April 12, 1966 M. W. PATRICK ET AL 3,245,458

RADIANT GAS BURNER

Filed Dec. 11, 1962 4 Sheets-Sheet 1

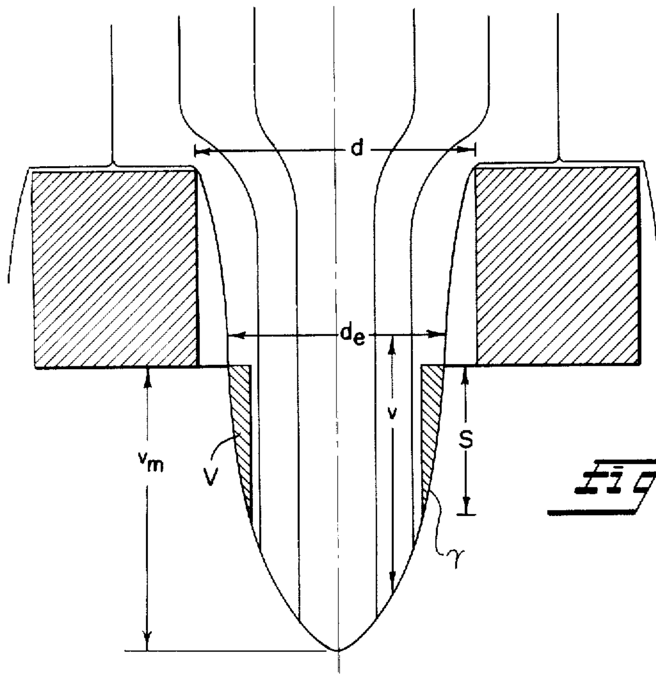

Fig. 1

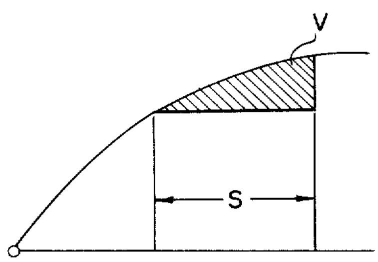

Fig. 2

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RADIANT GAS BURNER

Filed Dec. 11, 1962 4 Sheets-Sheet 2

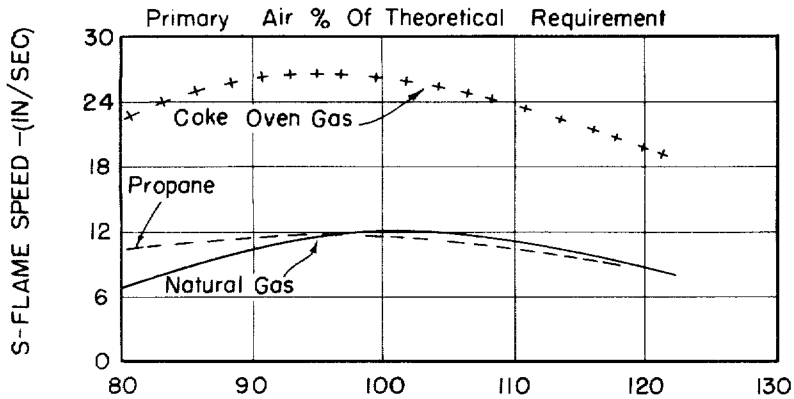

Fig. 3

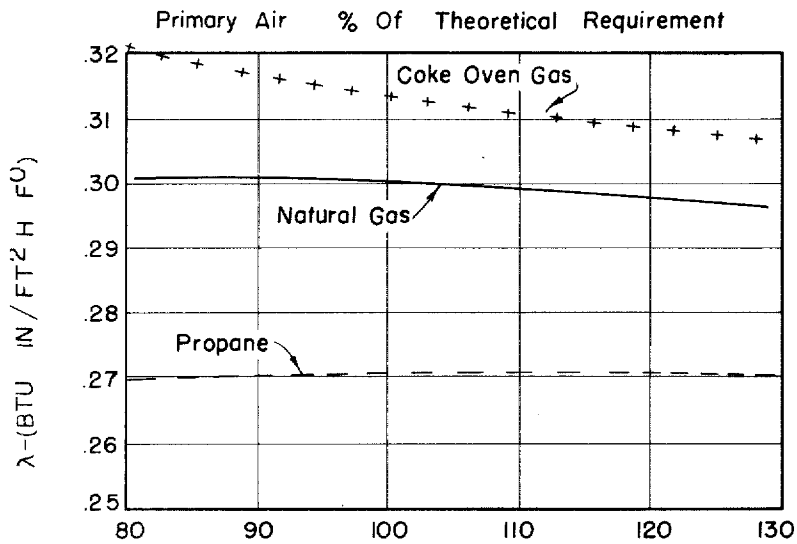

Fig. 4

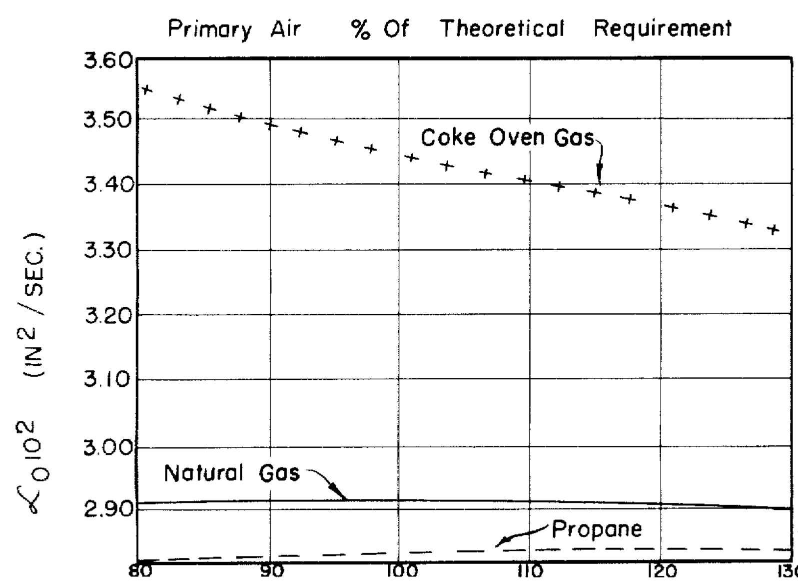

Fig. 5

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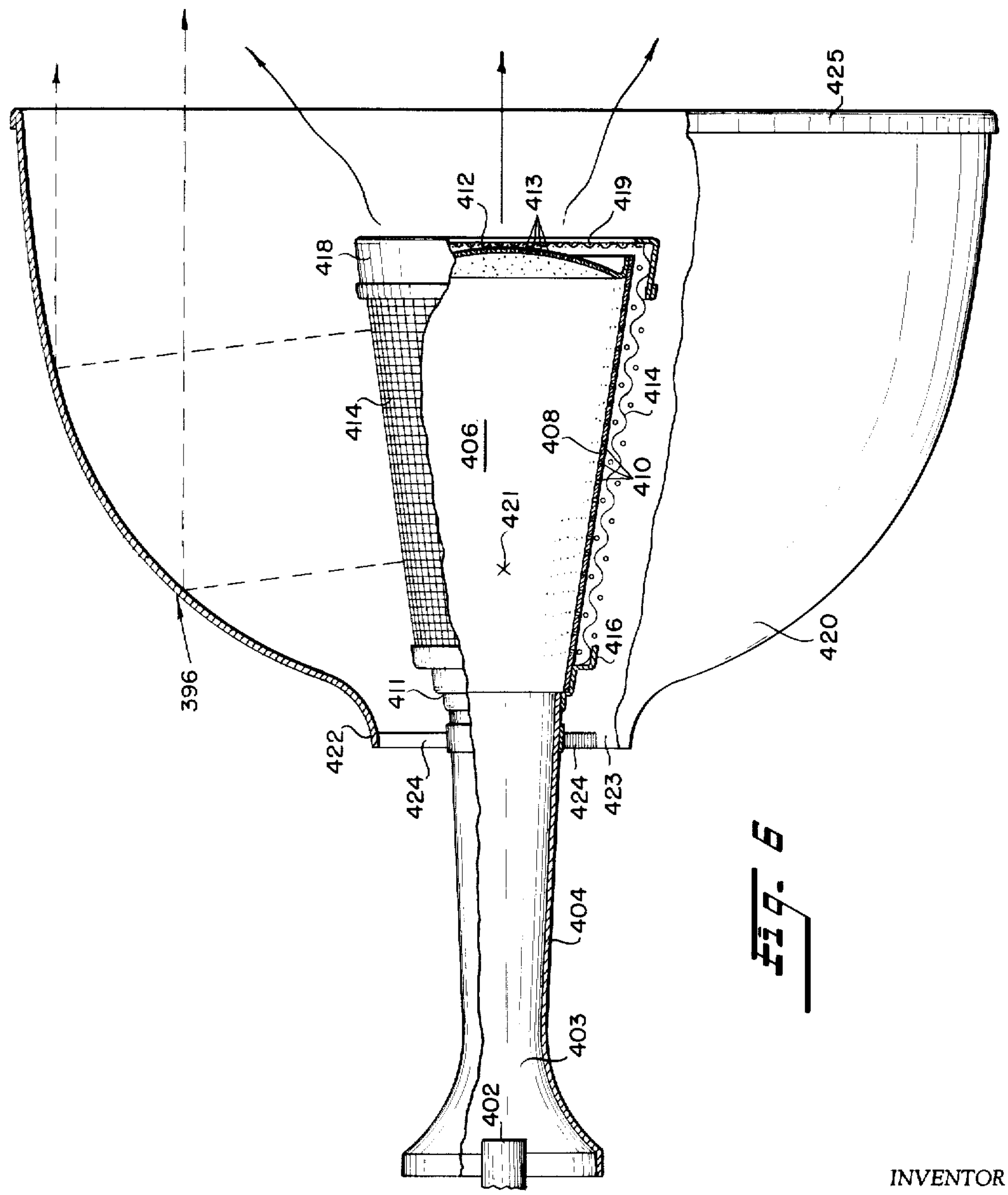

FIG. 6

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RADIANT GAS BURNER

Filed Dec. 11, 1962 4 Sheets-Sheet 4

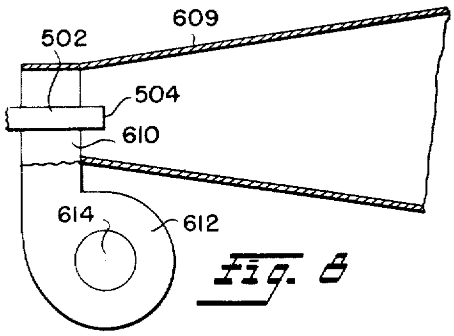

Fig. 6

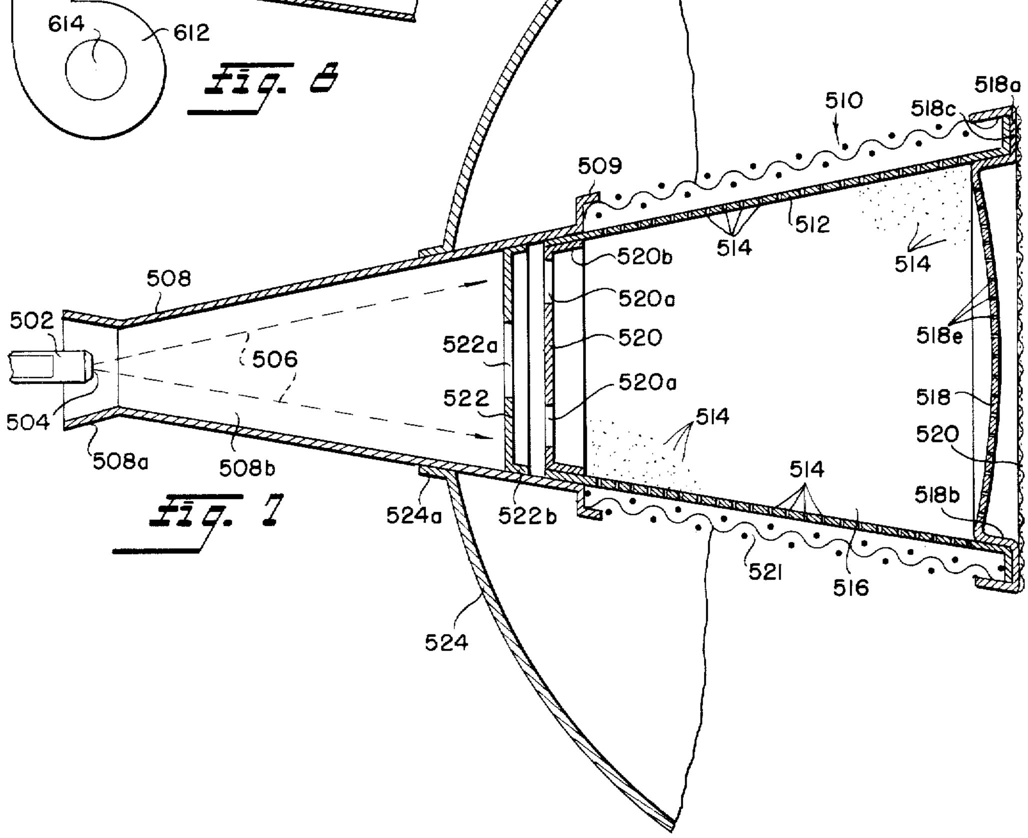

Fig. 7

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3,245,458

RADIANT GAS BURNER

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Filed Dec. 11, 1962, Ser. No. 243,916
2 Claims. (Cl. 158—53)

This invention relates to heating apparatus and, more specifically, to gas and liquid fuel fired infrared burners having radiant surfaces operating at temperatures above about 1200° F. and to improved methods of generating radiant energy in the intermediate and short wave portions of the infrared spectrum.

Gas-fired infrared burners of various types have heretofore been proposed. One type includes a distribution chamber into which a mixture of a combustible gas and combustion air are introduced. One face of the distribution chamber is perforated and the combustible mixture flows through the perforations and burns adjacent the outer surface of the plate, heating it to incandescence. A high percentage of the heating value of the combustible mixture is thus transferred from the incandescent plate to the space or objects to be heated in the form of infrared radiation. This type of burner is often equipped with a coarse mesh screen spaced a fraction of an inch from the outer surface of the radiant face beyond the combustion zone to provide a reradiating surface and to prevent the flame from being disturbed by air currents.

One major problem heretofore encountered with the type of burner described above is that of flashback; that is, the ignition of the combustible mixture in the distribution chamber by the flame passing back through the perforations in the radiant face or by heat transfer to the mixture as it circulates past the hot interior surface of the radiant face. This problem is particularly acute with burners of the type described above in which all of the combustion air is mixed with the gas before (or as) it enters the distribution chamber. Such a mixture is employed to attain as nearly perfect combustion as possible and to provide a short flame which is desirable since a maximum proportion of the heat of combustion is transferred to the radiant face and since the short flame is less susceptible to drafts. Such a mixture, however, is highly susceptible to flashback.

To minimize flashback, attempts have been made to construct burners of the above type in which the inner surface of the radiant face would remain relatively cool (that is, below the ignition temperature of the combustible mixture). In addition, the radiant faces have generally been made relatively thick and the perforations of very small diameter to prevent propagation of the flame through the perforations. One successful burner embodying these concepts is that shown in United States Patent No. 2,775,294 issued to G. Schwank December 25, 1956, for "Radiation Burners." In the Schwank type burner, the radiant face is relatively thick and is fashioned of a ceramic material having low heat conductivity to provide a substantial temperature gradient between its inner and outer surfaces. In addition, the perforations have a small diameter which together with their relatively great depth (provided by the thick face), prevents the flame from flashing back through them. The ceramic plates or tiles employed as radiant faces in these burners are expensive and difficult to manufacture and, in many applications, have a relatively short service life. In addition, it is impractical to form them other than as flat plates.

In other prior art burners the radiant face has been fabricated from a plurality of superimposed, fine mesh screens. In theory, the outer screen may be heated to

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a temperature at which it will emit short wave infrared radiation while the inner screen will remain relatively cool, preventing ignition of the combustible mixture in the distribution chamber.

Multi-screen burners have several serious drawbacks. The multi-screen radiant faces are expensive to manufacture. The burner must be operated at relatively low temperatures to prevent the inner screen from reaching the ignition temperature of the combustible mixture. The surface area of the radiant face which must be provided for a given heat output is relatively large which further increases the cost and reduces the usefulness of the burner. A further problem is warpage and destruction of the screen due to alternate expansion and contraction caused by large magnitude temperature changes. In addition, burned out screens are difficult to replace.

In order to obviate the undesirable features of burners in which the radiant face is a perforated ceramic tile or a multi-screen arrangement, it has been proposed that the radiant face be fabricated of a single, fine mesh screen. These burners have also proved unsatisfactory, mainly because flashback occurs at even lower temperatures than in multi-screen burners and because the heat output per unit of screen surface area is so low as to seriously compromise their usefulness. The single screen is also extremely fragile and, consequently, has a short life.

Another type of prior art burner (which, in some embodiments, is similar in appearance to the burners provided by the present invention) is disclosed in British Patent No. 494,087 issued to Charles Batt et al. for "Improvements in or Relating to Gas and/or Vapour Burners." In the Batt burners, the combustible mixture issues from a mixing chamber through a perforated metal plate and burns in a combustion zone between the plate and a coarse mesh screen spaced from the exterior surface of the plate. The Batt burners, however, are designed so that the outer screen is heated to incandescence and is the radiant face. The inner plate, on the other hand, is maintained at a temperature sufficiently low that it does not incandesce and functions, in effect, as a Davy screen to prevent flashback. The Batt burners are intended to be operated at relatively low temperatures in gas cooking apparatus and the like and not in the higher temperature ranges in which the burners of the present invention function.

In the Batt-type burner, also, the gas-air mixing tube is of the usual (Bunsen) type wherein only part of the combustion air is mixed with the gas, the balance of the combustion air being added to the outside of the flame. In fact, if 100% primary air were supplied to the Batt burner as is done in burners of the type to which the present invention relates, the radiant face would become incandescent and would not prevent flashback.

The burners of the present invention, like some prior art burners, have a distribution chamber in which a mixture of combustible gas and the air required for its combustion is formed. In contrast to the prior art burners, however, the radiant face is a single thin apertured member extended over at least one side of the distribution chamber. The combustible mixture flows from the distribution chamber through the apertures and burns on the outer surface of the member, heating it to incandescence. The radiant face providing member may be made of heat-resisting metal such as stainless steel or Nichrome or of any other material, metallic or nonmetallic, which will have a satisfactory life under the prevailing operating conditions. Unlike the prior art burners, the burners of the present invention can be operated at any desired incandescent radiant face temperature, on fuel gas of any composition, and with a gas-air mixture of any desired ratio, provided that the design of the radiant member conforms substantially to a formula set forth hereinafter and the material from which it is fabricated is suitable for the selected operating temperature.

In addition, the novel burners provided by the present invention can be operated at higher temperatures without flashback or unacceptably rapid deterioration than comparable prior art burners having thick ceramic plate or tile radiant faces. The thin perforated radiant members are cheaper to make than perforated ceramic tiles since the perforations can be formed by stamping, piercing, or similar process whereas the holes in the tile must be formed by molding followed by firing in a furnace. The radiant members of the present invention can be shaped as cylinders or cones or drawn into spherical or bulged forms, providing much greater latitude in the configuration of the burner. Moreover, they are much less liable to crack from mechanical or thermal stress or from deterioration due to high or changing temperatures than tiles or ceramic plates.

Because ceramic materials have low thermal conductivity, it is more difficult to maintain a ceramic plate or tile face at a uniform temperature, and since safe burner operation is limited by the temperature of the hottest spot on the radiant face, the average satisfactory practical operating temperatures of the prior art ceramic plate or tile burners are considerably below their theoretical maximum and much lower than the temperatures at which perforated plate radiant member burners may be safely operated. The high resistance to flow through the long holes in the tile also results in less air being induced into the burner venturi than in a thin plate burner operating under the same conditions. This makes it relatively more difficult to adjust a tile face burner to supply 100% the primary air.

Compared with the prior art burners in which the radiant face is formed of one or more woven wire screens such as is shown in U.S. Patent No. 3,021,893, the perforated sheet radiant face burners provided by the present invention have many advantages:

(1) Screens are more susceptible to flashback than the perforated plate radiant faces of the present invention since the well-defined orifices in the perforated plate are replaced by the spaces between the woven wires which are irregular in shape and form distorted irregular surfaces which cause turbulent flow of the mixture through the screen. A portion of the flame front will lie below the wires in the screen, increasing the possibility of flashback, and if the screen is very fine it is liable to be clogged by dust particles in the combustible mixture. In contrast, the well-defined orifices of the perforated plate provide relatively large unobstructed bases for the individual flames, minimizing the danger of clogging or flashback.

(2) The uniform structure and regular surface of the perforated plate provides a radiant face which may be uniformly heated, whereas screens tend to warp and buckle when heated, resulting in a non-uniform temperature pattern.

(3) Variations in temperature set up stresses in the individual wires forming a screen, shortening its life, a problem eliminated in perforated plates. Perforated plates have greater mechanical strength, expand more uniformly and are less easily damaged by handling than a screen, and therefore have a longer useful life.

(4) The size of the burner face orifices or perforations is important in the successful operation of a burner of this type. The perforated plate radiant face has fixed size orifices, which do not change although the plate is formed into a cylinder or cone. And, in drawn shapes, the holes can be dimensioned so that they will be correctly sized after drawing. The screen openings in even a flat screen are irregular and subject to manufacturing variations of substantial magnitude. If the screen is stretched, rolled or otherwise formed, the openings change in size and become nonuniform, providing a radiant face having an uneven temperature pattern and a tendency to flash back.

(5) Perforated plates provide simple structures which are easily supported whether flat, or rolled into cylinders or cones, or formed or drawn into other shapes. Screens, in contrast, require frames and supporting structures which result in added cost, reduced effectiveness, and greater expense when it is necessary to replace a burned-out radiant face, for example.

(6) Burners using perforated plate radiant faces are, as will be apparent from the above discussion, cheaper to construct than those employing screens as radiant faces.

The entirely different mode of operation and the consequent relatively low maximum temperatures attainable in Batt-type burners were discussed above. Another type of prior art perforated plate gas burner is exemplified by U.S. Patent No. 1,494,499 issued May 20, 1924 to H. W. O'Dowd. In this type of burner a perforated cone is heated to incandescence by a flame burning inside the cone. A combustible gas-air mixture is fed to the cone through a perforated plate fastened across its open end. This plate remains cool and prevents flashback. One of the disadvantages of this burner is that it will operate only in an upright position with the flame above the cool perforated plate. In contrast, the novel burners of the present invention can be oriented with the radiant face above, below or to one side of the mixture inlet. One of the most important applications of burners of the type to which the present invention relates is to project infrared radiation downward onto objects or an area to be warmed, an application for which O'Dowd burner is entirely unsuitable.

As in certain of the prior art burners, the efficiency of the burners provided by the present invention may be increased by arranging a reticulated member such as a large mesh screen adjacent but spaced from the outer surface of the primary radiant face to provide a reradiating surface. Preferably the reradiating surface is arranged beyond but adjacent the combustion zone so that it will enhance the efficiency of the burner and prevent the flame from being disturbed by air currents. This reradiating member also becomes incandescent, increasing the total radiating surface and raising the temperature of the radiant face, thereby increasing the amount of short wave length radiation emitted by it.

Such outer screens are the radiant faces of the Batt-type burners and have an additive effect in improving the operation of the other prior art burners in which they are used. In our invention, the thin perforated plate type radiant face and the adjacent screen have a synergistic effect providing a result never before achieved.

The radiant face or member employed in our burner may be a cone or other shape, adapting our burner to applications for which the prior art burners were not suited. Further, the three-dimensional shapes which the radiant face of our burner may take provide mechanical strength and prevent distortion at operating temperatures which would destroy or, at the least, seriously impair the efficiency of wire screens or ceramic plates.

In one embodiment of the invention the plate is formed into a frusto-conical configuration. The smaller end of the frustum is attached to the outlet of a tapered mixing tube so that the conical chamber formed within the radiant member is in effect an extension of the tapered mixing tube. In this embodiment the larger end of the radiant member has considerable area, and can be covered with a circular, preferably spherical perforated metal plate, adding appreciably to the radiant surface. This embodiment of the invention has all of the advantages of the cylindrical form, coupled with even greater mechanical strength, added radiant surface, and a smoother passage for the gas-air mixture, and is particularly well adapted for use with a surrounding parabolic reflector to provide a directed beam of radiant energy.

A further advantage of burners employing conical radiant faces becomes apparent by considering that, in a flat plate burner, perforations may occupy up to 45% of the surface, significantly reducing the total radiation since the holes do not emit radiant energy; and that with a conical radiant face, or structure having radiant faces on opposite sides of the chamber, radiation from the interior surface on one side may pass through the hollow interior and emerge through a hole in the opposite side. In addition, radiation emitted from the radiant member's inner surface impinges on oppositely located portions of the inner surface, increasing the temperature of the radiant face.

Conical face burners may be employed with or without reflectors. Without a reflector the radiant energy is dispersed in line of sight paths from the heated surface and may be employed to heat the walls of a chamber surrounding the burner, for example. Often, however, it will be desirable to direct the rays in a specific direction, or to prevent scattering of the rays in the direction of areas where heat is not needed. Since a radiant face in the form of a small diameter cone approaches a line or point source of radiant energy, the radiation can be directed by a suitable reflector with an effectiveness heretofore achieved only with tubular or conical electric heating elements but with the added advantage that the heater has a lower operating cost. By varying the shape of the reflector, the concentration of the beam may be varied.

Such reflectors may take the form of paraboloids with the axis of the radiant cone on the axis of revolution of the paraboloid.

Among the objects of the present invention are the following:

(1) The provision of improved infrared burners and heaters.

(2) The provision of novel infrared burners which have a perforated radiant face heated throughout its thickness to a substantially uniform temperature.

(3) The provision of novel infrared burners which can be operated on wide varieties of fuels and fuel-air ratios.

(4) The provision of infrared burners having substantially greater operating wave length ranges than those of the prior art.

(5) The provision of infrared burners having radiant members which are substantially less expensive to manufacture than those of the prior art.

(6) The provision of novel infrared burners having radiant members which have high structural stability combined with high thermal conductivity.

(7) The provision of novel infrared burners having thin perforated radiant faces and members providing reradiating surfaces substantially coextensive with and spaced from the exterior surface of the radiant face.

(8) The provision of novel infrared burners having a combustible mixture distributing chamber and spaced radiant members in fluid communication with the interior of said chamber and adapted to be operated with the one of the radiant members first contacted by the mixture at a temperature above the ignition temperature of the mixture.

(9) The provision of novel infrared burners having a perforated radiant face, a combustible mixture distribution chamber in fluid communication with one side of the radiant face and wherein the mixture is burned on the other side of the radiant face.

(10) In conjunction with the preceding objects, the provision of an infrared burner employing 100% primary air.

(11) The provision of novel and improved methods of operating infrared burners having combustible mixture distribution chambers and perforated radiant faces communicating therewith in which the entire radiant face is maintained throughout its thickness at a temperature above the ignition temperature of the combustible mixture.

(12) The provision of improved infrared heaters having burners conforming to the foregoing objects and reflectors for directing and concentrating the radiant energy emitted from the radiant surfaces of the burners in a wide variety of desirable patterns.

Other objects and further novel features of the present invention will become more fully apparent from the appended claims and as the ensuing detailed description and discussion proceeds in conjunction with the accompanying drawing, in which:

FIGURE 1 is a fragment of a radiant member employed in the burner of FIGURE 6 to a greatly increased scale, and illustrates the velocity profile of the combustible mixture as it flows through a perforation in the radiant member;

FIGURE 2 is a portion of the velocity profile of FIGURE 1 rotated through an angle of 90°;

FIGURE 3 is a chart showing, for three common fuel gases, the effect on the speed of flame propagation in a gas-air mixture of varying the percentage of the air theoretically required for complete combustion of the gas;

FIGURE 4 is a chart similar to FIGURE 3, illustrating, for the same three gases, the effect on the mean thermal conductivity of the gas-air mixture of varying the percentage of air theoretically required for complete combustion of the gas;

FIGURE 5 is a chart similar to FIGURE 3, showing the effect on the thermal diffusivity of a gas-air mixture of varying the percentage of the air theoretically required for complete combustion of the gas;

FIGURE 6 is an elevation, partly in section of a preferred form of the present invention;

FIGURE 7 is a section through an embodiment of the present invention which is particularly adapted to burn liquid fuel; and

FIGURE 8 is a fragment of the embodiment of FIGURE 7 with a modified fuel-air supplying arrangement.

Flashback inhibiting radiant members

The conditions under which prior art burners can be successfully operated are limited by the characteristic tendency of the flame to flash back into the distribution chamber through the apertures in the radiant face. Combustion within the distribution chamber prevents efficient burner operation and, if not promptly terminated, may destroy the burner.

Prior to our invention, it was assumed that a burner of the type to which this invention relates could not be operated with the radiant face incandescent throughout its thickness without flashback. We have discovered that, contrary to this belief, flashback will not occur during normal operation of our burner even though the radiant face is heated to incandescence throughout its thickness, even though a variety of gases and air-gas ratios are employed; if the radiant face conforms to certain structural requirements and dimensional limitations set forth in the ensuing discussion in which the following symbols and values are used:

α_0 (in.²/sec.)=thermal diffusivity (see FIGURE 5)
λ (B.t.u. in./sq. ft. °F. h.) (see FIGURE 4)=mean thermal conductivity
δ=specific gravity of fuel gas
γ (in.²)=cross sectional area of one perforation
γ_e (in.²)=effective cross sectional area of one perforation
A_V (in.²)=surface area of V
A_p (in.²)=radiant member surface area in contact with unburned mixture
a=theoretical ratio of air to gas for complete combustion
B (in.²)=radiant member area
c, c_1, c_2, c_3, C=dimensionless Peclet numbers based on flame speed
c_c, C_c=critical "C" numbers
c_p (B.t.u. lb. °F)=specific heat of fuel gas
c_m (B.t.u. lb. °F.)=specific heat of gas-air mixture
D (in.²/sec.)=diffusion coefficient

D_0 (in.²/sec.)=diffusion coefficient at 32° F. and 30" mercury column
d (in.)=perforation diameter
d_e (in.)=effective perforation diameter
d_c (in.)=critical width of gas pocket
f=perforation area factor=P/B
G=gas composition factor
g (cu. ft./hr.)=gas input rate per one sq. ft. of radiant member
H (B.t.u./cu. ft.)=heating value of gas
H_T (B.t.u./hr.)=heat transferred per hr. from radiant member to mixture before ignition
H_i (B.t.u./hr.)=heat required to raise mixture to ignition temperature
j=coefficient of jet contraction
j_e=effective coefficient of jet contraction (orifice factor for perforation)
K (sec./in.)=$1/V_m$ (reciprocal of V_m)
k (B.t.u. sq ft. °F. hr.)=heat transfer coefficient, radiant member to mixture
k_0 (sec./in.²)=heat transfer factor, radiant member to mixture
h (in.)=perforation depth
L=aeration factor or ratio of actual primary air to theoretical (a)
n=number of perforations per sq. in. of radiant member
P (in.²)=total perforation area
P_e (in.²)=effective total perforation area
p (in Hg)=gas pressure in combustion zone
P_0=30" Hg
S (in./sec.)=flame speed under burner operating conditions (see FIGURE 6)
T (° R.)=gas temperature
T_i (° R.)=minimum ignition temperature of mixture
T_0 (° R.)=492 R.
T_F (° R.)=flame temperature
T_p (° R.)=radiant member temperature
T_M (° R.)=temperature of mixture near radiant member
V (in.³)=volumetric increment of gas-air mixture
V_c (in.³)=critical volumetric increment of mixture
v_m (in./sec.)=maximum exit velocity of mixture through perforation
v (in./sec.)=exit velocity of mixture through perforation
v_a (in./sec.)=average exit velocity of mixture through perforation
w=channel factor for perforation

The following table gives values, for three of the more common fuel gases, of those factors which are constant for a given gas. These gases are:

(A) Natural gas (as furnished in the Cleveland, Ohio area).

(B) Coke Oven Manufactured gas (as specified in "Gaseous Fuels" p. 183).

(C) Propane (from "Gaseous Fuels").

Gas	H	a	T_F	T_i	δ	C_p
Natural	1,000	9.475	4,022	1,653	.65	.77
Propane	2,522	23.4	4,120	1,410	1.52	.743
Coke Oven	552	4.85	4,060	1,500	.416	.31

Values of factors dependent on both the composition of the gas and the air-gas ratio of the mixture are shown for the above gases in FIGURES 3, 4 and 5.

It should be understood, in relation to the following discussions, that the formulas hereinafter developed are believed to be accurate and comprehensive and have been verified by actual test. Regardless of these formulas, however, burners constructed in accordance with the principles set forth in the present application will provide the significantly improved results discussed above.

A combustible mixture is ignited by transferring sufficient heat to at least one volumetric increment V of the mixture to initiate the chemical reaction called combustion. To propagate a flame through the mixture from the initial volumetric increment, V must exceed a certain critical value, V_c.

For a perforated plate burner, the velocity profile of the gas-air mixture passing through the perforations is parabolic with the height of the parabola equal to the maximum exit velocity v_m. FIGURE 1 shows a velocity profile which will produce stable combustion as the profile exists just prior to ignition of the gas air mixture.

The volumetric increment V from which a flame front might propagate into the unburned mixture approaching the plate corresponds to that portion of the velocity profile paraboloid where the speed of flame propagation S exceeds the exit velocities v. In FIGURE 1, V is represented by an annular cross-hatched area having a maximum diameter slightly less than the diameter of the perforation through the plate. The height of the hatched area corresponds to the flame speed S. V is a function of the perforation area and depth, the perforation load, the primary air-gas ratio, the total area of the perforations, the ignition temperature and the flame speed of the gas-air mixture at the particular primary air-gas ratio and, therefore, will vary from installation to installation and as the operating parameters of given burners are altered.

For $V>V_c'$ the flame will propagate by thrusting out islets and peninsulas of hot gas into the unburned gas. For $V<V_c'$ the heat generated by the combustion of gas-air increment V is dissipated by conduction more rapidly than the flame is propagated and the reaction is extinguished.

Spalding, in "Some Elements of Combustion," p. 171, establishes a relation between the flame speed, that critical width of a slab-shaped gas pocket which will just propagate combustion, and thermal diffusivity:

$$\frac{Sd_c}{\alpha}=c$$

For gas pockets other than slabs, V/A_V is substituted for d_c' so that

$$c=\frac{SV}{\alpha A_V}$$

According to Spalding, $D=\alpha$.

The gas pressure in the combustion zone is very close to atmospheric, so that

$$\frac{p_0}{p}=1 \text{ and } T=T_i$$

Therefore,

$$\alpha=\frac{\alpha_0 T_i}{T_0}$$

$$c=\frac{SVT_0^2}{\alpha_0 A_V T_i^2}=\frac{SV(492)^2}{\alpha_0 A_V T_i}$$

and

$$c_1=\frac{SV}{\alpha_0 A_V T_i^2} \tag{2}$$

For c_1 values greater than a certain critical number c_c, the flame front will propagate from the initial volumetric increment V into the surrounding gas-air mixture. If c_1 is less than c_c, the combustion process propagating into the perforation will be extinguished.

Since part of the gas-air mixture increment V contacts the burner plate, the equation for determining C is corrected for heat generated by combustion in the increment and dissipated to the plate and for heat transferred to the mixture from the rear face of the burner plate and the walls of the ports prior to ignition of the mixture. As the heat transferred from the burned gas-air mixture to the plate is a linear function of T_F-T_p, the factor

$$\frac{T_F-(T_F-T_p)}{T_F}=\frac{T_p}{T_F}$$

must be introduced into the equation, giving a new c number

$$c_2=\frac{c_1T_p}{T_F}$$

or

$$c_2=\frac{SV1T_p}{\alpha_0A_VT_i^2T_F} \quad (3)$$

The heat H_T gained by the mixture prior to ignition depends on the temperature difference T_p-T_M, the area A_p of the plate in contact with the unburned mixture, and the heat transfer coefficient k, so that:

$$H_T=kA_p(T_p-T_M) \quad (4)$$

where k is proportional to the thermal conductivity λ of the gas-air mixture. The average exit velocity of the mixture through the perforations is $v_a=\frac{1}{2}v_p$, so that

$$k=k_0\lambda v_a=\frac{k_0}{2}\lambda v_p$$

and

$$H_T=\frac{k_0}{2}\lambda v_m A_p(T_p-T_M) \quad (5)$$

A_p increases with perforation depth or plate thickness. For safe operation, the mixture temperature should be kept below the ignition temperature until the mixture reaches the exit end of the perforation, since, if the mixture is ignited inside the perforation, a large portion of the heat developed by combustion is transferred to the perforation walls rather than to the front or exterior face of the plate and heat dissipation from the plate depends mainly on conduction through the plate to its surface. The advantage of heat transfer to the front face of the plate and immediate re-radiation therefrom are, therefore, minimized and, because of the heat build-up inside the perforation, the combustion zone will travel backwards toward the back or interior face of the plate and eventually flash back will occur.

The heat H_i (B.t.u./h.) required to raise the temperature of the mixture to ignition temperature T_i varies with the specific heat of the mixture, the quantity of gas and air, and the temperature differential between T_i and the temperature T_M of the mixture approaching the plate. The quantity of gas-air mixture delivered to one sq. ft. of burner surface in one hour at the temperature

$$\frac{T_M+T_i}{2} \text{ is } g(1+La)\frac{T_M+T_i}{2T_0}$$

Further,

$$H_i=c_M\frac{B_g}{144}(1+La)(T_i-T_M)\frac{T_i+T_M}{2T_0}$$

The mean specific heat of air from T_M to T_i of the common fuel gases is .24 B.t.u./lb. °F.

Therefore,

$$H_i=\frac{B}{144}(c_pg+.24gLa)\frac{(T_i^2-T_M^2}{2T_0} \quad (6)$$

Converting B.t.u. per pound to B.t.u. per cu. ft.,

$$\frac{1\text{ B.t.u.}}{\text{lb. °F}}=\frac{1\text{ B.t.u.}}{\frac{1\text{ cu. ft. °F}}{.08073}}=.08073\delta\frac{\text{B.t.u.}}{\text{cu. ft. °F}}$$

or

$$H_i=\frac{B}{144}(c_p\,.08073\delta g+.24\;.08073gLa)\frac{(T_i^2-T_M)}{2T_0}$$

and

$$H_i=\frac{.08073}{144}gB(c_p\delta+.24La)\frac{(T_i^2-T_M^2}{2T_0} \quad (7)$$

The ration H_T/H_i determines whether or not ignition will occur before the mixture exists from the perforations.

$$\frac{H_T}{H_i}=\frac{k_0144\lambda v_m(T_p-T_M^2)A_p2T_0}{2.08073Bg\;(c\delta+.24La)(T_i^2-T_M^2)} \quad (8)$$

For

$$\frac{H_T}{H_i}\leq 1$$

ignition will not take place until the gas-air mixture has reached the exit end of the perforation, a requisite for safe burner operation. For

$$\frac{H_T}{H_i}>1$$

combustion will occur inside the perforation and eventually cause flash-back.

Therefore, c_2 must be multiplied by H_T/H_i to correct for heat transferred to and from the gaseous mixture. Thus c number

$$c_3=c_2\frac{H_T}{H_i}$$

or

$$c_3=\frac{2.k_0144SV}{2.08073\alpha_0A_V}\;\frac{\lambda v_mA_p(T_p-T_m)}{Bg(c_p\delta+.24La(T_i^2-T_m^2)}\;\frac{T_pT_0^3}{T_FT_i^2} \quad (9)$$

The factor

$$\frac{2k_0144}{2.08073}$$

can be combined with the constant c_3.

The c number is different for different gas due to factors other than those considered in this analysis. For this reason, a dimensionless correction factor G, determined by test of each fuel gas, must be introduced into the formula for C. G has arbitrarily been assumed to be 1.0 for natural gas as available in Cleveland, Ohio. On this basis we have determined G for propane to be 1.0 and G for coke oven gas to be 0.4. For other fuel gases of differing characteristics G can be determined experimentally. Adding the correction factor G to the equation,

$$C=\frac{G\cdot c_3}{k_0\frac{144}{.08073}}=\frac{GSV}{\alpha_0A_V}\;\frac{\lambda v_mA_p(T_p-T_M)}{Bg(c_p\delta+.24LA)(T_i^2-T_M^2)}\;\frac{T_pT_0^3}{T_FT_i^2} \quad (10)$$

This final C number indicates whether a particular burner design under specified operating conditions will or will not perform satisfactorily. For C substantially less than C_c, the critical C value, flashback will not occur and the burner will perform satisfactorily under the specified operating conditions. For C substantially greater than C_c flashback is to be expected. Where C is close to C_c flashback may or may not occur since certain values of factors entering into the determination of the C number may be only approximately correct and it may therefore be difficult to calculate C_c with great accuracy. Calculated values of C may be checked by tests on burners.

Equation 10 is applicable to circular apertures, squares, slots, triangles, crescents, lanced openings and apertures of other regular and irregular shapes.

In calculating C for irregular openings, a value of δ equal to the area of the largest inscribed circle which will fit the irregular opening is employed. The number of the circular openings should be empirically determined so that the total area of the openings is the same in the actual and "equivalent" plates.

For a particular aperture configuration, V, A_V, H_T, and H_i are expressed in terms of plate design and burner operating conditions. Thus, for circular ports the equation for the C number reads as follows:

$$C=\frac{G\lambda}{\alpha_0}\frac{j_e dKS^3}{3(1-F^3)+2SKF}\frac{(1-f+\pi ndh)}{g(c_p\delta+.24La)}\frac{T_pT_0^3}{T_FT_i^2}\frac{T_p-T_M}{T_i^2-T_M^2}$$

Where $F=(1-KS)^{1/2}$

For plates with circular apertures or orifices, burning natural gas, the following factors are constant or substantially constant over the operating range of the burner:

$G=1$
$\lambda=.3$
$\alpha_0=2.9\cdot10^{-2}$
$j_e=.64$
$\delta=.65$
$c_p=.77$
$a=9.475$
$T_F=4022$
$T_i=1653$

Assuming that T_M is 100° F. above normal room temperature (660° R.) and substituting the above values in Equation 11, we have

$$C=1.37\cdot10^{-8}\frac{dKS^3}{3(1-F^3+2SK^3F}\cdot\frac{1-f+\pi ndh}{g(.2205+L)}\cdot T_p(T_p-660) \quad (12)$$

$$K=.237\frac{Bf}{g(.1056+L}$$

$$F=\sqrt{1-KS}$$

Designating the last three terms in Equation 12, X, Y and Z respectively,

$$C=1.37\cdot10^{-8}\cdot X\cdot Y\cdot Z$$

For plates with circular orifices, burning propane gas, the constants are as follows:

$G=1$
$\lambda=.27$
$\alpha_0=2.83\cdot10^{-2}$
$j_e=.64$
$\delta=1.52$
$c_p=.743$
$a=23.4$
$T_F=4120$
$T_i=1410$
$T_M=660$

Substituting these values in Equation 11,

$$C=1.015\cdot10^{-8}\cdot X\cdot Y\cdot Z$$

$$K=.0817\frac{Bf}{g(.0427+L)}$$

$$F=\sqrt{1-KS} \quad (13)$$

For plates with circular orifices, burning coke oven gas, the constants are as follows:

$G=.4$
$j_e=.64$
$\delta=.416$
$c_p=.31$
$a=4.85$
$T_f=4060$
$T_i=1500$
$T_M=660$

λ and α_0 are not constant for coke oven gas-air mixtures but can be obtained from FIGURES 7 and 8 respectively for various values of L.

Hence:

$$C=.4\frac{\lambda}{\alpha_0}\cdot.395\cdot10^{-8}\cdot X\cdot Y\cdot Z \quad (14)$$

$$K=.419\frac{Bf}{g(.2063+L)}$$

$$F=\sqrt{1-KS}$$

We have determined that C_c, the critical value of C, is 0.0005 for burners of the type to which this invention relates. Therefore, if the calculated value of C for a given burner design and given operating conditions is substantially less than 0.0005, the burner will operate without flashback. If the value of C is substantially greater than 0.0005, the burner will flash back. Where C is between 0.0004 and 0.0006 the burner may or may not flash back when operated at the given conditions, or its operation may be critical, since, for the reasons pointed out above, it is not always possible to calculate C with great accuracy.

Another limitation in addition to numbered limitations on radiant plate design is the minimum ratio of perforation area to total radiant face area. Preferably, the burners disclosed in this application are operated so that the burner has a continuous flame front; i.e., a flame front which extends across, or envelops, substantially the entire radiant face. The minimum ratio of perforation area to total radiant face area which will produce a continuous flame front may be as low as 10–15% or less depending upon a number of variables including the following:

(1) Gas input rate to the burner; (2) gas-air ratio; (3) flame speed of the combustible gas-air mixture; (4) temperature of the radiant face; (5) presence of a reradiating surface adjacent the radiant face; (6) shape of the radiant face; (7) whether air injection or a premixer is employed to form the combustible mixture.

To verify the accuracy of the theoretical determinations discussed above, a number of burners were constructed, all with perforated cylindrical radiant faces 2" in diameter and 3¾ inches long. The faces were of various thicknesses, the perforations were of various diameters and spacing, and the burners were operated with various gas-air mixtures and combustible mixture input rates. C numbers were calculated for each set of conditions. Typical results are listed below:

BURNERS AND OPERATING CONDITIONS GIVING SATISFACTORY PERFORMANCE WITHOUT FLASHBACK

Gas used	g	T_p, °F.	L	h	d	n	C
Natural	120	1,790	1.02	.027	.045	233	0.00053
Natural	84	1,660	1.025	.024	.040	233	0.00054
Natural	113	1,700	1.49	.019	.024	517	0.00001
Propane	52	1,740	1.25	.019	.024	517	0.00016
Propane	41	1,750	1.27	.008	.020	952	0.00012
Coke Oven	122	1,545	1.21	.009	.016	1,479	0.00033

BURNERS AND OPERATING CONDITIONS WHERE FLASHBACK OCCURRED

Gas used	g	T_p	L	h	d	n	C
Natural	62	1,450	1.0	.031	.065	98	0.00091
Propane	31	1,600	1.0	.024	.040	233	0.00092
Coke Oven	130	1,640	1.04	.009	.016	1,479	0.00077

Where the value of C for a given burner under given operating conditions indicates that there will be no flashback, the rate at which the combustible mixture is supplied to the burner can be reduced without flashback permitting the operating temperature of the radiant face to be altered by varying the mixture supply rate.

While, in the foregoing examples, different burner plates were employed for each gas, burner plates can be dimensioned so that they will operate successfully on more than one type of gas. Thus, a burner can be supplied for use with either natural gas or propane, for example.

If desired, the combustible mixture-forming venturi described above may be replaced with a premixer of conventional construction. Such a premixer is preferably arranged to effect the flow of a completely combustible mixture to the distribution chamber and through perforations in to the combustion zone adjacent the outer surface of radiant plates as described above. The "C" number for a burner fed a gas-air mixture from a premixing device is determined in the same manner as discussed previously, and the critical value C_c is the same.

Because of the large temperature change, a flat radiant plate will undergo substantial thermal flexing or warping as the burner is cycled between operative and inoperative conditions, especially when the plate attains temperatures of 2000° F. and higher. Hence, it is often desirable to form the radiant face of the burner into some other shape having greater structural stability under such conditions.

Conical radiant face burner

One such form of the invention is the gas-fired infrared burner **396** illustrated in FIGURE 6. Gas is supplied under pressure through an orifice spud **402** to the throat **403** of a venturi tube **404**. The flowing gas induces all of the combustion air required for complete combustion into venturi **404** where it mixes with the combustion gas.

The resulting gas-air mixture flows into a distribution chamber **406** which is the hollow interior of the frusto-conical radiant face **408** of burner **396** (which may be formed of the materials discussed above). A number of uniformly spaced perforations **410** are formed in radiant face **408**. The thickness of the sheet and the size and spacing of the perforations are determined in the same manner as for a flat plate.

One exemplary burner of this type which provides excellent results has a conical face varying in diameter from 2 to 3½ inches, an axial length of 6⅜ inches, and is formed of heat resistant metal plate 0.032 inch thick. There are 233 0.045 inch diameter apertures per square inch of conical surface. As with the previously described burners, no flashback will occur if the calculated C for given operating conditions is less than 0.0005.

The smaller end of the conical radiant face **408** is attached by an annular collar **411** to the outlet end portion of venturi **404**. The large open end of conical face **408** is closed by a spherically configured cap **412** made of the same material as radiant face **408** and perforated with holes **413** of substantially the same size and spacing as holes **410** although the material of the spherical end cap and the size and spacing of the perforations may be varied within the limits set forth in the preceding discussion entitled Flashback Inhibiting Radiant Members. If desired, cap **412** may be imperforate, but, in this case, it does not form part of the radiant face.

Spaced about ¼ inch from and surrounding conical radiant face **408** is a concentric conical wire screen **414** of about ¼ x ¼ inch mesh which is preferably fabricated from a heat resistant wire such as Nichrome. Screen **414** is substantially the same length as and is supported in concentric relationship to the radiant face by flanged rings **416** and **418** fixed to the opposite ends of radiant face **408**. Spaced about ¼ inch from spherical end cap **412** and supported by ring **418** is a ¼ x ¼ inch wire mesh screen **419**. This screen can be flat as shown in FIGURE 16 or the same shape as cap **412**. If cap **412** is imperforate, screen **414** is omitted.

Although burner **396** may be employed without a reflector, its design particularly suits it for use with a paraboloid reflector to heat a spot or small area. Such a reflector **420** is shown in FIGURE 6. The apex of reflector **420** is near the small end of conical face **408** and its focal point **421** is within chamber **406** about 4¾ inches from perforated cap **412**. A flange **422** surrounds the opening **423** at the apex of the reflector and is attached to the outlet end portion **411** of venturi tube **404** by a spider **424**. The conventional bead **425** is formed around the opening at the large end of the reflector. Infrared radiation is emitted from a radiant surface in every direction within sight of the surface. Most of the radiation from end cap **412** is radiated through the large open end of reflector **420** as shown by the wavy arrows in FIGURE 6. Most of the radiation from the large end portion of conical radiant face **408** strikes and is reflected from the large end of the reflector, as shown by the broken arrow. Most of the radiation from the small end portion of the conical face strikes and is reflected from the small end of the reflector as shown by the dot-dash arrow. The resulting beam or radiant energy has substantially uniform intensity and a concentration which depends upon the shape and depth of the reflector and can be varied to provide the optimum concentration for a specific application.

A further advantage of burner **396** is that the conical distribution chamber **406** forms a prolongation of venturi tube **404**, thus providing a smooth conduit for the gas-air mixture.

Liquid fuel burner

In the form of the invention shown in FIGURE 7, liquid fuel is forced under pressure from a pipe **502** through an atomizing nozzle **504** to provide a spray atomized oil as shown by broken arrows **506**. Nozzle **504** is located within the entrance bell **508*a*** of a venturi tube **508** which has a throat **508*b*** and oil sprayed through nozzle **504** therefore induces a flow of air through the venturi.

The burner indicated generally by reference character **510** is fixed to the outlet end of venturi tube **508**. Burner **510** includes a tapered tubular, frusto-conical radiant face **512** which is made of thin metal perforated with a large number of small holes **514**. The material and thickness of the radiant face **512** and the size and number of holes **514** are determined in the same manner as in the previously described form of the invention. The diameter and taper of radiant face **512** are selected so the face will form a prolongation of tapered venturi tube **508** to which the smaller end of face **512** is attached as by welding.

Radiant face **512** defines a frusto-conical distribution chamber **516**, the large end of which is closed by a perforated end cap **518** formed in a spherical shape with a U-section peripheral flange **518*a***. The material and thickness of end cap **518** and the size and spacing of the perforations **518*e*** in the end cap are preferably about the same as the material, thickness and the size and spacing of the perforations in radiant face **512**. An axially extending annular portion **518*b*** of flange **518*a*** is welded to the inside of face **512** to secure end cap **518** to the radiant face. A circular screen **520** of Nichrome or other heat resistant wire having a mesh of about ¼ x ¼ inch is welded to a transversely extending annular flange **518*c*** formed in end cap **518** to support the screen in spaced relation to the perforated end cap.

A second, frusto-conical screen **521** (also of Nichrome or similar heat resistant wire having a mesh of about ¼ x ¼ inch) is disposed around and spaced about ¼ inch from radiant face **512**. The larger end of screen **521** is supported by an annular flange **518*d*** of end cap **518** concentric with and spaced about ¼ inch outwardly of the larger end of radiant face **512**. The smaller end of screen **521** is supported by an annular flange **509** formed in the outlet end portion of venturi **508** which surrounds the smaller end of radiant face **512** and is spaced about ¼ inch therefrom.

The small end of radiant face **512** is closed by a flanged plate **520** having on the order of six equidistantly spaced ½ inch diameter holes **520*a*** adjacent its outer edge. An annular flange **520*b*** formed on plate **520** is dimensioned to fit within and is welded to the small end of radiant face **512** to fix plate **520** to the radiant face. A second flanged plate **522** having a central hole **522***a* about one inch in diameter is welded in the large end of venturi **508** adjacent outer flange **522***b*.

Fuel oil sprayed from nozzle **504** through venturi **508** impinges on plates **520** and **522** and is vaporized by the heat transmitted to these plates from the burning fuel-air mixture. The oil vapor mixes with air flowing into venturi **508** and forms a gaseous mixture having sufficient air for the complete combustion of the fuel which passes through holes **522***a* and **520***a* into distribution chamber **516**. From distribution chamber **516**, the mixture flows through perforations **514** and **518***e* and burns on the outer surfaces of plate **512** and cap **518** which are heated to incandescence by the burning fuel.

If desired, the energy emitted from radiant face **512** and perforated cap **518** may be concentrated by a paraboloid reflector **524** disposed with its focal point substantially coincident with the centroid of radiant face **512**. Reflector **524** has an annular flange **524***a* which may be welded to venturi **508** to retain the reflector in place.

The burner of FIGURE 8 is identical to burner **510** except that venturi tube **508** is replaced with a tapered tube **609** connected by a duct **610** to a blower **612** driven by an electric motor **614**. Blower **612** delivers the required combustion air to tube **609** where it is mixed with fuel oil supplied to tube **609** through tube **502** and nozzle **504**.

If desired, atomizing oil nozzle **504** may be replaced with a separate vaporizer for dividing and vaporizing the liquid fuel.

It may be desirable to reduce the intensity of the radiant energy and to spread the radiant energy beam over a wider area, as when the heater is suspended at a low height above a working area, for example. This may be accomplished by inserting bolts **735** in apertures **740***b* or **740***c*, increasing the spacing between the plate **708** fixed to the upper end of radiant face **714** and the top portion **724***b* of reflector **724** so that increasing proportions of the radiant energy are emitted at increased distances from the locus of focal points of the reflector, resulting in a more dispersed beam.

Radiant face **714** may be formed as any desired surface of revolution, such as the frustum of a cone, for example. In this form of the invention, as in those previously described, the combustible mixture passes through perforations in and burns on the exterior of the radiant face, heating it to incandescence and causing it to emit short and intermediate wave radiation. As in the previous embodiments, flashback is prevented by proportioning the size and number of the perforations and the thickness of the plate so that the value of C will be less than the critical value C_c which has been found to be approximately 0.0005.

In relation to the above detailed description, it is to be understood that the present invention is not limited to the specific, exemplary embodiments illustrated in the drawing, but that is intended to cover the many permutations and combinations of the burner components illustrated in these embodiments and variations of such components. For example, any of the several burners described may be provided with a reticulated reradiating member or a perforated reradiating member. As a further example, a combustible mixture forming premixer may be substituted for the venturi arrangement illustrated in conjunction with the various burners described above. As a final example, the other burners described above may be advantageously employed in various multiple unit radiant heating installations.

The invention may be embodied in other specific forms without departing from the spirit or essential characteristics thereof. The present embodiments are therefore to be considered in all respects as illustrative and not restrictive, the scope of the invention being indicated by the appended claims rather than by the foregoing description, and all changes which come within the meaning and range of equivalency of the claims are therefore intended to be embraced therein.

What is claimed and desired to be secured by Letters Patent is:

1. An infrared burner for generating short and intermediate wave radiant energy, comprising:

(a) a distribution chamber;

(b) a thin perforated radiant member, one side of said member being in fluid communication with the interior of said chamber;

(c) means for forcing a combustible mixture from said distribution chamber through the perforations in said member to a combustion zone immediately adjacent the exterior surface of said member;

(d) said distribution chamber being a tapered, circularly sectioned tube;

(e) said radiant member having a frusto-conical configuration and being supported adjacent one end of said tapered tube, said tube end and the adjacent end of said radiant member having substantially equal diameters and substantially the same amount of taper, wherein said radiant member forms a prolongation of said tube; and

(f) a thin, perforated, arcuately sectioned radiant member across the other end of said frusto-conical radiant member.

2. An infrared burner for generating short and intermediate wave radiant energy, comprising:

(a) a distribution chamber;

(b) a thin perforated radiant member, one side of said member being in fluid communication with the interior of said chamber;

(c) means for forcing a combustible mixture from said distribution chamber through the perforations in said member to a combustion zone immediately adjacent the exterior surface of said member;

(d) said distribution chamber being a tapered, circularly sectioned tube;

(e) said radiant member having a frusto-conical configuration and being supported adjacent one end of said tapered tube, said tube end and the adjacent end of said radiant member having substantially equal diameters and substantially the same amount of taper, wherein said radiant member forms a prolongation of said tube; and

(f) fuel vaporizing means including:

(g) a pair of spaced apart transversely extending conductive members adjacent the outlet end of said venturi in heat conductive relationship with said radiant member; and

(h) means forming non-aligned apertures in the respective conductive members to force the mixture in said distribution chamber to flow substantially parallel to said plates as it passes from said mixing chamber and the interior of the radiant member to insure complete vaporization of the fuel in said mixture.

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