, the jets will not meet properly at the axis of the combustion space and will produce axial velocities which are highly erratic and unpredictable, both in magnitude and direction. When this happens, the vortex flow pattern in chamber **30** may either be distorted, that is, unsymmetrical, or it may not be formed at all. Formation of a strong, symmetrical vortex flow pattern in chamber **30** has been found essential to optimum performance relative to ready ignition, wide range, and efficient combustion. With an erratic, unstable, or unsymmetrical flow pattern, the liberation of heat in the combustion chamber is less uniform, ignition and combustion characteristics are poorer, and "hot spots" may be formed which very shortly result in destruction of the liner.



There are many ways by which the required uniformity of air supply to the orifices may be obtained. The simplest is shown in Fig. 8. This represents diagrammatically a compressor supplying air at a suitable pressure to a plenum chamber **108** of comparatively large volume surrounding the end portion of the combustor liner **118**. The comparatively high velocity stream of air from the compressor will diffuse uniformly throughout the generously proportioned plenum chamber, so that the velocity with which the air enters the plenum chamber is substantially dissipated and the "total pressure" is equivalent to the common static pressure $p_0$, which exists throughout the plenum chamber. Thus there is obtained a uniform air supply as was assumed above in connection with Figs. 6 and 7.

Another arrangement for insuring uniform air supply is illustrated in Fig. 9. Here the liner **119** is provided with short radially extending pipes **120**, **121** connected to the respective orifices **104**, **105**. Each of the radial pipes is connected by separate conduits **122**, **123** to the discharge scroll or diffuser of the compressor. Thus if the compressor is arranged to discharge air uniformly into the conduits **122**, **123**, uniformity of the velocity of approach in the pipes **120**, **121** is assured. Because the pipe sections **120**, **121** are exactly radial, this velocity of approach will be normal to the axis of the liner and the jets produced will meet exactly at the axis as desired.

Still another arrangement for uniform air supply is illustrated in Fig. 10, in which the liner **124** is surrounded by an outer housing **125** defining a comparatively restricted air supply passage **126**. The compressor supplies air through the diffuser or transition section **127** to the passage **126**. Each of the air inlet orifices in liner **124** is provided with a short radially extending nozzle pipe **128**, each formed with a well-rounded inlet. The effect of these nozzles **128** is somewhat the same as that of the short, straight sections of pipe **120**, **121** in Fig. 9. With the arrangement of Fig. 10, the jets produced will be very nearly exactly radial, regardless of any non-uniformity in the air velocities through the space **126**. It has been found that nozzles such as those indicated in Fig. 10 make the combustion device less sensitive to variations in the direction or velocity at which the fluid in the transition section **127** approaches the liner **124**. A combustor in accordance with my invention and embodying the improved nozzle arrangement of Fig. 10 is disclosed more fully in United States Patent No. 2,510,645, issued June 6, 1950, on an application, Serial No. 705,866, filed October 26, 1946, in the name of Kenton D. McMahan and assigned to the same assignee as the present application.

Another particularly effective, yet structurally simple, method for obtaining uniformity of air supply is the perforated baffle arrangement shown in Figs. 1, 3, and 13, 14. It will be obvious to those skilled in the art that many different arrangement of baffles, shrouds, guide vanes, "honeycomb grids" and similar known expedients may be used to make sufficiently uniform the flow of air to the inlets of the liner orifices.

When the perforated inner liner of a combustor embodying my invention is surrounded with an outer housing defining an air supply passage, as 26 in Figs. 1–3, it is desirable that the velocity of approach in this air supply passage be roughly equal to the initial spouting velocity of the jets produced by the orifices. It has been found that velocities of this magnitude result in effective cooling of the liner. The maximum velocity of approach is limited by the permissible extent to which the velocity of approach (indicated by the vector $V_0$ in Fig. 2) produces a deviation of the spouting velocity vector $V_1$ from the exactly radial direction. It will be observed in Fig. 2 that the approach velocity $V_0$ gives the spouting velocity $V_1$ a slight axial component toward the left. This slight axial component is not harmful to operation of the combustor, since it somewhat tends to increase the flow of air from the initial holes 28 into the "tore chamber" 30. If on the other hand, the fluid in the supply passage 26 approached the orifices 28 from the left, then an axial component of $V_1$ to the right would be produced, which might tend to decrease the amount of air flowing into the tore chamber 30 from the initial row of jets. With such an arrangement, it would be necessary to decrease the approach velocity $V_0$, as by increasing the cross section area of the supply passage 26, so as to reduce this axial component of $V_1$. Otherwise some special means would be needed, for instance the nozzle arrangement of Fig. 10, to eliminate the axial component of the spouting velocity, introduced by the excessive velocity of approach. A further factor limiting the maximum value of the approach velocity $V_0$ is the increase in the overall pressure drop created if the approach velocity is too high.

Experience in the design of many forms of fluid fuel combustors embodying my invention has shown that the initial spouting velocity $V_1$ produced by the orifices in the liner should be of such a magnitude that the velocity head of the jets is roughly equivalent to 1% of the initial total head of the fluid approaching the orifices. If the spouting velocity is increased above this value, the total pressure losses through the combustor increase; whereas if the spouting velocity is decreased, the combustion efficiency decreases by reason of the decreased "strength" of the vortex flow path produced. The practical result of this decrease in combustion efficiency is that the flames produced by the combustor lengthen, and may extend beyond the exit of the combustor. It is of course desired that combustion go to completion within the combustion space so that a mixture of uniform temperature will be produced at the combustor exit. This is particularly important in a gas turbine powerplant, where it is highly undesirable that flames reach the turbine nozzles or buckets.

In the operation of any fluid fuel combustor of the general type represented by my invention, there appears to be an inherent loss of total head of the fluid flowing through the system. Apparently this is at least partly accounted for by the turbulence which it is necessary to produce in the device in order to secure effective mixing and complete burning. Experience has shown that with my combustion system the overall loss in total head, from the air supply passage approaching the liner orifices to the liner exit is roughly equivalent to the velocity head of the fluid jets issuing from the orifices into the combustion space. As indicated above, this is about 1% of the initial total head of the fluid. Thus a useful rule of thumb is that the total pressure drop inherent in a combustor embodying my invention is that head required to produce the initial spouting velocity $V_1$. This overall loss is very much less than that incident to the operation of the best combustors known to the prior art.

My invention readily lends itself to an almost infinite variety of arrangements. In Figs. 13 and 14 I have illustrated a form wherein the air, instead of being admitted adjacent the discharge end of the combustion unit, is admitted adjacent the inlet end in the vicinity of the fuel nozzle. In Figs. 13 and 14, 50 and 51 indicate inner and outer walls corresponding to walls 10 and 11 of Fig. 1 and 52 indicates perforated baffle strips corresponding to members 12 of Fig. 1. The air inlet is indicated at 53 and the discharge nozzle at 54. In this arrangement, walls 50 and 51 converge toward each other from the admission end to the discharge end, providing an annular plenum chamber 55 which in longitudinal section is tapering. The fuel nozzle is indicated at 56 and the ignition plug at 57. Otherwise, the arrangement may be the same as that shown in Fig. 1 and the operation is the same.

With respect to the arrangement of the nozzles for supplying the film of insulating and cooling air on the inner surfaces of the liner, a great many alternate arrangements are possible. Instead of the single transversely extending nozzles 41 between the longitudinal rows of holes 28, as in Figs. 1–3, there may be provided a plurality of smaller slots arranged as shown in Fig. 11. These cooling air nozzles may be formed by providing a slot 130 in the liner wall and then stamping the liner wall outwardly, downstream from this slot, so as to provide the "dimples" indicated at 131 in Fig. 11. These dimples with the slit orifices at their upstream side are arranged in groups between the longitudinal rows of air inlet holes 28.

A still further step in the development of the nozzle arrangements for providing the cooling and insulating film is shown in Fig. 12. Here the liner is made up of a plurality of coaxial cylindrical segments 132, 133, 134, 135, and 136. Each segment is of slightly greater diameter than the adjacent upstream segment and has an end portion in telescoping relation therewith. The segments are supported in concentric relation by means of "struck-out" dimples 137, a plurality of which are equally spaced circumferentially around the outer surface of each segment where it projects into the next adjacent larger diameter segment. These projections 137 may of course be spot-welded to the next succeeding segment so that the set of segments forms an integral liner. The liner may be supported within the outer housing 11 by means of perforated radially extending baffles 12, which are similar in structure and purpose to the baffles 12 of Fig. 1. With this arrangement, the telescoping portions of the liner segments form substantially continuous annular slots 138, which serve as orifices for forming the film of cooling and insulating air on the inner surface of the next succeeding segment, as indicated by the arrows in Fig. 12. It will be observed that the air inlet ports 28*a* which furnish the primary air to the initial mixing and ignition chamber defined by segment 132 are located in segments 132 and 133. The openings 28*b* which furnish the secondary air are arranged in segments

135 and 136, these secondary openings being separated from the "primary" air openings by the imperforate segment 134.

In carrying out my invention, suitable fuel injecting means other than that illustrated in the drawings may be employed. Any of the well-known types of "mechanical atomizing" nozzles may be used, such as the high pressure nozzles used in diesel engine fuel injection systems. Such nozzles require pressures in the neighborhood of 2,000 lb./in.$^2$ to produce effective atomization of the fuel oil. The pressure required may be greatly reduced by the use of the well-known "simple vortex" nozzle which requires pressures in the neighborhood of 5 to 400 lb./in.$^2$. A very considerable increase in the range, and improvement in other operating characteristics of the combustor, can be obtained by use of the so-called "duplex nozzle." This general type of nozzle is disclosed in the United States patent to Nightingale, 1,873,781, issued August 23, 1932. An especially advantageous arrangement for the duplex nozzle is disclosed in a copending application Serial No. 622,604, filed October 16, 1945, in the name of Charles D. Fulton, now Patent No. 2,590,853. Also, a nozzle of the "air-atomizing" type may be employed, in which a stream of high-pressure air helps to break up the liquid fuel into sufficiently fine particles. Suitable nozzles of this type are disclosed in the co-pending application of B. O. Buckland and D. C. Berkey, Serial No. 62,634, filed November 30, 1948, now Patent No. 2,595,759, and assigned to the same assignee as the present application. All of the above-mentioned types of nozzles have been successfully employed in connection with combustors embodying my invention.

Whatever the type of nozzle used, it is desirable that liquid fuel particles be introduced into the mixing and ignition chamber 30 with a spray pattern in the form of a hollow cone, as represented in Fig. 2. This is particularly important at low total rates of fuel flow. This avoids the projection of liquid fuel particles axially down the liner, and results in the particles being projected substantially transversely to the flow path of the air circulating in the double opposed vortex flow paths in chamber 30. This arrangement has been found most effective in producing quick and efficient mixing of the fuel particles with the combustion air, so that ignition is readily initiated under difficult conditions. In this connection it may be noted that the sparking device 20 (Fig. 1) should be so located that the spark gap will lie substantially in the surface of the conical spray pattern produced by the fuel nozzle. This insures that fuel will reach the spark gap when the sparking device is energized.

At high rates of air flow to the combustor, it it not quite so important that the fuel spray be supplied in the form of a hollow cone, for the air velocities in space 30 are then sufficiently great to pick up the fuel particles and sweep them backward and radially outward as indicated by the spray paths 36a in Fig. 2, so that no fuel particles are projected axially down the center of the liner at high velocity. Therefore, if the device is intended to operate only at high air flows, so that high gas velocities are maintained over the entire operating range, then it becomes more or less immaterial as to how the fuel particles are introduced into the chamber 30.

In addition to the ordinary light liquid fuels, such as gasoline, kerosene, it is entirely feasible to use heavy fuel oils, such as that known commercially as "bunker C." Furthermore, alcohol or the special fuels known to those skilled in the art as "100% aromatics" may be used.

I may also utilize solid fuel, such as pulverized coal. In the case of solid fuel, such as pulverized coal, fuel may be admitted through the ring of openings adjacent to the initial mixing and igniting chamber. Such an arrangement is shown in Fig. 15 wherein 60 indicates the inner wall, 61 the outer wall, 62 the air admission conduit and 63 the first ring of holes which is adjacent to the mixing and igniting chamber 64. In connection with the first ring of holes 63, there are provided fuel nozzles 65 through which fuel, such as powdered fuel, may be discharged into the combustion space. In the present instance, two fuel nozzles 65 are illustrated, the same being arranged diametrically opposite each other. Otherwise, the arrangement shown in Fig. 15 may be the same as that shown in Figs. 1 to 5, inclusive.

While pulverized coal is referred to as "solid fuel" it is to be noted that powdered solid fuel entrained in a stream of air is analogous to a "fluid fuel," and I intend the term "fluid fuel" to include this interpretation.

My invention is well adapted for use in connection with gas turbines. When utilized to drive a turbine wheel, a number of the individual units may be arranged circumferentially around the periphery of a turbine wheel so as to supply gases throughout the circumference of the wheel. Such an arrangement is illustrated in Fig. 16 wherein 70 indicates a number of combustion units spaced circumferentially and having their discharge ends connected to an annular nozzle box 71 from which gases may be fed through suitable nozzles to a turbine wheel.

Such arrangements are more fully disclosed in copending applications, Serial No. 506,930, filed in the name of Alan Howard on October 20, 1943, now Patent No. 2,479,573, and Serial No. 525,391, filed March 7, 1944, in the name of Dale D. Streid, now Patent No. 2,432,359, both assigned to the same assignee as the present application.

A combustion unit embodying my invention, because of its capacity to initiate combustion under conditions of relatively high air flow and relatively low fuel flow, has especially great utility in an arrangement such as that shown in Fig. 16. In such arrangements, it is important that ready ignition be effected in all the combustion chambers. In starting up, there is likely to be small time differences for ignition to take place in the several combustion chambers. As a result, there will occur an increase in air flow from the air compressor or other common air supply through the combustion chambers not ignited and a decrease in such air flow through the combustion chambers already ignited. Thus ignition must be initiated in the not already lighted chambers at a time of relatively large air flow and small fuel flow. And it is important that it be initiated promptly to maintain safe upper limits of temperature of the gases coming from the already ignited combustion chambers. By my invention, ignition under such conditions is obtained. Also, in the case of a multiplicity of combustion chambers, should some stoppage of fuel in one or a number of them occur, for instance due to a slug of water in the liquid fuel supply line, causing combustion to cease, and then the fuel starts flowing again, ignition in any such chamber would be again effected simply by turning on the spark ignition, even with relatively high rates of air flow.

A further important advantage of combustors incorporating my invention is that they are capable of operating at combustion space pressures over a wide range, for instance from ⅕ atmosphere to 8 atmospheres, as may be required for burning hydrocarbons in air in a high altitude aircraft powerplant. On the basis of present knowledge, I believe there is no upper limit of pressure at which my combustion system may be made to work satisfactorily. With specially selected fuels, the lower pressure limit may be 1/60 atmosphere or lower. Furthermore, my combustors may operate over extremely wide ranges in average exit temperature. They may operate with a minimum temperature rise through the system of only 100° F., up to a maximum on the order of 3000° F. temperature rise, while maintaining efficient, quiet, and stable combustion throughout this extreme range. The rate of air flow over the operating range of the combustor may be on the order of 30 to 1, as for example from 1000 lbs. of air per hour, total flow through one combustor, to a maximum of 36,000 lbs. per hour.

The figures given in the preceding paragraph are for a combustor which has a liner about eight inches in diameter and about twenty inches long. Tests have shown that my combustion principles can readily be applied to cylindrical combustors with liners ranging from one to eighteen inches in mean inside diameter; and I believe that units of larger sizes are entirely feasible.

In Fig. 17 is illustrated a modification wherein, instead of using a plurality of units after the manner shown in Fig. 16, I utilize a single unit which is in the form of an annulus and which is shown as being utilized to supply gases for operating a turbine wheel. Referring to Fig. 17, **80** and **81** are concentric spaced walls which define an annular combustion chamber **82** to which fuel is supplied by one or more fuel nozzles **83**. Surrounding walls **81** and **80** are two spaced concentric walls **84** and **85** which define annular air chambers **86** and **87** from which air is supplied through openings **88** in walls **80** and **81** to the combustion chamber. Air is supplied to chambers **86** and **87** through one or more air supply conduits **89**. At **90** is indicated an annular nozzle arranged to discharge gases to the buckets **91** of a gas turbine wheel **92**. In Fig. 17, the arrangement is illustrated only diagrammatically. It may embody the various details of construction illustrated more specifically in Figs. 1 to 15, inclusive.

It will be readily apparent that the annular chamber of Fig. 17 could be "developed" to form a flat combustor, the walls **80**, **81** being plane instead of annular. Such an arrangement would amount to a plurality of the elemental units represented by Figs. 6, 7 placed in side-by-side relation.

My invention has made possible heat release "space rates" hitherto thought impossible with known combustion devices. The maximum rates obtained are on the order of 200 million B. t. u./cu. ft./hr., or upwards of 1,000 times that obtained with the most efficient modern steam power boilers. The practical fuel rates for gas turbine operation are in the neighborhood of 2½ gallons of a liquid fuel such as kerosene per square inch of liner cross-section per hour at a combustion space pressure of 4 atmospheres. Even with such extremely high heat release rates, the combustion efficiency approaches very closely to the ideal or perfect condition.

In spite of the enormous heat release rates obtained, the arrangement I have provided for cooling the liner is so effective that this critical part may be made of an ordinary commercial stainless steel alloy, such as that known to the trade as "No. 2520," containing 25% chromium, 20% nickel, and the balance iron. Good operation has been obtained with average combustor exit temperatures in the neighborhood of 2000° F., with maximum temperature of 3000° F. at the center of the reaction space, while the temperature of the metal liner remains safely below 1500° F.

While I have shown and described numerous specific embodiments of my invention, it will be obvious to those skilled in the art that various additional modifications may be made without departing from my invention, and I intend the appended claims to cover all such modifications as fall within the true spirit and scope of the invention.

What I claim as new and desire to secure by Letters Patent of the United States is:

1. A reaction device comprising walls defining a primary mixing zone and a secondary reaction space, said walls including secondary spaced side wall portions forming an axially elongated secondary space, the primary zone being defined between spaced primary side wall portions and a transversely extending end closure wall, means for introducing a first fluid reactant into the primary space, the primary side wall portions defining at least two transversely spaced exactly opposed fluid inlet nozzles located at a common plane normal to the axis of the reaction space, said plane being spaced from the closed end wall of the primary space a distance on the order of .7 times the transverse spacing of said nozzles, and a source of supply of a second fluid reactant under pressure including walls associated with the primary walls and defining symmetrical flow paths communicating with the respective nozzles and of such size that substantially radial discrete free jets of the second fluid issue symmetrically from the nozzles and meet at the axis of the reaction space, with at least a portion thereof flowing axially toward the closed end wall and thence transversely away from the axis to describe a uniform symmetrical double opposed spiral path in the primary space, the reacting fluids flowing in a generally axial direction past the incoming jets to the open end of the reaction space, all inlets for said second fluid in the walls defining the primary space producing jets substantially tangential to said double opposed spiral flow path.

2. A reaction chamber comprising first and second opposed wall portions defining therebetween an axially elongated reaction space, a third portion forming a closure for one end of said space, the opposite end being open for the discharge of reaction products, means for introducing a first fluid reactant into said space adjacent the closed end of the chamber, and means for introducing a second fluid including opposed nozzle means in said first and second wall portions located in a common plane normal to the axis of the chamber and spaced from the closed end thereof, and means including walls defining passages for supplying a second fluid uniformly to said nozzle means whereby discrete jets of the second fluid issuing from said nozzles meet at

the axis of the chamber and thence flow axially with at least a portion of the fluid flowing toward the closed end of the chamber and then transversely away from the axis to describe a uniform symmetrical double opposed spiral flow path in the primary mixing space between the closed end of the chamber and said nozzle means, and orifice means in said opposed wall portions adapted to form a thin protective envelope of flowing fluid over the wall surfaces subject to contact with reaction products.

3. In a reaction chamber the combination of a liner of substantially circular cross section closed at one end and open for the discharge of reaction products at the other end, means for introducing a first fluid reactant into the liner adjacent the closed end thereof, means for introducing a second fluid comprising a plurality of circumferentially spaced inlet openings in the wall of the liner located in a common plane transverse to the axis of the liner and spaced from the closed end thereof, and means including walls defining passages for supplying the second fluid to said inlet openings uniformly whereby discrete jets of fluid produced by the circumferentially spaced openings meet at the axis of the liner and thence flow axially with at least a portion of the fluid flowing axially toward the closed end of the liner and then radially outward to described a uniform symmetrical substantially toroidal path in the space between the closed end of the liner and said inlet openings, and orifice means in the liner wall adapted to form a thin protective envelope of flowing fluid over the surfaces subject to contact with reaction products.

4. In a combustor for burning fluid fuel, the combination of a liner of substantially circular cross section closed at one end and open for the discharge of hot products of combustion at the other end, means for introducing fluid fuel into the liner adjacent the closed end thereof, means for introducing combustion air comprising a plurality of circumferentially spaced air inlet openings in the wall of the liner located in a common plane transverse to the axis of the liner and spaced from the closed end of the liner, and means for supplying combustion air to said inlet openings in such a manner that discrete jets of air produced by the circumferentially spaced openings meet at the axis of the liner and thence flow axially with at least a portion of the air flowing axially toward the closed end of the liner and then radially outward to describe a uniform symmetrical substantially toroidal path, and orifice means associated with the liner wall and arranged to form a thin protective envelope of flowing air over the surfaces subject to contact with hot products of combustion to prevent deposition of carbonized particles thereon.

5. In a combustor for burning fluid fuel, the combination of a liner of substantially circular cross section closed at one end and open for the discharge of hot products of combustion at the other end, fluid fuel spraying nozzle means adjacent the central portion of the closed end and adapted to deliver fuel particles into the liner with a spray pattern substantially in the form of a hollow cone coaxial with the liner, said liner having a plurality of combustion air inlet holes arranged in circumferential rows, each row lying in a common plane transverse to the axis of the liner with corresponding holes in the respective rows arranged in a straight substantially longitudinal row, there being no combustion air inlet holes adjacent the closed end of the liner in the area subject to direct impingement by fuel particles in the spray pattern, and means for supplying combustion air to said inlet openings uniformly so that discrete jets produced by the openings in each circumferential row meet at the axis of the liner and thence flow axially with at least a portion of the air from the circumferential row of holes nearest the nozzle end of the liner flowing axially towards the nozzle and then radially outward to pick up and mix with the fuel particles in the spray pattern.

6. In a combustor for burning fluid fuel, the combination of a liner of substantially circular cross section closed at one end and open for the discharge of hot products of combustion at the other end, fluid fuel spraying nozzle means adjacent the central portion of the closed end and adapted to deliver fuel particles into the liner with a spray pattern substantially in the form of a hollow cone coaxial with the liner, said liner having a plurality of combustion air inlet holes arranged in circumferential rows, each row lying in a common plane transverse to the axis of the liner with corresponding holes in the respective rows arranged in a straight substantially longitudinal row, there being no combustion air inlet holes adjacent the closed end of the liner in the area subject to direct impingement by fuel particles in the spray pattern, and means for supplying combustion air to said inlet openings uniformly so that discrete jets produced by the openings in each circumferential row meet at the axis of the liner and thence flow axially with at least a portion of the air from the circumferential row of opening nearest the nozzle flowing axially toward the nozzle and then radially outward across the fuel spray pattern.

7. In a combustor for burning fluid fuel, the combination of a liner of substantially circular cross section closed at one end and open for the discharge of hot products of combustion at the other end, fluid fuel spraying nozzle means adjacent the central portion of the closed end and adapted to deliver fuel particles into the liner with a spray pattern substantially in the form of a hollow cone coaxial with the liner, said liner having a plurality of combustion air inlet holes arranged in circumferential rows, each row lying in a common plane transverse to the axis of the liner with corresponding holes in the respective rows arranged in a straight substantially longitudinal row, there being no combustion air inlet holes at the nozzle end of the liner in the area subject to direct impingement by fuel particles in the spray pattern, means for supplying combustion air to said inlet openings uniformly so that discrete jets produced by the openings in each circumferential row meet at the axis of the liner and thence flow axially with at least a portion of the air from the circumferential row of openings nearest the nozzle flowing axially toward the nozzle and then radially outward across the fuel spray pattern, and orifice means associated with the liner wall and arranged to form a thin protective envelope of flowing air over the surfaces subject to contact with hot products of combustion to prevent deposition of carbonized particles thereon.

8. In a combustor for burning fluid fuel, a substantially cylindrical liner closed at one end and open for the discharge of hot products of combustion at the other end, the closed end and adjacent portion of the liner defining a primary air and fuel mixing and ignition space having no

openings for the admission of combustion air, fluid fuel spraying nozzle means adjacent the central portion of the closed end and adapted to deliver fuel particles into the primary mixing and ignition space with a spray pattern substantially in the form of a hollow cone coaxial with and intersecting that portion of the liner wall defining said primary space, the remainder of the liner defining a secondary combustion space adjacent said first space and having a plurality of circumferential rows of combustion air inlet openings, each circumferential row lying in a common plane transverse to the axis of the liner with corresponding holes in the respective rows arranged in a straight substantially longitudinal row, means for supplying combustion air to said inlet openings uniformly so that discrete jets produced by the openings in the circumferential rows nearest the closed end of the liner meet at the axis of the liner and thence flow axially with at least a portion of the air flowing axially toward the nozzle and then radially outward and across the fuel spray pattern in the mixing and ignition space.

9. A combustion unit comprising an annular wall shaped to define a discharge opening at one end, a head which closes the other end, said wall being provided with rings of circumferentially spaced openings, the several rings of openings being spaced axially from each other and the ring of openings nearest the head being spaced from the head to form an initial mixing and ignition chamber adjacent said head to which primary combustion air is supplied by axial flow of air from the radial jets formed by the spaced openings next to said mixing and ignition chamber, a fuel supply means adjacent the center of the head which directs fuel into said mixing and ignition chamber in the form of a substantially hollow conical spray at an angle to the direction of air flow therein whereby the fuel and air are mixed initially in said mixing and ignition chamber and then flow axially toward said discharge end through the spaces defined between said circumferentially spaced radial jets.

10. A combustion unit comprising an annular wall shaped to define a discharge opening at its one end, a head which closes the other end, said wall being provided with rings of circumferentially spaced openings, the several rings of openings being spaced axially from each other and the ring of openings nearest the head being spaced from the head to form an initial mixing and ignition chamber adjacent said head to which primary combustion air is supplied by axial flow of air from the radial jets formed by the spaced openings next to said mixing and ignition chamber, and a fluid fuel nozzle in said head adapted to direct fuel in the form of a substantially hollow conical spray outward toward the wall of said mixing chamber with a small axial component of velocity, the air flowing axially into said mixing and ignition chamber picking up the fuel in such chamber, mixing with it and then carrying it axially through the spaces defined between said circumferentially spaced radial jets to said discharge opening.

11. A combustion unit comprising an annular wall shaped to define a discharge opening at one end, a head which closes the other end, said wall being provided with rings of circumferentially spaced openings, the several rings of openings being spaced axially from each other and the ring of openings nearest the head being spaced from the head to form an initial mixing and ignition chamber adjacent said head to which primary combustion air is supplied by axial flow of air from the radial jets formed by the spaced openings next to said mixing and ignition chamber, a fuel supply means adjacent the center of the head which directs fuel into said mixing and ignition chamber in the form of a substantially hollow conical spray at an angle to the direction of air flow therein whereby the fuel and air are mixed initially in said mixing and ignition chamber and then flow axially toward said discharge end through the spaces defined between said circumferentially spaced radial jets, and means for directing an envelope of air along the inner surface of said wall to prevent carbon from depositing thereon.

12. A combustion unit comprising an annular wall shaped to define a discharge opening at one end, a head which closes the other end, said wall being provided with rings of circumferentially spaced openings, the several rings of openings being spaced axially from each other and the ring of openings nearest the head being spaced from the head to form an initial mixing and ignition chamber adjacent said head to which primary combustion air is supplied by axial flow of air from the radial jets formed by the spaced openings next to said mixing and ignition chamber, a fuel supply means adjacent the center of the head which directs fuel into said mixing and ignition chamber in the form of a substantially hollow conical spray at an angle to the direction of air flow therein whereby the fuel and air are mixed initially in said mixing and ignition chamber and then flow axially toward said discharge end through the spaces defined between said circumferentially spaced radial jets, and means for directing an envelope of air along the inner surfaces of said wall and head to prevent carbon from depositing thereon.

13. A combustion unit comprising spaced coaxial tubular inner and outer walls which define a combustion chamber and an annular air chamber surrounding the combustion chamber, an end head at one end of the inner wall, the other end being shaped to define a discharge opening, said inner wall being provided with rows of spaced openings which terminate short of said end head whereby there is defined in the vicinity of such head an initial mixing and ignition chamber, axially extending baffles in said annular air chamber for directing air flow in the chamber, said baffles being provided with spaced openings for flow of air, means for supplying air to said air chamber at one end of the chamber, and nozzle means for supplying fuel to said mixing and ignition chamber having an angle of discharge such that the sprayed fuel is confined to said initial mixing and ignition chamber.

14. A combustion unit comprising an annular wall shaped to define a discharge opening at one end, a head which closes the other end, said wall being provided with rings of circumferentially spaced openings, the several rings of openings being spaced axially from each other, and the ring nearest the head being spaced from the head a distance of the order of .7 the diameter of the wall to form an initial mixing and ignition chamber, means for supplying air uniformly through said rings of openings to the space within said wall, means for supplying fuel to said mixing and ignition chamber, and means for directing an envelope of air along the inner surfaces of said wall and head to prevent carbon from depositing thereon.

15. A combustion unit comprising an annular wall shaped to define a discharge opening at one end, a head which closes the other end, said wall being provided with rings of circumferentially spaced openings, the several rings of openings being spaced axially from each other, and walls defining slots between the openings for directing an envelope of air along the inner surface of said first-named wall to prevent carbon deposits from forming thereon.

16. A combustion unit comprising an annular wall shaped to define a discharge opening at one end, a head which closes the other end, said wall being provided with rings of circumferentially spaced openings, the several rings of openings being spaced axially from each other, and the ring nearest the head being spaced from the head a distance of the order of .7 the diameter of the wall to form an initial mixing and ignition chamber, means for supplying air through said rings of openings to the space within said wall, and means for supplying fuel in a radial direction through one or more of the holes of the ring of holes adjacent to such chamber whereby it will be picked up by rearward flow of air and carried rearwardly into said initial mixing and ignition chamber.

17. A liner for use in a combustor having a fluid fuel spraying nozzle adapted to discharge fuel particles with a spray pattern in the form of a substantially hollow cone of a known vertex angle, comprising a substantially cylindrical wall defining an opening for the discharge of hot products of combustion at one end and having a head member closing the other end, the head end of the liner being provided with an opening for introducing fuel, the liner wall having a plurality of straight longitudinal rows of air inlet openings each of a diameter of the order of one-tenth the mean inner diameter of the liner, corresponding holes in each row being circumferentially spaced at intervals of the order of one-seventh the circumference of the liner and lying in a common plane transverse to the axis of the liner, the plane of the first circumferential row being spaced from the head end at a location beyond the intersection of the fuel spray cone with the inner surface of the liner, the last circumferential row being spaced axially from the first row a distance of the order of one and one-half to two times said diameter of the liner, and the axial spacing of the holes center-to-center being of the order of one-sixth said diameter of the liner.

18. A liner for use in a fluid fuel combustor comprising a substantially cylindrical wall defining an opening for the discharge of hot products of combustion at one end and having a head member closing the other end, the head end of the liner having a portion defining an opening adapted to receive means for introducing fluid fuel with a spray pattern in the form of a substantially hollow cone coaxial with the liner and having a vertex angle of at least 80 degrees, the wall having a plurality of straight longitudinal rows of air inlet openings each of a diameter of the order of one-tenth the mean inner diameter of the liner, corresponding holes in each row being circumferentially spaced at intervals of the order of one-seventh the circumference of the liner and lying in a common plane transverse to the axis of the liner, the first circumferential row being spaced from the head end a distance of the order of seven-tenths said diameter of the liner, the last circumferential row being spaced from the first row a distance of the order of one and one-half to two times said diameter of the liner, and the axial spacing of the holes center-to-center being of the order of one-sixth said diameter of the liner.

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