March 14, 1961 R. B. SCHIEFER **2,974,485**

COMBUSTOR FOR FLUID FUELS

Filed June 2, 1958

FIG. 1.

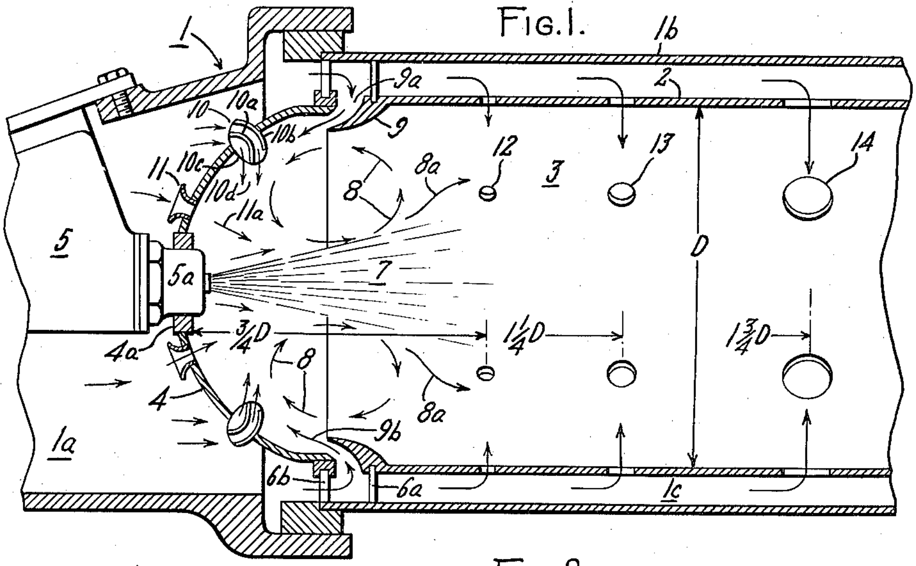


FIG. 2.

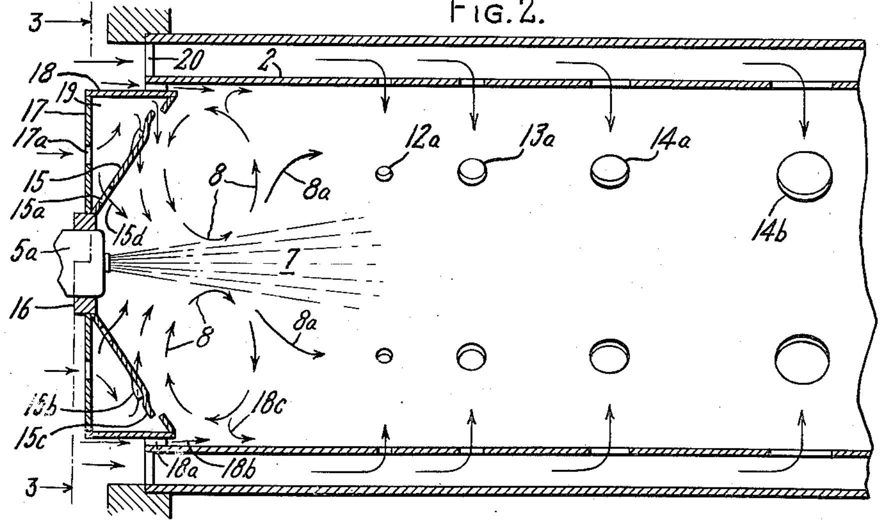


FIG. 3.

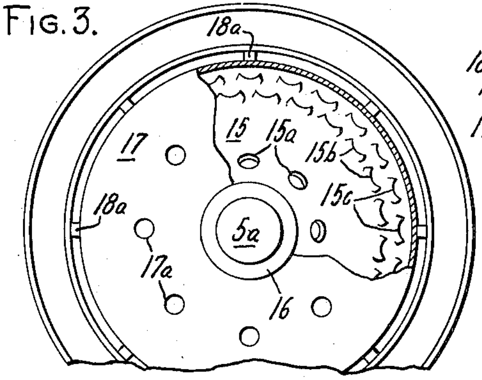
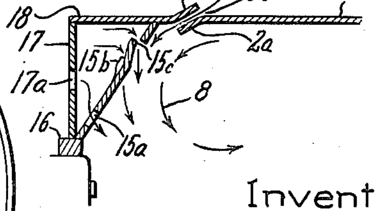


FIG. 4.



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COMBUSTOR FOR FLUID FUELS

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4 Claims. (Cl. 60—39.65)

This invention relates to combustion apparatus, particularly to an improved combustor for fluid fuels as may be used in gas turbine powerplants, rocket engines, jet engines for aircraft, and similar apparatus.

Difficulty has been encountered in applying the so-called "Nerad type combustor," described in United States Patent 2,601,000, issued June 17, 1952 and assigned to the same assignee as the present application, to the burning of heavy residual fuel oils, such as those known to the trade as "Bunker C." These are extremely viscous hydrocarbons, so thick as to be solid at temperatures below about 30° F. Because of the low cost, it is of substantial economic importance to the gas turbine user to be able to burn such fuel. Special air-atomizing type nozzles have been developed for this purpose, one of which is shown in the patent to Neugebauer et al.—2,801,134, issued July 30, 1957 and assigned to the same assignee as the present application.

Specifically, certain Nerad type combustors, equipped with an air-atomizing nozzle of the type described for burning Bunker C oils, have been found to produce quantities of smoke which would render a gas turbine powerplant unacceptable in railway locomotive service, or in stationary plants in residential areas. The incomplete combustion of course may increase troubles due to carbon deposition in the combustion chamber and on the stationary nozzles of the turbine, in the bucket passages, etc.

In studying this smoke problem, I conceived the basic difficulty to to be that the Nerad combustor introduces too much cold air into the fuel-air mixing and primary combustion zone, this large flow into the closed end of the combustion space being necessary in order to establish the strong central reverse flow toward the fuel nozzle, so as to create the double opposed vortex flow referred to as the "tore" in the above-mentioned Nerad patent. Because of the difficulty of getting the heavy residual fuel particles to mix with the combustion air and begin burning, it is particularly important to have a strong tore formed in the primary combustion zone. Introducing more air for this purpose in the manner of the Nerad invention increases the problems due to unburned fuel particles resulting from burning particles being "quenched" by the strong tore-forming air jets.

The problem is still further complicated by the fact that the significant quantity of air employed in the air atomizing type fuel nozzle to spray the heavy residual fuel oil produces high axial velocity components down the central core of the combustion space, which velocities are in opposition to the reverse circulation which the jets of combustion air are intended to create. Thus, the air-atomizing nozzle produces a spray which tends to oppose the basic flow pattern required in the primary mixing and ignition zone for successful operation of the Nerad combustor.

I have found that in trying the use an air-atomizing type nozzle for residual fuels in a conventional Nerad combustor, an over-rich fuel-air mixture tends to accumulate in the closed or "dome end" of the combustion space. Particles of unburned or partly burned fuel from this zone tend to migrate along the side walls of the combustion chamber liner, apparently carried by the film of cooling air which is ordinarily provided in the Nerad combustor to shield the cool metal surfaces from contact with unburned fuel. These particles may traverse this cooling air film without ever being drawn into the combustion zone; and of course they show up as smoke.

Accordingly, the principal object of the present invention is to provide an improved fluid fuel combustor which introduces smaller quantities of air into the primary mixing and combustion zone, and in such a manner as to cooperate with the axial velocities created by the fuel nozzle to produce a strong toroidal circulation to insure effective ignition and complete combustion, the flow of combustion air into the primary zone being arranged to avoid quenching of the burning fuel particles.

A further object is to provide an improved fuel-air mixing arrangement for a fluid fuel combustor in which the primary combustion flow pattern completely fills the closed end of the combustion space, so as to effect a larger ignition zone, higher temperatures in the primary combustion zone, and lower "through-flow velocities," so the fuel particles tend to remain for a longer time in the primary mixing and ignition zone.

Another object is to provide a combustor of the type described in which the flow into the closed end of the combustion space which comprises the primary mixing and ignition air is more definitely separated from the side-wall air jets which provide the secondary combustion air and the cooling and dilution air flow, so that the flow for each may be more clearly determined and the respective quantities and velocities better controlled.

Other objects and advantages will become apparent from the following description taken in connection with the accompanying drawings, in which

Fig. 1 is a longitudinal sectional view of a fluid fuel combustor in accordance with the invention;

Fig. 2 is a longitudinal section of a modified combustor;

Fig. 3 is an end view of the end dome of Fig. 2, taken on the plane 3—3; and

Fig. 4 is a partial sectional view of a detailed modification of the end dome of Fig. 2.

Generally stated, the invention is practiced by providing a combustor end dome structure having nozzle means for injecting a precisely controlled amount of air, both to supply the quantity of oxygen required for best ignition characteristics and to set up a predetermined flow pattern which will cooperate with the jet from the fuel nozzle to produce a strong reverse flow or "toroidal" recirculation completely filling the primary mixing zone, to insure a longer time of retention of the fuel particles in the mixing and ignition zone, the secondary air inlets in the side wall of the combustor liner being of carefully coordinated size and location so as to furnish just the right quantity of additional air required to carry out the combustion process effectively, without tending to quench the burning fuel particles or disrupt the toroidal flow in the mixing zone.

Referring now more specifically to the drawings, it will be seen that the invention is illustrated as applied to a gas turbine combustor comprising an outer housing identified generally at 1 defining an air inlet passage 1*a* and having a cylindrical portion 1*b* surrounding and spaced from a cylindrical liner 2 which forms the side walls of the combustion space 3. It will be apparent that the annular passage 1*c* forms a cooling and air supply passage surrounding the liner 2. The inlet or "closed" end of the combustion space is defined by an end dome or closure identified 4. The fuel is injected by a suitable fuel spray nozzle **5**, which may be of the type described by the above-identified Neugebauer et al. Patent 2,801,134 when the fuel is a heavy residual type oil.

While such mechanical details are not necessary to an understanding of the present invention, the liner is shown as supported from the cylindrical outer housing **1***b* by a plurality of radially extending dowels or struts **6***a*. Similarly, the end dome **4** is supported by radial dowels or struts **6***b*, while the central portion of the end dome defines a reinforcing ring **4***a* having a central opening fitting the end portion **5***a* of the fuel nozzle **5**.

The fuel nozzle **5** is of a type adapted to project a fuel-air spray pattern in the form of a solid, rather than hollow, conical spray pattern, shown at **7**. It is significant to note that the vertex angle of this spray pattern is shown in Fig. 1 as being on the order of 20°, but may be up to a maximum of about 60°. It is important to note that the fuel nozzle **5** is of a type which employs air or other auxiliary fluid as an atomizing agent to break up the viscous fuel oil into a fine spray, and that the quantity of this auxiliary fluid and the vertex angle of the spray pattern is such that the fuel pattern **7** has very high axial velocity components, the importance of which will be noted more particularly hereinafter. As in the Nerad type combustor, the end dome **4** and the extreme upstream end of the cylindrical liner **2** cooperate to define a primary mixing and ignition zone, while the succeeding downstream portions of the liner **2** define the secondary combustion zone and a cooling and dilution zone. The location and extent of these respective combustion zones will be noted later.

In accordance with the present invention, the end closure member **4** and the extreme upstream end portion of the liner **2** define a plurality of jet-forming means for injecting the primary mixing and ignition air into the combustion space in carefully controlled amounts and directions so as to produce the characteristic double opposed toroidal flow path or "smoke ring vortex" represented by the arrows **8** in Fig. 1. The formation of this smoke ring vortex or "tore" goes to the very essence of the present invention; and it will be seen that the direction of rotation of this tore is in the reverse direction as compared with the tore of the Nerad combustor of Patent 2,601,000.

The primary air inlet nozzle means comprise an annular nozzle identified generally at **9**, radial jet-forming nozzle means **10**, and generally axial jet-forming means **11**. The secondary air-admitting nozzle means comprise a plurality of rows of circumferentially spaced ports identified **12**, **13**, and **14**.

Referring now more specifically to the primary jet-forming means, the annular nozzle **9** is formed by an inwardly and axially projecting portion formed integral with or secured to the extreme upstream end of liner **2**. This liner upstream end portion is supported in carefully spaced relation to the downstream end of the dome **4** by the support means **6***a*, **6***b* so as to define a uniform annular nozzle identified **9***a*. It will be seen that this nozzle directs a strong annular jet of fluid in an upstream direction as indicated by arrows **9***b*. This annular jet tends to flow upstream and radially inwardly along the inner surface of the dome **4**. It is to be particularly noted that this annular jet **9***b* is generally tangential to, and in the same direction as, the toroidal flow path **8**.

The radial jet-producing nozzles **10** comprise a circumferential row of ports having curved vanes designated **10***a*, **10***b*. These vanes may be supported from the end dome by a plate member identified **10***c*. This may be a single support plate disposed across the middle of the air inlet opening in dome **4**, or the opening may be square or rectangular in shape, with an end plate **10***c* at either side of the opening. Other mechanical arrangements will be obvious to those skilled in the art, and it is to be understood that the structure shown in Fig. 1 is merely representative of any suitable nozzle means for producing strong jets having a discharge velocity component generally radial to the axis of the liner **2**, these radial jets being identified by the arrows **10***d*. Here again it will be observed that these radial jets are generally tangential to, and in the same direction as, the toroidal flow **8**.

The third primary jet-forming means associated with the end dome **4** comprise the circumferential row of flaring inlet nozzles identified **11**. It will be seen that these project jets identified by the arrows **11***a* in a generally axial direction and tangent also to the toroidal flow path **8**. Flaring inlet nozzles of this type are described more specifically in the patent to K. D. McMahan, No. 2,510,645, issued June 6, 1950, and assigned to the same assignee as the present application.

It will of course be understood that other mechanical structures may be employed for the three different types of primary jet-forming nozzles shown in Fig. 1. For instance, the annular nozzle **9***a* could be formed by structure such as that shown in the patent to Garber—2,555,965, issued June 5, 1951, or in the patent to Blatz—2,581,999, issued January 8, 1952, both assigned to the same assignee as the present application. Also, the vane-type nozzle **10** could be replaced by the flaring inlet type nozzle **11**. Or, the nozzle **11** might be replaced by a simple circular hole in the end dome, as noted more particularly in connection with Fig. 2.

It will be seen that the important criterion is that all the jet-forming means associated with the initial mixing and ignition zone are of types capable of injecting strong jets of air in precisely controlled quantities and with a carefully controlled direction so that all such jets are generally tangent to the desired toroidal flow path **8**. It will be obvious from Fig. 1 that the jets **9***b*, **10***d*, and **11***a* will cooperate to produce a strong reverse circulation represented by the tore **8**. The creation of such a strong and stable tore is particularly important in a combustor burning viscous residual fuels like Bunker C oil. This tore insures retention of the fuel particles in the primary mixing and ignition zone for a sufficient length of time to bring them to ignition temperature and into contact with oxygen and hot gases adequate to effect ignition and initial combustion of the fuel particle. Failure to so retain the fuel particle in this initial mixing zone for a sufficient period of time is a prime cause of incomplete combustion and smoke. This toroidal flow path is also of great importance with respect to the problem of "blow-out," which becomes particularly important at low load. With the primary air jet-forming means disclosed herein, a strong stable tore **8** is formed and maintained over the complete range of operation from maximum capacity down to flow rates on the order of 5% of the maximum fuel flow rate.

It is important to note in Fig. 1 that the kinetic energy of the fuel particles and the air or other fluid employed in nozzle **5** to effect atomization of the fuel oil has, by reason of the high axial velocity component, a strong tendency to augment the tore-forming action of the air inlet nozzle means **9**, **10**, **11**. Thus the fuel injection means cooperates with the primary air injection means in forming the strong, stable tore **8**.

The disposition and size of the secondary air inlet ports **12**, **13**, **14** may take several forms, but certain fundamental principles must be observed. It is most important that the initial row of ports **12** should not be so close to the initial mixing zone as to produce jets which would interfere with the indicated rotation of the smoke ring vortex **8**. Specifically, it is believed that this first row of secondary air nozzles should be a minimum distance from the fuel nozzle **5***a* on the order of ¾ the diameter of the liner, identified D in Fig. 1. It will be seen from the drawing that this places the nozzles **12** a sufficient distance downstream from the tore **8** that there will be little, if any, tendency for the jets from the nozzles **12** to counteract the desired direction of rotation of the tore. In addition, it is to be noted that the diameter of the initial ports **12** is sufficiently small as to produce jets long enough to produce adequate mixing with the burning gases, but not strong enough to produce any significant reverse circulation of this secondary air to the left into the area occupied by the tore **8**. In other words, the ports **12** are merely of a size to provide the additional air required for the combustion process without having any significant tendency to set up a characteristic flow pattern of their own, or to interfere with the flow pattern **8**. Specifically, the diameter of the first row of holes **12** may be $\frac{1}{20}$ of the liner diameter D.

The second row of inlet ports **13** is spaced somewhat downstream from the ports **12**, and as shown in the drawing they are approximately at a distance $1\frac{1}{4}$D from the fuel nozzle. Because of their greater distance from the primary mixing and ignition zone, these ports may be of larger diameter without producing any deleterious effects on the tore **8**. Specifically, these ports may be on the order of $\frac{1}{15}$, for example from about $\frac{1}{13}$ to $\frac{1}{16}$ the diameter D.

Likewise, the third row of ports **14** may be spaced on the order of $1\frac{3}{4}$D from the fuel nozzle, and may be on the order of $\frac{1}{10}$D in diameter.

As shown in Fig. 1, there are six holes in each of the circumferential rows **12**, **13**, **14**, but it is to be understood that a different number may be used, specifically the number may range from 6 to perhaps 10. A normal number would be about 8.

The operation of the combustion chamber shown in Fig. 1 will be fairly obvious from the above description. A suitable compressor (not shown) supplies air at a pressure which may be on the order of 90 p.s.i.a. through the air supply passage **1***a* and to the annular air supply space **1***c*. The annular nozzle **9**, the vaned nozzles **10**, and the flared entry nozzles **11** produce strong jets of primary air to establish the tore **8**, aided by the kinetic energy of the fuel and air ejected from nozzle **5**. The strong vortex flow **8** exerts a "tearing" effect on the surface of the spray pattern **7** tending to break it up and initiate the mixing and ignition process. The strong vortex **8** retains the fuel particles in this initial mixing zone for an interval of time sufficient to initiate combustion. The spark plug or other igniter device has been omitted from the drawings because not material to an understanding of the present invention. As primary air continues to enter through the nozzles **9**, **10**, **11**, a corresponding amount of hot gasses leave the vortex **8** and progress axially down the combustion space, as indicated by the arrows **8***a*. The secondary inlets **12** add air in quantities required to keep the combustion going. The larger nozzles **13** add still more air for combustion; and the still larger ports **14** admit air in sufficient quantities to cool the mixture to the temperature desired at the turbine inlet. It will be appreciated that there may be additional circumferential rows of ports, of perhaps even larger diameter, downstream from the ports **14**, depending on the final temperature desired. Ordinarily, it is believed that about three or four circumferential rows of secondary inlet ports will be adequate.

It is also to be noted that in Fig. 1 the cooling louvers for providing a film of cooling and insulating air on the inner surfaces of the liner **2** have been omitted, for the sake of clarity. It will be understood from the Nerad Patent 2,601,000 that it is advisable, if not essential, to provide the liner wall **2** with any one of many possible patterns of louvers for admitting a thin film of cooling and insulating air to the inner surface of the liner.

While Fig. 1 illustrates the basic concept and method of operation of the invention, the actual mechanical construction may take many other forms. Specifically, the end dome **4** of Fig. 1 may be replaced by a somewhat simpler and cheaper end closure, as shown for instance in Fig. 2. Here it will be seen that the end closure comprises a generally conical member **15** having an inner periphery connected to a reinforcing ring **16** engaging the nozzle **5***a*, and surrounded by a shroud comprising a radially extending annular disk member **17** and a cylindrical peripheral member **18**. Fig. 3 shows the plan views of the shroud end disk **17** and of the louvered conical member **15**. It will be seen that end disk **17** has a circumferential row of inlet ports **17***a* for admitting air in metered quantities to the air supply chamber **19**. The peripheral cylindrical member **18** may be supported from the adjacent end of liner **2** by a plurality of spacer members **18***a*. In turn, the upstream end of liner **2** may be supported by a plurality of dowel pins or support struts **20**.

The conical member **15** is provided with a central circumferential row of air inlet ports identified **15***a* and two circumferential rows of louvers identified **15***b*, **15***c*. It will be apparent in Fig. 3 that these louvers are in staggered arrangement so that each one in the inner row **15***b* overlaps the gap between adjacent louvers in the outer row **15***c*. It will be apparent from Fig. 2 how these louvers are stamped from the conical member so as to provide a nozzle which projects a jet of air in a generally radial direction into the combustion space in a direction generally tangent to the tore **8**. It will be equally obvious how the plain holes **15***a* provide jets identified **15***d* in Fig. 2 which perform the functions of the jets **11***a* of Fig. 1. In this connection it will be noted that the air supply ports **17***a* are so located in the end disk **17** so as not to project a strong jet of fluid directly impinging on either the louvers **15***b*, **15***c*, or the row of ports **15***a*. Thus the air entering through the metering ports **17***a* diffuses so as to fill the chamber **19** at a substantially uniform pressure and random velocity so that there is no strong "velocity of approach" to either the ports **15***a* or the louvers **15***b*, **15***c*. This provides uniform supply to the jet-producing nozzles so that they form stable jets of readily predictable direction.

A significant difference between the fluid flow shown in Fig. 2 and that of Fig. 1 lies in the fact that the outer cylindrical end dome member **18** is spaced radially from the liner **2** by means of the spacers **18***a* so as to define a very narrow annular nozzle projecting a thin annular jet of cooling and insulating fluid along the inner surface of liner **2**, as represented by the arrows **18***b*. It will be seen that, unlike the primary jets associated with the end closure member, this annular jet **18** does have some tendency to counteract the rotation of the tore **8**. It should be noted, however, that the annular jet **18***b* is of very small radial thickness so that the kinetic energy thereof is not great enough to seriously disrupt the toroidal flow **8**. It will be seen by comparison that the annular nozzle **9** in Fig. 1 provides an annular jet of substantially greater radial thickness. The small flow of cooling and insulating air indicated by the annular jet **18***b* has some slight tendency to cause hot gases rotating in the smoke ring vortex **8** to be "pulled away" and carried along with the jet **18***d*, as indicated by the arrow **18***c*.

As in Fig. 1, the liner of Fig. 2 is provided with a plurality of circumferential rows of secondary air inlet ports, identified **12***a*, **13***a*, **14***a*. Fig. 2 shows the circumferential row of ports **13***a* closer to the initial row **12***a* than was the case in Fig. 1. Likewise, the row of ports **14***a* is somewhat closer to the fuel nozzle than the row **14** in Fig. 1. Fig. 2 shows an additional row of still larger ports identified **14***b*.

The mechanical details of liners and end closure members incorporating the invention may obviously take many forms, another of which is shown in Fig. 4. The end closure is generally similar to that shown in Fig. 2 having an end disk **17** and a circumferential member **18**, with air supply ports **17***a* and jet-forming nozzles **15***a* and louvers **15***b*, **15***c*. The difference is that the downstream end of member **18** has a flaring portion **18***d* which cooperates with an adjacent inwardly flaring portion **2***a* of the liner **2**, defining an annular clearance space which serves as the primary nozzle **9***c*, performing the same function as the nozzle **9***a* of Fig. 1.

Numerous other modifications and substitutions of mechanical equivalents will occur to those acquainted with the combustor art; and it is of course intended to cover by the appended claims 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. In a fluid fuel combustor having a generally cylindrical liner forming the side walls of an elongated combustion space with an open discharge end, an end closure member defining the fuel inlet end of the combustion space, and walls surrounding and spaced from the liner to form passages for supplying combustion air uniformly under pressure to the combustion space, the combination of fuel injection means disposed to spray fuel particles into the primary mixing and ignition zone adjacent the end closure with a high velocity spray pattern in the form of a cone having a vertex angle not exceeding about 60° and with its axis generally coincident with the axis of the liner, primary nozzle means comprising directed jet-forming air metering means disposed on the wall of said end closure forming varying angles of incidence with the liner axis and disposed to receive air from said supply passages and to project strong primary jets of air into said mixing zone in a direction generally tangent to a double-opposed-toroidal flow path created by said primary jets and substantially filling the primary mixing zone adjacent the end closure member, said toroidal flow being also generally tangent to and in the same general direction as said conical fuel spray pattern whereby the velocity energy of the fuel spray augments the tore-forming action of said primary nozzle means, and secondary nozzle means in the liner wall for injecting additional secondary air to support the combustion process in a secondary zone downstream from the primary mixing zone, said secondary nozzle means being disposed at a transverse plane located a distance at least equal to ¾ of the liner diameter D downstream from the fuel nozzle means, said secondary nozzle means producing jets of a size and direction to insure good mixing of secondary air with the burning fuel in said secondary zone but substantially without tending to quench the flame in the primary mixing and ignition zone and substantially without impinging upon said double-opposed-toroidal flow in the primary mixing zone.

2. A fluid-fuel combustor in accordance with claim 1 having additional secondary jet producing means comprising a circumferential row of on the order of eight secondary air inlet ports equally spaced around the liner and being of a diameter on the order of $\frac{1}{15}$ the liner diameter D, said circumferential row of secondary ports being spaced on the order of 1¼D from the inlet end of the combustion space.

3. A fluid fuel combustor in accordance with claim 2 and including third secondary air jet means comprising an additional circumferential row of air inlet openings each being on the order of $\frac{1}{10}$D in diameter and spaced on the order of 1¾D from the inlet end of the combustion space.

4. In a fluid fuel combustor having a substantially cylindrical liner forming the side walls of an elongated combustion space with an open discharge end, an end closure member defining the fuel inlet end of the combustion space, and walls surrounding and spaced from the liner to form passages for supplying combustion air under pressure to the combustion space, the combination of fuel injection means disposed to spray fuel particles into the primary mixing and ignition zone adjacent the end dome with a high velocity fuel spray pattern in the form of a cone having a vertex angle not exceeding 60° and with its axis substantially coincident with the axis of the liner, primary nozzle means comprising directed jet-forming air metering means disposed on the wall of said end dome forming varying angles of incidence with the liner axis and disposed to receive air from said supply passages and to produce strong primary jets of air into said mixing zone in directions generally tangent to a double-opposed-toroidal flow created by said jets and substantially filling said primary mixing zone, said toroidal flow being also generally tangent to and in the same general direction as said conical fuel spray pattern whereby the velocity energy of the fuel spray augments the tore-forming action of said primary air jets, and secondary nozzle means in the liner wall for injecting additional secondary air to support the combustion process in a secondary zone downstream from the primary zone, said secondary nozzle means including a first circumferential row of on the order of eight equally spaced secondary air inlet ports disposed at a common transverse plane located at a distance on the order of ¾ of the liner diameter D downstream from the fuel nozzle means, each of said first row of secondary ports being of a diameter on the order of $\frac{1}{20}$D and disposed to project a jet of air into the combustion space in a direction to insure good mixing with the burning fuel in said secondary zone but substantially without tending to quench the flame, and at least a second circumferential row of secondary air inlet ports in said liner wall and located downstream from and being of a larger diameter than said first row of secondary ports, whereby secondary combustion air and cooling and dilution air are admitted to the combustion space in progressively larger quantities in the secondary zone as the burning fuel passes toward the open end of the liner, without impinging upon the toroidal flow in the primary mixing zone.

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