Aug. 21, 1951 H. C. HOTTEL ET AL 2,565,308

COMBUSTION CHAMBER WITH CONICAL AIR DIFFUSER

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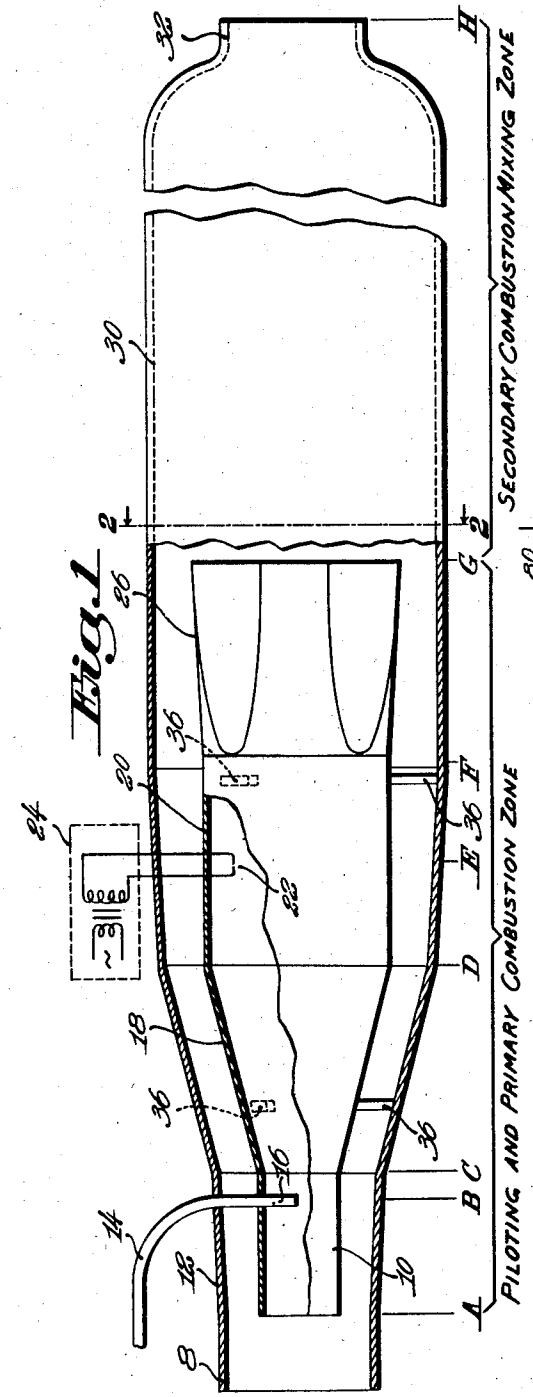


Fig. 1

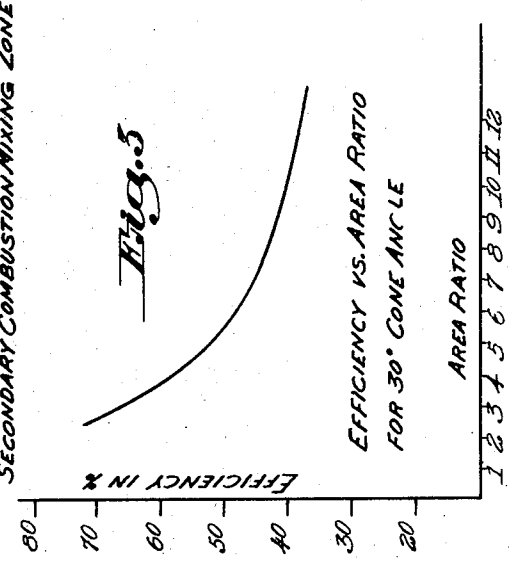


Fig. 3

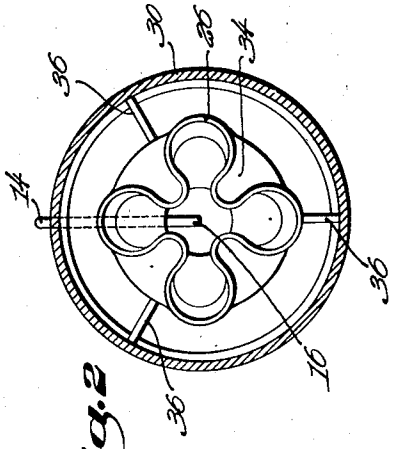


Fig. 2

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COMBUSTION CHAMBER WITH CONICAL AIR DIFFUSER

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2 Claims. (Cl. 60—44)

1

The present invention relates to a method and apparatus for producing combustion at high volumetric rates, and has particular, though by no means exclusive, application to gas turbine operation and jet propulsion.

For these applications it is essential to provide continuous combustion of fuel and air at extremely high rates of heat release in a relatively confined space. In addition, it may be necessary, as in the case of gas turbine operation, to lower the temperature of the gases entering the turbine to a point below the temperature resulting from combustion at normal fuel-air ratios, in order to afford reasonable life to the turbine parts.

Since large volumes of air are required for the combustion process the air is generally supplied to the combustion apparatus at high velocity, far in excess of that permissible for flame propagation. For continuous and stable combustion, therefore, it is necessary to diffuse or decelerate this high velocity air stream to a lower velocity, and to provide sufficient turbulence for adequate mixing of fuel and air. Since turbulence represents a loss of mechanical energy of the high velocity entering air, the deceleration should be so carried out as to give rise to the minimum turbulence consistent with proper combustion.

To diffuse or decelerate a high velocity air stream with minimum dissipation or degradation of mechanical energy and at the same time effect the production of flames having high stability and completeness of combustion, it is generally necessary to divide the entering air into separate streams, particularly where the air/fuel ratios to be employed lie outside the ratio for a combustible mixture. The ratio of division of the two streams is usually such that in the primary or piloting stream, into which the fuel is subjected and in which combustion is initiated, combustion may proceed without undue cooling due to excess air. The two streams are thereafter recombined for mixing and completion of combustion at air/fuel ratios which bring about the desired exhaust temperatures.

One method of effecting the required deceleration involves decelerating the two streams as reversibly as possible, that is, by expanding the streams in such fashion that no substantial eddying or turbulence occurs. This may be done by limiting the expansion angles to about 7° and thereby avoiding flow separation and thus minimizing the loss of mechanical energy. To minimize loss at the points of separation and recombination of the streams, the pressure rise in the two streams may be made substantially equal. Since, in general, the entering velocities of the

2

two streams will not be the same because of non-uniform velocity distribution in the supply, the pressure rise for each stream may be made identical by providing unequal expansion ratios. For the stream having the higher entering velocity, the expansion ratio will accordingly be less than for the stream having the lower entering velocity. Due to the unequal expansion ratios, the two streams at the end of the expansion will have different velocities, and this velocity difference is available to effect mixing.

The objection to the above method, for such applications as are contemplated by the present invention, is the considerable over-all length required to carry out the expansion with expansion angles that do not exceed approximately 7°.

According to the present invention, therefore, in order that expansion up to the point of initiation of combustion may be carried out in the shortest possible axial length consistent with minimum loss of energy, the piloting stream into which the fuel is injected is expanded at angles substantially greater than for reversible non-turbulent diffusion, so that flow separation occurs. The consequent recirculation of fuel and air permits in a short axial length the formation of an ignitable mixture at a region of relatively low velocity. Entrance and exit losses are minimized by selecting expansion ratios such that the pressure rise for the two streams is made equal. In cases where the air stream prior to separation has a non-uniform velocity, it is advantageous to perform the separation so that the piloting stream has the higher entering velocity. Thus the kinetic energy per unit mass of this stream will be higher than for the other stream, and such excess energy is available for mixing with relatively low overall loss in mechanical energy.

It has been found that the production of stable flames is dependent not only on the degree of irreversibility in the expansion of the piloting stream, that is, the extent to which mechanical energy or total pressure is lost as the piloting stream is expanded, but also on the intensity of such energy loss. Thus, under conditions where the flow separation in the piloting diffuser is asymmetrical, the energy loss in the pilot stream may be sharply localized so as to provide a high intensity of energy loss for a given overall loss, with consequent improvement in flame stability as compared with a diffuser exhibiting more symmetrical separation with the same overall energy loss.

It has also been established that the axial length required for turbulent mixing of air atomized liquid fuel is a function of the path length which must be traversed by the mixing streams in

a direction normal to the stream flow. In general, therefore, the scale of the apparatus is determined by the design limitation set on axial length. As the scale is reduced, provided no appreciable change is made in the droplet size of the fuel injected, it becomes necessary to provide a somewhat greater expansion ratio for the piloting stream in order that the time of travel of the fuel may remain adequate for vaporization and mixing.

An additional problem is presented where the combustion apparatus is to be employed in conjunction with gas turbines and other devices actuated by or exposed to the high temperature combustion products. In such applications, not only must the average exhaust temperature lie below a predetermined limit, but in addition the localized variations in temperature must not appreciably exceed the mean temperature so as to avoid distortion in the structure due to uneven temperature distribution and also so as not to exceed at any point the safe temperature limit for the material.

With the above considerations in view, the invention has as one of its objects the provision of a method and apparatus for producing continuous combustion at extremely high rates of heat release per unit of combustion chamber volume, with minimum expenditure of mechanical energy and with minimum heat loss and loss of unburned fuel.

It is likewise an object of the invention to provide a method and apparatus for producing high-output continuous combustion with stable flames over a wide range of air/fuel ratios, of inlet air velocities, and of combustion-chamber pressures.

The invention also has as an object to provide a method and apparatus for efficiently producing stable continuous flame in a confined space at high rates of heat release over a relatively wide range of output temperatures with substantial uniformity of temperature over the outlet flow cross-section.

It is a further object of the invention to provide a combustion method and apparatus adapted to accomplish the aforesaid objects with air-atomized as well as with pressure-atomized liquid fuel.

With these and other objects in view, as will hereinafter more fully appear, the present invention involves as a feature a method and apparatus for carrying out continuous combustion wherein high velocity air is divided into primary and secondary streams which are expanded with unequal efficiencies and in unequal ratios. The primary, or piloting stream, into which the fuel is injected and burned, is expanded at such angle or rate and in such ratio as provides sufficient flow separation for effective mixing of fuel and air, while the secondary stream is expanded with substantial reversibility that is, with as high mechanical efficiency as possible. Expansion with minimum loss of mechanical energy or total pressure may be accomplished, as has already been pointed out, by so confining the stream that the rate of change of flow cross section with path distance corresponds approximately to that provided by a cone of about 7° angle of divergence. The streams are then recombined, with or without the injection of additional fuel, depending on the desired outlet temperature. The method thus combines, for compactness, the process of expanding the air for combustion from a high entering velocity to a lower velocity within the chamber, with the process of preparing a combustible mixture and stabilizing the flame,

through utilization of the energy in the form of turbulence made available from the relatively less efficient expansion and larger expansion ratio of the primary stream. The design characteristics governing the division of the entering air into primary and secondary streams, the expansion ratios of the two streams, the degree of irreversibility of flow in the primary stream and the amount of combustion occurring in the primary stream prior to recombination with the secondary stream are so correlated that entrance and exit losses, i. e., those accompanying division and recombination of the two streams, are minimized. Combustion chambers designed in accordance with these principles, hereinafter more fully explained, are capable of operating at high mechanical efficiency and with substantial completeness of combustion at heat release rates measured in millions of B. t. u.'s per hour per cubic foot of flame volume per atmosphere of pressure.

The invention likewise contemplates as a feature the provision of devices which, without constricting the areas of the flow paths in the combustion apparatus, and with minimum energy loss, insure effective mixing of the recombined gases to provide substantially uniform temperatures across the stream after a relatively short distance in the direction of flow.

In the drawing illustrating the combustion apparatus of the invention, Fig. 1 is a diagrammatic view in side elevation of a combustion chamber embodying the principles of the invention; Fig. 2 is a cross-sectional view of the apparatus shown in Fig. 1 taken along the line 2—2 of said figure, and Fig. 3 is a plot typifying the relation of efficiency to area ratio for a diffuser expansion angle of 30°. To aid in the description of the apparatus and its mode of operation, Fig. 1 has been marked with identifying letters for convenient reference to the significant points in the flow expansion and combustion.

The apparatus is supplied with high velocity air from a compressor or other suitable source, not illustrated. The air enters through inlet section 8, which has a length dependent on the specific application in which the combustion apparatus is to be employed. For such applications as gas turbine operation, where according to conventional practice a plurality of combustion chambers may be arranged directly between compressor and turbine in annular fashion around the connecting shaft, the overall length of the combustion apparatus is generally sharply limited by permissible shaft length, with the result that the inlet section 8 may be relatively short. In the majority of applications, its length will be less than that at which the velocity distribution or gradient in the air flow becomes substantially independent of distance from the source.

The entering air, which may have a velocity of several hundred feet per second, is divided at point A into inner and outer streams. The inner stream constitutes the piloting stream into which the fuel is initially injected and wherein combustion is initiated, while the outer or annular stream is by-passed around the piloting stream, later to rejoin and mix therewith to complete the combustion.

The division of air is effected by the entrance section 10 of the diffuser-pilot. This section, which extends from point A to point C, is positioned within the outer shell section 12 so as to intercept a predetermined portion by weight of the total air stream. The diffuser-pilot may advantageously although not necessarily be posi-

tioned to intercept that portion of the air stream which has the highest velocity. The fuel, which is supplied through tube 14 to nozzle 16, is injected into the inner stream between points A and D, for example at B. In general, the preferred location within this region is best determined experimentally.

The nozzle 16 may be either of the air-atomizing or the pressure-atomizing type. In the drawing, 16 is a simple open-ended tube intended for air atomization, and is therefore placed in the high velocity region upstream from section C. The apparatus has been found to operate with high efficiency with air atomization, which is frequently advantageous, as it permits operation with low pressure differential on the fuel. In most designs, and particularly in symmetrical chambers, it is preferable, for reasons of flame stability, to employ an asymmetrical nozzle arrangement, such as a single nozzle feed extending into the air stream approximately to the center of the passage.

From C to D the inner stream is expanded rapidly by the diffuser section 18. It has been found that expansion angles of the order of 30°, corresponding to an expansion efficiency of approximately 50% for expansion ratios within the range generally employed, are required to provide sufficient turbulence for proper mixing of the fuel and air in the inner stream for combustion, and to provide the flow separation and accompanying recirculation necessary for flame stabilization. Appreciably smaller expansion angles do not afford adequate flame stabilization, while angles that are appreciably greater than about 30° result in an unnecessarily large loss of mechanical energy. For chambers of non-symmetrical or non-circular cross section, the expansion rate, or expansion ratio per unit of chamber length, preferably approximates that provided by a 30° expansion angle for a substantially conical expansion.

To initiate combustion of the mixture in the inner stream, a spark discharge may be provided within the cylindrical extension 20 of the downstream end of the diffuser 18. For this purpose electrodes 22 may be supplied with high tension current from a source generally indicated at 24. Once combustion has been initiated, the spark discharge may be discontinued.

A portion of the combustion takes place in the section C—F of the pilot, and in the mixer 26, section F—G, hereinafter more fully described. The combustion continues, with the additional air supplied by the outer stream, in the flame chamber 30, extending from G to H. In general, this portion of the apparatus will be somewhat greater in overall length than the diffuser pilot section A—G. The design of the flame chamber will of course depend on the specific application in which the combustion process is to be used. In the illustrative embodiment, the end 32 of the chamber is formed with an opening of reduced size, as for connection to the inlet port of a gas turbine.

The mixing section F—G is arranged to effect intermingling of the burning pilot stream with the annular air stream so that combustion may be completed in the shortest possible distance consistent with low energy loss, and likewise so that the exhaust temperatures over the discharge cross-section may be substantially uniform. To this end, the mixing shield 26 is shaped to progress from the cylindrical section 20 of the pilot to a cross-sectional shape resembling a cloverleaf (see Fig. 2), this transition being accomplished by means of gradually deepening flutes 34. These flutes are so shaped that the cross-sectional areas of the piloting and annular passages are not appreciably modified, so that no expansion or contraction of flow results. By this construction, portions of the piloting stream are carried into the annular stream, and conversely, portions of the annular stream are directed into the piloting stream, resulting in effective mixing of the two streams within the flame chamber.

The fabrication of the combustion apparatus may follow conventional practice, in the use of thin-walled material such as sheet metal. Where the parts are exposed to high temperatures, particularly the mixer 26, special heat resistant materials are used. The pilot-diffuser is positioned within the outer section by means of struts 36 which are preferably so shaped as to offer minimum resistance to the air flow. Such joints as may be necessary for the assembly of the various sections should be smoothly formed for the same reason.

The actual design of the apparatus is dependent on the various limitations and requirements of the specific application. Thus, for gas turbine operation, a limit will generally be placed on outlet temperature, in order to prevent premature destruction of the turbine rotor. Also, there will generally be a limit on the allowable overall length, being the distance from A to H, within which not only the mixing and diffusing process but also the combustion itself must be substantially completed. This limitation influences the scale which is adopted for the design. For air-atomized fuel, or for a given droplet size of pressure-atomized fuel, the flame length and therefore the length of the combustion chamber G—H, which represents the major portion of the overall length A—H, can be made short while retaining efficient operation, only by reducing the scale of the apparatus and employing a larger number of small size units.

A further limitation usually is present, in that the diameter or cross-sectional size of the unit must be as small as possible consistent with allowable pressure loss, in order that the maximum number of chambers may be arranged on a given radius around the shaft connecting the turbine and compressor, or nested in a bank in the case of jet propulsion applications. Thus a limit is placed on the degree to which expansion may be carried, even though cross-sectional shapes are adopted which utilize as effectively as possible the available space.

In general, therefore, the overall expansion ratio will be fixed in advance of the design of the actual chamber, since the maximum cross-sectional area is fixed and the limitations of the air supply determine the cross-sectional area of the air inlet. Also, the outlet temperature, or alternatively the ratio of the outlet temperature to entering air temperature, will be fixed by the requirements of the application in which the chamber is to be used.

The prescribed outlet temperature establishes the overall air/fuel ratio for the chamber, based on the particular fuel to be used. The appropriate air/fuel ratio may readily be determined by reference to a plot of flame temperature vs. air/fuel ratio for the specific fuel.

The air/fuel ratio in the piloting stream is determined by the area of the pilot inlet relative to the total area. The air/fuel ratio of the piloting stream is chosen to provide flame stability with rapid flame propagation, so as to achieve maxi-

mum effectiveness of piloting consistent with low pressure loss. Chosen on this basis the air/fuel ratio for typical gasolines will generally lie within the range of ratios for an explosive mixture, for example between 15/1 and 10/1 lbs. of air per lb. of fuel.

In most cases, due to the non-uniform velocity distribution of the entering air, the fraction of the total air which flows through the pilot inlet will not equal the fraction of the total inlet area occupied by the pilot inlet. The actual velocity distribution is influenced by numerous factors, related principally to the character of the air supply and its distance from the chamber inlet. Accordingdy, the actual velocity distribution for the particular inlet distance and character of the source is preferably ascertained by means of velocity traverses, which may be taken with an exploratory pitot tube. On the basis of the actual velocity distribution, the area and disposition of the pilot inlet may be calculated to give the desired division of air. This division will actually occur provided the sum of the pressure changes in each stream subsequent to its separation from the other is the same for the two streams; and such changes, dependent on inlet velocity, expansion ratios, expansion efficiencies, and momentum changes attending combustion, are capable of calculation.

As has previously been indicated, the expansion of the piloting stream is caused to take place, with a predetermined mechanical energy loss deliberately introduced in order that there may be effective vaporization and mixing of fuel and air, as well as a localized reduction in forward velocity sufficient to permit combustion to be initiated and stable flames to be maintained. Since it is within the expansion section of the piloting stream that energy loss by reason of eddying flow conditions is most productive of beneficial results, it is essential that energy losses in other regions of the chamber be kept as low as possible. Accordingly, the expansion of the outer stream is caused to be efficient as possible, and the dimensions of the two streams over the zone A—G are so chosen that the calculated static pressures of the two streams at the point of recombination are substantially alike in order to avoid losses due to irreversible contraction or expansion of the streams.

For velocities nowhere substantially greater than one-half the local sonic value, the matching of the pressure rise for the inner and outer streams may be carried out in the following manner:

The pressure rise for the outer (in this case annular) stream may be expressed as follows:

$$p_{2\,\mathrm{ann}}-p_{1\,\mathrm{ann}}=\eta_{\mathrm{ann}}\frac{\rho_1}{2g}u_{1\,\mathrm{ann}}^2\left[1-\left(\frac{A_{1\,\mathrm{ann}}}{A_{2\,\mathrm{ann}}}\right)^2\right] \quad (1)$$

and for the piloting stream as

$$p_{2\,\mathrm{pilot}}-p_{1\,\mathrm{pilot}}=\eta_{\mathrm{pilot}}\frac{\rho_1}{2g}u_{1\,\mathrm{pilot}}^2\left[1-\left(\frac{A_{1\,\mathrm{pilot}}}{A_{2\,\mathrm{pilot}}}\right)^2\right] \quad (2)$$

where

ρ = density of air or mixture

p = static pressure

u = mean air velocity

A = cross sectional area

η = expansion efficiency

Subscripts 1 and 2 indicate entrance and exit of piloting zone (points A and G, respectively, of Fig. 1 and subscripts "ann" and "pilot" indicate the annular and piloting streams. Expression (2) takes no account of combustion occurring within the piloting stream prior to mixing with the annular stream. If the effects of combustion are to be included and are for simplicity assumed all to occur downstream from section D, then (2) requires an additional term, becoming

$$p_{2\,\mathrm{pilot}}-p_{1\,\mathrm{pilot}}=\eta_{\mathrm{pilot}}\frac{\rho_1}{2g}u_{1\,\mathrm{pilot}}^2\left[1-\left(\frac{A_{1\,\mathrm{pilot}}}{A_{2\,\mathrm{pilot}}}\right)^2\right]-u_{1\,\mathrm{pilot}}^2\frac{\rho_1}{g}\left[1-\frac{\rho_1}{\rho_{2\,\mathrm{pilot}}}\right]\left(\frac{A_{1\,\mathrm{pilot}}}{A_{2\,\mathrm{pilot}}}\right) \quad (3)$$

where 2 pilot represents the density of the partially burned mixture after the desired percentage of combustion has taken place. For equal pressure rise

$$p_{2\,\mathrm{pilot}}-p_{1\,\mathrm{pilot}}=p_{2\,\mathrm{ann}}-p_{1\,\mathrm{ann}}$$

Hence the right hand sides of (1) and (3) may be equated, and the already ascertained values of u_1, A_1 and ρ_1 may be substituted therein, the values of u and A for pilot and annular streams being based on the velocity traverse of entering air and the pilot inlet area relative to overall inlet area.

In addition, it is necessary, because of the absence of precise data, to make certain assumptions. For example, the expansion efficiency of the outer stream may be assumed to be between 80% and 90% in the absence of expansion efficiency data for an annular stream. It has been found that assumed efficiencies within the above range lead to satisfactory results. Also, it is necessary to estimate the amount of combustion that occurs within the piloting zone. This is dependent, for the most part, on the length of the mixing shield, and alteration of this dimension in the finished chamber provides a ready means for precisely balancing the pressure rise of the two streams. In general, it has been found satisfactory to base the term

$$\frac{\rho_1}{\rho_{2\,\mathrm{pilot}}}$$

on 50% completion of combustion for mixing shields of the type herein disclosed.

The equated expression for balancing the pressure rise in the two streams may thus be reduced to an expression containing only η_{pilot} and $A_{2\,\mathrm{pilot}}$, since $A_{2\,\mathrm{ann}}$ is equal to $A_{2\,\mathrm{overall}}-A_{2\,\mathrm{pilot}}$. The proper value of $A_{2\,\mathrm{pilot}}$ is obtained by means of graphical correlation, using a plot of expansion efficiency vs. area ratio based on empirically determined data for streams of the same cross-sectional shape and expansion angle as employed in the pilot-diffuser. A representative plot of such data for a conical stream of 30° expansion angle is shown in Fig. 3. As has been previously indicated, for combustion chambers embodying the principles of the present invention, expansion angles for the diffuser pilot of approximately 30° have been found to provide good piloting without excessive energy loss.

By substituting, in the expression for balanced pressure rise, various assumed values of

$$\frac{A_{2\,\mathrm{pilot}}}{A_{1\,\mathrm{pilot}}}$$

the corresponding values for η_{pilot} may be obtained, and the values so obtained may be plotted on the graph of empirically obtained data. The proper area ratio, and hence the correct value of $A_{2\,\mathrm{pilot}}$, is then given by the intersection of the two curves. With $A_{2\,\mathrm{pilot}}$ determined, $A_{2\,\mathrm{ann}}$ is

readily calculated, the expansion ratios of the two streams are obtained, and the actual physical dimensions of the chamber are substantially determined for the design conditions.

Reference has previously been made to the fact that, other factors being equal, the flame length is a function of the scale of the apparatus, and that limitations on overall length may in certain instances require relatively small scale units. While it has been found entirely practical to vary the scale of the chamber over a considerable range of sizes with but little variation in the efficiency of the several units, it may be necessary with very small units to make some modification in the design in order to allow sufficient vaporization time for the fuel. This is more apt to be the case with air-atomized fuel than with pressure atomization, since with the former the droplet size is more or less constant while with pressure atomization the droplet size may be decreased, where necessary, by increasing the atomizing pressure. In general, an increase in vaporization time may be provided by increasing the expansion ratio for the inner stream so as to provide somewhat greater energy loss in the form of turbulence.

For purposes of illustration only, the pertinent data of certain combustion chambers constructed in accordance with the invention will be given. It is to be understood that these chambers are merely representative of the design principles, and are not to be considered as indicating the optimum design for the prescribed conditions. The significant data are presented in tabular form:

	Burner No. 1	Burner No. 2	Burner No. 3
Overall air/fuel ratio	70/1	50/1	70/1
Percent air through pilot ... per cent	12	30	21
Diameter inlet ... inches	.82	1.61	2.07
Overall diameter ... do	1.38	3.07	3.49
Overall expansion ratio	2.81	3.63	2.84
Pilot stream expansion ratio	11.9	5.38	8.18
Annular stream expansion ratio	1.55	3.02	1.65
Expansion angle ... degrees	30	30	30

Each of the above chambers represents a design arrived at in accordance with the teachings of the present invention, wherein the piloting and secondary air streams are divided on the basis of the actual velocity distribution provided by the air supply, the piloting stream expanded with predetermined energy loss while the secondary stream is expanded as reversibly as possible, and the pressure rise for the two streams matched for minimum entrance and exit losses. Combustion chambers constructed in accordance with these principles exhibit highly satisfactory performance characteristics with low pressure loss.

We claim as our invention:

1. Apparatus for effecting efficient combustion of fuel and air in a relatively short linear distance and at high combustion rates per unit of combustion volume, said apparatus comprising a chamber having an inlet adapted to receive high-velocity air and an outlet for the discharge of high velocity gas at elevated temperature, a diffuser-pilot within said chamber for dividing the air entering the chamber into primary and secondary streams, the diffuser-pilot extending from a point adjacent the chamber inlet to a point intermediate the inlet and outlet of said chamber, said diffuser-pilot having an inlet passage to receive a portion of the high-velocity air entering the combustion chamber inlet, the diffuser-pilot having substantially imperforate walls diverging at an angle corresponding substantially to a 30° expansion for a conical diffuser, the walls diverging until the cross-sectional area of the passage is approximately five to ten times the area of the inlet to the diffuser-pilot, means for introducing fuel within the diffuser-pilot and for initiating combustion therein, the diffuser-pilot including a section of substantially constant cross-sectional area for isolating the primary stream while combustion proceeds to partial completion, a passage for the secondary air stream to the downstream end of the diffuser-pilot, said secondary air passage expanding in cross-sectional area at a rate corresponding approximately to a 7° conical expansion, and means adjacent the down-stream end of the diffuser-pilot to effect mixing of the partially-burned primary stream with the secondary stream prior to discharge through the chamber outlet.

2. Apparatus for initiating and stabilizing combustion in a high velocity air stream, comprising a diffuser-pilot having an inlet at one end and an outlet at the other with a substantially unobstructed passage there-between and disposed within and substantially aligned with the axis of the high velocity air stream, the diffuser-pilot having substantially imperforate walls to isolate the air stream entering the diffuser-pilot from the air stream external thereto, the diffuser-pilot having an expansion section the walls of which diverge at an angle corresponding substantially to a 30° expansion for a conical diffuser, the length of the expansion section being such that the area of the downstream end is approximately five to ten times the area of the inlet thereto, means for introducing fuel into the diffuser-pilot adjacent the inlet and for initiating combustion in the fuel and air mixture, and means at the outlet end of the diffuser-pilot for mixing the burning fuel and air from the diffuser-pilot with the air stream external thereto.

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