United States Patent [19]

Markowski

[11] **3,811,277**

[45] **May 21, 1974**

[54] **ANNULAR COMBUSTION CHAMBER FOR DISSIMILAR FLUIDS IN SWIRLING FLOW RELATIONSHIP**

[75] Inventor: **Stanley J. Markowski,** East Hartford, Conn.

[73] Assignee: **United Aircraft Corporation,** East Hartford, Conn.

[22] Filed: **Apr. 18, 1973**

[21] Appl. No.: **352,138**

Related U.S. Application Data

[62] Division of Ser. No. 84,086, Oct. 26, 1970.

[52] U.S. Cl. .... **60/39.65,** 60/39.69, 60/39.72 R, 431/173, 431/183, 431/354

[51] Int. Cl. **F02c 3/00**

[58] Field of Search......... 60/39.65, 39.69, 39.72 R, 60/39.74 R, 39.06, 39.82 P; 431/350–354, 9, 173, 182, 183, 185, 349

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Primary Examiner—Carlton R. Croyle
Assistant Examiner—Robert E. Garrett
Attorney, Agent, or Firm—Vernon F. Hauschild

[57] **ABSTRACT**

The characteristics of thermodynamically and aerodynamically dissimilar fluids in swirling flow relationship are established and/or varied to accelerate mixing and hence combustion in the combustion zone and mixing and hence cooling of the products of combustion, in the dilution zone of an annular burner.

19 Claims, 49 Drawing Figures

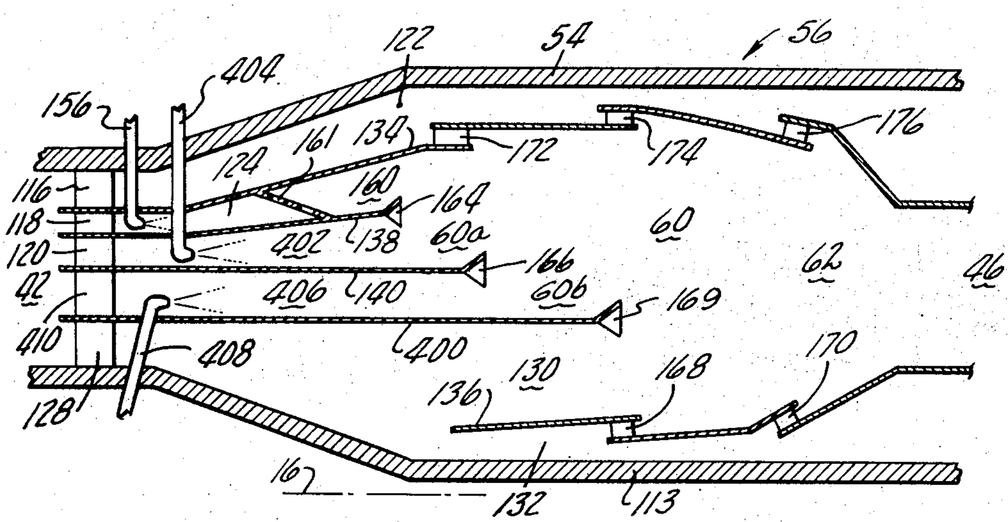


FIG.1

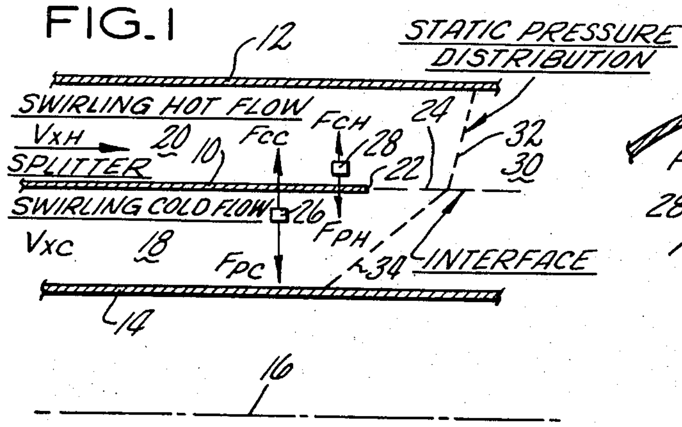


FIG.2

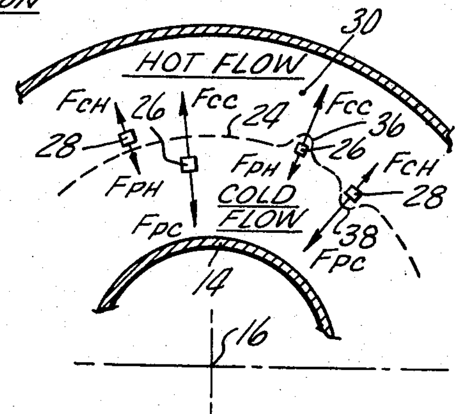


FIG.3

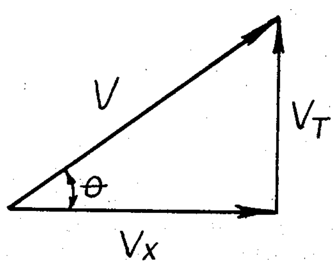


FIG.4

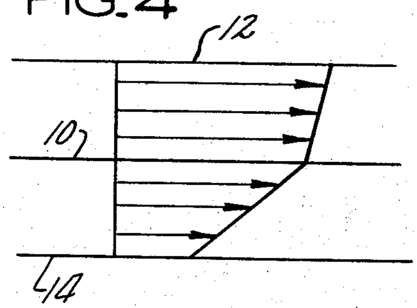


FIG.5

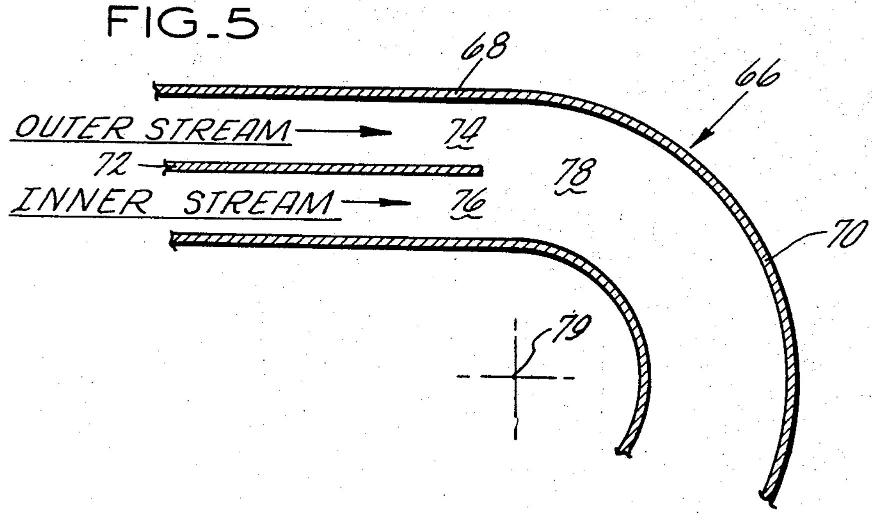


FIG. 6

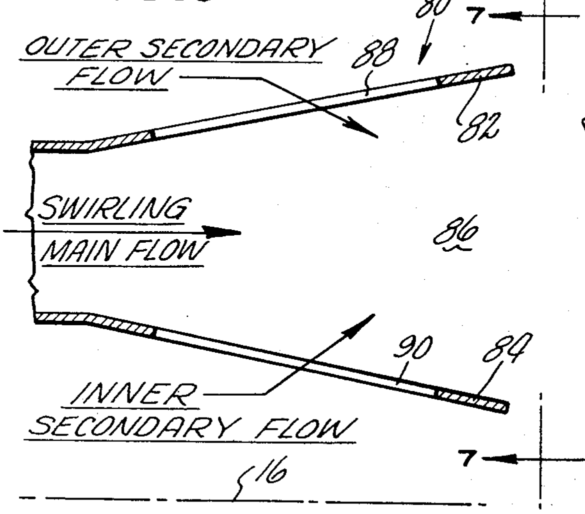


FIG. 7

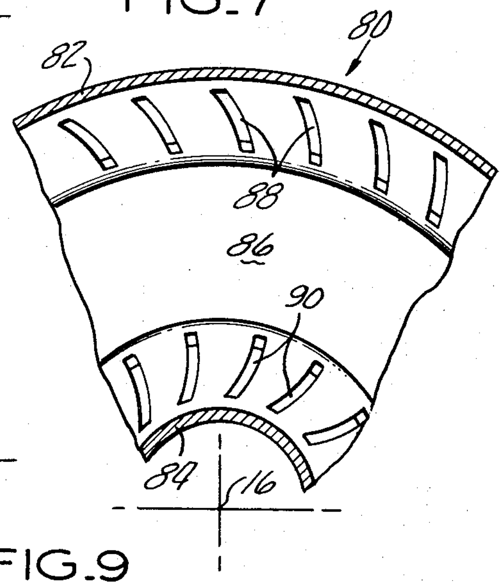


FIG. 8

PREMIXED BURNING IN CONCENTRIC MIXER

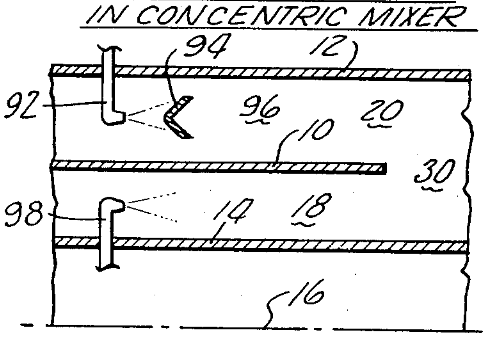


FIG. 9

DIFFUSION BURNING IN CONCENTRIC MIXER

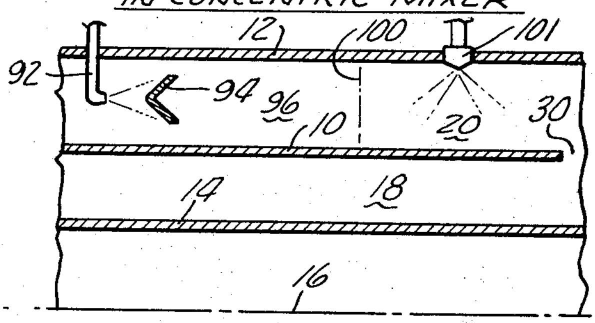


FIG. 10

BARBERPOLE MIXER USED AS A PREMIXED BURNER

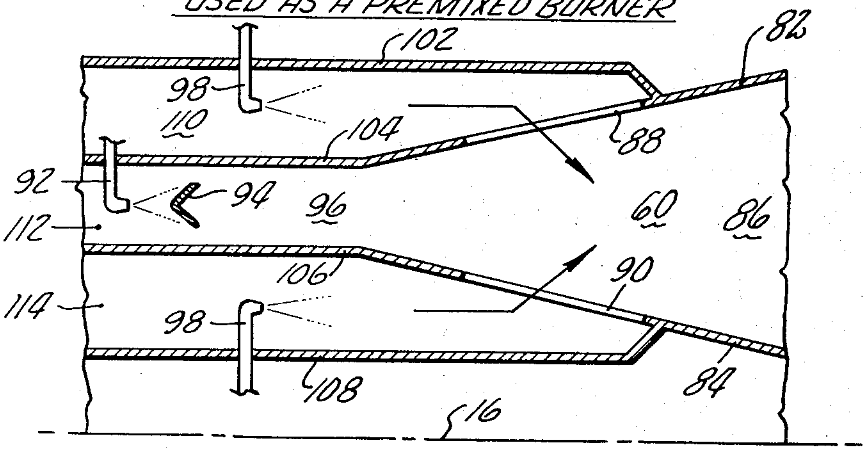


FIG. 11

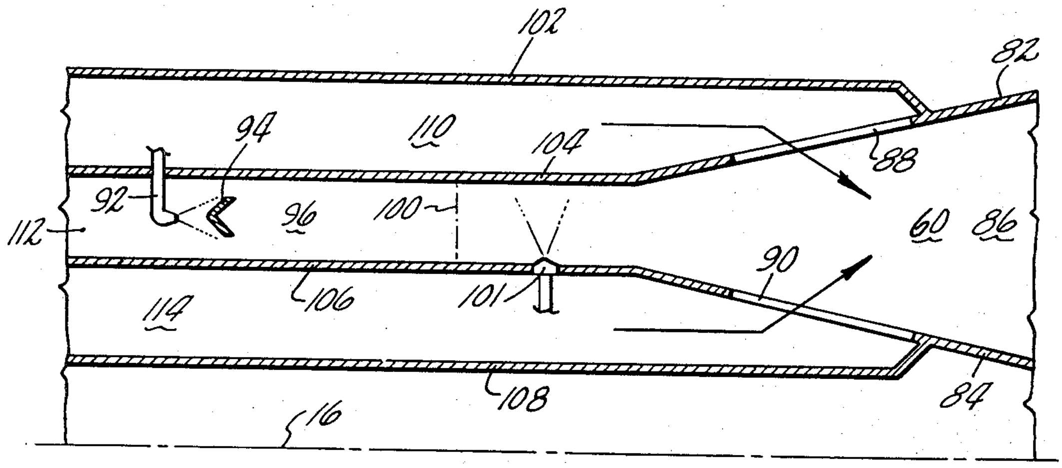


FIG. 12

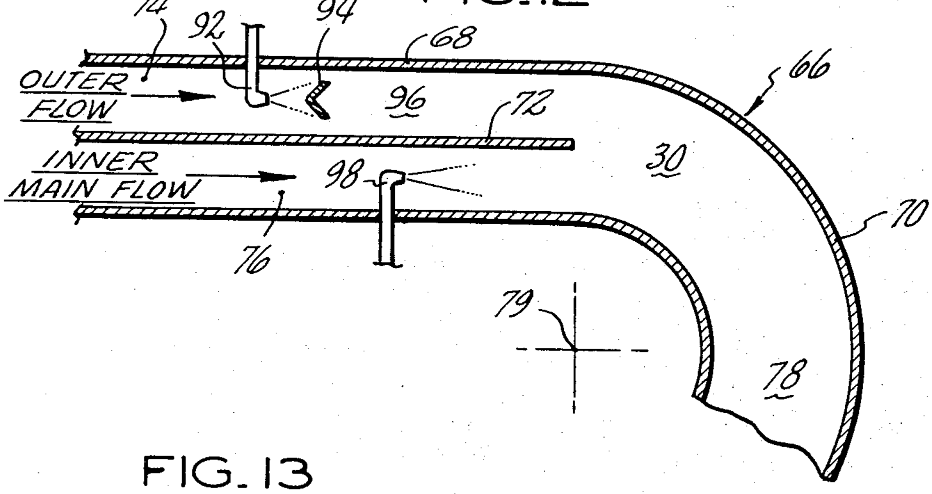
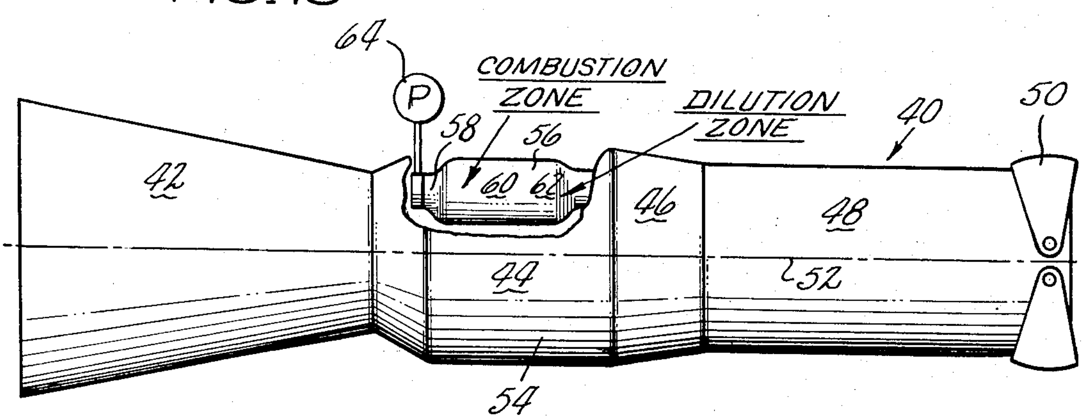


FIG. 13



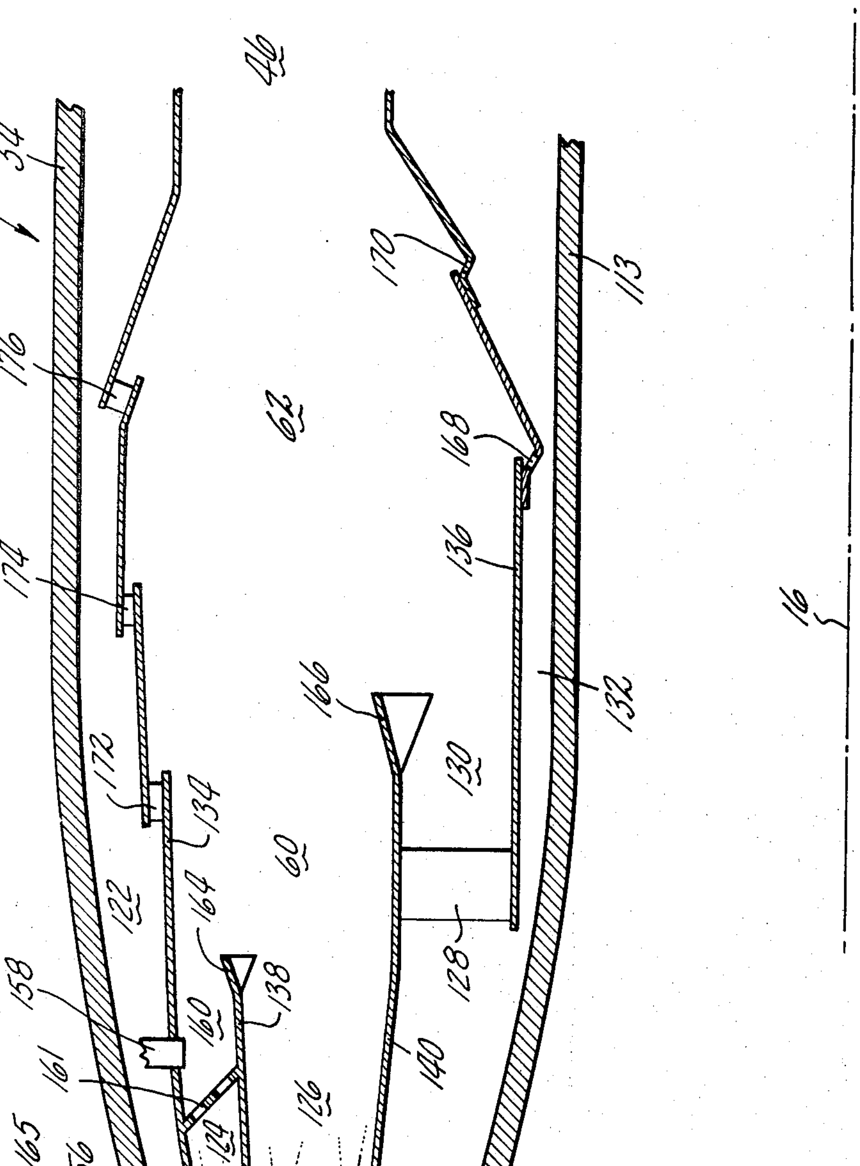


FIG.14

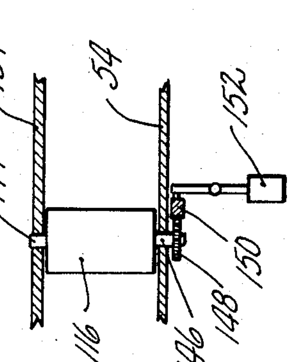


FIG.15

FIG_16

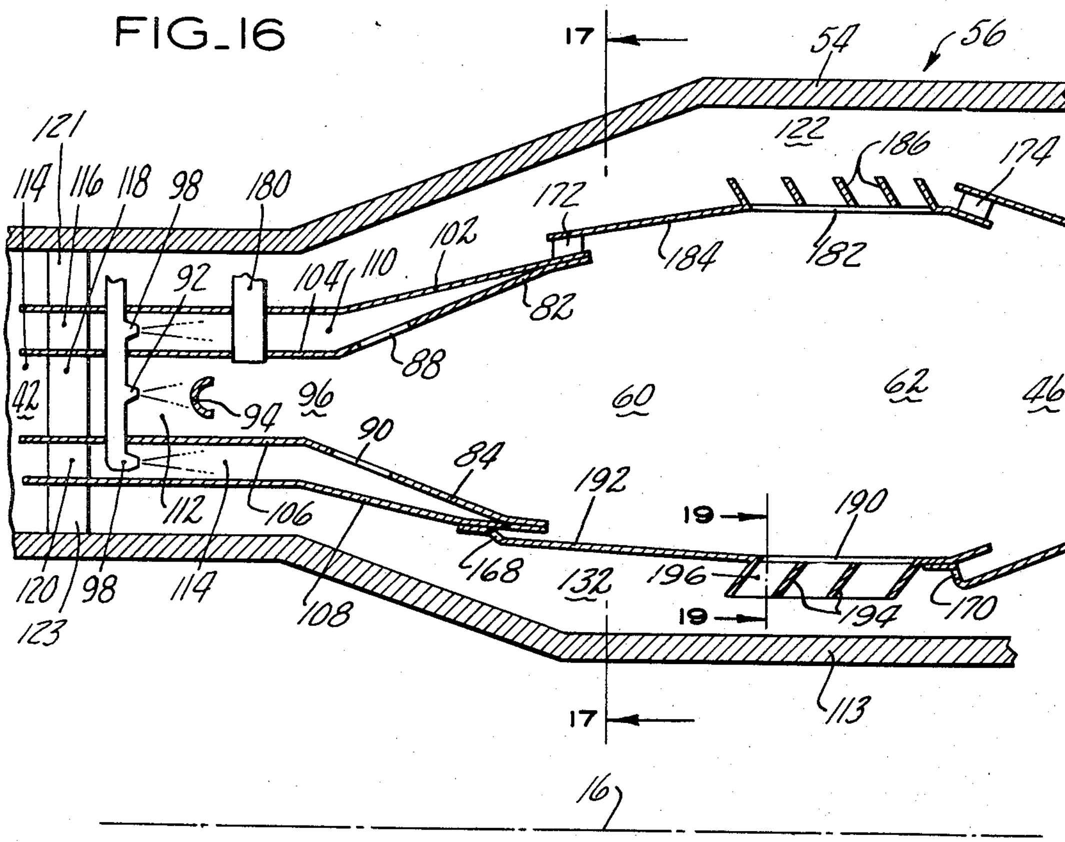


FIG_17

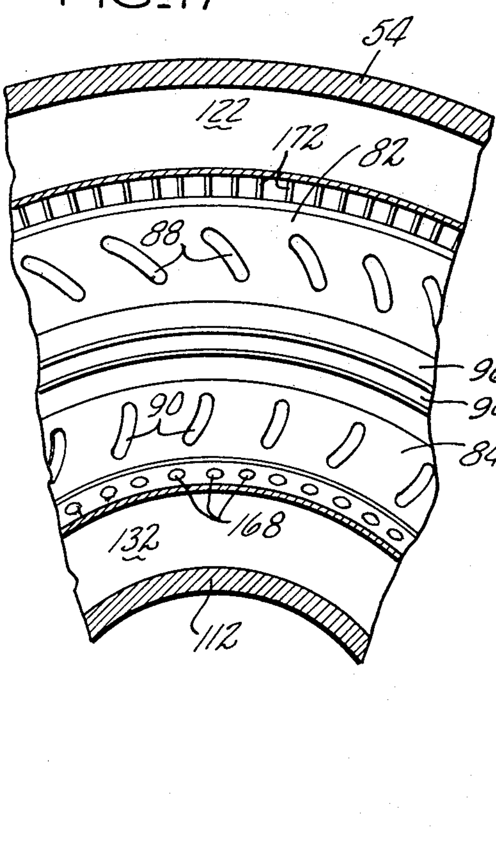


FIG_18

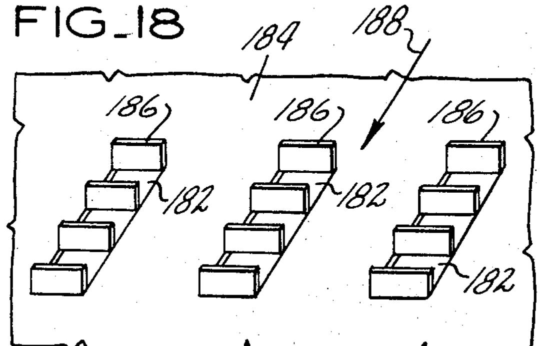
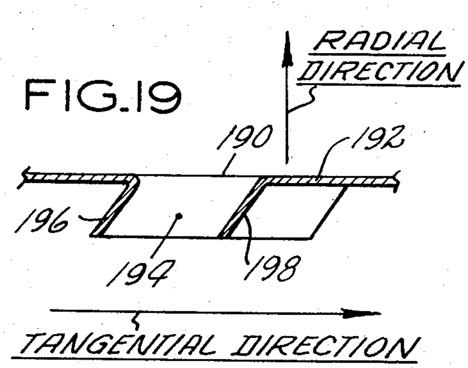


FIG.19



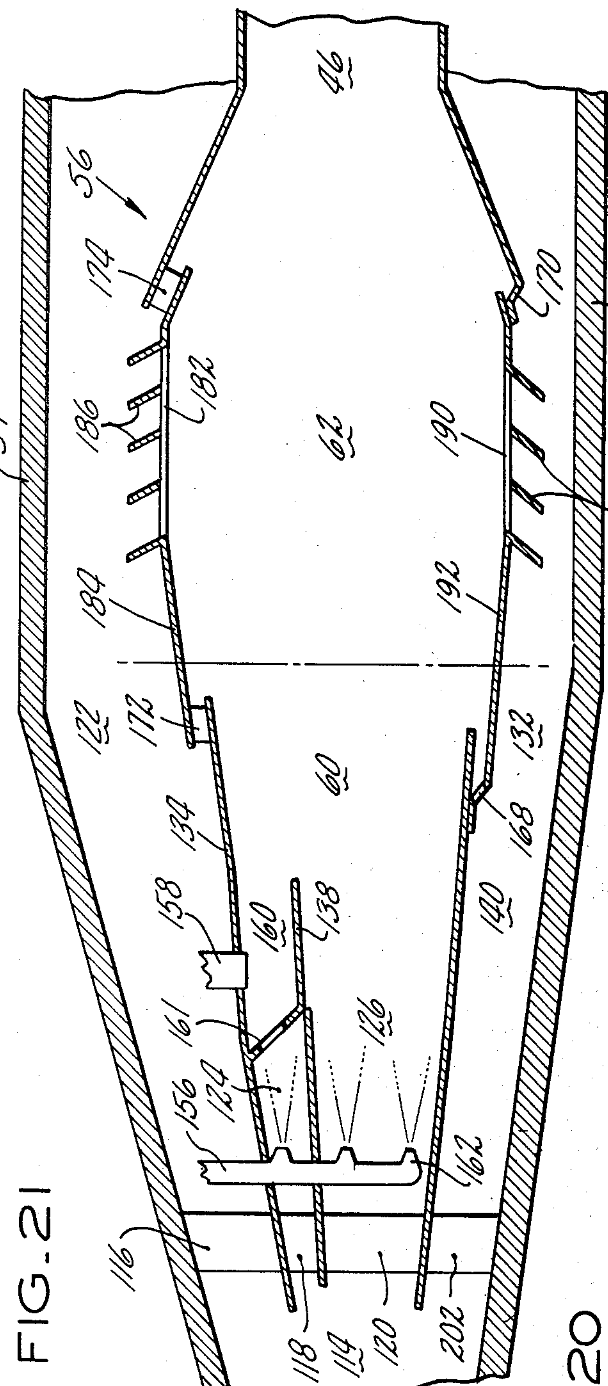

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FIG. 21

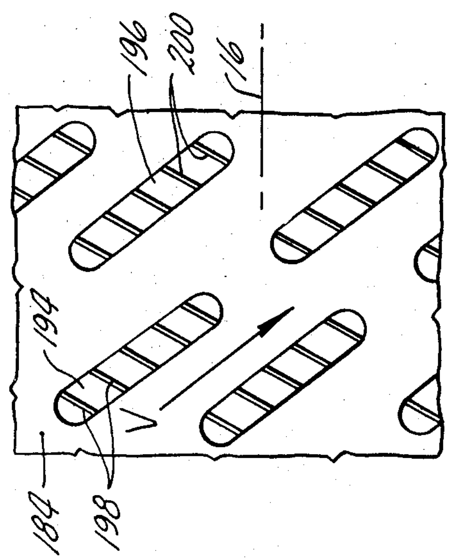
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FIG. 20

FIG.22

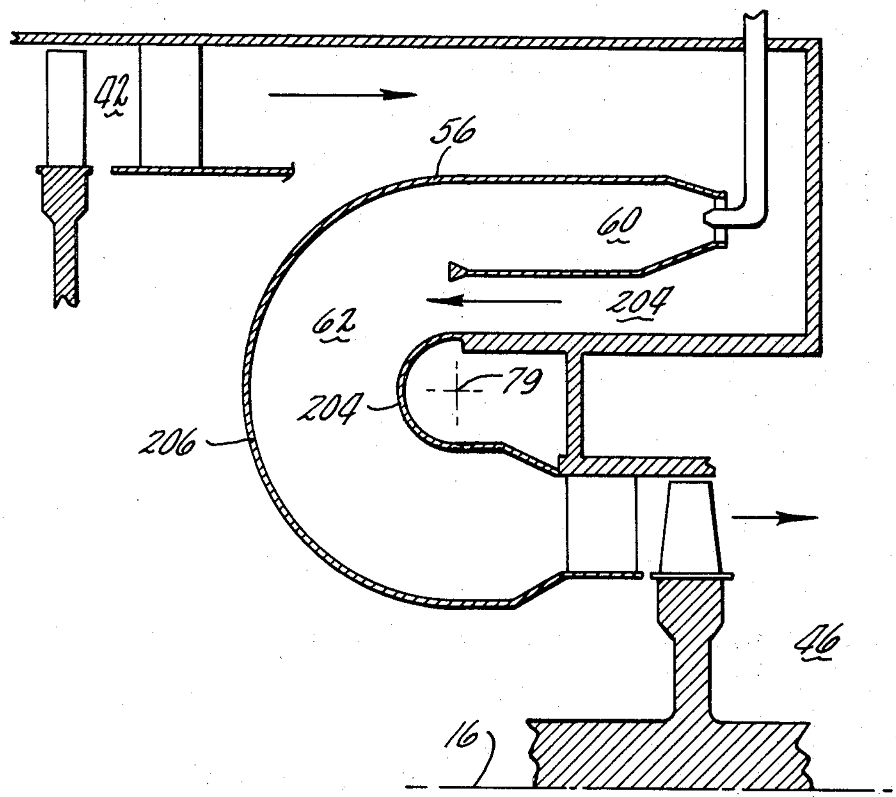
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FIG.23

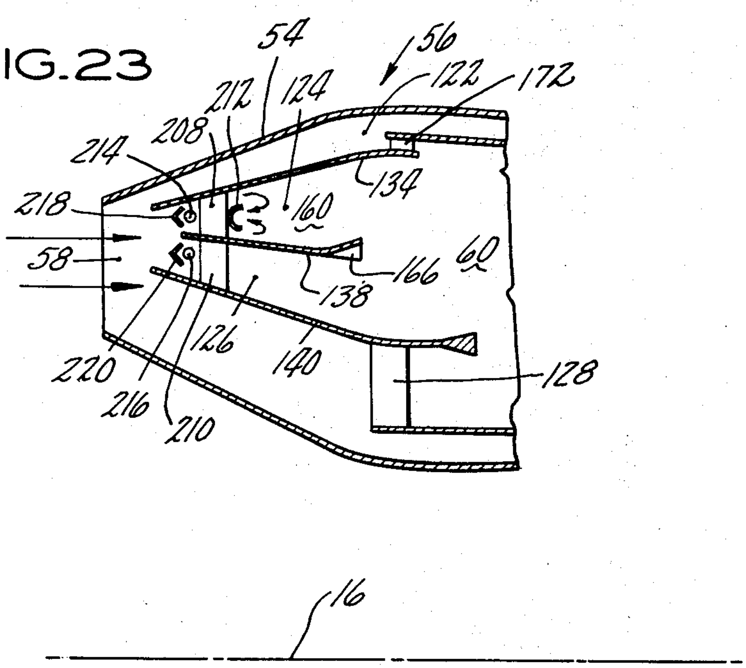
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FIG. 24

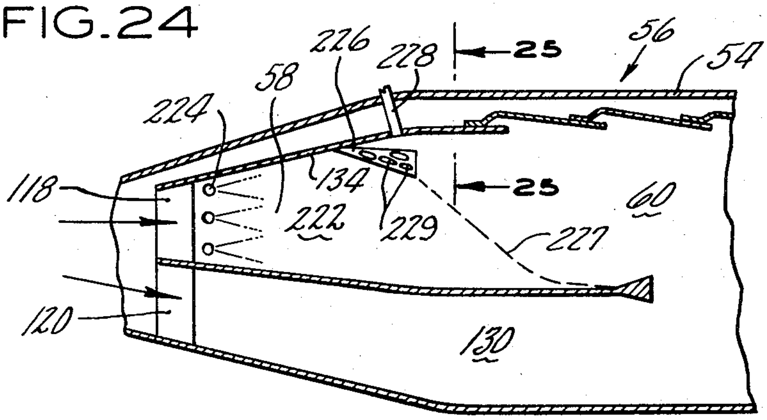


FIG. 25

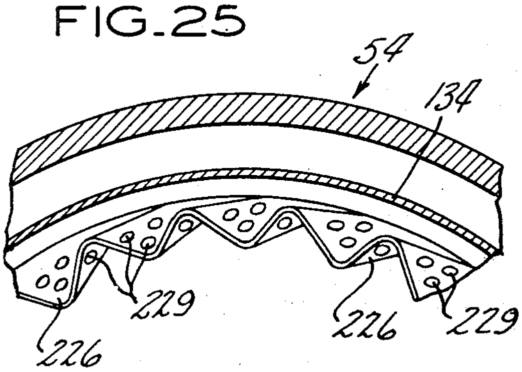


FIG. 26

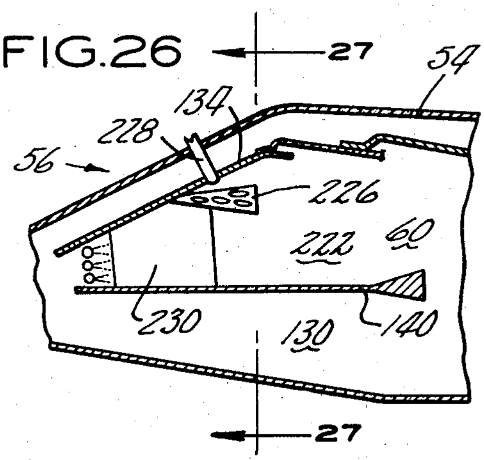


FIG. 27

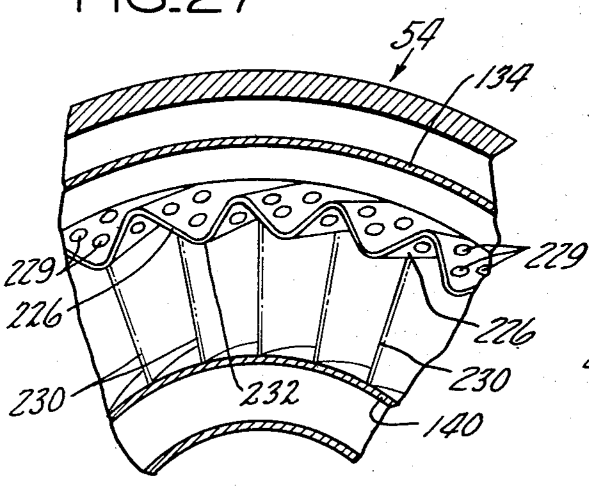


FIG. 28

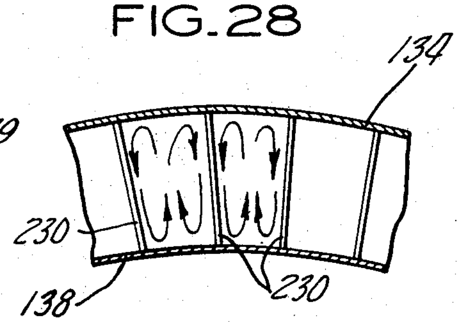


FIG. 29

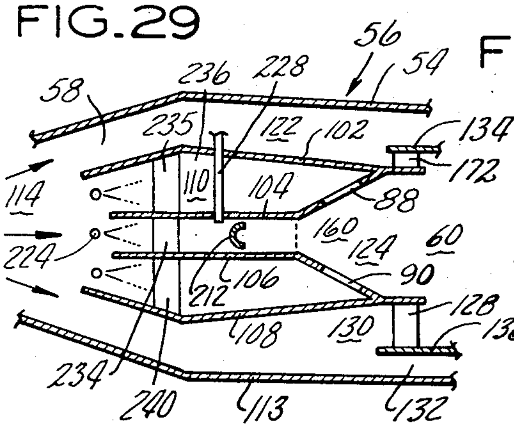


FIG. 32

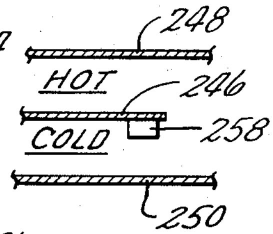


FIG. 33

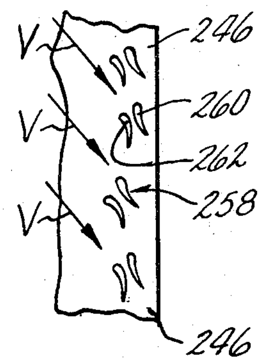


FIG. 30

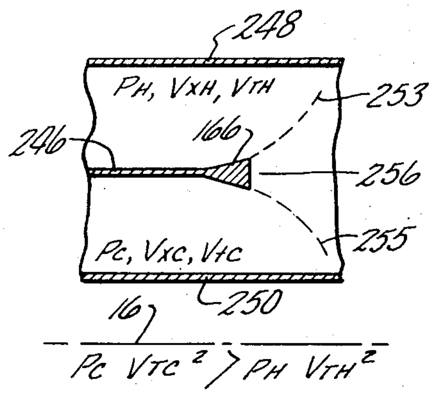


FIG. 31

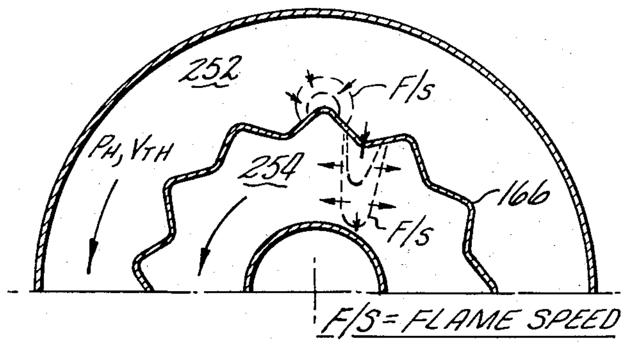


FIG. 34

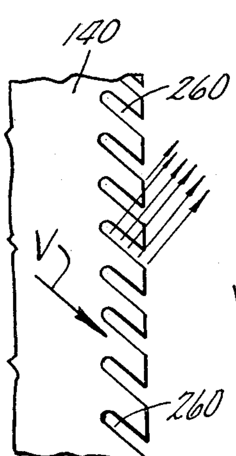


FIG. 35

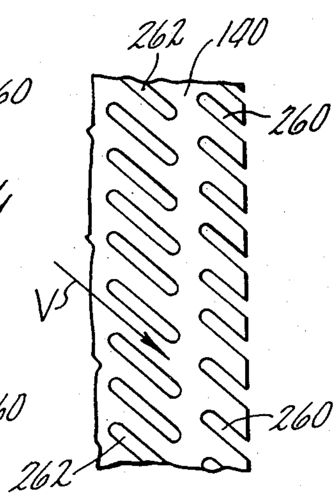


FIG. 36

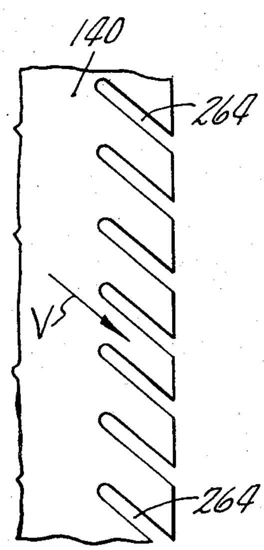


FIG. 37

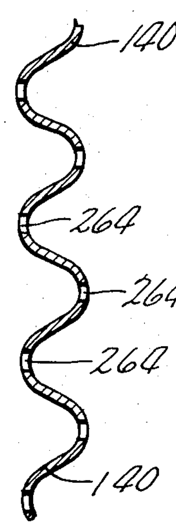


FIG_38

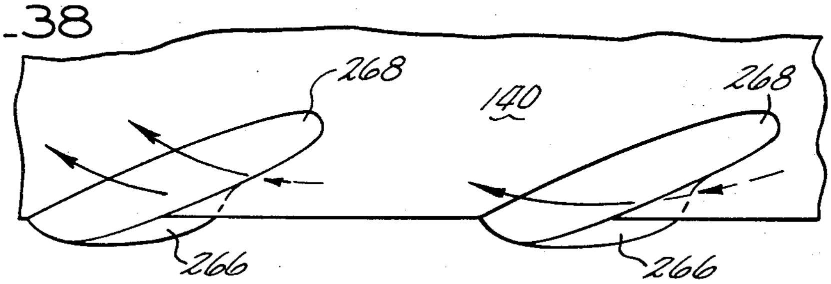


FIG.39

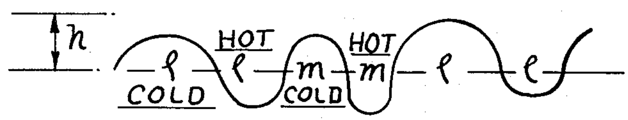


FIG_40

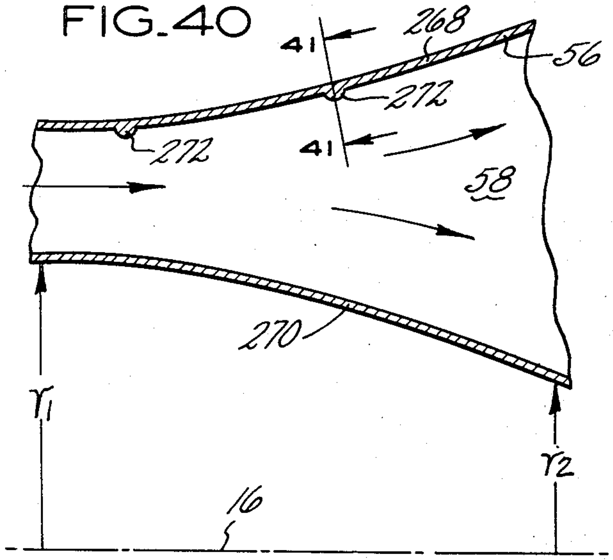


FIG_41

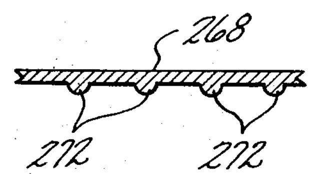


FIG_45

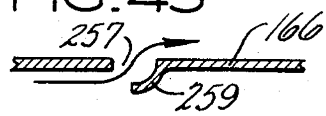


FIG.42A

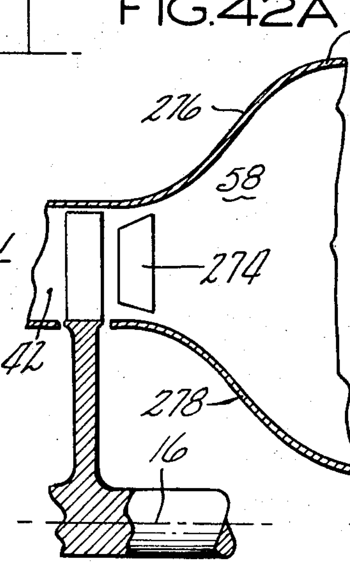


FIG.42B

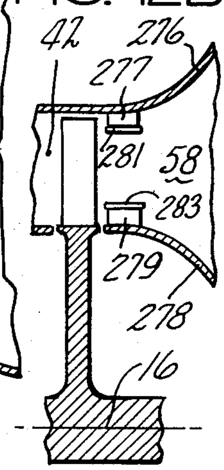


FIG_43

V_x DISTRIBUTION

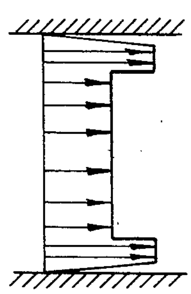


FIG_44

V_t DISTRIBUTION

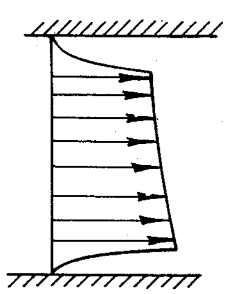


FIG. 46

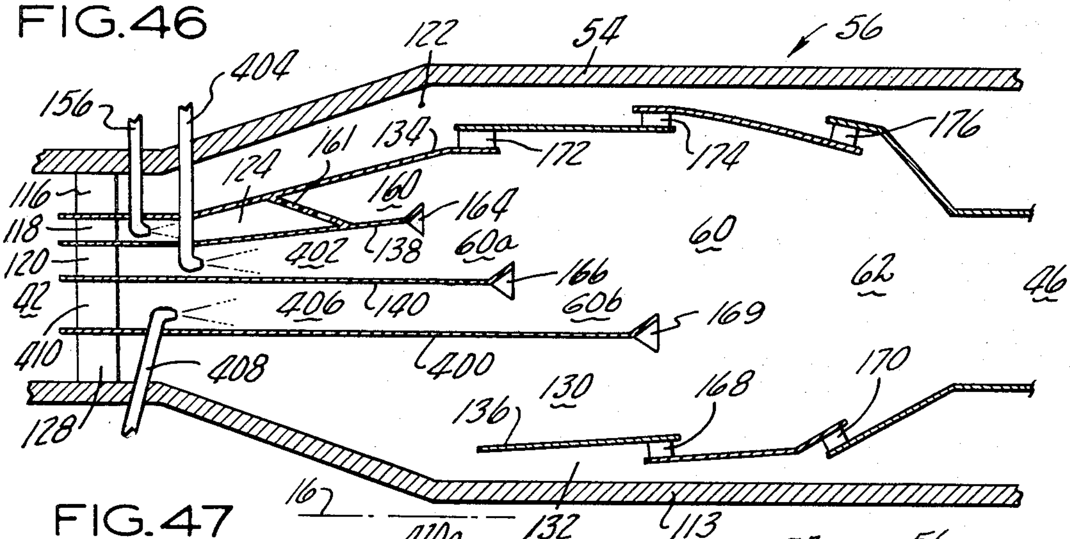


FIG. 47

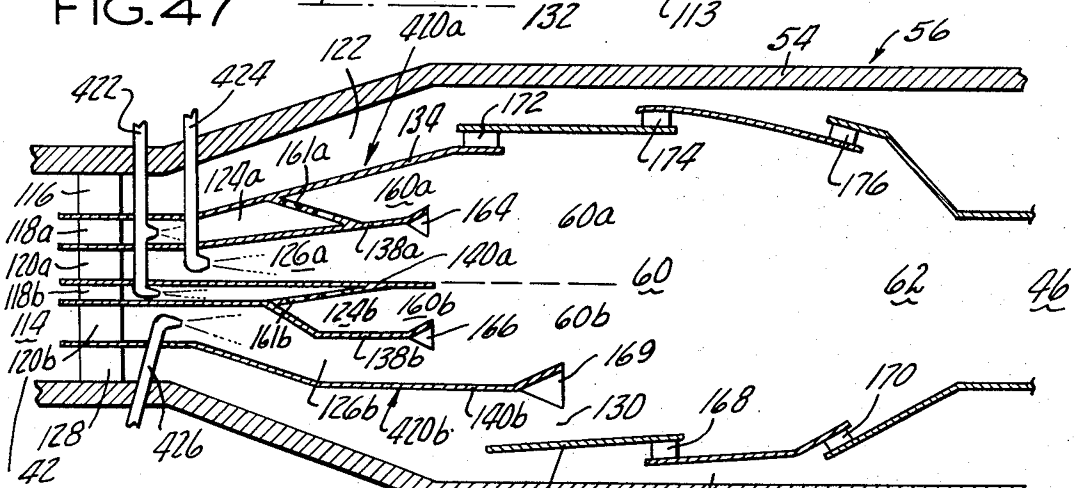
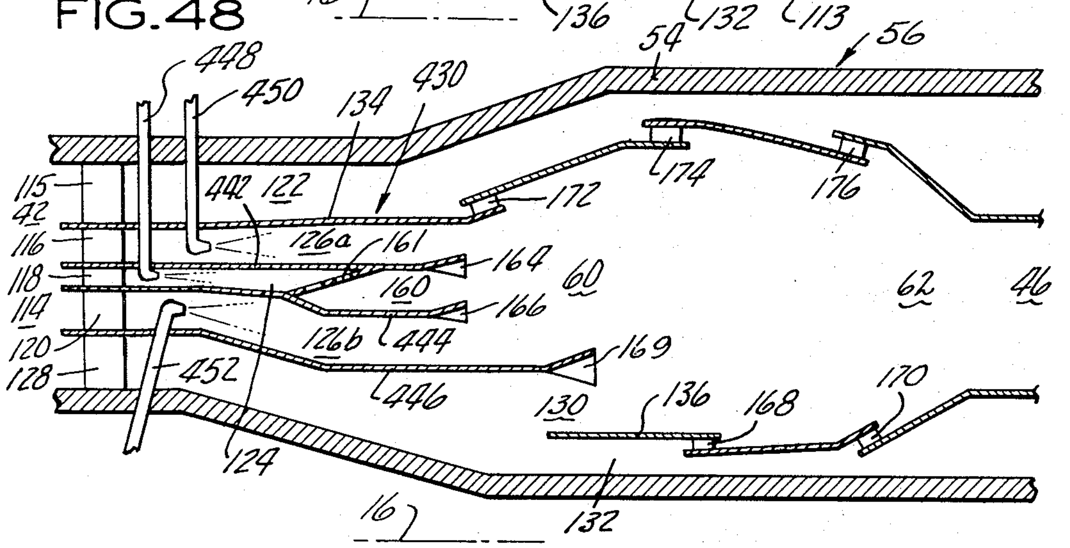


FIG. 48



ANNULAR COMBUSTION CHAMBER FOR DISSIMILAR FLUIDS IN SWIRLING FLOW RELATIONSHIP

This is a division of application Ser. No. 84,086, filed Oct. 26, 1970.

CROSS-REFERENCES TO RELATED APPLICATIONS

This application contains subject matter related to the following two applications assigned to the same assignee:

1. Application Ser. No. 84,087, now U.S. Pat. No. 3,701,255, filed concurrently herewith for "Shortened Afterburner Construction for Turbine Engine" and
2. Application Ser. No. 84,088 now U.S. Pat. No. 3,675,419, filed concurrently herewith for "Combustion Chamber Having Swirling Flow."

BACKGROUND OF THE INVENTION

1. Field of Invention

This invention relates to the controlled mixing of two thermodynamically and aerodynamically dissimilar fluids and particularly to the use of swirling flow between two dissimilar fluids in annular combustion chambers, such as the burners and afterburners of turbine engines, to accelerate both the combustion process and the temperature reduction process of the products of combustion in the dilution zone of the burner.

2. Description of the Prior Art

In the combustion chamber and burner art, it has been conventional to burn in a cylindrical chamber by discharging an atomized fuel spray into the center thereof with air being discharged therearound through a vaned cascade at tangential velocity V_t so as to form a recirculation zone of the atomized fuel and swirling air so mixing. This recirculation zone is formed because the angular momentum of the air is proportional to the tangential velocity V_t thereof times the radius of the air particle involved from the burner central axis, accordingly, any air which is at or near the burner axis is of minimal or zero radius so that the tangential velocity attempts to go to infinity with the result that non-swirling secondary air is brought in around the recirculation zone for mixing with the stagnated fuel-air mixture downstream of the recirculation zone and for cooling the walls of the combustion chamber, as typically shown in U.S. Pat. No. 3,498,055.

These prior art burners are called "can burners," because of their cylindrical shape, or "can-annular burners," because they have a series of can-shaped inlet sections opening into an annular main section. The momentum-velocity system of establishing a recirculation zone is used in the can portion of both.

The momentum-velocity system of establishing a recirculation zone does not work in an annular combustion chamber because all combustion stations are of substantial radius and therefore I utilize the interdigitation of the swirling sheets of dissimilar fluids to perform this function.

The patents to Johnson, U.S. Pat. No. 3,030,773 and Sanborn, U.S. Pat No. 2,473,347 utilize swirling flow in combustion chambers but it will be noted that these are cylindrical or can type combustion chambers and that none of this prior art teaches the use of establishing an unstable interface between two swirling dissimilar fluids for the purpose of accelerating mixing and combustion therebetween by the establishing and/or control of the fluid density and tangential velocity V_t to produce dissimilar product parameters ρV_t^2 between the two fluids. The conventional can or cylindrical burner is shown in afterburner form in U.S. Pat. No. 2,934,894.

Other than the aforementioned type of swirling flow to assist in establishing a recirculation zone in a cylindrical or can burner or in an annular burner having a plurality of substantially cylindrical, circumferentially extending can burner spray nozzles positioned circumferentially thereabout as in U.S. Pat. No. 3,000,183, swirling flow is generally discouraged in conventional combustion chambers and straightening vanes are provided for this purpose.

Swirling flow has been suggested for combustion chambers in certain patents, however, including Ferri et al. U.S. Pat. No. 2,775,623 which teaches the concept of causing the fuel-air mixture passing through a combustion chamber to flow in swirling motion so as to improve combustion, however, it should be noted that in the Ferri et al. patent there is but a single swirling stream and he therefore does not achieve the mixing and accelerated combustion advantages of my invention. The patent to Meurer, U.S. Pat. No. 3,078,672 causes swirling air to be passed through a can-type burner and causes a solid sheet or film of fuel to be passed along the inner surface of the burner outer wall to be vaporized and to burn with the swirling air at the outer wall. Combustion takes place at the interface between the air and the fuel at the outer wall of the combustion chamber and the products of combustion move inwardly to be gathered and recycled through duct **22.** Meurer clearly does not teach the concept of mixing and combusting two dissimilar fluids by control of the parameter products taught herein. My U.S. Pat. No. 3,393,516 illustrates curved flow in an exhaust gas deflector of a turbo-fan engine but it should be noted that there is no mixing and combustion in connection with the curved flow, in fact, such would be undesirable.

SUMMARY OF THE INVENTION

A primary object of the present invention is to provide a mixer configuration which can be used to increase mixing between dissimilar swirling flow fluids in the combustion zone of an annular combustion chamber to accelerate combustion by increasing the mixing rate between the cool fuel-air mixture and the hot gases and which can also be used to accelerate mixing in the dilution zone of an annular combustion chamber between the products of combustion and the cooling air to accelerate temperature reduction. Combustion is mixing limited. The time or burner length required to obtain complete combustion can be limited by that necessary to mix together the hot gases and the cool fuel-air mixture. Accelerated mixing in both the combustion and dilution zones will shorten the length of the combustion chamber and hence shorten the length and weight of the engine.

A primary object of the present invention is to provide an improved annular combustion chamber by establishing, controlling and/or varying the product parameter ρV_t^2, where ρ is fluid density and V_t is fluid tangential velocity, between two dissimilar swirling fluids to establish an unstable interface therebetween to accelerate mixing and hence combustion in the combustion zone and mixing and hence cooling in the dilution zone of the combustion chamber.

In accordance with the present invention, this product parameter is established, controlled and/or varied so that the product parameter of the fluid which is flowing at the lesser radius about the combustion chamber axis is greater than the product parameter of the fluid which is flowing at the greater radius, so that the mixing ratio in the combustion chamber is determined by the ratio ρV_t^2 (inner flow) $\div$ ρV_t^2 (outer flow).

In accordance with a further aspect of the present invention, the interface between two dissimilar swirling combustion chamber fluids are established or controlled so that outside-inside burning occurs in the combustion chamber.

The invention permits accelerated mixing and combustion or accelerated mixing and dilution to occur in several annular combustion chamber configurations, for example, in the concentric flow mixer configuration, the "barberpole" mixer configuration, and the bent tube or folded combustion chamber mixer configuration.

In accordance with a further aspect of the present invention, a combustion chamber can be fabricated so as to consist of a combustion zone and a dilution zone with either or both of these zones utilizing a concentric mixer, a barberpole mixer, or a bent tube mixer and any of these mixers can be used with a conventional combustion zone or dilution zone.

It is a further aspect of the present invention that utilizing any of these mixing constructions, combustion can take place utilizing either the premixed or diffusion principle.

It accordance with a further aspect of this invention, hardware is provided to establish, control or vary the orientation of two concentric fluid streams of different thermodynamic and aerodynamic states in such a way that the product parameter density, ρ, of the inner stream times the tangential velocity V_t of the inner stream is greater than the corresponding product parameter of the outer stream.

In accordance with still a further feature of the present invention, compound mixing in radial, parallel staging occurs both in the combustion zone and the dilution zone of an annular combustion chamber in which the combustion zone and the dilution zone are axially staged in series so as to reduce the overall length of the combustion chamber and hence the engine length and weight.

In accordance with still a further feature of this invention, several modifications of the pilot combustion zone in a concentric mixer for a primary combustion zone are usable and of advantage depending upon the particular requirements of the combustion chamber configuration involved.

In accordance with still a further aspect of the present invention, triggers are used to disturb the unstable interface between two swirling streams to accelerate mixing and either combustion or cooling therebetween.

In accordance with still a further aspect of this invention, a combination flameholder and/or trigger can be used in a swirling flow annular combustion chamber to accelerate mixing and burning of the products of combustion from the recirculation zone established downstream of the flameholder and the fuel-air mixture passing around the flameholder.

In accordance with still a further feature of this invention, swirling fluid interface trigger mechanisms are provided in the form of a corrugated and tapered rings, which may have holes or scoops therein for noise deadening and trigger mechanism cooling purposes.

In accordance with still a further feature of this invention, combustion apparatus is provided in which combustion or dilution zones are located in series in which mixing occurs in both zones at parallel radial stations.

In accordance with a further teaching of this invention, the unstable interface between two swirling streams of fluid which are established by the product parameter criterion taught herein can be physically interrupted or disturbed by a variety of trigger mechanisms.

It is a further teaching of this application to establish a stable interface criteria between the cooling air for a combustion chamber liner and the products of combustion.

In accordance with still a further feature of my invention, swirling flow in an annular combustion chamber invites the use of flameholders therein and the use of a substantial variety of fuel injecting devices to be used therewith.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** is a schematic representation of two dissimilar fluids flowing in swirling relationship in separated coannular passages and then joining and mixing in a single annular passage.

FIG. **2** is a schematic showing in cross-section of the FIG. **1** flow representation.

FIG. **3** is a vector diagram of the fluid flowing in swirling fashion in the FIG. **1** and **2** environment and the other environments disclosed herein.

FIG. **4** is a showing of the static pressure distribution across the outer and inner swirling fluid flows of the FIG. **1** and **2** environment.

FIG. **5** is a schematic representation of mixing occurring in two fluid streams flowing in side-by-side relationship and which are caused to swirl in passing through a bent tube.

FIG. **6** is a schematic cross-sectional showing of a "barberpole" swirl mixer.

FIG. **7** is an end view taken along line **7—7** of FIG. **6**.

FIG. **8** is a showing of an annular combustion chamber concentric mixer utilizing the premixed burning principle.

FIG. **9** is similar to FIG. **8** but utilizing the diffusion burning principle.

FIG. **10** is a cross-sectional showing of an annular combustion chamber barberpole mixer used in the combustion zone and utilizing the premixed principle.

FIG. **11** is similar to FIG. **10** but utilizing the diffusion burning principle.

FIG. **12** is a showing of a premixed combustor employing bent tube mixing in a folded combustion chamber which is preferably of the annular type.

FIG. **13** is a showing of a modern turbine engine of the type used in the modern aircraft and shown utilizing my invention.

FIG. **14** is a cross-sectional showing of an annular combustion chamber using a concentric mixer in both the combustion zone and the dilution zones.

FIG. 15 is a showing of a vane of an annular vane cascade and its actuating mechanism to make the cascade variable angle so as to vary the angle at which the gases passing therethrough are discharged.

FIG. 16 is a cross-sectional showing of an annular combustion chamber using a barberpole mixer in both the combustion zone and dilution zones thereof.

FIG. 17 is taken along lines 17—17 of FIG. 16.

FIG. 18 is an enlarged, unrolled showing of the combustion chamber outer liner of FIG. 16 to illustrate the orientation of the outer liner helical slots in the barberpole mixer of the dilution zone.

FIG. 19 is a cross-sectional showing of the vaned, helical slots used in the inner wall of the dilution zone mixer of FIG. 16 and is taken along line 19—19 of FIG. 16.

FIG. 20 is a modification of the helical slots shown in FIG. 18 and can be used in the barberpole mixer either in the combustion zone or the dilution zone of an annular combustion chamber.

FIG. 21 is a cross-sectional showing of an annular combustion chamber having axially staged combustion and dilution zones and utilizing a concentric mixer in the combustion zone and a barberpole mixer in the dilution zone.

FIG. 22 is a cross-sectional showing of an annular combustion chamber having a conventional combustion zone and dilution zone of the folder burner or bent tube variety utilizing my invention.

FIG. 23 is a modification of the primary combustor portion of the combustion zone mixer shown in FIG. 14.

FIG. 24 is a modification of the concentric mixer used in the combustion zone of an annular combustion chamber which may be substituted for the type shown in FIG. 14.

FIG. 25 is an enlarged, partial, cross-sectional showing of the flameholder member taken along line 25—25 of FIG. 24.

FIG. 26 is a showing of a modification of the combustor shown in FIG. 25.

FIG. 27 is an enlarged showing of the FIG. 26 construction taken along line 27 of FIG. 26.

FIG. 28 corresponds to FIG. 27 and shows the secondary flow patterns between the helical guide vanes.

FIG. 29 is still another modification for the primary combustion chamber shown in FIG. 14.

FIG. 30 is a schematic representation of two swirling fluids flowing through annular passages with a splitter duct therebetween and with a trigger mechanism attached to the downstream end of the splitter duct.

FIG. 31 is an end view of the FIG. 30 construction.

FIG. 32 is a cross-sectional showing of a trigger mechanism which may be substituted for the trigger mechanism shown in the splitter duct of FIG. 14.

FIG. 33 is a showing of the trigger mechanism of FIG. 32 shown with the splitter duct unrolled for purposes of better illustration.

FIG. 34 shows another modification of trigger mechanism of FIG. 14.

FIG. 35 is a showing of a further trigger mechanism modification utilizing plural rows or patterns of helical slots in or near the trailing edge of a splitter duct.

FIGS. 36 and 37 are plan and end views of still another trigger mechanism modification of the variety which utilizes both a helically slotted and helically corrugated downstream end on a splitter duct to perform their swirling fluid interface triggering functions.

FIG. 38 is a showing of still another trigger mechanism modification utilizing a combination of helical slots and scooped projections cooperating therewith at the downstream end of a splitter duct to accelerate mixing.

FIG. 39 is a representation of irregular trigger corrugation utilized for the purpose of noise suppression.

FIGS. 40 and 41 depict annular combustion chamber flow passage modifications which can be used because of the swirling flow therethrough to retard or prevent flow separation of the boundary layers along the diffuser walls.

FIGS. 42*a* and 42*b* are showings or an annular combustion chamber utilizing swirl flow and further utilizing a compound vane cascade at the inlet thereof to control the amount of swirling at the various radial stations across the cascade so as to discourage boundary layer flow separation and permit the utilization of shortened diffuser section in the combustion chamber, thereby reducing the length of the combustion chamber.

FIGS. 43 and 44 and showings of the axial velocity profile and tangential velocity profile of the air immediately downstream of the cascade of compound vanes of FIG. 42.

FIG. 45 is a cross-sectional showing of a scooped-aperture which may be used with trigger mechanisms, such as those shown in FIG. 14.

FIGS. 46 thru 48 are showings of annular combustion chambers utilizing radially staged combustion for reduced combustion chamber and engine length and having provisions for engine power performance control.

DESCRIPTION OF THE PREFERRED EMBODIMENT

To fully explain the subject matter of this application, it is deemed desirable to first describe the theory involved.

My observation of the dynamic behavior of concentric dissimilar swirling flows leads to the discovery of a fluid interface instability phenomenon that can be used to increase the mixing rate between the dissimilar fluids and which therefore is of particular interest in combustion chambers to accelerate combustion by increasing the mixing rate and hence the effective flame speed and also to accelerate the mixing which takes place in the combustor dilution zone wherein the products of combustion are cooled by mixing with cooling air before being passed through the turbine. AS used herein the term dissimilar fluids means fluids which are thermodynamically and aerodynamically dissimilar. This phenomenon of interest and its characteristics will now be described by referring to FIGS. 1 and 2. In these figures, two dissimilar fluids are flowing in concentric swirling flow patterns and are isolated initially by a cylindrical separator wall 10, which is positioned between cylindrical ducts 12 and 14 so that walls 10, 12 and 14 are concentric about centerline or axis 16 and cooperate to define concentric annular passages 18 and 20. While the outer fluid will be described as the hot fluid and the inner fluid the cold fluid, this does not have to be the case. As the swirling fluids pass downstream of the separator termination point 22, interface 24 is established therebetween. As best shown in FIG. 3, the velocity of each fluid may be represented by the flow vector diagram shown where V_x is axial velocity, V_t is tangential velocity and V is actual velocity in the indicated direction. Fluid flowing in such a manner comes under the primary influence of two forces of significant magnitude, namely, centrifugal forces and forces due to the pressure gradient which exists in the duct through which the fluid is flowing. At a given radius, the centrifugal force, F_c, is proportional to the mass of the fluid, and consequently the density, ρ, of the fluid, and the square of the tangential velocity or tangential velocity component V_t, of the fluid. The pressure gradient force, F_p, is proportional to the radial pressure gradient and results from the radial difference in static pressure across the radially projected area of the fluid element. During the passage of the two fluids through annular passages **20** and **18**, these forces are in equilibrium, as best shown in FIG. **1** with respect to simulated fluid particles **26** and **28**, and the fluid flows in its helical path.

Downstream of separator **10**, where both fluids enter common annular passage **30**, the two fluids are in direct contact with each other and therefore are capable of influencing one another.

By viewing FIGS. **1** and **4** it should be noted that the static pressure distribution profile **32** for the outer swirling, usually hot fluid is considerable less steep than the static pressure distribution profile **34** of the inner swirling cold fluid, and this is reflected in the magnitude of the pressure gradient force, F_p, indicated to be acting upon the outer stream element **28** and the inner stream element **26** in FIG. **1**. These pressure gradient forces acting on elements **28** and **26** are balanced by the centrifugal force, F_c, action thereon because of the radial equilibrium of each individual stream.

By study and observations have lead me to the discovery that interface **24** between these two dissimilar fluids is unstable if the product parameter ρV_t^2, i.e., the product of the fluid density ρ and the square of the tangential velocity V_t of the fluid, of the outer radial fluid is less than that of inner radial fluid. This instability is demonstrated by introducing a disturbance into the interface **24** such that a local interface convolution **36** projects radially outwardly into the outer radius fluid region. The element of fluid **26'** in this projection **36** is exposed to the relatively small radial pressure gradient, F_{ph}, to the outer radius fluid region but still retains its high centrifugal force, F_{cc}. This establishes an unbalance of forces on element **26'** and results in an acceleration of the disturbance radially outward to cause the convolution size and penetration into the outer radius fluid to increase, thereby increasing the rate of mixing between the two fluids. In similar fashion, a convolution **38** of the interface **24** projecting radially inward will result in a force unbalance on fluid element **28'** which remains under the relatively small centrifugal force, F_{CH}, and comes under the influence of the substantially larger pressure gradient force, F_{pc}, and is consequently accelerated radially inward to result in rapid inward growth of convolution **38** and accelerated mixing between the two streams.

The relative magnitude of the unbalanced forces just described may be assessed by considering the outer fluid as a combusted gas from a combustion chamber which typically would lower the density by a factor of perhaps four relative to the unvitiated innerstream. Since the tangential velocity of the gas in a typical combustor pilot will change relatively to a smaller magnitude, the unbalanced force is seen to be three-quarters or more of the maximum centrifugal force on the two fluids. This magnitude of the unbalanced force is decidedly first order and represents a large acceleration potential available to expedite the radial movement of the two concentric fluids into a helical sheet mode of flow.

My invention is the utilization of this phenomenon in accelerating mixing between two dissimilar swirling fluids in annular combustion chambers of the type used in turbine engines to both accelerate combustion and accelerate the dilution of the hot products of combustion with cooling air before passage through the turbine.

While I have described this mixing phenomenon in FIGS. **1** and **2** in the context of coannular, dissimilar, swirling streams, it should be borne in mind that the same mixing acceleration can be achieved in other environments such as the bent tube environment shown in FIG. **5** wherein both dissimilar streams flow through duct **66** which includes a straight portion **68** and bent portion **70**, which has center of curvature **79**, and which has splitter or separation member **72** at its upstream end cooperating with duct **66** to define two passages **74** and **76** through which the two dissimilar streams flow with the fluid in the outer passage **74** having lower ρV_t^2 than the fluid in the inner passage **76** so that when the two fluids join in passage **78** they establish the unstable interface and accelerate mixing described in connection with FIGS. **1** and **2** as they become concentric swirling streams upon entering bent tube section **70**, in view of the fact that the product parameter relationship $\rho_h V_{th}^2 < \rho_c V_{tc}^2$, where ρ_a and ρ_c are the density of the hot outer, swirling stream and the cold, inner, swirling stream respectively, and V_{th} and V_{tc} are their respective tangential velocities, which are actually their through-flow velocities in the bent tube construction.

This accelerated mixing can also be established by use of the "barberpole" swirl mixer **80** shown in FIGS. **6** and **7**. The term "barberpole" is selected to describe this mixer because it causes the two dissimilar fluids to form into a series of interdigitated, swirling sheets or fingers. This mixer consists of outer wall **82** and inner wall **84** which preferably diverge to form diverging passages **86** through which the swirling main fluids flow and which have selectively oriented helical slots **88** and **90** extending therethrough, respectively, through which the secondary fluids flow and are caused to enter parallel to the main stream flow. As best shown in FIG. **7** the direction of helical slots **88** and **90** are such that they are locally parallel to the direction of the swirling main flow. By use of appropriate guide vanes and inlet conditions for the secondary flows the product parameter flow criterian: ρV_t^2 inner secondary $<\rho V_t^2$ main flow and ρV_t^2 outer secondary $< \rho V_t^2$ main flow are attained. With this flow criteria the sheets of secondary flow will penetrate rapidly across the main flow because the same mixing phenomenon previously described in connection with the FIG. **1** and **2** construction occurs here between each swirling fluid sheet and the two swirling sheets of dissimilar fluids adjacent thereto. Accordingly, total required mixing will occur more rapidly. In certain situations, it may be desirable to use a barberpole mixer of the type shown in FIGS. **6** and **7** in which the helical slots are used in one of the walls **82**, or **84** only. In the FIG. **6** and **7** "barberpole" construction, the main flow is preferably hot air and the secondary flows are cooler air and the slots **88** and **90** are oriented to bring about not only helical flow but helical flow substantially parallel to the main flow direction.

Any of these mixers, that is, the concentric mixer, barberpole mixer and the bent tube mixer can be effectively utilized in the combustion zone of a combustor or burner to increase the rate of mixing and hence rate of combustion and effective flame speed so as to reduce overall burner length as illustrated in FIGS. **8–12.** To emphasize similarity of function the reference numerals of FIGS. **1, 2, 6** and **7** will be repeated in describing the FIGS. **8–12** constructions.

In practice when using these mixers in the combustion zone of a combustor, one of the swirling streams is used as a hot pilot to initiate combustion in the other swirling stream, which is a fuel-air mixture. Burning occurs when the two streams mix.

We will now consider which stream to select as the pilot stream.

In the case of the concentric mixers and combustion chambers shown in FIGS. **8** and **9** and the bent tube combustion chamber shown in FIG. **12**, it is apparent that the pilot stream should be the outer stream because the density depression caused by heating helps in achieving the desired interfaced instability criteria ρV_t^2 inner > ρV_t^2 outer. In the barberpole mixers and combustors shown in FIGS. **10** and **11**, the choice of which stream will act as the heated pilot is not as obvious. In view of the density depression associated with fluid heating, it is apparent that the pilot stream should be one of the streams requiring a low ρV_t^2 product parameter and hence the pilot stream should not be the secondary flow in inner passage **114.** The main stream **112** should be chosen as the pilot stream to avoid the severe wall cooling problems which would be caused by injecting a hot gas secondary stream from passage **112** along outer walls **82.** In view of the low density of the pilot stream, the product parameter ρV_t^2 for the outer secondary fluid can be made smaller than the product parameter ρV_t^2 of the pilot to obtain the desired rapid mixing by permitting little or no tangential velocity V_t as it passes through slots **88.** The desired interface instability criteria between the pilot flow from passage **112** and inner secondary flow from passage **114** is satisfied by the use of the required turning vanes or the like to adjust the tangential velocity (V_t) level to satisfy the required criteria ρV_t^2 inner > ρV_t^2 pilot. Of course, the combustion process in the pilot decreases the density of this stream thereby assisting in satisfying this criteria.

FIG. **8** depicts a concentric mixer in a combustion chamber combustion zone where concentric passages **18** and **20** are formed between concentric ducts **12, 10** and **14** and wherein splitter duct **10** terminates short of the outer ducts so that the outer ducts form combustion zone **30** downstream thereof. Appropriately positioned inlet guide vanes or other mechanisms cause swirling fluid to pass through each of passages **18** and **20.** The flow in passage **20** serves as the pilot combustion stream in that pilot fuel is injected thereinto through pilot fuel nozzle mechanism **92** which sprays atomized fuel into the fluid passing therethrough just upstream of flameholder **94** to form pilot combustion zone **96** downstream thereof wherein the fuel-air mixture is burned and vitiated after appropriate ignition in combustion zone **96** so that the swirling fluid discharging from passage **20** becomes a pilot to ignite and sustain combustion in the swirling fluid passing through passage **18.** This fluid in passage **18** has fuel added thereto by secondary fuel injector **98** to form a fuel-air mixture of the characteristics that the product of its density and tangential velocity squared ρV_t^2 is greater than the corresponding product parameter for the outer swirling pilot stream of passage **20** so that accelerated mixing and subsequent combustion takes place between the two fluids in combustion zone **30.** The burner shown in FIG. **8** utilizes the premixed burning principle in that fuel is sprayed into the secondary stream **18** prior to entering the mixing and combustion zone **30** and this stream becomes a combustible fuel-air mixture that is subsequently ignited and vitiated when it is mixed with the hot pilot gases or flame from stream **20.**

Such a concentric mixer used as a combustor utilizing the diffusion burning principle is shown in FIG. **9.** The diffusion burning technique works on a different principle than the premixed burning technique. In the diffusion burning technique, the pilot fuel from nozzle **92** is fully combusted and fully vitiated in pilot combustion zone **96** such that little or no oxygen remains therein and, accordingly, any fuel added thereto downstream of fully vitiated interface **100** can be vaporized only by the hot products of combustion from pilot zone **96.** This phenomenon is taken advantage of in the diffusion burning principle and secondary fuel is discharged into stream **20** by secondary fuel nozzles **101** but this secondary fuel cannot burn until it is mixed with the secondary air being passed in swirl fashion through in stream **18.** In this case it will be seen that no fuel whatsoever is directed into stream **18** and that the pilot stream **20** carries not only the heat necessary to initiate combustion and mixing in mixing and combustion zone **20** but also carries the fuel to support this combustion process, when mixed with the air from passage **18.**

FIGS. **10** and **11** depict barberpole mixers of the type shown in FIGS. **6** and **7** utilized to form combustion chambers of the premixed burning and diffusion burning variety. In the FIG. **10** construction, ducts **102, 104, 106** and **108** are positioned concentrically about center line **16** to form coannular passages **110, 112** and **114** therebetween. Guide vanes or the like are used to produce swirling flow in passages **110, 112,** and **114** to achieve the desired tangential velocity V_t or, as in all other configurations disclosed, this flow may be accepted directly from a compressor which does not have straightening vanes at its outlet. Ducts **104** and **106** join walls **82** and **84** which define passage **86,** which is preferably divergent and is the main combustion zone **60.** Fuel is sprayed through pilot nozzles **92** into annular passage **112** to be combusted in pilot combustion zone **96** downstream of flameholder **94** to serve as the pilot stream. Secondary fuel is injected into passages **110** and **114** through secondary fuel nozzles **98** in atomized form to be mixed with the air passing therethrough and to pass therefrom through opposed helical slots **88** and **90,** respectively, to be discharged as a fuel-air mixture flow substantially parallel to the swirling pilot stream being directed from pilot combustion chamber **96** for accelerated mixing and subsequent combustion with the pilot stream in mixing and combustion zone **60.** As in the case of the "barberpole" mixer, the direction of flow of the secondary fuel-air mixture through slots **88** and 90 are adjusted by suitable guide vanes to satisfy the instability criteria ρV_t^2 outer secondary $<\rho V_t^2$ pilot and ρV_t^2 inner secondary $> \rho V_t^2$ pilot.

In the FIG. 10–11 construction, all air entering passage 96 enters with a selectively established tangential velocity V_t. This spinning of the air will lower the static pressure in the pilot combustion chamber 96. The premixed fuel-air mixture passing at a larger radius through passage 110 does not necessarily have swirl added thereto. In passage 110 air enters the combustion zone 60 through slots or helical hole pattern 88 in wall 82, such holes 88 are helical in nature or holes or slots designed in helical pattern. This air will accelerate radially through the holes 88 due to the static pressure drop across the holes or slots and once inside primary or pilot combustion zone 60, this air will continue to be accelerated radially inward because of the radial pressure gradient established by the swirling pilot fluid from passage 96 in combustion chamber 86. By admitting this fuel-air mixture through helical slots or holes or slots in a helical pattern, 88, a very rapid combustion pattern of helical layers will be established in the main combustion zone 60. The fuel-air mixture layers thus formed are burned as interdigitated mixing with the swirling air from the pilot proceeds. As the fuel-air mixture through slot 88 is burned, its radial inward motion is locally further accelerated because the consequent decrease in the density lowers its ρV_t^2 product parameter even further and the radial pressure gradient will accelerate a small portion of burned gas faster than unburned gas. The portion of the fuel-air mixture which passed through helical slots or hole pattern 90 has a tangential velocity V_t imparted thereto that is sufficiently high for $\rho V_t^2 > \rho V_t^2$ of the vitiated pilot gases. Therefore the admitted fuel-air mixture will form helical sheets which will interdigitate with the hot spinning air entering zone 60 from the pilot region 96 and be accelerated radially outward. While the density, ρ, of the locally burned surface layer of the swirling fuel-air mixture streams will decrease substantially during burning, it will retain the same tangential velocity, V_t, since its angular momentum is unaffected by the change of thermodynamic state. Consequently, the local ρV_t^2 product parameter of the sheets entering through the slots 90 will be substantially reduced and its acceleration due to the radial pressure gradient will also be reduced as the sheet burns. However, the unburned portion of the helical layer will continue to be accelerated radially outward, thus continuing to stir the flame front until it is completely burned.

Viewing FIG. 11 we see the barberpole mixer used as a combustion chamber utilizing diffusion burning in which concentric, preferably cylindrical ducts 102, 104, 106 and 108 are positioned concentrically about center liner axis 16 to form coannular passages 110, 112, and 114 therebetween, with ducts 104, 106 extending into preferably divergent walls 82 and 84 to form section 86 which defines the main combustion zone 60. Pilot fuel from nozzles 92 is admitted in atomized form to passage 112 upstream flameholder 94 to be fully conbusted and vitiated in pilot combustion chamber 96 so that the products of combustion are fully vitiated upstream at interface 100. Secondary fuel is admitted to annular passage 112 downstream of interface 100 through secondary fuel nozzle 101 to be heated and carried with swirling combustion products of the pilot combustion chamber 96 into combustion zone 60, secondary air is passed through annular ducts 110 and 114 and through opposed helical slots 88 and 90, respectively, into mixing and combustion chamber 60 to be mixed with, the hot, fuel rich, flow from pilot stream duct 112. As the mixing process proceeds the excess fuel in the pilot stream comes into contact with the sheets of secondary air entering through slots 88 and 90 and combustion occurs at the multiplicity of interface between these flows.

FIG. 12 depicts a bent tube mixer in the form of a folded burner or combustor of the premixed burning variety. In the FIG. 12 premixed burning configuration, the first fluid is passed through passage 74 to have atomized fuel added thereto from pilot fuel nozzle 92 and so that a pilot combustion zone is established at 96 so as to provide an outer pilot stream entering the curved section 70 of curved duct 66 to serve as a pilot to institute mixing with and subsequent combustion of the fuel-air mixture being introduced through passage 76 into mixing and combustion chamber 30. The fuel-air mixture in passage 76 is generated by the passage of fluid therethrough and the introduction of atomized fuel thereinto through secondary fuel spray nozzles 98. It will accordingly be seen in the FIG. 12 construction that a hot pilot stream is established as the outer swirling stream with respect to the inner colder fuel-air mixture stream, both of which are concentric about center of curvature 79 to cause accelerated mixing and combustion therein in view of the flow criteria ρV_t^2 inner $> \rho V_t^2$ outer. It will be evident to those skilled in the art that the construction shown in FIG. 12 could be made of the diffusion variety by moving pilot fuel nozzle 92 and flameholders 94 farther upstream so that combustion in the pilot combustion zone 96 is completed and a fully vitiated interface corresponding to 100 of FIG. 9 is established sufficiently far upstream of the termination of splitter member 72 that secondary fuel can be injected into passage 74 upstream of the termination of splitter member 72 to be introduced into combustion chamber 30 in uncombusted form for mixing and combusting with secondary air which would flow through passage 76.

To assist in accelerating mixing between the two swirling flows in the concentric and bent tube mixers, it is sometimes desirable to use trigger mechanisms at the end of ducts which serve as splitter ducts between the swirling flow of two different fluids, such as triggers 164 and 166 shown in FIG. 14, to physically disturb the interface between the swirling fluids. A discussion of the theory of operation of these trigger mechanisms is believed to be helpful at this point and reference is first made to FIGS. 30 and 31 in this regard. In FIG. 30 we see trigger mechanism 166 positioned at the downstream end of splitter duct 246 which is of circular cross section and positioned concentrically about axis 16 and cooperates with outer cylindrical duct 248 and inner cylindrical duct 250 to define outer annular gas passage 252 and inner annular gas passage 254. For purposes of illustration, it should be considered that a hot fluid, which is to be the pilot fluid, is passed through passage 252. This hot outer fluid has a density ρ_h and a tangential velocity V_{th}. A second fluid, which is preferably a cold (high density) combustible mixture, is passed through inner annular passage 254 and has a density of ρ_c and a tangential velocity V_{tc}. To effect accelerated mixing between these two fluids of passage 252 and 256, it is essential that the mixing criteria ρ_h

$V_{th}^2 > \rho_c V_{tc}^2$ exists to establish an unstable interface between two swirling fluids. Above and beyond this, the use of trigger **166**, which is shown to be a convoluted sheet metal ring member attached to the downstream end of splitter duct **246** further serves to accelerate mixing and combustion. Trigger **166** defines convolutions which follow helical paths growing in amplitude in a downstream direction and as the fluids of passage **252** and **254** pass thereover, a regular pattern of radial fluid motion will be initiated outwardly and inwardly due to the change of flow direction imparted to the fluids by trigger mechanism **166.** The motion thus initiated will grow because of the instability of the interface. Such a trigger mixer has been successfully demonstrated using air at 200° Fahrenheit and 800° Fahrenheit as working media.

The amount of tangential mixing induced by fluid shearing at the helical sheet interface will depend upon the difference between the circulation per radian of the fluids in ducts **252** and **254.**

The use of trigger mechanisms provides the advantage of controlling the location, size and shape of the disturbance at the interface between the two fluids and it will be appreciated that in constructions where trigger mechanisms are not used the disturbance of the interface is caused by turbulence only and is therefore random in nature.

Of particular interest is a piloted combustion application of such a triggered inside-out mixing configuration as shown in FIGS. **30** and **31.** Here, the hot vitiated pilot flow would be the outer radius fluid having a low ρV_t^2 product parameter, while the cold combustible mixture would be the inner radius fluid having a high ρV_t^2 product parameter. FIG. **31** is a showing of the combustion-pilot primary combustion zone downstream of trigger **166.** The flame front where active combustion occurs is located at the interface **255** and **253,** respectively, of the triggered helical sheets of hot pilot flow from duct **252** and cold combustible mixture flow from duct **254.** As shown in FIG. **31,** the flame speed, F/S, moves against the trigger helical current of the combustible mixture flowing radially outward and into the hot mass of pilot flow. As the combustion occurs at the flame front, elements of air undergo an abrupt density change in a high centrifugal field with resultant release of the acceleration potential to magnify the local turbulence and effective flame speed. This local stirring action, i.e., increased turbulence, is superimposed upon the interface of the triggered mixing of the initial hot pilot and cold combustible mixture flows. The triggered hot pilot gas from passage **252,** which comprises a radially inward directed current, has an interface flame speed that moves with the current, as well as laterally into the unburned mixture. Again, the local magnitude of turbulence is increased at the flame front by the abrupt fluid density changes in a strong centrifugal field which increases the effective flame speed. The difference in circulation per radian for the initial hot pilot flow and cold combustible mixture provides a superimposed tangential mixing through tangential shearing action.

Another trigger mechanism, which could be used as a substitute for trigger **166** in the FIG. **14** and **30** construction, is shown in FIGS. **32** and **33.** As shown in FIG. **32,** splitter duct **246** and ducts **248** and **250** are used in the same fashion as in the FIG. **30** construction. Hot products of combustion flow between ducts **246** and **248,** while the cooler fluid, such as a fuel-air mixture, flows in the passage between ducts **246** and **250.** Trigger mechanism **258** is located at the downstream end of splitter duct **140** and consists of a series of oppositely oriented vane **260** and **262** pairs forming vortex generators which are spaced circumferentially about splitter duct and extending radially outwardly from the splitter duct and in any desired number of axially spaced rows. Once again, it is the object of trigger mechanism **258** to convolute the interface between the hot products of combustion flowing on one side of splitter duct and the cooling air or fuel-air mixture flowing in passage **130** on the other side of the splitter duct so as to take advantage of the mixing criteria in that the ρV_t^2 product parameter of the hot gases flowing at the greater radius is less than the ρV_t^2 product parameter of the cold air or fuel-air mixture flowing at a lesser radian at the interface therebetween and any convolution will react with the respective pressure gradients in the hot and cold regions to cause radial mixing currents with cold air currents moving into the hot flow in helical sheets and the hot fluid currents moving into the cold region in helical sheets. The flow at the interface downstream of the trigger plane is unstable and the trigger configuration establishes the helical sheet mixing patterns. This mixing occurs from the inside (minimum radial station) to the outside (maximum radial station) and shortens the length of the combustion chamber and engine by accelerating the mixing process.

Referring to FIG. **34** we see still another modification of a splitter duct trigger which could be used in place of trigger **166** of FIG. **14.** The trigger of FIG. **34** consists of a series of helically oriented and circumferentially positioned slots **260** at the downstream end of splitter duct **140.** The slots are preferably oriented to be parallel to the direction of flow, V, of either the hot or cold gas streams and serves to trigger or disturb the unstable interface which exists between the swirling hot gas flow from the combustion chamber flowing outside splitter duct **140** and the swirling colder air of the cooling gas stream flowing inside of the splitter duct **140** so as to accelerate intermixing.

An additional trigger embodiment is shown in FIG. **35** wherein a plurality of helically extending and circumferentially positioned slots **262** are positioned forward or upstream of slots **260** of the type shown in FIG. **34.** Thereby adding to the mixing advantage of the trigger device by utilizing plural slot rows and/or patterns.

Still a further trigger configuration is shown in FIGS. **36** and **37** wherein slots comparable to slot **260** of FIG. **34** are fabricated so as to be elongated and are circumferentially positioned helical slots **264.** In this configuration, the after end of splitter duct **140** is fabricated, as shown in FIG. **37,** to be corrugated in shape so that the FIG. **36** and **37** trigger is a combination of the slotted trigger of FIG. **34** and the convoluted trigger of FIG. **30.**

Still another form of trigger is shown in FIG. **38** wherein scoops **266** are added to helical slots **268,** which are comparable to slots **260** of FIGS. **34** and **35** and which serve to scoop the cold spinning air from a construction comparable to the FIG. **14** construction flowing on the outside of splitter **140** into the hot region radially inward of the splitter duct **140** where the products of combustion from combustion chamber **60** flow, thus triggering the mixing pattern downstream of the splitter duct plane. This FIG. **38** construction will set up helical spinning layers of hot and cold air to mix downstream of the splitter duct. While but a single row of such scooped slots are shown in FIG. **38**, it should be realized that more than one row or a pattern thereof could be used, as is shown in FIG. **35** without scoops.

For improved acoustic properties and for improved combustion of the trigger **166**, it is recommended that trigger **166** be made of sheet metal with a series of small holes **257** therein and preferably, scoop member **259** (see FIG. **53**) to be associated with holes **257** to force small jets from the cold side of the trigger to flow to the hot side to cool the trigger and to also introduce a fine scale of disturbance or turbulence to improve combustion.

As mentioned previously, acoustic benefit can be gained by utilizing perforations in the corrugated trigger of the type shown in FIG. **50** and this is important because large amplitude noise has been shown to affect combustion efficiency adversely. Additional noise suppression can be achieved by varying the height and width (distance between) of the trigger corrugations or other trigger mechanisms, and also varying the cycle of the trigger pattern peripherally to achieve noise suppression, thus producing spiraling or helical sheets of hot and cold gases having different frequency response. Such a configuration is depicted in FIG. **39** wherein *h* represents height or amplitude of the convolutions and *l* and *m* represent different corrugation widths.

An engine of the type in which my invention may be used is shown in FIG. **13** as turbine engine **40**, which consists of a compressor section **42**, a burner or combustion section **44**, a turbine section **46**, and may have an afterburner section **48**, which terminates in a variable area nozzle **50**. Engine **40** is preferably of circular cross-section and concentric about axis **52**. Combustion section **44** includes outer casing **54** and and annular combustor combustion chamber **56**, which consists of diffuser inlet section **58**, combustion zone **60** and dilution zone **62**. As used herein, the term "annular combustion chamber" means a combustion chamber having an annular passage extending from the inlet, or upstream end, to the outlet, or downstream end thereof. Fuel is supplied to combustor **56** by variable output fuel pump **64** which is either under pilot manual or pilot set automatic control, and is fed into the inlet of combustor **56** in a fashion to be described hereinafter, to be mixed therewith with a portion of the pressurized gas from compressor section **42** to form a combustible fuel-air mixture to be burned in combustion zone **60**, from which the products of combustion pass into dilution zone **62** for mixing with dilutant cooling air also from the compressor to lower the temperature thereof prior to entry into turbine section **46**. Engine **40** may be of the type more fully described in U.S. Pat. Nos. 2,747,367, 2,711,631 and 2,846,841.

A typical combustor system or section **44** of a turbine engine of the type shown in FIG. **13** may be considered to be composed of two components in series, namely, a combustion zone **60** in which fuel is burned in a portion of the total engine air flow from the compressor and a dilution zone **62** in which the balance of the air flow is mixed with the hot products of combustion from the combustion zone so that a substantially cooler mixture than the products of combustion is passed through the turbine **46**. Any combination of concentric mixtures, barberpole mixers, and bent tube mixers, can be used to perform the combustion zone region mixing and combustion function and the dilution zone region mixing and cooling functions of such a combustion section **44**.

Referring to FIG. **14** we see annular combustion chamber **56** which comprises outer case **54** and inner case **113**, which are preferably of circular cross-section and mounted concentrically about axis or center line **16**. The air from the compressor section **42** of FIG. **13** enters annular inlet **114** in either swirling flow or non-swirling flow depending upon the discharge conditions from the compressor section **42**, and portions thereof pass through pilot passage **124**, main combustion zone fuel preparation passage **126** and the dilutant air passage **130**. Further quantities of air flow through passages **122** and **132** to provide for cooling the walls of the combustor chamber. Vanes **116, 118, 120** and **128** are employed as required to swirl or straighten the flow in the respective passage so as to satisfy the previously defined mixing instability criteria. Each of the passages **122, 124, 126, 130** and **132** are of annular shape since the outer burner liner **134**, the inner burner liner **136** and splitter ducts **138** and **140** are of circular cross-section and concentric about axis **16**. Turning vanes **116** and **118, 120** and **128** may be fixed or any or all vanes could be of the variable angle type as shown, for example, in FIG. **15** wherein each of vanes **116** is pivotally connected to duct **134** and outer housing **54** by pivot pins **144** and **146**, respectively. Pivot pin **146** extends through outer case **54** and carries ring gear **148** at its outer end, which engages circumferentially rotatable ring or annular gear **150**, which is pilot operated to rotate circumferentially about axis **16** by motion of pilot actuated lever **152** into and out of this plane of the paper, thereby causing vanes **116** to rotate in unison and thereby vary the tangential velocity V_t of the gas or fluid passing thereby. The swirling air which entered passage **124** has atomized fuel added thereto by fuel injection device **156** to form a fuel-air mixture which is ignited by ignitor **158** and vitiated in pilot combustion chamber **160** which is located downstream of aperture-type flameholder **161**, which is a tilted and apertured plate extending between ducts **134** and **138**. The hot swirling stream emerging from passage **124** serves as a pilot stream for combustion chamber **60**. The swirling air entering passage **126** has atomized fuel added thereto by injection member **162** and the amount of fuel to be discharged into passage **124** and **126** can be regulated by the size and number of fuel nozzles, such as **162** located therein and by pilot controlled valves **163** and **165** located in the fuel line thereto. The atomized fuel entering passage **126** mixes with the swirling gas passing therethrough to provide a combustible fuel-air mixture to combustion chamber **60** for accelerated mixing pilot stream emerging from passage **124** and subsequent combustion of this flow. It will accordingly be seen that hot swirling pilot stream emerging from passageway **124** to mix with and sustain combustion in the fuel-air mixture emerging from passageway **126** and the thermodynamic and aerodynamic characteristics of these two streams are established so as to satisfy the rapid mixing criteria $\pi V_t^2 > \rho V_t^2$ outer. This may be attained by adjusting the tangential velocity V_5 in each stream through a suitable selection of the discharge angle of the vanes **118** and **120**. It should be noted that the combustion process in the pilot duct **124** depresses the density ρ of this stream relative to that in duct **126** which assists in satisfying the desired rapid mixing criteria. The products of combustion from combustion zone **60** then pass into dilution chamber **62** in swirling, concentric flow relationship to the cooling air being passed into dilution zone **62** through cooling air passage **130** to again satisfy the aforementioned unstable interface product parameter criteria ρV_t^2 (cooling air) $>\rho V_t^2$ (products of combustion) between the swirling product of the combustion stream and the swirling cooling air stream to accomplish accelerated mixing and hence accelerated reduction of the temperature of the products of combustion before passage into turbine section **46.**

It will therefore be seen that in the FIG. **14** configuration, the unstable interface criteria between two swirling, dissimilar fluids is used in the concentric mixer hardward shown therein to constitute the combustion zone and the dilution zone of an annular combustion chamber.

The means and method for establishing, regulating or varying the density and tangential velocity of the swirling fluids described in connection with FIG. **14** can also be used with all other constructions previously described or to be described hereinafter.

Trigger members **164** and **166** are positioned at the downstream end of splitter ducts **138** and **140** to perform a function to be described in particularity hereinafter.

The cooling air from passage **132** passes through apertures **168** and **170** in inner liner **136** to perform a cooling function with respect to the liner. The outer liner is cooled by cooling air from passage **122** which is passed through vane cascades **172, 174,** and **176** to cause the cooling air to flow along the inner wall of outer line **134.** The angularity of the vanes in the cascade is selected so that a stable interface criteria exists between cooling air and the hot gases of the combustion chamber, that is, so that the product ρV_t^2 (cooling air) $>\rho V_t^2$ (combustion gas). Apertures **168** and **170** of the inner liner **136** may be replaced by vane cascades such as **172** and a stable interface would be established by selective vane positioning so that ρV_t^2 (products of combustion) $>\rho V_t^2$ (cooling air).

Referring to FIG. **16** we see another annular burner but this time of the type in which both the mixing and the combustion zone and the mixing in the dilution zone is accomplished by means of a barberpole mixer. Again the combustor **56** includes outer housing **54** and inner housing **113.** The air again enters annular inlet **114** from compressor section **42** and after a portion of the flow is mixed with fuel and combusted in combustion chamber **60** and having the products of combustion diluted in dilution zone **62,** the hot gases then pass through turbine section **46.** The air from inlet **114** flows either through selectively positioned guide vanes **121** and **123** into cooling annular passage **122,** annular cooling passage **132,** respectively, or through selectively positioned guide vanes **116, 118, 120** as required into combustion zone **60.** Vanes **116** through **123** could as well be the variable area type shown in FIG. **15.** The barberpole mixer for combustion zone **60** operates much as previously described in connection with the comparable premixed combustor mixer application shown in FIG. **10** and comparable reference numerals will be repeated to emphasize similarity. The air which passes vanes **116** and **120** enter annular passages **110** and **114** respectively, and have fuel added thereto by secondary fuel nozzles **98** before passing through helical slots **88** and **90** into divergent section **60** as swirling fuel-air mixtures of the tangential velocity V_t of which has been established so as to produce the desired product parameter ρV_t^2. As best shown in FIG. **17,** helical slots **88** and **90** are directed locally parallel to the direction of the flow leaving passage **112** and are shown in opposite directions and while but a single row of slots is shown in both outer duct **82** and inner duct **84,** it should be borne in mind that any number of rows of slots or slot patterns could be selected. The remainder of the inlet air passes through guide vanes **118** as required has fuel added thereto through the fuel nozzles **92** and is ignited by ignitor **180** to establish a swirling pilot flame in combustion zone **96** entering the main combustion section **60** with selected ρV_t^2 product parameter, that is, so that product parameter ρV_t^2 for the inner fuel-air mixture from passage **114** is greater than the product parameter ρV_t^2 for the pilot zone from passage **112,** which is in turn greater than the product parameter ρV_t^2 of the outer fuel-air mixture from passage **110** to produce accelerated compound, radially staged mixing and combustion in combustion zone **60** from which the product of combustion then pass into dilution zone **62.**

Cooling air enters dilution zone **62** from cooling passage **122** through a plurality of helical slots such as **182** which extends about the periphery of outer line **184** and includes inlet guide vanes **186** extending across passages **182** to control the direction of flow inlet in cooperation with the helical slots **182.** An unwrapped view of liner **184** is shown in FIG. **18** and the direction of local flow along the inner liner **184** is shown by arrow **188** in direction V (see FIG. **3**) with slots **182** helically inclined to axis **16** and extending in the local flow direction V. Guides **186** are selected to direct the dilutant coolant flow into dilutant zone **62** from cooling air annulus **122** in the desired direction, that is, with little or no tangential velocity so as to satisfy the desired accelerated mixing by satisfying the mixing criteria that the ρV_t^2 product parameter of the dilutant flow from passage **122** is less than the ρV_t^2 product parameter of the products of combustion. Similarly, a series of helical slots **190** are positioned in inner liner **192** and a series of such slots extend circumferentially around the periphery thereof and include inlet guides **194.** An unwrapped view of inner liner **192** will show that slots **190** are similar slots **182** of the outer liner **184** and guide vanes **194** are similar to guide vanes **186,** except that it is desirable that slots **192** and guide vanes **196** cooperate to produce a dilutant or coolant flow into the dilutant zone **62** which has a high tangential velocity V_t and therefore, as best shown in FIG. **19,** the guide vanes **194** include side guides **196** and **198** to produce the desired tangential velocity V_t to satisfy the mixing criteria that the ρV_t^2 product parameter of the cooling air or dilutant passing through slots **90** is greater than the ρV_t^2 product parameter of the products of combustion in dilutant zone **62.** The products of combustion so diluted by compound, radial staged mixing then pass into turbine **46.** It will be noted that in the combustion chamber construction shown in FIG. **16,** barberpole mixing from both walls is shown both in the combustion zone and in the dilutant zone. To be specific, mixing occurred in the combustion zone both between the pilot zone flow from passage **96** and the fuel-air mixture entering through slots **88** and **90.** It will be noted that similar mixing occurs through radially spaced slots **182** and **190** in dilution zone **62.**

It should be noted that while a particular type of guided vane slot is shown in connection with the FIG. **16–19** construction, multiple slots can also be employed in the combustion or dilution zones, as best shown in FIG. **20** where a plurality of vaned, helical slot rows are utilized.

As previously described in connection with FIG. **14,** cooling air enters the interior of outer liner **184** of FIG. **16** through selectively positioned guide vanes **172** and **174** so as to hug the interior wall of liner **184** for liner cooling purposes. In similar fashion, cooling air enters dilution zone **62** through aperutures **168** and **170** to perform the function of cooling inner liner **192.**

Now referring to FIG. **21,** we see another modification of my annular burner which utilizes a concentric mixer in the combustion zone and a barberpole mixer in the dilution zone. In operation, the concentric mixer of the combustion zone is the same as the mixer previously described in connection with the combustion zone of the burner of FIG. **14** and the barberpole mixer in the dilution zone is the same as previously described in connection with the dilution zone mixer of FIG. **16,** the same reference numbers will be used herein, as in FIGS. **14** and **16** and a brief description only of the operation will be given here and reference directed to the previous detailed descriptions. Again, the compressed air from the compressor, which may or may not be swirling depending on the discharge conditions from the compressor, enters annular inlet **114** and then divides to pass through vanes **116** and **202** and enter either annular cooling passages **122** or **132,** respectively, or through inlet guide vane **118** and **120** to have fuel added thereto by fuel spray nozzle **162** to form pilot combustor **160** in annular passage **124** the hot gases from which mix with and sustain combustion in the fuel-air mixture passing through passage **126.** The products of combustion then pass into dilution zone **62** for accelerated mixing with the cooling or dilutant air from passages **122** and **132** which enter through the previously described slots **182** and **190** to form helical sheets of cooling air to interdigitate with the products of combustion in the dilution zones **62** for accelerated cooling thereof prior to passage into the turbine **46.** In all other respects the concentric mixer of the combustion zone **60** and the barberpole mixer of the dilution zone **62** of the FIG. **21** construction are fabricated and operate as previously described in connection with the concentric mixer of combustion zone **60** of FIG. **14** and the barberpole mixer of the dilution zone **62** of FIG. **16.**

Once again, the important feature is to control the ρV_t^2 product parameter of the swirling streams so as to accelerate mixing therebetween as required and described supra primarily by the use of vanes **116, 118, 120** and **202,** as required.

Referring to FIG. **22,** we see a modification in which a bent tube mixer is used to form the dilution zone in a folder burner or combustion chamber. In the FIG. **22** construction, annular bent tube or folded combustion chamber **56** is position between compressor **42** and turbine **46** and includes combustion zone **60** of any selected type, such as a conventional zone chamber as shown in U.S. Pat. No. 3,498,055, a concentric mixer combustion zone shown in FIG. **14** or a barberpole mixer combustion zone shown in FIG. **16.** The portion of the compressed air from compressor **42** which does not go through combustion zone **60** flows as coolant or dilutant flow through annular passage **204** and enters dilution zone **62** with the products of combustion from combustion zone **60** but a smaller radius with respect to center of curvature **79,** about which coannular bent ducts **204** and **206** are concentric as previously described in connection with FIG. **12.** The swirling motion about center of curvature **79** imparted to the dilutant flow and the products of combustion in bent tube dilution zone **62** establishes the accelerated mixing criteria required in this construction wherein the ρV_t^2 (dilutant flow)$>\rho V_t^2$ (products of combustion) to effect maximum mixing and hence cooling of the products of combustion before passing through turbine **46.**

It will be evident to those skilled in the art that following the teachings of my invention, either the combustion zone or dilution zone can be conventional as taught in U.S. Pat. No. 3,498,055, and the nonconventional zone, whether combustion or dilution zone, can be either of the concentric mixer construction, the barberpole mixer construction, or the bent tube mixer construction previously described.

While a particular type of pilot combustor is shown and described in the concentric mixer used in the combustion zone of the FIG. **14** construction, there are modifications which can be used as the pilot combustor construction in this concentric mixer environment and these modifications will now be discussed.

In configurations using the previously described premixed principle, where vanes are used, it may be of advantage in injecting the fuel upstream of the vanes. These advantages include the fact that the presence of the vanes between the fuel source and the combustion zone will prevent flashback from the combustion zone to the fuel nozzle location. Secondly, secondary flows will be established in the vane passage to assist fuel atomization and disperson. Examples of this type of construction are shown in FIG. **23** for a burner using a concentric mixer and in FIG. **29** for configurations using a barberpole mixer.

FIG. **23** shows fuel injection forward of the flow turning vanes in a combustion chamber using a concentric mixer and could be used as a substitute for the FIG. **14** mixer. The remainder of combustion chamber **56** is shown in previously described FIG. **14.** FIG. **23** shows a primary combustion zone for a swirl type annular combustion chamber. Pilot zone **124** is used in conjunction with secondary fuel-air mixture preparation zone **126.** The turning vaned cascades **208** and **210** are shown at the same axial stations but may be displaced axially if desired. In the FIG. **23** construction the vane cascades **208** and **210** are positioned close to the entrance of diffuser section **58** to impart additional swirl velocity to the incoming air beyond what is imparted thereto by the compressor **42** and could simultaneously diffuse the axial component V_x of the total gas velocity. Fuel is injected upstream of cascades **208** and **210** through apertured fuel manifold rings **214** and **216** which spray fuel forwardly against splash plates **218** and **220** to be atomized in this fashion and carreid through vanes **208** and **210** into passages **124** and **126.** Thus fuel injection mechanism may be of the type taught in U.S. Pat. No. 3,269,115. Fuel injection mechanism **214** is preferably placed in alignment with the flameholder **212**, to minimize drag and aid in maintaining stable combustion on said flame holder. It should be noted that when the cascades **208** and **210** are used, thus there is no change in static pressure, and the axial velocity V_x component is reduced at the same time that the tangential or swirl velocity V_t is increased. Since a small rise in static pressure can be tolerated in the cascade, when properly designed the cascade is a more effective method of reducing velocity V_x than thebasic diffuser itself, within the limits of the desired magnitude of tangential velocity V_t of the gas. It is preferable that the vanes of cascades **208** and **210** be closely spaced so that a flame trap is simultaneously achieved.

The higher velocity gas flow through the closely spaced vanes of cascades **208** and **210** will prevent flashback of the flame from the combustion chamber to the fuel nozzles. A small trough-shaped flameholder ring **212** is positioned concentrically about the axis **16** and is utilized to stabilize the recirculation zone **160** of the pilot zone. Recirculation affects axial velocity V_x only, and has no effect upon the swirl velocity V_t.

An ignitor such as **158** of FIG. **14**, ignites the fuel-air mixture in passage **124** and this ignited mixture serves as a pilot for the fuel-air mixture being passed through passage **126** for accelerted mixing and combustion zone **60**. A trigger **166** may be utilized if desired.

The second advantage to be gained in the FIG. **23** construction by positioning turning vanes **208** between the combustion chamber **60** and the fuel injection means **214** is best illustrated by referring to FIG. **28**. As best shown in FIG. **28**, the helically disposed vanes **208** generate boundary layers along their radial surfaces which interact with the pressure gradients in the gas flow passing between the vanes to generate a secondary flow pattern shown in FIG. **28**. This pattern stirs the droplets and vapor of the fuel-air mixture to effect a more uniform mixture as well as accelerate fuel droplet evaporation. Downstream of vanes **208**, the vane wakes continue to react with the radial pressure gradient and the secondary flow resulting from this interaction moves helically in a pattern downstream of the helical vanes. The same secondary flow recirculation pattern illustrated in FIG. **28** and described above in connection with vanes **208** will also be occuring between vanes **210** in the FIG. **23** configuration.

The barberpole construction utilizing fuel injection upstream of the flow turning vanes to achieve advantages of the flashback abatement and secondary flow fuel dispersion assist is shown in FIG. **29**.

The FIG. **29** construction is a modification to the barberpole mixer of the combustion section of the FIG. **15** construction. In this construction of the modified annular burner, which operates like the previously described FIGS. **10-11** constructions, and corresponding reference numbers will be used where possible, the combustion air which enters annular inlet **114** with virtually no swirl in it passes either into cooling annular passages **122, 130** or **132** and the remainder passes into the divergent portion **58** of the combustion chamber **56**. Atomized fuel is added to the air early in the diffusion process by conventional fuel nozzle manifolds **224**. The manifolds being placed so that one or more serves each passage. A cascade of turning vanes **234** is located at the entrance of annular passage **124**, which defines pilot zone **160** and in passing through vanes **234**, the air is caused to swirl as it flows into the early sections of the diffuser shaped pilot combustion zone **160**. A conventional flameholder ring of trough-shaped cross-section **212**, which could be V or U shaped or round, is positioned radially mid-way of vane cascade **234** to stabilize a recirculation zone for supporting combustion downstram thereof after the fuel-air mixture is ignited by an appropriate sparking device, such as spark plugs **228**. The annular construction of passage **124** will result in flow recirculating rearwardly of flameholder **212**. The premixed fuel-air mixture passing at a larger radius through passage **236** does not have swirl added thereto and may have residual swirl removed therefrom by vane cascade **235**. In passage **236** air enters the combustion zone **160** through slots **88**. The portion of the fuel-air mixture which passes through vaned cascade **240** has a tangential velocity V_t imparted thereto equal to or greater than that of the vitiated pilot gases and this swirling mixture from cascade **240** is introduced through helical slots **90** into the main combustion chamber **60** at a ρV_t^2 product parameter higher than that of the hot products of combustion entering zone **60** from the pilot. The operation of the FIG. **29** construction is as previously described in connection with FIGS. **10–11** except that fuel is injected upstream of the turning vanes to gain the two advantages discussed above.

A modification of my swirl burner concentric combustion zone mixer of the type shown in FIG. **14** is shown in FIG. **24**. In the FIG. **24** construction, turning vanes **118** and **120** may be used at the entrance of the diffuser section **58** of annular combustion chamber **56** to impart the necessary swirl to the incoming air, if the normal compressor does not have the proper swirl for the particular environment. Fuel is added to the air passing through annular passage **222** as spray from conventinal fuel spray manifolds, such as **224**. Instead of the use of a splitter duct, such as duct **138** of FIG. **14**, the FIG. **24** modification proposes a selectively shaped and positioned flameholder mechanism **226**, which is shown as a combined flameholder trigger mechanism, to cooperate with spark plug **228** in igniting and sustaining combustion in the swirling fuel-air mixture passing through passage **222**. As best shown in FIG. **25**, flameholder **226** is preferably shaped to constitute a spiral (helical) type of convoluted flameholder ring attached to and carried by the outer burner case **134**. The helical orientation of the convolutions of flameholder **226** are selected to essentially conform with the helical path of the fuel-air mixture, direction V of FIG. **3**, flowing in passage **222** in the vicinity of the flameholder. Flameholder **226** has a plurality of holes or slots **229** therein through which a premixed and preferably all vaporized or partially vaporized, fuel-air mixture passes to burn inside and downstream of flameholder **226**. The hot combusted gases passing out of and downstream of the flameholder also have a tangential velocity component V_t imparted thereto by the shape of the convolutions of the flameholder and by their initial swirl. The product of the density, ρ, and the tangential velocity, V_t, squared, that is, the product parameter ρV_t^2 of the hot mixture downstream of the flameholder is established to be smaller than the comparable product parameter of the fuel-air mixture passing outside of the flameholder and, accordingly, at the interface **227** just downstream of this convoluted flameholder **226**, the hot gases of combustion and the unburned fuel-air mixture mix and burn rapidly as a result of this product parameter difference. Accordingly, rapid mixing and combustion takes place in the combustion zone **60** for eventual mixing and dilution of the products of combustion thereof with the mixing air passing through passage **130** as in the FIG. **14** construction. In the FIG. **24** construction, a spirally shaped flameholder serves to hold pilot flame and physically disturb the unstable interface between the pilot products of combustion and the fuel-air mixture, and thereby trigger this instability to accelerate mixing and combustion.

A variation of my FIG. **24** construction is shown in FIGS. **26** and **27**. This construction is otherwise similar to the FIG. **25** and the FIG. **14** construction, and operation is the same. The advantage taught in the FIGS. **26–27** modification is that when inlet turning vanes are required they may be selectively positioned and used in conjunction with the helical, spiral flameholder **226** of FIG. **25**. Vanes **230** are helically disposed at the entrance portion of combustion chamber **56** and generate secondary flows inside the vane defined passages previously described in connection with FIG. **28** and to continue this secondary flow pattern downstream of the vane passages so that the triggering or mixing function of the helically disposed and convoluted pilot combustion chamber is enhanced.

The helically disposed vanes **230** generate boundary layers along their radial surfaces which interact with the radial pressure gradient of the gas flow passing through passage **222** to generate a secondary flow pattern shown in FIG. **28**. This pattern stirs the droplets and vapor of the fuel-air mixture to effect a more uniform mixture as well as accelerate fuel droplet evaporation. Downstream of vanes **230**, the vane wakes continue to react with the radial pressure gradient and the secondary flow resulting from this interaction moves helically in a pattern downstream of the helical vanes. By having the helical vanes **230** oriented so that their radial intersection with the spiral, convoluted and perforated flameholder **226** occurs at the flameholder troughs **232** and the trailed edge of vane **230** is upstream of the end of flameholder **226**, the result is that the trailing secondary flows align themselves to foster and assist the mixing instigation or triggering action of flameholder **226**. It will accordingly be seen that the spirally shaped turning vanes **223** coact with the spirally shaped flameholder **226** to foster the hot products of combustion fuel-air mixture mixing and burning function of the flameholder.

My experieince has further shown that a swirling type combustion chamber of the type taught herein lends itself to effecting improved diffuser performance in a manner now to be described.

As best shown in FIG. **40**, the diffuser section **58** of annular combustion chamber **56** is define between outer wall **268** and inner wall **270** which cooperate to form divergent diffuser section **58**. Swirling air enters diffuser section **58**, either due to compressor swirl or swirl imparted thereto by inlet guide vanes (not shown) and establishes a mixing criterion wherein the boundary layer is unstable at the outer wall **268** in that, ρV_t^2 for the boundary layer air is less than ρV_t^2 for the main stream air. This phenomenon alone will substantially increase the mixing rate at the outer wall and allow a higher static pressure gradient axially along the wall before flow separaiton occurs. However, triggering the unstable boundary layer with knubs **272**, which are preferably formed in axially spaced circumferentially directed rows as best shown in FIGS. **40** and **41**, will increase the mixing rate substantially and will increase the rate of fluid momentum transfer to the boundary layer region from the main stream, thus permitting a still higher rate of diffusion without separation of the flow from the outer wall **268**.

In addition, by positioning the inner wall **270** of annular diffuser **58** so that its radial distance, that is the distance from the engine center line **16**, decreases along the axis in the direction that air travel will result in decreasing the inner wall static pressure gradient in the axial direction. This is accomplished, as best shown in FIG. **40** by making radius r_2 less than radius r_1. This results from the local acceleration of the tangential component of the velocity, V_t, from consideration of the principle of conservation of angular momentum. This allows means for alleviating the axial static pressure gradient which affects, as regards separation, only the axial velocity component. Accordingly, a more rapid deceleration of the axial velocity, V_x, is permitted which is along the inner wall.

I have further found that an annular burner of swirl flow configuration of the type taught herein lends itself to permitting the utilization of a very wide and short cone angle diffuser to reduce burner length. This can be accomplished in an annular burner using swirling flow by preventing or retarding separation of the boundry layers along the walls of the diffuser. It is common practice to energize boundary layers by blowing from a slot in the surface but this requires an expenditure of power to pump the blwon air. In a diffuser passing swirling flow, the axial boundary layer is prone to separation and the kinetic energy of the tangential motion in the boundary layer does not provide any assistance in overcoming the adverse pressure gradient. However, if this energy is directed into the axial boundary layer, energization of the axial boundary layer is obtained without the expenditure of external pumping power. The essential feature is not the energization of the axial boundary layer itself, but the means of accomplishing it by straightening the boundary layer at the diffuser inlet and effectively adding the kinetic energy of the tangential boundary layer to that of the axial. The straightening can be accomplished in either of two ways. If the approaching flow is axial and is to be turned by vanes in the diffuser inlet these vanes are uncambered or cut back at the diffuser inlet walls to permit a continuing axial flow in these regions. Conversely, if the approach flow is already swirling, short vanes are mounted on the wall at the diffuser inlet to straighten the flow near the wall only. These vanes should not be confused with the vortex generators of FIG. 33 which enhances diffuser performance by promoting turbulence downstream through break-up of their tip vortices. Geometrically, these turning vanes would be cambered to provide a low angle of attack on the leading edge and proivde an axial discharge, while vortex generators are usually airfoils of low camber set at a high angle of attack to the approaching flow in opposing pairs.

Constructions using proper vanes are shown in FIGS. **42*a*** and **42*b***. The **42*a*** construction is intended for use with air which is to be swirled upon entering diffuser section **58**. In this construction, a compound stator or vane cascade **274** is placed at the diffuser inlet and is shaped to permit axial flow past the upper and lower edges of the gas flowing therepast so that nonswirling air flows along the outer diffuser wall **276** and the inner diffuser wall 278, while imparting swirling flow to the central portion of the diffuser, 58, thus establishing velocity profiles of axial velocity, V_x, and tangential velocity, V_t, as shown in FIGS. 43 and 44, respectively. The permissible amount of diffusion and consequently the location of separation is determined by the axial velocity V_x distribution principally. Since the greatest part of the V_x distribution shown in FIG. 43 is in the center portion of the diffuser inlet and determines the static pressure rise in the diffuser. The wall boundary layers have a larger axial component V_x than the central portion and therefore a greater amount of energy permitting them to continue flowing against the adverse pressure gradient thereby delaying or avoiding flow separation. Consequently, the diffuser cone angle can be increased substantially without flow separation.

FIG. 42*b* shows the vane construction intended for use in an embodiment in which swirling air is being passed from compressor 42 into diffuser 58. A plurality of flow straightening vanes 277 and 279 are positioned at the inlet of the diffuser 58 and serve to remove the tangential velocity V_t from the air passing thereby so that axially directed air only will be passed along the diffuser wall. Ring shaped covers 281 and 283 preferably extend concentrically around axis 16 and attach to the free ends of vanes 277 and 279, respectively, and serve to prevent the formation of vane tip vortices. This is a material distinction between the function of straightening vanes 277 and 279 and the function of vortex generators, in that the formation of tip vortices is the primary action of vortex generators.

In both FIG. 42a and 42b constructions, by diverting a part of the energy in the tangential boundary layer into the axis boundary layer, a means of energizing the axial boundary layer has been obtained similar to that employed in blowing along the boundary but without the expenditure of external power.

Another advantage of may annular swirl burner construction is that the length of the combustion chamber and the engine can be reduced and/or imporved control of the power performance of the engine can be achieved by radially staged combustion. Illustrations of annular combustion chambers having radial combustion staging therein are shown in FIGS. 46-48 and, since these constructions are similar in detail to the FIG. 14 construction, except for the radial combustion staging, common reference numerals will be used wherever applicable.

As best shown in FIG. 46, primary combustion zone 60 and dilution zone 62 are axially oriented in series within housings 54 and 113 which are concentric about axis 16. The annular dilution zone 62 is defined between outer liner 134 and inner liner 136, which are concentric about axis 16. Ducts 138, 140 and 400 are preferably of circular cross-section and positioned concentrically about axis 16 within outer liner 134, with duct 140 extending farther downstream than duct 138 and duct 400 extending farther downstram than duct 140. Pilot combustion zone 160 is defined between duct 138 and 134 in annular passage 124 and the annular pilot is established therein due to the coaction of fuel spray chamber 156 and flameholder member 161. Annular passage 402 is defined between ducts 138 and 140 and constitutes the outer main stream through which a swirling fuel-air mixture flows, with fuel spray mechanism 404 discharging atomized fuel thereinto. Annular passage 406 is defined between ducts 140 and 400 to constitue the inner main stream of swirling fluid with atomized fuel sprayed thereinto by fuel spray means 408. Flow turning vane cascades 116, 118, 120, 410 and 128 are located at the inlet portion 114 of combustion chamber 56 to receive the air from compressor 42 and change its direction as required to establish the desired tangential velocity V_t, of the fluid flowing past the vane. The compressor air which passes vanes 116 flows between the outer burner casing 54 and the outer liner 134 to cool both parts and flows through vanes 172–176 along the interior wall of the outer liner, as previously described, for liner cooling purposes. Part of the air which flows through vanes 128 enters cooling air passage 132 to cool the inner burner casing 113 and the inner burner liner 136 and through vanes 168 and 170 to cool the inner surface of the inner liner 136. The remainder of this cooling air, that which does not pass through passages 132 after passing vanes 128 passes into dilutant air passage 130 to be mixed with the products of combustion from combustion chamber 60 in dilution zone 62. The air which passes vanes 118 has fuel added thereto as it passes fuel injection mechansim 156 and has a stabilization zone created herein downstream of aperture plate flameholder 161 so that when ignited by mechanism such as 158 of FIG. 14, a primary combustion zone of flame is formed at 160.

In practice in the FIG. 46 construction, the pilot combustion zone or flame at zone 160 will remain in operation at all times. When more power is required from the engine, fuel is commenced to be injected through fuel injection mechanism 404 so that the fuel-air mixture passing from annular passage 402 will be ignited by, mixed with, and burned with the pilot flame from 160 in a portion of the primary combustion zone designated as 60*a*. When still further engine power is required fuel is also discharged into annular passage 406 by fuel spray mechanism 408 to mix with, be ignited by and combust with the products of combustion from primary combustion zone 60a in secondary combustion zone 60*b*. It will therefore be noted that there are three main power output possibilities for the engine in which the FIG. 46 construction is used, the first when the pilot flame in passage 124 only is being used, second when combustion is taking place in passage 124 and 402, and third when combustion is taking place in passage 124, 402 and 406. In fact, since the flow in each fuel stream can be modulated within its range of stable operation, there are enumerable power levels at which the engine utilizes the FIG. 46 construction of operation. The addition of a second combustor doubles the stable range for the entire burner.

Dilution air from passage 130 will mix with and cool the products of combustion from primary combustion zone 60 in dilution zone 62 before entering turbine 46. As described before, the flow turning vanes 116, 118, 120, 410 and 128 are selected so as to establish the product parameter inequality ρV_t^2 (dilution air)>ρV_t^2 (second primary combustion zone 60*b*)>ρV_t^2 (first primary combustion zone 60*a*)>ρV_t^2 (pilot flame 160).

Trigger mechanisms 164, 166 and 169 may be of the type previously described and performs the previously described functions.

When there is no fuel added in passages 402 or 406, of FIG. 46 these streams act like a dilutant stream in that they will rapidly mix with the hot gas from the passages radially outboard thereof.

It will be evident that the FIG. **46** construction is much like the FIG. **14** construction except that the main fuel preparation stream is divided into two main streams in passages **402** and **406**, to be ignited and burned, when required, from a pilot flame immediately radially outboard thereof. In the FIG. **54** construction, the main advantage to be gained is the improved power control in that combustion is taking place in the main pilot **160** at all times and solely therein at the lower power levels, in pilot zone **160** and main combustion zone portions **60**a at the intermediate power levels, and in pilot combustion zone **160**, main combination zone portion **60**a and main combustion zone portion **60**b at the high power levels. In this manner, the range of power levels attainable is roughly double that of the FIG. **14** burner.

FIG. **47** shows another concentric burner construction with radial staging for combustion and this construction is similar to the FIG. **14** construction except for the radial staging of the concentric mixer in the combustion zone. The previous description relative to the construction of the inner and outer burner liners **134** and **136** and its cooling vanes **168–176** will suffice to describe the FIG. **55** construction as well, and the compound concentric mixer only will be described. FIG. **47** is actually two concentric mixers located in radial orientation to one another and has the advantage of shortening the combustion chamber and engine length by shortening the radial distance across which the flame must propagate during combustion. In this construction, outer concentric mixer **420**a is positioned concentrically about axis **16** and envelopes inner concentric mixer **420***b*, which similarly concentrically envelopes axis **16**. The outer mixer includes ducts **134**, **138***a* and **140***a*, which are preferably of circular cross-section and concentric about axis **16** and cooperate to define annular passages **124**a and **126***a* therebetween. Flameholder **161***a*, which is preferably of the perforated plate type, extends across passage **124***a* and is operable to define a pilot combustion zone **160***a* downstream thereof. Inner concentric mixer **420***b* includes ducts **140***a*, **138***b* and **140***b*, which are preferably of circular cross-section and concentric about axis **16**, and cooperate to define annular passages **160***b* and **126***b* therebetween. Flameholder **161***b* extends across passage **124***b* to define pilot combustion zone **160***b* downstream thereof. Flow turning vane cascades **116**, **118***a*, **120***a*, **118***b*, **120***b* and **128** serve as previously described to impart the required tangential velocity V_t to the fluid passing therethrough. Fuel is injected into annular passages **124***a* and **124***b* through fuel injection nozzle system **422** and is ignited in conventional fashion downstream of flameholders **161***a* and **161***b* to establish pilot combustion zones **160***a* and **160***b* extending in annular fashion about axis **16**. A swirling fuel-air mixture, due to the action of the turning vanes and fuel injection mechanisms **424** and **426**, pass through passages **126***a* and **126***b* and mix with, are ignited by, and burn with the products of combustion of pilot combustion zone **160***a* and **160***b*, respectively. Trigger mechanisms **164**, **166** and **169** may be of any of the types previously described. The turning vanes are selectively oriented such that the product parameter ρV_t^2 of the fuel preparation passages **126***a* and **126***b* is greater than the product parameter ρV_t^2 of the pilot combustion zones **160***a* and **160***b*, respectively, to accelerate mixing and burning therebetween and, similarly the product parameter ρV_t^2 of the dilutant air passing through passage **130** is greater than the corresponding product parameter of the flow leaving zones **60***a* and **60***b*.

The construction shown in FIG. **48**, which also corresponds generally to the construction in FIG. **14** except for the radially staged concentric mixer **430** which forms the forward part of combustion zone **60**. This FIG. **56** embodiment has the advantage of both shortening the length of the combustion chamber and hence the engine and of providing for multiple power operation control of the power plant. This construction is sufficiently similar to the FIG. **14** construction that the construction and the operation of the inner and outer liners **136** and **134** which are as previously described, will not be described again here. The description of FIG. **48** will be confined to the compound, radially staged concentric mixer **430**. This mixer, basically, includes an annular pilot combustion zone defining mechanism, with fuel preparation annular passages located immediately radially outboard and inboard thereof to both mix, be ignited by, and burn with the pilot flame. Ducts **134**, **442**, **444** and **446** are concentrically positioned about axis **16** and cooperate to define annular pilot combustion zone passage **124** and outer and inner annular fuel preparation passages **126***a* and **126***b* therebetween. Fuel is injected into the pilot passage **124** through fuel injection means **448** and passes through flameholder **161** to establish pilot combustion zone and pilot flame **160** downstream thereof. Fuel injection mechanism **450** injects fuel into outer annular fuel preparation passage **126***a* and fuel injection mechanism **452** injects atomized fuel into inner annular fuel preparation passage **126***b*. Turning vane cascades **116**, **118** and **120** are used to provide the required tangential velocity V_t to accomplish the desired intermixing in these annular chambers. Turning vanes **115** and **128** provide a similar function with respect to the cooling air going through passages **122**, **130** and **132**. To accelerate mixing, ignition and combustion between the pilot flame and its products of combustion and the fuel-air mixtures of passages **126***a* and **126***b*, the interface instability criterion ρV_t (passage **126***b*)$>\rho V_t$ (pilot flame and products of combustion)$>\rho V_t$ (passage **126***a*). Trigger mechanisms **164** and **166**, which may be any of the types described previously perform the function of disturbing the interface between the pilot flame and the fuel-air mixtures of passages **126***a* and **126***b* to accelerate mixing and burning. Trigger **169** performs a similar function between the products of combustion of main combustion zone **60** and the dilutant air entering the dilution zone **62** through annular passage **130**.

In the FIG. **48** construction, multipowered operation can be achieved by keeping the pilot flame at **160** in operation at all times and in use solely for low power operation, by cutting the fuel supply to either passage **126***a* or **126***b* for intermediate power operation, and cutting in the fuel supply in both of the fuel preparation passages **126***a* and **126***b* for high power operation.

It will therefore be seen from the foregoing that there are many advantages to be gained from a swirl burner configuration both with respect to mixing the fuel-air mixture for burning and vitiating in the combustion zone and for mixing the hot products of combustion and the cooling air in the dilution zone to cool the products of combustion prior to passage through the turbine section. It will further be seen that many modifications of swirl burning are available.

I wish it to be understood that I do not desire to be limited to the exact details of construction shown and described, for obvious modifications will occur to a person skilled in the art.

I claim:

1. In an annular combustion chamber, means to establish compound radially staged mixing comprising:

A. means to establish swirling flow pattern of a first fluid of product parameter $\rho_1 V_{t1}^2$ where ρ_1 is the fluid density and V_{t1} is the tangential velocity of the swirl motion in a central portion of the combustion chamber,

B. means to establish a swirling flow pattern of a second fluid of density ρ_2 and a tangential velocity V_{t2} of selected product parameter $\rho_2 V_{t2}^2$ radially inward of and in interface engagement with the first fluid flow so that the ρV_t^2 product parameter of the second fluid being greater than that of the first fluid to accelerate mixing therebetween and,

C. means to establish a swirling flow pattern of a third fluid of density ρ_3 and tangential velocity V_{t3} radially outward of the first fluid and in interface engagement therewith and having a product parameter $\rho_3 V_t^2$ less than the $\rho_1 V_{t1}^2$ product parameter of the first fluid to accelerate mixing therebetween.

2. Apparatus according to claim **1** including means to add fuel to said first, second and third fluids to create a first, second and third fuel-air mixture, respectively, and means to ignite said first fuel-air mixture to serve as a pilot for said second and third fuel-air mixtures.

3. Apparatus according to claim **1** wherein said first fluid is a fuel-rich, vitiated mixture and wherein said second and third fluids are air.

4. An annular burner concentric about an axis and having a combustion zone and a dilution zone in series therein,

A. a compound, concentric mixer with radial stage combustion in said combustion zone including:

1. a first duct surrounding said axis,
2. a second duct surrounding said axis and position within said first duct to cooperate therewith to define a first annular passage therebetween,
3. a third duct surrounding said axis and positioned within said second duct and cooperating therewith to define a second annular passage therebetween and extending farther downstream in said combustion chamber than said second duct,
4. a fourth duct enveloping said axis and positioned within said third duct and cooperating therewith to define a third annular passage therebetween and extending farther downstream than said third duct,
5. means to establish swirling combustion in said first annular passage to serve as a first pilot flame,
6. means to pass a swirling fuel-air mixture through said second annular passage to mix with and be ignited by and burn with said pilot flame and to produce a second pilot flame extending downstream thereof,
7. means to pass a swirling fuel-fluid mixture through said third annular passage to mix with, be ignited by and burn with said second pilot flame to thereby provide a concentric mixer with radial staged combustion, and
8. wherein the products of combustion of the first pilot flame are of density ρ_1 and rotating at tangential velocity V_{t1}, and wherein the fuel-air mixture flowing through said second annular passage is of density ρ_2 and tangential velocity V_{t2}^2 so that the relationship therebetween is such as to satisfy the product parameter ratio $\rho_2 V_{t2}^2 > \rho_1 V_{t1}^2$, and wherein the products of combustion of said second pilot flame have a density ρ_3 and a tangential velocity V_{t3}, further wherein the fuel-air mixture being passed through said third annular passage has a density ρ_4 and a tangential velocity V_{t4} which bear a relationship to the characteristics of the second pilot flame to satisfy the product parameter ratio $\rho_4 V_{t4}^2 > \rho_3 V_{t3}^2$, where ρ is density and V_t is tangential velocity.

5. Apparatus according to claim **4** and including means to cool the products of combustion in said dilution zone.

6. Apparatus according to claim **4** and including trigger mechanism located at the downstream end of at least one of said second, third and fourth ducts to physically disturb the interface between the swirling fluids flowing on opposite radial sides thereof.

7. Apparatus according to claim **4** and including means to pass cooling air into said dilution zone as swirling flow and passing immediately radially inboard of said fourth duct and so that the product parameter ρV_t^2 of the cooling air is greater than the product ρV_t^2 of the products of combustion from the third annular passage to accelerate intermixing and cooling therebetween, where ρ is density and V_t is tangential velocity.

8. Apparatus according to claim **4** and including means to selectively establish combustion in said first annular passage, means to selectively establish combustion in said first and second annular passages, means to selectively establish combustion in said first, second and third annular passages.

9. An annular combustion chamber concentric about an axis and having a main combustion zone positioned axially forward of a dilution zone and including a concentric mixer with radial staging forming part of the main combustion zone and including:

A. means to establish an annular pilot combustion zone positioned concentrically about said axis,

B. at least two ducts of substantially circular cross section positioned concentrically about said axis within said annular pilot combustion zone and with each smaller diameter duct extending farther downstream axially than the duct outboard thereof so as to form a first annular passage between the pilot zone forming means and the radially outer duct and a second annular passage between the radially outer duct and the radially inner duct,

C. means to pass a swirling fuel-air mixture through said first annular passage to mix with, be ignited by, and burn with the products of combustion from the pilot combustion zone to thereby establish a second pilot combustion zone from the products of combustion thereof,

D. means to pass a swirling fuel-air mixture through said second annular passage to mix with, be ignited by and to burn with the products of combustion of the second pilot combustion zone, and

E. wherein the product parameter ρV_t^2 of the swirling fluid passing through each annular passage decreases from the radially innermost passage to the radially outermost passage, where ρ is fluid density and V_t is fluid tangential velocity.

10. Apparatus according to claim **9** and including trigger means located at the downstream end of at least one of said ducts.

11. An annular combustion chamber concentric about an axis and having a combustion zone and a dilution zone positioned axially therewithin, said combustion zone including:

A. a compound concentric mixer with radial staging including:
  1. a plurality of at least five ducts positioned concentrically about said axis within said combustion chamber and spaced radially from one another to form at least four concentric annular passages therebetween,

B. means to establish a pilot combustion zone in alternate annular passages,

C. means to pass a fuel-air mixture through the other alternate passages to mix with, be ignited by, and burn with the products of combustion of the pilot combustion zones so as to establish combustion in radial stages across said combustion zone, and

D. wherein the product parameter ρV_t^2 of the fluid passing through each of said other alternate annular passages is greater than the product parameter ρV_t^2 of the products of combustion of the pilot zone immediately radially outboard thereof wherein ρ is fluid density and V_t is fluid tangential velocity.

12. Apparatus according to claim **11** and including trigger means located at the downstream end of the duct separating each pilot combustion zone from the adjacent other alternate passage to physically disturb the interface between the swirling fluids passing on opposite radial sides thereof to accelerate mixing therebetween.

13. An annular combustion chamber having an axis and main combustion zone positioned axially forward of a dilution zone and wherein the combustion zone includes:

A. a compound concentric mixer with plural radial staged combustion including:
  1. a plurality of concentric mixers positioned in radial relation to one another and each including:
     a. means defining an annular pilot combustion zone forward of said main combustion zone,
     b. means defining an annular fuel preparation chamber immediately adjacent and in radial relation to said annular pilot combustion zone,
     c. means to establish combustion in said annular pilot combustion zone,
     d. means to pass a swirling fuel-air mixture through said annular fuel preparation passage to mix with, be ignited by, and to burn with the products of combustion of said annular pilot combustion zone in said main combustion zone, and
     e. wherein the fuel preparation chamber is positioned immediately radially inward of said pilot combustion zone and wherein the product parameter ρV_t^2 of the fuel air mixture being passed through the fuel preparation passage is greater than the corresponding product parameter of the products of combustion of the pilot combustion zone, where ρ is density and V_t is tangential velocity.

14. Apparatus according to claim **13** and including means to trigger the interface between the products of combustion of the pilot combustion zone and fuel-air mixture from said annular fuel-air passage.

15. An annular combustion chamber concentric about an axis and having a main combustion zone positioned forward of a dilution zone and including:

A. a compound concentric mixer positioned forward of the combustion zone and adapted to accomplish combustion in radial staging and including:
  1. first and second ducts positioned concentrically about said axis to define an annular pilot combustion passage and zone therebetween,
  2. a third duct positioned concentrically about said axis and enveloping said first and second ducts and cooperating with said first duct to dfine a first fuel preparation annular passage therebetween,
  3. a fourth duct positioned concentrically about said axis and within said first and second ducts and cooperating with said second duct to define a second fuel preparation annular passage therebetween,
  4. means to establish an annular combustion pilot in said pilot combustion zone,
  5. means to pass a swirling fuel-air mixture through said first fuel preparation annular passage to mix with, be ignited by, and to burn with the products of combustion from the pilot zone in said main combustion zone,
  6. means to pass a swirling fuel-air mixture through said second fuel preparation annular passage to mix with, be ignited by, and combust with the products of combustion of the pilot flame in the main combustion zone, and
  7. wherein the product parameter ρV_t^2 of the fluid passing through the second annular passage is greater than the corresponding product parameter ρV_t^2 of the pilot products of combustion, which is in turn greater than the corresponding product parameter ρV_t^2 of the fluid passing through the said first annular passage, where ρ is density of the fluid and V_t is tangential velocity of the fluid.

16. Apparatus according to claim **15** and including trigger means located at the downstream end of said first and second ducts to physically displace the interface between the pilot products of combustion and the swirling fluids of the first and second fuel preparation annular passages, respectively.

17. Apparatus according to claim **15** and including means to dilute and cool the products of combustion in the main combustion zone in said dilution zone.

18. An annular combustion chamber concentric about an axis and including a main combustion zone located forward of the dilution zone and wherein the main combustion zone has a concentric mixer including:

A. means establishing an annular pilot combustion zone flame,

B. means for passing a swirling fuel-air mixture along said axis and immediately radially outboard and inboard of said annular pilot flame to mix with, be ignited by, and to burn with said pilot flame in said main combustion zone, and

C. wherein the product parameter ρV_t^2 of the radially innermost fuel-air mixture is greater than the corresponding product parameter ρV_t^2 of the pilot flame, which is in turn greater than the corresponding product parameter ρV_t^2 of the radially outer fuel-air mixture, where ρ is fluid density and V_t is fluid tangential velocity.

19. Apparatus according to claim **18** and including means to physically disturb the interface between said pilot flame and at least one of said fuel-air mixtures.

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