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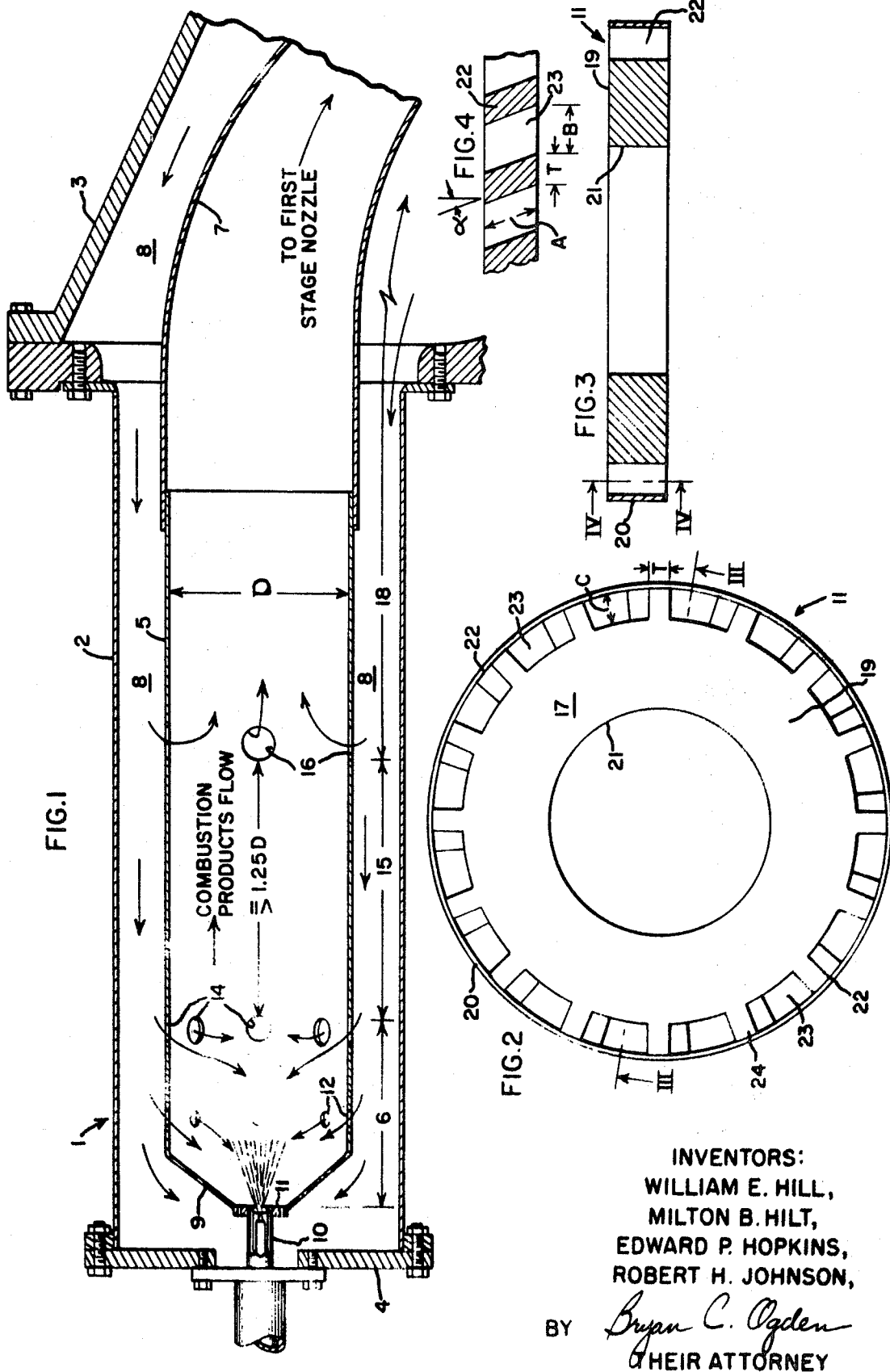
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3,608,309

LOW SMOKE COMBUSTION SYSTEM

Filed May 21, 1970

3 Sheets-Sheet 1



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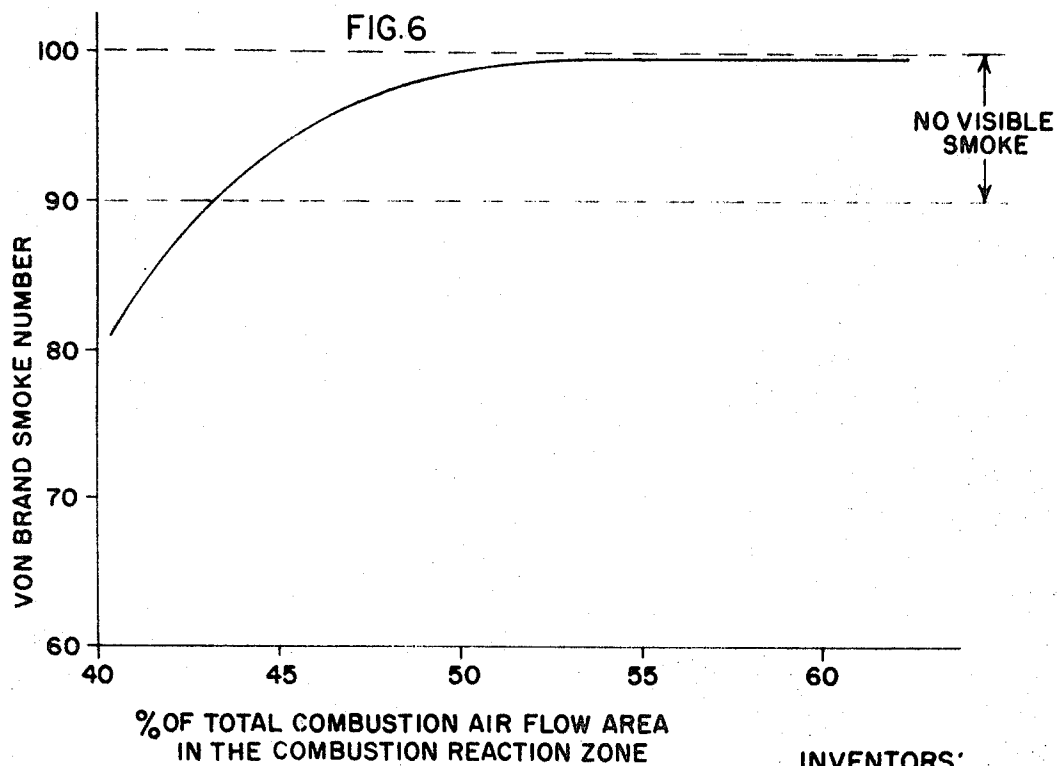
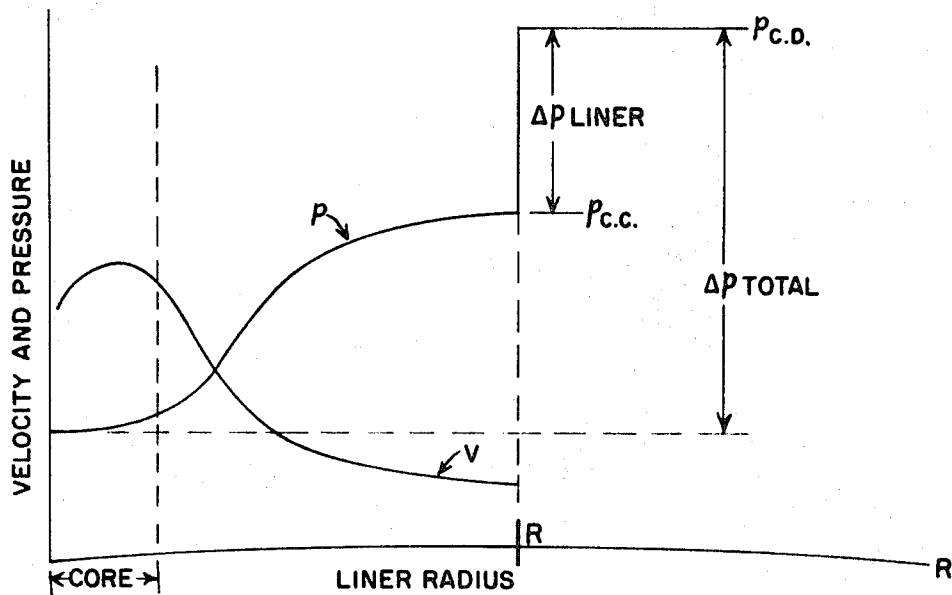
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3 Sheets-Sheet 2

FIG. 5



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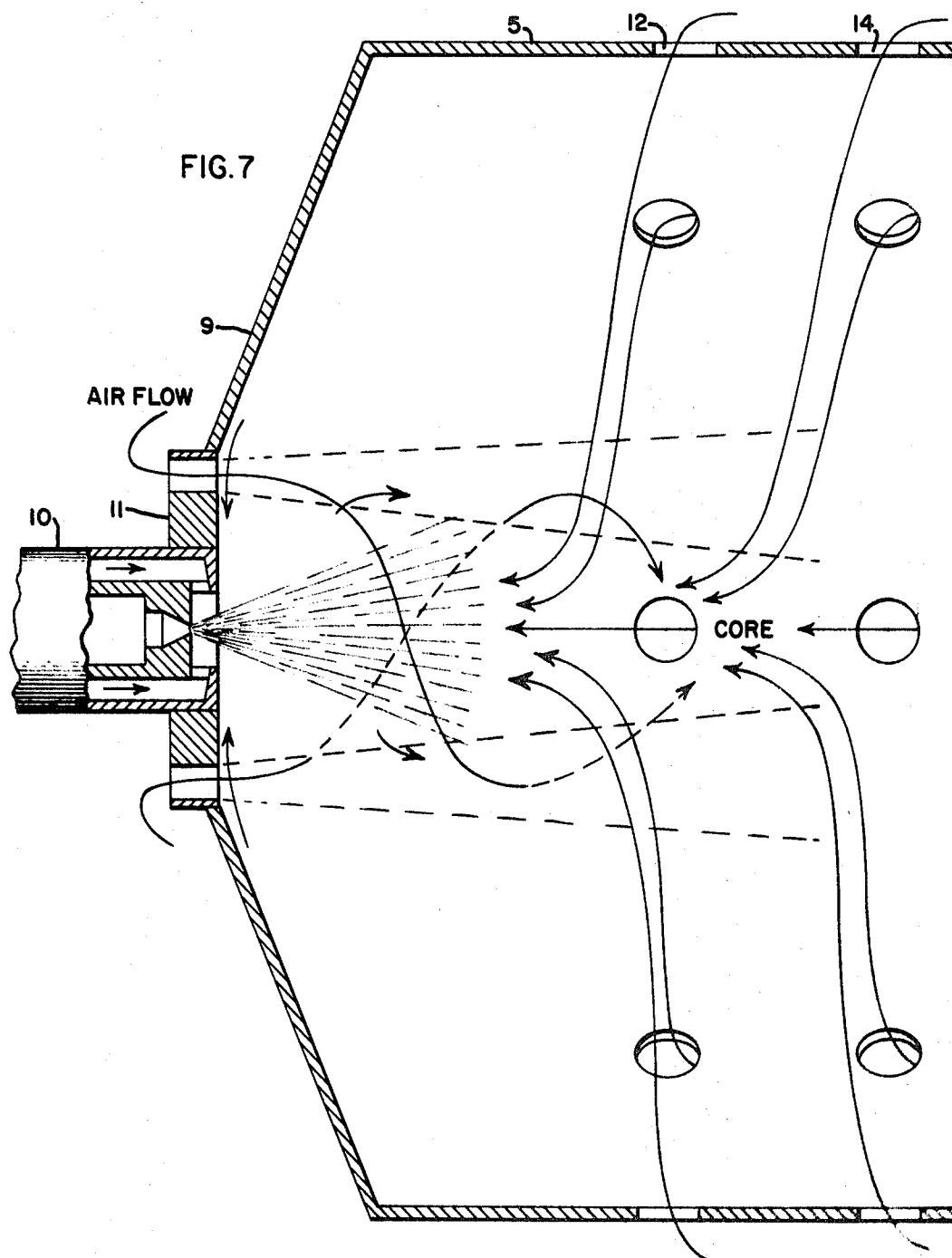
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LOW SMOKE COMBUSTION SYSTEM

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3 Sheets-Sheet 3



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1

3,608,309

LOW SMOKE COMBUSTION SYSTEM

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U.S. Cl. 60—39.65

4 Claims

ABSTRACT OF THE DISCLOSURE

A combustion system for a gas turbine which produces a smokeless exhaust stack is constructed such that the combustion reaction zone will operate with a lean fuel-air mixture. The lean combustion zone is stabilized by a vortex generated around the centerline of the liner, creating gas flow patterns that cause strong back flow in the combustion reaction zone. This vortical flow also sweeps out the fuel-rich pockets, thus facilitating complete combustion. A thermal soaking region with no air holes in the liner is provided downstream of the last row of combustion air holes having an axial length of at least 1.25D wherein that soot which may be formed in the combustion process is consumed by a very fast chemical reaction. The temperature throughout the soaking region is maintained sufficiently high to induce such a reaction. Axially downstream of this region, tempering air is added to the combustion products such that they are cooled sufficiently in order to enter the first stage nozzle at the desired temperature.

BACKGROUND OF THE INVENTION

The present invention relates to gas turbine combustion systems of the can type, and more particularly, to a combustion system which is smokeless throughout its operating range.

A negative result of today's mechanized society is the ever-increasing problem of air pollution. Many of today's fuel-burning machines exhaust pollutants into the air causing a variety of harmful effects to nature's balance. The industrial gas turbine is no exception and efforts have been made to reduce the smoke production in such gas turbines in order to limit the amount of this pollutant exhausted into the atmosphere.

The operation of a gas turbine combustor and the combustion process is complicated; however, it is known that the amount of smoke emitted from gas turbines depends upon two criteria. One criteria for the amount of smoke or soot produced depends upon the amount of incomplete combustion and fuel cracking in the rich combustion reaction zone or region of the combustor. The second criteria, which heretofore has not been considered, is the amount of this soot that is consumed, that is, eliminated, in high temperature chemical reactions subsequent to the combustion in the reaction zone. These two criteria present themselves such that an ideal combustion system would keep the soot production to a minimum and the subsequent soot consumption at a maximum.

The gas turbine exhaust is relatively free of air pollutants because the combustion process is carried out with air greatly in excess of a stoichiometric mixture and is comparatively complete. In an ideal hot oxidizing atmosphere, using a hydrocarbon fuel combusted with air, the following generalized formula presents itself for perfect and complete combustion: $C_nH_m + O_2 \rightarrow CO_2 + H_2O$, yielding a smokeless exhaust stack. In the other extreme of a hot inert atmosphere, where there is incomplete mixing of the hydrocarbon with air, the following chemical reaction (thermal cracking) takes place: $C_nH_m \rightarrow C + C_{(n-1)}H_m$, yielding carbon atoms and subsequently polyacetylene-like compounds which coagulate to form soot particles on

2

the order of one micron in diameter. Most combustors operate in a range between the two above cited limiting reactions. The soot particles formed in a less than perfect combustor are generated in fuel-rich regions that may exist in the combustion reaction zone and they subsequently grow in regions that are not conducive to further oxidation in the post reaction zone. To oxidize the soot particles in the post reaction zone, the following reaction could occur: $C + 2O \rightarrow CO_2$ which is too slow to yield the desired result in the short residence time in a gas turbine combustor. If the temperature is high enough in the post reaction zone of the gas turbine combustion chamber, water vapor will dissociate as: $2H_2O \rightarrow H_2 + 2OH$, thus forming a pair of negative hydroxyl radicals. These highly reactive hydroxyl radicals then combine with the soot as in the following reaction: $C + 2OH \rightarrow CO_2 + H_2$ which is a sufficiently fast reaction for the time involved. It is this last reaction that consumes the soot in the present combustion system.

In the first instance, the rich fuel pockets should be eliminated in order to keep the soot production to a minimum. It is known to the prior art that by "leaning out" the combustion reaction zone, this may, to a certain extent, be accomplished. When leaning out the combustion reaction zone, the flame stability is decreased as the minimum fuel/air ratio is approached, thus indicating the necessity for providing means to maintain the flame stability.

It has been suggested in the prior art that by imparting a swirling motion to a portion of the incoming combustion air, the stability of the flame will be increased. We allow additional air to be added so as to further "lean out" the combustion reaction zone. Here, this vortex flow is also used to create a well mixed reactor by sweeping out the fuel rich pockets.

The problems of trying to reduce smoke associated with the prior art were essentially twofold. Firstly, additions were made to the gas turbine combustion system, such as additives in the fuel (for example, manganese) and cumbersome and complex "air scrubbers" which acted directly on the gas turbine exhaust. These additions to the combustion system usually represented both increased cost and lower performance characteristics. In the second instance, it was oftentimes felt that the added expense and complexity of such a combustion system did not warrant their use on a particular gas turbine, thereby simply allowing the smoke to exhaust into the air.

The smoke density in the gas turbine exhaust may be measured as the Von Brand reflective smoke number which is determined by drawing turbine exhaust gas at a specified rate of flow through a strip of filter paper moving at a fixed rate. The smoke trace produced on the filter paper is evaluated by measuring light reflectance using a photometer. The Von Brand smoke numbers range from 0 to 100 with 100 being the reflectance of a clean tape. A Von Brand smoke number of 90 and above is generally considered a clear exhaust. In the prior art, by using additives and "air scrubbers," it was possible to increase the Von Brand smoke number to the low 90's at high loads.

Also used in the prior art to reduce the smoke of a gas turbine were air swirlers or vortex nozzles. The air swirler was used alone to impart a swirling motion to the incoming combustion air such that many of the fuel-rich pockets would be eliminated, thus adding to complete combustion. The optimum design for one air swirler relating to smoke elimination is the subject of a separate patent application, Ser. No. 7,947, filed on Feb. 2, 1970 in the name of Edward P. Hopkins and assigned to the assignee of the present invention. It is the particular

design of the air swirler, which is described in the aforementioned patent application, together with the further subject matter to be described herein, which effectively eliminates smoke and increases the Von Brand smoke number well into the 90's. By leaning out the combustion reaction zone with a certain percentage of combustion air, imparting an optimum swirl, and then providing a post reaction zone where there are no air holes such that a thermal soaking region is formed, the maximum reduction of smoke in the exhaust stack can be realized.

Accordingly, the primary object of the present invention is to reduce the amount of smoke exhausted to the atmosphere.

Another object is to decrease the smoke production without a sacrifice in performance over the entire load range of a power generating gas turbine.

Still a further object as to improve combustion stability so as to extend the operating range of the system.

SUMMARY OF THE INVENTION

Briefly stated, the present invention is practiced in one form by providing a gas turbine combustion chamber with a lean combustion reaction zone which is stabilized by a vortex formed through an air swirler having 3 to 10% of the total combustor open area formed by blades of critical thickness and critical angle. Combustion air holes are provided in the liner which are then followed by an axially extending "thermal soaking" region of at least 1.25 times the diameter of the combustor liner in which only metal cooling air is provided. A set of large holes is then provided for the entry into the combustion liner of the final cooling or tempering air. It is the air swirler which provides the required flow and mixing capabilities together with a strong feedback in the combustion reaction zone that increases the combustion stability so that practically no soot is produced. The region with no air holes along the combustion liner provides the high temperature region (thermal soaking) where the soot particles that may have been produced in the combustion reaction zone are consumed in high temperature fast chemical reactions. A balance of the parameters making up the system is necessary in order to accomplish the objects of the invention.

BRIEF DESCRIPTION OF THE DRAWING

FIG. 1 is a view in section of a typical gas turbine combustion chamber showing the present invention.

FIG. 2 is a view of the face of the air swirler which is mounted around the fuel nozzle in the head end.

FIG. 3 is a view taken along lines IH—III of FIG. 2 and shows a sectional view of the air swirler.

FIG. 4 is a partial view of the swirler blades and slots taken along lines IV—IV of FIG. 3 and indicates some of the critical dimensions of the air swirler.

FIG. 5 is a graph showing the variation in velocity and pressure as the dimension outwardly from the liner centerline increases.

FIG. 6 is a graph showing a curve which indicates the change in Von Brand smoke number as the total flow area in the combustion reaction zone is varied.

FIG. 7 is a detailed view of the air swirler and fuel nozzle in the head end showing the general flow pattern.

DESCRIPTION OF THE PREFERRED EMBODIMENT

Referring now to FIG. 1, a typical combustion chamber for use in a gas turbine is generally indicated at 1. Combustion chamber 1 is of the type where the compressed air from the compressor (not shown) is directed in a reverse flow. The reverse flow of such a combustion chamber is well known in the art and provides the advantage of heating the compressed air before its use in the combustion processes.

Combustion chamber 1 is comprised of a generally cylindrical outer casing 2 to which is attached the casing 3. Casing 3 in turn connects with the turbine section (not

shown). The outer casing end cover 4 closes off the end of outer casing 2 opposite the casing 3 such that the volume within outer casing 2 is sealed from the atmosphere. Extending in a generally axial direction and generally coaxial with outer casing 2, is the combustor liner 5 having a diameter indicated as D. As is well known in the art, it is within the liner 5 at the head end or combustion reaction zone 6 where the combustion process takes place in an operating combustor for gas turbines. As the hot combustion products proceed through the cylindrical liner 5, they are tempered with diluting air. They then reach the transition liner 7 which directs the tempered combustion products to the first stage nozzle (not shown). An annular air space 8 surrounds the liners 5 and 7 in order to accommodate the flow of the compressed air.

Generally closing off the end of liner 5 toward the outer casing end cover 4 is the liner end cap 9 which accommodates the fuel nozzle generally indicated as 10. The liner end cap 9 is generally in the shape of a truncated cone, the top of which is for the accommodation therein of the fuel nozzle assembly 10. The air swirler assembly generally indicated as 11 in FIGS. 2 and 7 is attached to the cap 9 in the preferred embodiment but may also be attached to the fuel nozzle. The fuel nozzle assembly 10 may be any convenient type known to the art which can be accommodated in the head end of the liner 5 and particularly in the end cap 9. Fuel nozzle 10 is of the variety which is capable of atomizing hydrocarbon fuels, that is, those fuels which tend to create smoke in the gas turbine exhaust. The fuel nozzle 10 may be of the air atomizing type or pressure atomizing type, both operating equally well in this combustion system.

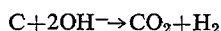
It is known in the art that the liners of combustion chambers are provided with spaced holes for the entry thereto of the air which supports the combustion and also cools and dilutes the products of combustion. We have found that by positioning these holes in a certain manner along the length of liner 5, the object of reducing the smoke in the gas turbine exhaust may be realized. It has also been found that the combustion process takes place in combustion reaction zone 6 which is defined approximately by an axial length which is equal to the diameter dimension (D). That is, within the axial length corresponding to the liner diameter (D), the fuel-combustion air mixture is burned, to either the point of complete combustion or if incomplete combustion, forming the soot particles. In the combustion reaction zone 6, there are positioned two rows of combustion air holes. Although two rows are shown, this is not to be taken as an upper or lower limit.

Referring to FIG. 6 in addition to FIG. 1, it will be seen that the curve in FIG. 6 indicates that as the percentage of combustion air flow area in the combustion reaction zone increases, so too does the Von Brand smoke number, and as previously mentioned, an increase in this smoke number indicates a decrease in the amount of smoke in the gas turbine exhaust. It is the first two rows of air holes in the liner 5, together with the open area of the air swirler 11, that constitutes the combustion air flow area in the combustion reaction zone 6. As will be described later, when referring to the details of air swirler 11, the open area of the air swirler 11 must be maintained at between 3–10% of the total air flow area, which is defined here as the combustion air flow area, plus the area of the downstream tempering holes plus the liner open area comprising the cooling louvers (not shown). As such, the rows of combustion air holes in the liner 5 located in the combustion reaction zone 6 should provide approximately 25–50% of the total air flow area into the liner 5. As indicated on FIG. 1, there are two rows of combustion air holes. A first row 12 is comprised of 8 holes circumferentially spaced about the liner 5, and have a hole diameter to liner diameter ratio of about .075. A second row 14 is again comprised of 8 holes circum-

5

ferentially spaced about liner 5 and have the aforementioned ratio on the order of .12. Rows 12 and 14 are axially within the 1D dimension, that is, they are within combustion reaction zone 6.

Following the row of holes 14 downstream (in relation to the flow of combustion products) in an axial direction, is the "thermal soaking" region of the liner 5. This is indicated as 15 on FIG. 1. The "thermal soaking" region 15 is closed in that there are no large circumferentially spaced holes along this axial length of liner; however, louvers or slits for metal cooling air are positioned throughout the length of liner 5, but are not shown for clarity. The louvers are utilized for cooling the liner 5 and the air which enters the louvers does not contribute to the combustion process to an important degree. The soaking region 15 must be at least 1.25D in axial length. It is in the region 15 where the "thermal soaking" of the combustion products takes place, that is, it is here where, if the temperature is high enough, the following chemical reactions will occur: $2H_2O \rightarrow H_2 + 2OH^-$ and



thereby consuming the soot particles of carbon and carbonaceous material which are produced by the incomplete combustion or thermal cracking in the reaction zone 6. The axial length of at least 1.25D is provided so that a sufficient time is allowed for these reactions to take place.

Positioned at the end of the thermal soaking region 15 are a plurality of circumferentially spaced tempering air holes 16. In FIG. 1, holes 16 are comprised of four circumferentially spaced holes having a hole diameter to liner diameter ratio of about .20. These dimensions are given by way of example only and should not be taken as an upper or lower limiting value. The actual size and number of tempering air holes 16 will depend upon the amount of tempering air to be added to the combustion products as they leave the soaking region 15. The tempering region of the liner 5 is indicated on FIG. 1 as 18 and extends generally from the tempering air holes 16 to the first stage nozzle. The purpose of the tempering air holes 16 is to allow a portion of the compressed air which is relatively cool as compared to the hot combustion products to temper the combustion products before the overall air-combustion product mixture enters the first stage nozzle. Tempering holes 16 are large enough to allow sufficient penetration of the cooler tempering air into the combustion products so that the desired first stage turbine inlet temperature is achieved.

Turning now to a detailed description of the air swirler 11, one example of which may be found in the aforementioned copending application of E. P. Hopkins (Ser. No. 7,947) reference will be made to FIGS. 1 through 4. It is air through swirler 11 which provides the necessary stabilizing effect to allow a "lean" combustion zone to be formed as well as the swirling air to sweep out the fuel-rich pockets in the combustion reaction zone 6.

Air swirler 11 is comprised of an annular body portion 17 which defines a centrally positioned hole 21 for the accommodation therein of the fuel nozzle assembly 10. The face side 19 of the body portion 17 is that side which looks directly into the cylindrical liner 5 and which faces the combustion process.

Spaced about the circumference of annular body portion 17 are a plurality of blade members 22. Blade members 22 may be formed in the body portion 17 by any suitable means such as by machining or casting. Surrounding the blade members 22 is an annular shroud band 20 which serves to provide an attachment member when the swirler 11 is secured to the end cap 9.

There are certain critical dimensions which must be maintained when constructing the blades 22. The first critical dimension is that of the slots 23 which are formed between adjacent blade members 22. The total flow area on a plane perpendicular to the axis of the slot should be from between 3 to 10% of the total air flow area into the

6

cylindrical liner 5. This slot area is established by having certain dimensional ratios fall within certain limits. The first such dimensional ratio is defined as the length of a slot 23 (indicated as the letter "A" on FIG. 4) to the width of the slot (indicated as "B" on FIG. 4). The ratio, that is, A/B, is such that it falls within a range of from 1.15 to 1.85; or the length is less than twice the slot width.

The blade thickness is critical at the trailing edge surface 24, and it should be noted that this thickness is substantial as compared to prior art air swirler blades and is on the order of from .4 to .8 times the swirler slot width B. The trailing edge surface 24 is provided with a comparatively large dimension in order to provide an inward flow path for the air in the wakes which are generated by that portion of the air flowing through the swirler slots. This inward flow may be seen by reference to the flow arrows in FIG. 7.

Another of the critical dimensional ratios provided on the air swirler 11 in order to accomplish the objects of the invention is that of the depth of a slot 23 (indicated as "C" on FIG. 2) to the blade thickness (indicated as "T" on FIG. 2). This ratio C/T, must be maintained within the range of 1.5-3.5 as it is this ratio which helps to determine the radial inward flow of hot gases in the stagnant wakes behind the relatively thick trailing edges. It will, of course, be realized that the angle α of an individual blade member 22 will determine the strength of the vortex. This angle is indicated on FIG. 4 and must fall within a range of from 25° to 35° with 30° being the preferred angle for optimum smokeless operation.

Having described the structural elements which must be combined together in order to accomplish the objects of the present invention, that is, decreasing smoke so that the Von Brand smoke number will be well above 90 over the entire gas turbine load range, the combustion system 1 will now be described in terms of its operation.

OPERATION OF THE INVENTION

During operation, compressed air from the compressor will fill the annular air space around the liners and end cap such that as the air enters the various openings in the liner, a pressure drop is apparent and necessary for operation. Starting with the compressed air flow through the air swirler slots in the combustion reaction zone, the air flow and attendant flow of combustion products will be described at various points along the axial length of the liner.

As approximately 3 to 10% of the air passes through the air swirler, it is imparted with a swirling motion such that a vortex is formed in a portion of the liner volume. This will be apparent in referring to the various air flows shown in FIG. 7. The characteristics of the vortex may be seen when referring to FIG. 5 where the variation in velocity and pressure is plotted against the increasing radial distance from the liner centerline out to the liner.

In the core area, that is, the central part of the swirling air, it is seen from the curves that the pressure is at its lowest while the velocity is at its highest. This indicates that, in a zone down stream from the air swirler, the pressure at a larger radial dimension is increased over the pressure in the core which is at a pressure level below that in the liner volume in general. The result of this is that the air which enters the liner through the combustion air holes will penetrate the swirling core air and tend to flow toward the face of the air swirler and fuel nozzle.

It will be appreciated that such a feedback effect adds to the overall mixing of the combustion air with the fuel. The incoming air (from the holes) which penetrates the swirling core, of course, mixes with the atomized fuel, and then begins to react with the fuel. The effect of the swirling air, together with the feedback effect, stabilizes the flame over the full operating range and thus allows the additional air, which is added to the combustion reaction zone to form a stabilized "lean head end." The addition of more air will tend to prevent the formation of the unwanted soot particles by allowing more complete

7

combustion in the reaction zone. Furthermore, the vortical mixing will sweep out any fuel rich pockets that may have formed.

The various pressure drops across the liner and to the centerline of the liner are indicated on FIG. 5. The top line indicated p_{cd} is the pressure in the annular air space before the pressure drop across the liner which is indicated as Δp_{liner} . The decrease in pressure inwardly from the liner is then indicated by the sloping curve p and the full pressure drops from the annular air space to the centerline of the liner is indicated as ΔP_{total} .

Now, as the combustion air has been mixed with the fuel and a stabilized flame formed, with the attendant combustion products being formed, the "thermal soaking" region of the liner is operative. Any soot which may have been formed in the combustion reaction zone due to inadequate mixing or fuel-rich pockets which were not swept away by the swirling motion of the air is allowed to react with the hydroxyl radicals in high concentration at elevated temperatures.

At an axial point at least $1.25D$ from the last row of combustion air holes, tempering air is added to the combustion products in order to cool them to a point where they may enter the first stage nozzle at the temperature required in the gas turbine cycle and at a value that will not harm the ensuing hot gas path parts.

It will thus be appreciated that a gas turbine combustion system has been described which produces a minimal amount of smoke pollutant to exhaust into the atmosphere. This is accomplished through the use of an air swirler which provides the maximum mixing capabilities of the combustion air with the fuel by stabilizing the flame so that a "lean head end" can be formed, and by providing a "thermal soaking" region along the liner such that any soot which is formed in the combustion process is consumed by a fast chemical reaction.

What is claimed is:

1. In a gas turbine combustion chamber, the combination of:

- (a) an outer casing closed by an end cover at one end and leading to the first stage nozzle at the other end,
- (b) a liner surrounded by said casing and having a generally circular cross section with said casing and liner together defining an annular air space therebetween,
- (c) a cap closing off one end of said liner and defining a hole therein,
- (d) an air swirler disposed in the hole in the cap and comprising:

8

- (1) an annular body portion having a face normal to the axis thereof and defining a central hole for the accommodation therein of a fuel nozzle, and
- (2) a plurality of angled blade members disposed about the circumference of said body, each having an average thickness greater than one-fourth the depth, arranged and sized so that the open area between blades is 3-10% of the total air flow area in said liner,

- (e) a plurality of combustion air holes defined by said liner and positioned within an axial length corresponding to the liner diameter, said holes arranged and sized such that they define 25-50% of the total air flow area in said liner,
- (f) a thermal soaking region extending from said combustion air holes axially at least 1.25 times said liner diameter dimension and void of any combustion air holes, and
- (g) a plurality of tempering air holes positioned downstream of said thermal soaking region, with respect to the flow of combustion products, arranged and sized such that they define 35-55% of the total air flow area in said liner.

2. A gas turbine combustion chamber according to claim 1 wherein said angled blade members on the air swirler are at an angle of from between 25 to 35° measured from a plane parallel to the swirler axis.

3. A gas turbine combustion chamber according to claim 1 wherein said air swirler is attached to the cap.

4. A gas turbine combustion chamber according to claim 1 wherein said air swirler is attached to the fuel nozzle.

References Cited

UNITED STATES PATENTS

2,398,654	4/1946	Lubbock	60—39.65
2,638,745	5/1953	Nathan	60—39.65
3,099,910	8/1963	Schirmer	60—39.65
3,490,230	1/1970	Pillsbury	60—39.65
3,498,055	3/1970	Faitani	60—39.65
2,586,751	2/1952	Watson	60—39.65
3,447,317	6/1969	Dakin	60—39.65

DOUGLAS HART, Primary Examiner

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