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# A Critical Review of Noise Production Models for Turbulent, Gas-Fueled Burners

J. R. Mahan
*Virginia Polytechnic Institute and State University*
*Blacksburg, Virginia*

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## Introduction

The fundamental aspects of noise production by unsteady combustion continue to be of great interest to combustion system manufacturers and users. Because an unsteady flame is inherently more compact and homogeneous than a steady flame, it offers certain potential advantages in chemical processing and heating applications. Commercially successful pulse combustion water heaters have been designed which take advantage of the oscillating flow produced by controlled unsteady combustion to increase the mean heat transfer coefficient in the heat exchanger [1]. Whether spontaneous or induced, unsteady combustion can enhance mixing, thereby encouraging more complete combustion and thus reducing harmful emissions. Acoustically induced mixing has even been investigated as a means for decreasing the temperature spread at the outlet of a gas turbine combustor [2]. However, in most cases unsteady combustion is undesirable because it can lead to unwanted environmental noise and premature component failure. In the latter case, failure may occur either because of enhanced heat transfer to critical surfaces (burnout) or because of fatigue of components driven by the concomitant unsteady pressure field.

The spectrum of combustion noise in ducted combustion systems extends from low-frequency "chugging" at one extreme to high-frequency reheat "screech" at the other. Between these two extremes lies a broad band of activity associated with turbulence and other unsteady flow phenomena. In some cases, such as classical feed instability, the combustion heat release process becomes coupled with the acoustic response of the combustion chamber in such a way that self-sustained, nearly pure tone oscillations are produced. The present critical review is limited to the literature which deals with the more usual situation where unsteady combustion and the resulting sound pressure field are somehow associated with turbulent mixing of the hot products of combustion with the unburned reactants.

We will see that the physics of combustion noise production by turbulent flames is fairly well understood in terms of randomly distribured acoustic monopoles produced by turbulent mixing of products and reactants. However, in spite of this understanding, the principal goal of combustion noise research, which is the a priori prediction of the sound pressure in the acoustic farfield of a practical burner, remains unattained. The main reason for this is the lack of a proven model which relates the combustion noise source strength at a given frequency to the design and operating parameters of the burner. Before such a model can be developed, either semi-empirically or from first principles, more fundamental information must be obtained about the details of the combustion noise production process. In particular, a benchmark-quality data base is needed against which candidate source models can be tested. Specific recommendations for establishing such a data base are given at the end of this critical review.

## Literature Review

The following literature review deals exclusively with that important component of direct combustion noise, sometimes called combustion "roar", believed to be associated with turbulent processes in the reaction zone. In particular, the extensive body of literature dealing with feedback-supported combustion oscillations is excluded, as are papers treating all forms of indirect combustion noise, such as entropy noise. Primary emphasis is placed on past theoretical and semi-empirical attempts to predict or explain observed direct combustion noise characteristics of turbulent, gas-fuel flames; works involving liquid-fuel burners are reviewed only when ideas equally applicable to gas-fuel burners are presented. Individual contributions are cited more or less in the order of their appearance in the literature, except where a certain amount of coherence can be gained by grouping together a series of papers by a given author.

Most of the papers dealing with the theoretical aspects of noise generation in turbulent flames have been published since 1952. In that year Lighthill [3] published his remarkable aeroacoustics theory which has become the point of departure for many subsequent combustion noise theories. One of the earliest attempts to estimate the thermoacoustic efficiency* of a turbulent flame was made in 1963 by Bragg [4]. His development, which makes no distinction between open and confined flames, is based on two assumptions about the fundamental nature of combustion noise generation: (1) the radiated acoustic power is proportional to the mean square of the rate of change of volume evolution by combustion heat

*The thermoacoustic efficiency is defined as the fraction of the chemical heat release in the combustion process which appears as acoustic energy in the farfield of the burner.

release (i.e., the sources are of the monopole variety), and (2) a turbulent flame can be treated as a laminar flame whose surface is continuously wrinkled and distorted by turbulence. His resulting model predicts that combustion noise should increase with the reactivity of the fuel and with the square of the flow velocities (or with the pressure losses), intuitively pleasing ideas that have since been verified experimentally. Although the model predicts reasonable values of thermoacoustic efficiency, $\sim 10^{-6}$, and peak frequency, $\sim$500 Hz, for a typical hydrocarbon fuel flame, it is too simple to predict combustion noise for the wide range of parameters encountered in practical burners. Bragg's pioneering effort provided a great deal of insight into the combustion noise generation mechanism and was instrumental in stimulating further serious research into noise generation by turbulent flames.

Of historical interest is a published discussion [5] of Bragg's paper in which several other researchers comment on his results. G. M. Lilley suggested, on the basis of an experiment he had himself run on an open hydrogen flame burning in a low-velocity wind tunnel, that the increase in noise level noted when the initially nonreacting fuel jet was ignited was due more to the observed increase in the size of the mixing region than anything else. Bragg responded that this explanation was not consistent with the fact that the noise radiated from a ducted burner, such as a gas turbine combustor, increased when the nonreacting fuel jet was ignited even though the mixing volume was fixed by the geometry. P. E. Doak suggested that in a real combustion zone in which the overall combustion heat release rate was constant, there would be, on the average, the same number of contracting monopole sources as expanding monopole sources at any given instant. As a consequence destructive interference should occur and the net effect would be the same as a collection of quadrupole sources. He went further to suggest that in this case Lighthill's theory, with local entropy fluctuations acting as the quadrupole sources, might still reasonably be expected to predict combustion noise.* F. J. Weinberg wondered if perhaps, in view of Bragg's results, something might be learned about the turbulence parameters in flames by listening to them in much the same way researchers now use optical techniques to look at them. Bragg responded that a much more detailed mathematical model relating turbulence and combustion noise would first be needed.

Later that same year Smith and Kilham [6] undertook an experimental study of noise generation by open, turbulent, premixed gas flames with the goal of providing fundamental measurements that would lend physical insight into the noise generating processes. They interpret their results as indicating that radiated sound may be considered as arising from an uncorrelated collection of monopole sources being convected through the combustion zone. However, they do not postulate an empirical expression for the sound power as a function of the other parameters of the problem.

In 1965 Kotake and Hatta [7] derived a nonhomogeneous wave equation using reasoning similar to that of Lighthill [3] but including the energy equation. The acoustic source represented by the nonhomogeneity in their wave equation is composed of four terms, two of which, representing turbulent dispersion of pressure waves, are deemed negligible on the basis of physical arguments. The remaining two terms are identified as repre-

*Doak follows up on this idea ten years later. See discussion of Ref. [22].

senting the contribution to the sound field due to velocity turbulence and entropy turbulence. The authors apply this result to an open "premixed diffusion" flame (a rich premixed flame burning in air). An order of magnitude analysis is used to argue that the velocity turbulence term, whose form suggests dipole behavior, contributes to the farfield sound intensity as the fourth power of the mixture flow velocity, while the entropy turbulence term, whose form suggests monopole source behavior, contributes as the square of the mixture flow velocity. They conclude from geometrical considerations that the velocity turbulence source term should dominate in the turbulent brush of the flame while (curiously) the entropy "turbulence" source term should dominate in the laminar stem. The net result according to their theory is that for a dominantly turbulent flame the farfield sound intensity should vary as the fourth power of mixture flow velocity. Although they do not develop an expression suitable for estimating the farfield sound intensity, they do present experimental results which tend to verify the predicted fourth power dependence on mixture flow velocity.

In 1966 Thomas and Williams [8] report the results of an ingenious theoretical and experimental program of great fundamental importance. Starting with the classical expression for sound pressure radiated by a monopole in terms of the second derivative of its volume, they formulate a surprisingly simple yet rigorously correct expression for the sound pressure that should be radiated by a centrally ignited bubble of combustible mixture. The only assumption made which could possibly limit the validity of the expression is that the burning and subsequent expansion of the bubble proceeds at constant pressure. They then perform experiments in which a soap bubble containing a combustible mixture of a hydrocarbon fuel and air is centrally ignited by a spark gap. The experimental results for the farfield sound pressure versus time are in remarkably good agreement with theory. They show that if the initiating spark is off center or if ignition is initiated at several locations near the surface of the soap bubble, the sound wave produced in the farfield is much weaker. They are able to explain this effect in terms of their theory as follows. For a centrally ignited bubble the expanding products of combustion must push back the unburned mixture as the flame front spreads outward, while for surface initiated combustion no such displacement of the unburned gases occurs. For asymmetrical combustion the sound-producing process of pushing back the unburned gases takes on a dipole aspect and is thus much less efficient. According to their theory the amplitude of the pressure pulse associated with the centrally ignited bubble should exceed that of the surface ignited bubble by a predictable factor. Although uniform surface ignition could not be achieved experimentally, experiments in which ignition was initiated at four equally spaced locations near the surface tend to confirm this theory, thus lending support to their basic assumption of constant pressure burning.

The most important results of Thomas and Williams' research are: (1) a simple monopole source theory predicts the sound pressure produced by a centrally ignited spherical gas bubble almost perfectly, (2) the thermoacoustic efficiency in this ideal case increases with burning velocity over a range of about two orders of magnitude centered about a value near $10^{-5}$, and (3) the thermoacoustic efficiency can be expected to be reduced by about an order of magnitude if ignition is initiated near the bubble surface. This latter situation seems to be more in line with what might occur in a turbulent flame where combustion of a cell of mixture would be initiated at its outer surface by intimate contact with the surrounding hot products of combustion. Also, a significant amount of asymmetry would be expected for the ignition of a given cell of unburned mixture in an actual turbulent flame, thus further reducing the thermoacoustic efficiency. Then this work seems to establish that, to the extent that a turbulent hydrocarbon flame can be regarded as a randomly distributed collection of burning cells of mixture (and to the extent that destructive interference among individual cells can be ignored), the thermoacoustic efficiency should be in the $10^{-7}$ to $10^{-5}$ range, depending on the stoichiometry.

In a 1968 extension of Thomas and Williams' work, Hurle, et al. [9] postulate, on the basis of simple monopole source theory, that the sound pressure radiated from an open turbulent premixed flame should vary as the time rate of change of light emission by certain free radicals in the reaction zone. A key element in the development is their demonstration that the intensity of emission by these free radicals increases directly as the flow rate of combustible mixture for both laminar and turbulent flames. They interpret their experimental confirmation of this idea for an ethylene-air flame as supporting both the monopole source nature of combustion noise and the wrinkled flame model of turbulent flames. This result is significant because it establishes a direct relationship between the radiated sound pressure and the combustion heat release fluctuation.

A. A. Putnam, whose work is characterized by an interest in "real" rather than laboratory-scale burners, has made several significant contributions to the understanding of noise production by large industrial combustion systems. Putnam's first contribution in the open literature in this field was evidently in 1968 [10] when he reported the results of noise measurements on a burner consisting of eight fuel nozzles directed from the corners of a cube toward the center. He found acoustic activity in two frequency ranges: a high-frequency range ($\sim 10^4$ Hz) which he interpreted as representing simple amplification of the jet noise, and a low-frequency range (100 - 500 Hz) representing direct combustion noise. The thermoacoustic efficiency of this burner varied with firing rate (fuel flow rate), nozzle diameter and spacing, and degree of convergence of the nozzles toward a common center over a range from about $10^{-8}$ to about $10^{-7}$, which is comparable to values obtained by other investigators. Although he does not give an expression, Putnam claims a satisfactory correlation of these data based on an assumption of monopole-type sources.

Putnam returns to the problem of combustion roar* in turbulent diffusion flames in a 1970 paper with Giammar [11]. A critical review of the literature is presented aimed at clarifying the question of whether the noise reported by earlier investigators is independently produced combustion noise or merely frequency selective amplification of turbulence already present in the cold jet. They point out, as will others, that the noise spectra of all hydrocarbon-fuel burners peak in the 300 to 600 Hz frequency range, suggesting that the peak frequency may be chemically controlled. They argue that Bragg's [4] theory can lead to a wide range of scaling laws for noise production as a function of firing rate, depending

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*"Combustion roar" is the generic term, generally attributed to Putnam, for noise generation by turbulent flames in the absence of combustion-driven oscillations. See discussion of Ref. [30] for a more complete classification of combustion noise.

on the model adopted for the distribution of the turbulent cells. If the number of cells is constant, the noise power should vary as the square of the firing rate, whereas if the number of cells increases with mixture flow but the reaction rate of each cell is constant, the noise power should vary directly as the firing rate. They also predict that as the flame characteristic dimension approaches one-quarter wavelength, cancellation effects (interference) should occur which decrease the efficiency of the flame as a noise source. This idea, reminiscent of Doak's remarks in Ref. [5], will find strong support in the experimental results of Ref. [27]. Finally, they point out that the flame front is actually defined by a constant temperature surface, which is a concept needed to interpret noise production theories proposed by others* based on motion of the flame front.

Giammar and Putnam [11] also report results from their own experimental study of two industrial natural gas diffusion-flame burners: a coaxial impinging jet burner and the so-called "octopus" burner from Ref. [10]. Results indicate that jet noise (high frequency range) is amplified on the order of 20 dB when the impinging fuel jets are ignited. For the combustion noise from the impinging coaxial jet burner, the Strouhal number based on the spacing between the fuel nozzles and the peak frequency is constant at about 0.24. This value is consistent with the idea, mentioned above, of destructive interference between two sources which occurs as their spacing exceeds one-quarter wavelength. Two burner operating regimes are identified: bouyancy controlled, in which the flame volume increases with firing rate, and thrust controlled, in which

*See discussion of Refs. [16], [21] and [31], for example.

the flame volume is independent of firing rate. For the bouyancy controlled operating regime of the octopus burner, combustion noise increases with the square of the firing rate, indicating a monopole-type source behavior, whereas for the thrust controlled regime, the noise level increases directly as the firing rate, indicating a constant thermoacoustic efficiency. Thermoacoustic efficiencies ranging from about $10^{-8}$ to about $10^{-6}$ are reported, which are consistent with values already in the literature. Although they present evidence supporting their contention that there is a characteristic spectral shape associated with a given fuel, Giammar and Putnam also point out the strong resemblance in many cases between the spectrum without and with combustion. Thus left largely unanswered is the question of whether combustion noise is independently produced or merely the amplification of pre-existing turbulence in the fuel jet.

In 1971 Knott [12] reiterates the development of Bragg's [4] theory of combustion noise with some refinements and then presents experimental results for reacting coaxial jets of fuel and oxidizer as well as for reacting impinging jets of fuel and oxidizer. His measured values of thermoacoustic efficiency for all cases are of the order of magnitude predicted by Bragg's theory, i.e., $10^{-6}$. He found that the most important correlating parameter for the thermoacoustic efficiency was the fuel volume flux, with the thermoacoustic efficiency varying as the cube of this parameter for turbulent coaxial jet diffusion flames, and varying inversely with this parameter for turbulent impinging jets of reacting fuel and oxidizer. He concludes, as did Bragg, that the simple monopole source model adequately describes the general trends of combustion-generated noise.

Later that same year Strahle [13] presents two theories of combustion noise based on extensions of Lighthill's [3] aeroacoustic theory. Both follow from rather rigorous application of the principles of fluid mechanics up to a point, beyond which intuitive reasoning is relied upon. In both cases he argues that, of the two terms in Lighthill's turbulent stress tensor which are normally neglected under isentropic flow conditions, one dominates in the presence of combustion. A key assumption in both theories is that the turbulent field dominates the sound field to the extent that the latter exerts no appreciable influence on the source activity. Although probably inexact, it is not clear that this assumption seriously impacts the resulting sound power estimate. The degree of agreement actually obtained between Strahle's theory and experimental trends from the literature tends to justify the assumption.

The first theory developed by Strahle [13] depends, as did Bragg's, on the wrinkled flame concept of a turbulent flame. Rather than introduce the energy and entropy principles from thermodynamics to rigorously account for density fluctuations in the turbulent reaction zone, as Kotake and Hatta [7] attempted to do, he invokes an interpretation of the wrinkled flame model which permits the introduction of two time scales, one due to convection and one due to diffusion. This leads to an expression for the thermoacoustic efficiency estimate having two adjustable exponents whose values depend on the relative dominance of the two rate processes. Strahle demonstrates that the experimental trends from the literature for open premixed flames can be predicted by this theory if appropriate values of the two adjustable exponents are chosen. The expression reduces, to within a constant multiplicative factor, to Bragg's result if all of Bragg's assumptions are invoked.

Strahle's second theory differs from his first only in that the wrinkled flame model is replaced by the distributed reaction model of turbulent combustion. In this latter model, isolated cells of mixture distributed through the reaction zone burn in such a way that the fluctuating heat release is balanced by velocity divergence rather than molecular conduction. He argues that this interpretation, reminiscent of the "expanding balloon" idea often cited when describing monopole sources, is consistent only with nonlaminar flame propagation. Although Strahle admits that the applicability of the distributed reaction model in this situation is open to question, he demonstrates that it is able to explain the relationship between the sound pressure field and the light emission intensity fluctuation noted by Hurle, et al. [9], something which he argues that the wrinkled flame model is unable to do.* The second theory results in an estimate for the thermoacoustic efficiency whose form is simpler than that of the first theory in that it does not have adjustable exponents. Consequently it has insufficient flexibility to predict the wide range of trends observed in data from the literature, for example those of Smith and Kilham [6] and of Kotake and Hatta [7]. However, it is consistent with the results of Hurle, et al. [9] and, when typical values are introduced for the parameters, gives a value much closer to unity for the multiplicative constant in the thermoacoustic efficiency expression than does the estimate based on the wrinkled flame model. The second theory predicts the same velocity dependence as Bragg's theory but predicts a much stronger dependence on the flame reactivity. While the first theory seems more capable of correlating an extensive body

*The reader will recall that Hurle, et al. [9] interpret their results as supportive of the wrinkled flame model.

of experimental data, both point to the acoustic monopole as the dominant source mechanism in combustion generated noise.

In a 1972 extension of his earlier attempt to establish scaling rules for sound power radiation from turbulent flames, Strahle [14] presents a general expression for the farfield density fluctuation which is in agreement with the data and theoretical development of Hurle, et al. [9] His analysis begins with his previous expression [13] relating the farfield density fluctuation to the second time derivative of the retarded-time global "turbulent" density in the reaction zone. By introducing an appropriate combustion energy equation to account for the turbulent density fluctuations in the reaction zone, he is able to relate the farfield density fluctuation directly to the global time rate of change of the reaction rate. This result is interpreted as lending support to the series of assumptions which must be made to obtain the farfield density fluctuation from Lighthill's nonhomogeneous wave equation.

Once having obtained a general expression valid for both premixed and diffusion flames and independent of assumptions about the turbulent structure of the flame, Strahle [14] then considers three turbulent flame structure models: the wrinkled laminar flame model and two extremes of the distribution reaction model. In the first of these latter, the so-called "slow" distributed reaction model, it is assumed that the chemical reaction rate is sufficiently slow that the time derivatives are determined by the rate at which slowly reacting turbulent eddies are convected past the observer; whereas in the second, the so-called "fast" distributed reaction model, the time derivatives are determined by the reaction rate and the eddies can be regarded as stationary. Comparison of sound power estimates based on these theories with data from the literature indicates that no one of them exactly explains all the experimental trends, even though all explain the observed orders of magnitude and signs. When numbers from Smith and Kilham [6] are introduced, of the three turbulent flame models, the slow distributed reaction model yields a coefficient for the radiated power estimate which is nearest to unity. When predicted and measured center frequencies are compared, both the wrinkled flame and slow distributed reaction models are in good agreement for the one case for which comparisons are made, while all three models give values in the right range.

Strahle also considers directionality in this paper and concludes on the basis of an involved order of magnitude analysis that the slight directionality observed in some data from the literature cannot be due to the source behavior, but instead must be attributed to convection and refraction effects.

In 1972 Giammar and Putnam [15] report the results of experiments on industrial premixed gas-flame "simplex" burners operating singly and in pairs at slightly fuel rich conditions at firing rates in the 250,000 to 670,000 Btu/hr range. The measured sound pressure levels are presented in three formats: as a function of the firing rate squared, as a function of the product of the Mach number squared and the firing rate, and as a function of the product of the relative nozzle pressure drop and the firing rate. Although all three presentations yield fairly linear variations of the sound pressure level, the latter seems to exhibit the least scatter. They interpret this as supporting their own combustion noise theory, based on the assumption of a turbulence dominated source mechanism, which is a derivative of the theories of Bragg [4] and Hurle, et al. [9] The authors concede that the observed agreement between experiment and theory in this case is by no means definitive because it is based on very little data. They call for additional experimental work.

Later in 1972 Arnold [16] gives a descriptive account of combustion noise generation whose most innovative feature is the idea that the pressure fluctuation associated with unsteady combustion should be directly proportional to the flame surface area fluctuation. This is once again consistent with a monopole-type source structure, but viewed from a slightly different perspective. It is a plausible interpretation and, as such, focuses attention on the question of what is meant by the "flame surface". It is here perhaps that Giammar and Putnam's [11] 1970 interpretation of the flame front as a constant temperature surface would be useful. No experimental results or thermoacoustic efficiency estimates are provided.

1973 was a banner year for combustion noise studies. In that year Chiu and Summerfield [17] present a unified combustion noise generation theory in which a convected wave equation is formulated from the principles of conservation of mass, momentum, energy, and chemical species for a reacting mixture of ideal gases. The result includes source activity due to chemical reactions (both nonsteady heat release and nonsteady convection of steady heat sources), heat conduction, species diffusion, and viscous dissipation. The general convected wave equation is specialized to each of three zones: an inner reaction zone, an intermediate nonisothermal layer, and an external radiation zone. A general series solution obtained within each zone is matched at the zone boundaries and the usual farfield approximation is invoked which allows higher order terms in distance between the source point and the field point to be neglected. The resulting expression for the farfield sound pressure may be interpreted as describing a composite layer consisting of a monopole source distribution surrounded by an attenuating nonisothermal layer. The corresponding source function consists of six individual double correlation source terms, each accounting for a different source mechanism available to turbulent flames, and a common multiplying factor whose value depends on the thermochemical parameters and the upstream flow conditions. The relative importance of the six source terms cannot be determined from the general theory, although certain hypotheses can be made based on assumptions about the turbulence scale and intensity. This implies that the central problem which remains is that of identifying the structural details of given turbulent combustion processes.

Chiu and Summerfield specialize their general theory to two flame models: a modified wrinkled flame model and the distributed reaction model. In the former case the flame is regarded as a collection of small flamelets for which the total sound intensity is calculated as the sum of the noise produced by the individual flamelets. The farfield sound pressure and intensity are then directly related to the ratio of the turbulent to the laminar flame speed, among other parameters. In the latter case expressions are obtained for the six correlation functions in terms of the Reynolds number, thus in principle permitting estimation of the velocity regimes governing the various source mechanisms.

A one-dimensional version of the theory is applied to a turbulent flame consisting of an upstream zone, a reaction zone containing the source activity, and a downstream zone. A fluctuating heat release rate is assumed for the compact reaction zone, and solutions are obtained which are matched at the zone interfaces. The results are interpreted to show that the conversion of thermal energy into acoustic energy corresponds to a pseudo sound field in the reaction zone, and thus that the energy conversion process is less efficient than it would be if the same energy were supplied directly to the true sound field as in certain types of combustion instability. The paper also considers noise generation by liquid spray burners, but this topic is beyond the scope of the present review.

Later in 1973 Chiu, et al. [18] report the results of a theoretical and experimental study of noise generation by ducted combustion systems. They solve a three-dimensional wave equation, which is nonhomogeneous in the source region, subject to the constraint that the solutions match at the interface between the source and propagation regions. The steady flow field is one-dimensional and assumed uniform throughout the combustor so that the wave equation has constant coefficients. The nonhomogeneity in the source region wave equation is a specified three-dimensional monopole source function whose assumed form is independent of the resulting pressure field; that is, there is no possibility for feedback coupling between the acoustic field and the source field. A farfield sound pressure spectrum is computed based on the velocity fluctuations at the exit plane of the combustor. This leads to a pressure spectrum which resembles measured spectra in that it exhibits low frequency spectral peaks roughly corresponding to odd integer multiples of the quarter-wave resonant frequency of the combustion system. The important result is that confinement of the flame in a duct has a significant impact on emitted sound even when the source structure itself is (by assumption) not affected by the resulting sound field.

Also in 1973 Shivashankara, et al. [19] report experimental results of directionality, spectral content, and radiated sound power for premixed open turbulent flames burning in an anechoic chamber. The acoustic behavior of gaseous propane, propylene and ethylene flames, all burning in air and stabilized by a concentric hydrogen flame, was studied for a range of flow velocities, burner port diameters, laminar flame speeds, and fuel mass fractions. Directionality is shown to be slight, less than 4 dB of variation, with the peak shifting toward the downstream axis with increasing flow velocity and decreasing port diameter. The authors interpret these results as consistent with the idea of monopole sources being convected downstream with the flow.

The results for radiated power are interpreted using a regression analysis in which flow velocity, port diameter, laminar flame speed, and fuel mass fraction are taken as parameters. For lean flames the radiated power is shown to vary roughly as the cube of the product of flow velocity and port diameter, and with laminar flame speed with an exponent of 1.36. Its variation with fuel mass fraction is weak, having an exponent of 0.4. Some of the data of Smith and Kilham [6] are also shown to fit this regression. The regression gives values of the thermoacoustic efficiency between about $10^{-8}$ and $10^{-6}$.

In each case the farfield sound pressure spectrum is limited to low frequencies and exhibits the features typical of combustion noise, that is, it is broadband with a single peak. A regression analysis of the peak frequency as a function of the same four parameters used in the radiated power regression indicates that it is not very sensitive to any of these parameters, thus seemingly ruling out the use of a Strouhal number correlation. The greatest influence is due to the laminar flame speed and the fuel mass fraction, suggesting that the chemical reaction rate determines the characteristic time of the flame.

The only significant difference between lean flames, discussed above, and rich flames (which behave somewhat like diffusion flames in this case) is in the exponent of the port diameter in the sound power regression which, in the case of rich flames, is nearer to 2 than 3. The experimentally determined exponents are not completely in agreement with any of the theories discussed previously.

Later still in 1973 Strahle [20] reconsiders his previous combustion noise theory [14] and discusses it in light of that of Chiu and Summerfield [17]. It will be recalled that both theories are based on extensions of Lighthill's classical aeroacoustics theory, the main difference being that, beyond a certain point in the development, Strahle [14] appeals to physical reasoning to arrive at a radiated sound power estimate, while Chiu and Summerfield derive and solve the appropriate nonhomogeneous wave equation. In the present article Strahle demonstrates that his estimate and the result of Chiu and Summerfield differ primarily by a factor of the square of the ratio of the adiabatic flame temperature to the mixture temperature upstream of the flame. He points out that this factor appears because of the difference in choice of scaling laws between the two theories. He then shows, using the scaling laws of Chiu and Summerfield, that an estimate of the radiated sound power can be obtained whose exponents on flow velocity, port diameter, laminar flame speed, and fuel mass fraction are in remarkably good agreement with those in the regression of Shivashankara, et al. [19] The time scaling required to obtain this result is based on the flow velocity and port diameter rather than on the characteristic chemical time. Yet it has already been suggested [11, 19] that the peak frequency of the combustion noise spectrum is relatively independent of flow and geometry but depends rather on the fuel reactivity and flame temperature. Thus theory can still only partially explain observed behavior, perhaps, as Strahle suggests, because too much still remains unknown about turbulent flame structure.

In 1973 Roberts and Leventhall [21] offer compelling evidence that the predominant noise generating mechanism in open turbulent premixed flames is the turbulent velocity fluctuation at the flame front rather than the entrainment and subsequent combustion of individual turbulent eddies, or "cells", of mixture as they penetrate into the combustion zone. This then is similar to Arnold's [16] theory if it is assumed that a "velocity fluctuation at the flame front" is equivalent to a flame surface area fluctuation, as suggested by Giammar and Putnam's [11] interpretation of the "flame front" as a constant temperature surface. They argue that if combustion noise in this type of flame is due to the burning of individual turbulent eddies of mixture ignited at their outer surface, the peak frequency should vary as the ratio of the laminar flame speed to the average turbulent eddy size. However, they show that for a fixed eddy size (established by the height above the mixture port where the flame was anchored by an array of pilot flames) varying the flame speed (by changing fuels) has no effect on the peak frequency of the resulting combustion noise. On the other hand, they report a "close relationship" between the peak frequency of the mixture velocity fluctuation at the flame front location before ignition and that of the combustion noise after ignition. They also give experimental results which show that the A-weighted sound pressure level varies as the log of the product of the mixture flow velocity, the port diameter, and the laminar flame speed.

It was also in 1973 that Doak [22] published his unified theory of sound generation in turbulent flows which, by virtue of its sweeping generality, includes combustion noise. The theory, like so many others, develops along the lines of Lighthill's acoustic analogy, at least up to a point. The first improvement offered by Doak is to include the conservation of energy principle in a formally rigorous way. Then, by splitting the momentum density potential into purely solenoidal and purely irrotational parts and further splitting the irrotational part into an acoustic part and a thermal part, Doak is able to decompose the time dependent motion of the flow into vortical (which includes but is not limited to turbulence), acoustical, and thermal components, rather than just into vortical and acoustical components as is traditionally done. The result is a system of five coupled nonlinear partial differential equations with variable coefficients in the three components of the solenoidal part of the momentum density and the two scalar quantities whose divergences are the acoustic and thermal parts of the momentum density. Although it is not immediately clear, due to its extreme mathematical complexity, how this theory could actually be used to predict, or even estimate, combustion noise generation in a turbulent flame, it does seem to "consistently and unambiguously" (using Doak's words) account for all forms of internally generated sound, including combustion noise. In fact, the theory even describes the nonlinear interactions between the three types of motion as well as their individual interactions with the mean flow variables that could account for refraction and convection effects, i.e., directionality. Perhaps this generalized theory based on Lighthill's acoustic analogy is what Doak had in mind ten years earlier when discussing

Bragg's theory in Ref. [5].

Doak's unified theory is remarkable in that it is based entirely on first principles and rigorous mathematical formalism—it does not depend on any assumptions or models of turbulent combustion to explain the physics of combustion noise generation. Although conservation of chemical species and mixture effects are not included in the formalism, Doak makes clear his belief that the theory could be extended to include these effects in a "straightforward manner." He implies that the theory as presented could be used to characterize combustion noise if appropriate measurements of the spatial and temporal variations of the external heating function were available. Unfortunately, the form of the theory and, to a lesser extent, the use of a momentum density potential function to represent the acoustic and thermal motions preclude the direct application (short of a formal solution of the equations) of the theory to infer scaling parameters or otherwise help interpret experimental results.

In 1974 Abdelhamid, et al. [23] investigate the importance of combustion noise relative to jet noise for a small liquid-fueled combustor exhausting into the atmosphere through a converging nozzle. This study does not address the question of the origin of combustion noise per se, but rather lumps all noise sources within the combustor under the general heading of "combustion roughness" as evidenced by the measured combustion chamber pressure fluctuations. Combustion noise is shown to dominate jet noise over the spectral range investigated. The dominant frequencies were observed to change with combustion chamber geometry and air/fuel ratio. Of principal interest to the present review, however, is the fact that the authors were able to predict with fairly good accuracy the observed farfield spectra on the basis of measured combustion chamber pressure fluctuations. They accomplished this by treating the nozzle exit plane as a monopole source; that is, they related the far-field sound pressure to the flow fluctuations at the nozzle exit where these latter were computed by applying a perturbed Bernoulli equation to the measured chamber pressure fluctuations. This tends to support the monopole nature of combustion noise favored by previous investigators while demonstrating the possibility of placing this interpretation on an analytical footing, at least in the case of a ducted burner.

Reference [23] is also significant because it signals the beginning of a trend in combustion noise research away from fundamental studies on gas-fueled laboratory-scale burners toward liquid-fueled burners whose sizes and designs approach those of gas turbine combustors. For example, it is about this time that the Princeton group led by Summerfield and the Georgia Tech group led by Strahle begin to focus their attention on the problem of "core noise"* in gas turbine engines. The period 1973-74 also saw a significant increase of activity on the part of NASA and the engine manufacturers in this area.

In another 1974 paper Riley, et al. [24] report measurements of the volume transfer function (magnitude and phase) of a Meker burner propane flame for a range of air/fuel ratios. Speakers in an upstream pressure chamber were used to produce sinusoidal fluctuations of the mixture flow into the burner for frequencies ranging from 40 to 600 Hz. The volume fluctuation entering the flame was independently inferred from both

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*"Core noise" is the name given to that component of gas turbine engine noise that can be attributed neither to jet noise nor to compressor blade passing tones. Thought to be closely related to the combustion process, it is generally dominant at the higher flight speeds and at idle conditions when jet noise is negligible.

acoustical and hot wire measurements, and the corresponding volume fluctuation of the flame itself was independently inferred from both optical and acoustical measurements. The results show clearly that the ability of the flame to amplify volume (i.e., purely irrotational) disturbances diminishes monotonically with frequency at a rate which decreases with the air/fuel ratio. This implies that at least one reason for the low frequency content of combustion noise is the natural frequency response characteristic of the flame itself, which evidently behaves as a low-pass filter.

Also in 1974 Hassan [25] reports the results of a theoretical study in which he derives estimates of the radiated sound power and peak frequency of combustion noise on the basis of an extension of Lighthill's acoustic analogy. He treats the mass density, which appears in the term in Lighthill's equation which is normally neglected in jet noise studies, as a function of pressure, entropy, and the mass fractions of the various chemical species present. Its variation is accounted for by introducing the principles of conservation of chemical species and energy and assuming ideal gas behavior. Hassan derives a form of the nonhomogeneous wave equation containing the usual quadrupole term (Lighthill's stress tensor), a monopole term directly related to combustion, a dipole term (which Hassan suggests could at least partially explain observed directionality), and terms of order three or higher in the reciprocal of the acoustic velocity in the reaction zone. After introducing reasonable scaling law assumptions, he deduces that any dimensionless quantity characterizing combustion noise must be a function of two other dimensionless parameters that emerge from the nondimensionalization of his wave equation. Thus he argues that the Strouhal number and the dimensionless radiated sound power must be functions of these two parameters. He establishes estimates of these two functional relationships on the basis of the experimental results of Smith and Kilham [6] and of Shivashankara, et al. [19] which in turn result in estimates of the peak frequency and radiated sound power. The estimate for the radiated power can be made to agree, with suitable assumptions, with the regression formula of Shivashankara, et al., except for the exponent of the fuel mass fraction, which is greatly overpredicted. The peak frequency estimate, while correctly predicting greater sensitivity to the fuel properties than to the flow and geometry, is not in good agreement with the corresponding regression formula of Shivashankara, et al. Hassan conjectures that, because the turbulent flame velocity plays an important role in his theory, better agreement could have been obtained with experiment if Reynolds number, turbulence intensity, and length scales had been available for the data of Refs. [6] and [19].

In 1975 Strahle [26] attempts a further refinement, based on his general theory of Ref. [20], of his estimate of the radiated sound power and dominant frequency from a turbulent flame. While once again conceding that his theory is not as exact as that of Chiu and Summerfield [17], Strahle argues that it is adequate for deducing the scaling laws for sound radiated from premixed and diffusion gas flames even, subject to certain specified conditions, when the flame is ducted. The new aspect of this latest attempt is the expression of the mean normal velocity fluctuation across the flame surface as a time-independent correlation function whose value can be estimated in terms of the parameters of the problem. The physical interpretation of the correlation distance associated with this function is as the distance between neighboring fluid elements whose differential heating causes the observed velocity fluctuations. Strahle presents a new correlation for the radiated sound power and predominant frequency from an open turbulent flame based on his previous experimental work already in the literature and some new as yet unreported results. Although not used in formulating this new correlation, the results of Smith and Kilham [6] are evidently also correlated by it. Strahle demonstrates that this correlation can be adequately recovered from his theory if reasonable assumptions are made about the scaling of the velocity fluctuations, correlation distance, and correlation frequency. The main shortcoming of the procedure is its inability to accurately estimate the frequency content of the radiated sound.

In 1975 Chillery [27] reports the results of an experimental study which compares the source behavior of a single open turbulent premixed flame with that of an array of two flames aligned on parallel axes. He uses standard acoustical techniques as well as the optical technique of Hurle, et al. [9] to verify the monopole source behavior of the single flame reported by most earlier investigators. He then shows that the array of two parallel flames exhibits either monopole behavior or dipole behavior, depending on the frequency range and spacing of the flames. At low frequencies, for which one-quarter wavelength is greater than the spacing between the flames, the same monopole behavior is obtained as in the case of the single flame. However, at higher frequencies, for which one-quarter wavelength is less than the spacing between the flames, the array takes on a definite dipole behavior, exhibiting directionality and decreased source efficiency. The clarity with which the dipole behavior manifests itself is surprising in view of the fact that the turbulence fields in the two flames which presumably give rise to the sound field are expected to be uncorrelated.

Kumar [28] reports results of a 1975 experimental study of open turbulent flames, both premixed and nonpremixed, burning in air at the end of a simple concentric-tube burner. Results are presented for both hard-walled and anechoic environments. The "nonpremixed" flame is actually a diffusion flame of coflowing fuel and oxidizer in which the fuel, methane, is introduced through the inner pipe and the oxidizer, air or oxygen, is introduced concentrically through the annular space between the inner pipe and the outer pipe. For the premixed flame the mixture is introduced through both passages with a minimum relative velocity. The stoichiometry is not reported for either type of flame.

Some of the results obtained in Ref. [28] are surprising in view of earlier studies by other investigators. For example, in every case the observed directionality is characterized by slightly higher sound pressure levels in directions normal to the flame axis rather than in directions near the downstream jet axis as reported by other investigators [6, 19, 33]. Also the spectra corresponding to the premixed flames, whether obtained in the hard-walled or anechoic room, exhibit a surprising amount of high frequency content and unusually strong harmonic structure. Three distinct peaks are present whose frequencies depend on mixture flow but which range between about 2000 and 7500 Hz, with the highest peak being the second at around 4500 Hz. A correlation of these peak frequencies based on the inner and outer diameters of the inner pipe and the inner diameter of the outer pipe yields a constant Strouhal number of about 0.3 for the hard-walled room data; a slightly lower number is obtained for the anechoic room data. The spectra for the nonpremixed flames, on the other hand, are similar to those reported by other investigators, being limited to relatively low frequencies and having a single broad peak. A Strouhal number correlation of this peak frequency with flame length and fuel flow velocity yielded a constant value once again near 0.3. High-speed photography of the nonpremixed flame reveals a large-scale eddy structure not visible in the premixed flame, suggesting that the characteristic frequencies are higher in the latter case.

For the case of nonpremixed flames Kumar attributes the acoustic sources to large-scale turbulent eddies whose sound emission frequencies are directly related to the reciprocal of their life times, where the life times themselves are statistically distributed about the ratio of the mean flow velocity in the flame to the average flame length. In the case of premixed flames the sources are attributed to small-scale, relatively short-lived turbulent eddies of mixture, perhaps due in part to the wake created by the thick wall of the inner pipe, which are consumed at axial locations distributed along the length of the flame. This reasoning seems to indicate that the spectral content of combustion noise is determined in both types of flame by both the turbulent structure, which determines eddy size, and the flame chemistry, which determines the rate of consumption of the eddies. Kumar concludes that premixed and nonpremixed flames are significantly different in their physical structure and thus in the way they generate noise.

In 1976 Putnam [29] provides more data from a wide variety of gas-fired industrial burners which tend to lend further support to the hypothesis that combustion roar is the result of a turbulence driven monopole-type source mechanism. He reports that for seven practical burners of widely differing design (including four nozzle mix burners and three premix burners) whose rated firing rates range from 400,000 Btu/hr to 750,000 Btu/hr, the thermoacoustic efficiency varies as the 1.8 to 2.0 power of firing rate. This is in excellent agreement with simple Bragg/Hurle/Putnam theory, based on the hypothesis that the sources are acoustic monopoles created by the turbulent mixing of unburned mixture with the hot products of combustion, which predicts an exponent of 2.0. He explains the deviation from this law, which occurs when the burners are operated above their rated firing rates, in terms of "superturbulence", defined as combustion induced turbulence related to incipient blowoff. Noting that the thrust of a burner should also vary as the square of the firing rate, Putnam postulates that the thermoacoustic efficiency should be related to thrust. He finds that in general the ratio of thermoacoustic efficiency to the thrust per unit area (made nondimensional by the ambient pressure) for a given burner is independent of firing rate but varies widely from burner to burner. This observation tends to verify the intuitively pleasing idea that the thermoacoustic efficiency must be intimately related to other burner performance parameters.

Putnam [30] also presents a review of combustion noise in industrial burners in 1976. Although no new data or theories are presented, the paper is of significant pedagogical value because it classifies combustion noise according to how it is produced: combustion-driven (feedback) oscillations, combustion roar, superturbulent combustion noise, and combustion amplification of periodic flow phenomena (Strouhal-type combustion noise). This is a useful classification system because it helps the researcher focus his efforts on a given aspect of combustion noise generation.

Putnam points out that two or more of these combustion noise mechanisms can and generally do coexist in a given situation, thus making it difficult to isolate one from the other experimentally. This is particularly true of combustion roar and Strouhal-type combustion noise, the latter correlating with characteristic length and velocity scales of the burner. Both lead to a rather smooth noise spectrum with a single broad peak in the same (low) frequency range, and are thus hard to separate. This probably partly explains why some investigators [6, 7, 12*, 28] favor a Strouhal number correlation for the peak frequency of combustion noise while others [11, 19, 20*, 25] insist that the peak frequency depends chiefly on the fuel reactivity. Putnam states that the mechanism for combustion roar in the turbulent flame is "the movement of the flame front . . ., as the volume of the gas increases on passing through [the] flame front," but that the specific details which would permit prediction of combustion roar are still unknown.

In 1977 Roberts and Leventhall [31] report the results of an experimental study of noise production by an open, turbulent, premixed, natural gas/air flame. They first develop a simple model, based on one-dimensional conservation of mass and momentum for an ideal gas, which, not surprisingly, predicts that pressure fluctuations sensible as noise in the farfield will result from velocity fluctuations at the flame front. When typical values are introduced into this model, the predicted noise

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*While the experimental data of Ref. [12] seem to indicate that a Strouhal number correlation of the peak frequency is inappropriate, the author of Ref. [12] argues that they can be interpreted as supporting such a correlation. It is indicative of the controversial nature of this question that Ref. [20] cites Ref. [12] as evidence that a Strouhal number correlation is inappropriate.

levels exceed those generally observed for such flames, probably because the real flame front is not as sharply defined as the idealization supposes. They then describe an experiment in which either an ionization current technique or hot wire anemometry is used to measure the velocity fluctuations immediately upstream of the flame front. The cross-correlation of this signal with the corresponding farfield sound pressure signal clearly establishes the expected causal relationship between the two. However, an alternative explanation for this result, which the authors do not consider, is that the flame surface area and volume also fluctuate with the flow fluctuations, phenomena which could equally well account for the observed correlation between flow velocity fluctuation and farfield noise. The authors also demonstrate that anchoring the flame with a bluff body leads to a significant reduction in noise production, as expected.

In his 1978 review of combustion noise, Strahle [32] concludes that the physics of combustion noise generation is sufficiently well understood to explain observed experimental trends for radiated power but that, owing to a lack of detailed knowledge about turbulence in a turbulent flame, it is still not possible to predict the noise output and its spectral distribution. He reconsiders his theory of Ref. [26] in a further comparison with that of Chiu and Summerfield [17]. In this latest version he now allows a variable speed of sound in the wave operator (corresponding to the homogeneous wave equation) rather than restricting the development to a constant speed of sound as he had previously done. This modification leads to a solution for the farfield sound pressure which differs from that of Chiu and Summerfield only in that it is simpler, the latter containing three additional terms beyond the single term in the former. The source term common to both theories is that attributable to monopole behavior. Strahle judges his modified theory to be preferable to that of Chiu and Summerfield because it "does the best job of recovering the simple flame theory result, is simpler, conforms to the light emission results [of Hurle, et al.], and has been tested against the most [experimental] flame results." Another insight offered by Strahle on the basis of this review is that previous work tends to support the assumption, made by himself and most other theoreticians, that the influence of the sound field on the source behavior is negligible, even in ducted burners as long as resonant conditions are avoided.

In 1979 Dowling [33] extended Lighthill's acoustic analogy to the case of unburned mixture flowing into a plane flame front where all the steady and unsteady flow variables suffer discontinuous changes in value due to combustion. In an elegant analysis Dowling derives a Green's function which represents the radiated sound pressure due to a distribution of point sources near the flame front. Since the conservation of energy principle was not used, the analysis really addresses the question of what would be the expected behavior, consistent with the Navier-Stokes equation, if the flow variables did suffer step changes across the flame front. The behavior obtained is that consistent with an acoustic monopole source distribution near the flame front having a directionality due to two distinct mechanisms: its downstream motion (the convection effect) and the reflection coefficient at the flame front due to the discontinuity in mean temperature. In the case of an unbounded flame, the two directionality mechamisms are shown to be competing, with the convection effect producing a peak normal to the flow direction* and the mean temperature effect producing a peak in the flow direction. However, because the mean temperature effect is dominant, the net effect is a slight attenuation in the sound field in the flow direction and a strong attenuation normal to the flow. This is the tendency observed in most experimental directionality results [6, 19]†, although the magnitude of the roll-off with angle is much less pronounced in reality. The fact that experimental directionality is much less pronounced than that predicted by Dowling is explainable; the flame front of a real flame is neither infinite in extent nor perfectly plane. Also, there would be further competing refraction effects at the interface of the flame with the surrounding air in the case of a real open flame. Thus, although Dowling's analysis cannot be expected to accurately predict directionality for a real flame, it is useful for identifying possible directionality mechanisms and estimating their relative importance.

Mahan and his students began their study of combustion generated noise in 1977. This work was initially motivated by the problem of fatigue damage to components in large industrial gas turbines due to combustion-driven pressure oscillations. Later, emphasis shifted to reducing the environmental impact of aircraft jet engine combustion noise. Under contract to General Electric, Mahan developed a one-dimensional analytical model [34] for combustion noise generation and

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*This is unexpected in view of Lighthill's [3] prediction for lateral and longitudinal quadrupoles and the observations of Shivashankara, et al. [19] for monopoles, both of which indicate a downstream enhancement of the sound pressure field with flow.

†Reference [28] is an exception.

propagation in long ducted combustion systems typical of those in industrial gas turbines. The model, which is based on the linearized one-dimensional conservation equations for an ideal gas, include steady flow effects, such as axial gradients in temperature, velocity and pressure, which occur as a result of combustion heat release and heat loss to the walls. The acoustic source activity is modeled as an unsteady heat release term in the linearized energy equation which is assumed proportional to the local steady heat release.* In 1979 Mahan and Kasper [35] report the results of a study, based on this model, of the influence of the steady combustion heat release distribution on the acoustic response of ducted burners. In this study the source field is suppressed and only the influence of flow and the associated axial gradients on the propagation of acoustic waves through the combustor is investigated. It is shown that the dynamic response of the combustor, as characterized by its local driving point impedance, is sensitive to the axial distribution of steady combustion heat release as well as the total burner power.

In 1981 Valk [36] reports the results of a very clever experimental study of the acoustic power produced by a premixed stoichiometric propane/air flame burning near the pressure antinode in a quarter-wave tube. Acoustic drivers in the fuel supply line and in the quarter-wave tube itself are coordinated and matched to the geometry such that the mixture supply does <u>not</u> oscillate even though the pressure in the quarter-wave tube at the burner face does. It is emphasized here that this is not another study of combustion feed instability; the only acoustic source

*An assumption later verified in Ref. [42].

in the quarter-wave tube is the driver without which the flame would presumably be very quiet. Valk demonstrates convincingly that the acoustic power produced by the otherwise laminar flame is entirely due to the response of the flame itself to this externally applied excitation. An energy balance is performed on the burner which permits direct calculation of that part of the total acoustic energy produced by the flame itself according to Rayleigh's criterion [37]. Values of the thermoacoustic efficiency as a function of frequency may be inferred from Valk's results. These values are seen to decrease with frequency from a value of around $8 \times 10^{-5}$ at 3 Hz to a value of around $5 \times 10^{-6}$ at 90 Hz for a wide range of firing rates. Valk is able to explain this result, reminiscent of that obtained in Ref. [24], in terms of the convective wavelength in the flame (based on the frequency of the sound and the convective velocity in the flame) relative to the physical length of the flame. At convective wavelengths which are more than twice as long as the flame length, the flame responds more or less as a unit and is thus an efficient monopole-type acoustic source. However, as the convective wavelength becomes less than twice the flame length, the flame is subdivided into separate parts which respond out of phase with each other as in the case of an acoustic dipole, thereby reducing its efficiency as an acoustic source. It is perhaps significant that the thermoacoustic efficiencies inferred exceed those from earlier investigations of turbulent premixed propane/air flames. This may be explained in terms of the fact that in this case thermal energy is added in phase with the pressure peak of the true sound rather than the pseudo sound (see discussion of Ref. [17]). Also, the disturbance field itself is irrotational rather than vortical.

The impedance condition at the exhaust end of the duct is also known to be of great importance to the ducted combustion noise generation and propagation problem. The duct radiation resistance determines the degree to which acoustic energy in the duct is radiated into the surroundings, and may even influence the efficiency of the noise generation process itself as implied in Ref. [36]. Mahan, et al. [38] establish that while the radiation reactance is insensitive to the difference between the temperature of the gas flowing from the duct and the surrounding air temperature, the radiation resistance does depend on this temperature difference. They present a temperature correlation which gives the radiation resistance to within ± 1.0 dB for a wide range of temperature differences.

In a direct application of the one-dimensional nonhomogeneous wave equation developed earlier by Mahan [34] and modified by Mahan and Kasper [35], Mahan, et al. [39] and Mahan and Jones [40] are able to recover the variation with frequency of the thermoacoustic efficiency for a ducted turbulent hydrogen-flame burner from the measured farfield sound spectrum. The only assumption required, other than that the wave propagation model used is valid, is that combustion noise is a direct consequence of unsteady heat release. The range of thermoacoustic efficiency obtained, $10^{-5}$ - $10^{-4}$, is consistent with values obtained by previous investigators for hydrocarbon fuels if the predicted increase in thermoacoustic efficiency with reactivity of the hydrogen fuel is taken into account. Also, the thermoacoustic efficiency is shown to decrease monotonically with frequency between 150 Hz and 1500 Hz, a trend which is reminiscent of the flame transfer function of Ref. [24] and the sound power results of Ref. [36]. References [39] and [40] also provide further experimental evidence that at sufficiently low frequencies the acoustic source activity is enhanced by the resulting acoustic field to an extent beyond that predicted by Rayleigh's [37] criterion.* That is, the turbulent mixing and subsequent unsteady combustion heat release may be enhanced by the acoustic (irrotational) component of the velocity field at low frequencies. The reader will recall that this phenomenon was also in evidence in Refs. [24] and [36]. Finally, Refs. [39] and [40] also provide experimental and analytical evidence that the thermoacoustic efficiency decreases with frequency as the wavelength of the acoustic waves in the reaction zone become shorter than the flame length. In this case the flame is subdivided into segments which add energy to the acoustic field out of phase with each other, thereby reducing the source efficiency of the flame at that frequency.

In a 1983 report Mahan [41] presents data that show that the far-field noise spectra of a ducted turbulent hydrogen-flame burner depend on the combustion liner hole pattern. An analysis of these results is presently underway to determine if the observed variation is due to a change in the source structure itself or is instead a result of a concomitant change in the acoustic response of the combustion chamber to an otherwise unchanged source spectrum. This question, which can be answered using the approach presented in Refs. [39] and [40], is of critical importance to understanding combustion noise generation in ducted burners. The timing of this on-going study should be such that

*Rayleigh's criterion states that an acoustic standing wave will be amplified if heat is released in an antinode of pressure in phase with pressure; if the heat is released 180 degrees out of phase, the wave will be damped.

the results can be presented at the next AIAA Aeroacoustics Conference in October, 1984.

Also in 1983 Ramachandra and Strahle [42] report the results of an attempt to infer the axial distribution of the fluctuating heat release in an open turbulent premixed propane/air flame from nearfield sound pressure measurements. The link between these two physical quantities is a finite-range Fourier transformed nonhomogeneous wave equation for which the source (the nonhomogeneity) is assumed proportional to the unsteady combustion heat release. The solution is expressed in the classical integral form where the integrand is the product of the source function and the appropriate Green's function. A series of simplifying assumptions based on physical reasoning allows this six-dimensional integral to be reduced to the point where it can be inverted to obtain an estimate of the source function from the measured nearfield sound pressure level. The results are presented in the form of a dimensionless function which is proportional to the local heat release fluctuation. The axial distributions obtained for this function are verified optically to within a constant factor using the method of Hurle, et al. [9] The results vindicate the assumption made in Refs. [34], [39] and [40] that the local heat release fluctuation is proportional to the local steady heat release. The good agreement between the acoustic and optical techniques seems to justify once and for all the supposition that source activity in an open turbulent flame is dominated by the fluctuating heat release.

Mahan, working with Yeh [43], recently extended his ducted combustor acoustic propagation research to include the cutoff of transverse modes. They present the results of an analysis which shows that under certain circumstances the first radial mode in a circular combustor, although damped in the inlet region of the burner, could recover and even grow as it passed through the combustion zone. This anomalous recovery of transverse modes in a ducted burner is an important phenomenon because it means that their cutoff cannot be predicted simply on the basis of, say, the mean burner temperature.

## Discussion of Literature Review

The three turbulent flame structure models for premixed flames which emerge from the literature review are illustrated in Fig. 1. Figure 1(a) represents the wrinkled laminar flame model, interpreted here for a two-dimensional flame. In reality the laminar flame sheets would be more irregular than shown and would also exhibit a spiral structure. The thickness of the sheets, the number of folds per unit length, and the pitch of the spirals would all depend on the turbulence size and intensity scales. The flame sheets become thinner as they are convected downstream by the steady flow and consumed by burning normal to their surfaces. Because this burning process proceeds at the laminar flame speed, the flame length (i.e., the distance required to consume all the mixture) is given by

$$L_{WF} = U\ell/v_{\ell} \quad , \tag{1}$$

where U is the average convective velocity in the flame, $\ell$ is the average initial flame sheet thickness at the burner face, and $v_{\ell}$ is the laminar flame speed. Because Eq. (1) is patently true and the flame length, average convective velocity, and laminar flame speed are measurable physical quantities, this can be taken as the defining relation for the abstract idea of an average initial flame sheet thickness in the wrinkled flame model of turbulent combustion. This result strongly suggests a Strouhal number correlation for the peak frequency based on the flame length and some physical flow velocity, V, which characterizes the convective velocity in the flame, i.e.,

$$f_p \ell / v_\ell \propto f_p L_{WF} / V = \text{constant} \quad . \tag{2}$$

In Eq. (2) V, which is taken as a measure of U, might be the mean mixture flow velocity at the burner face, for example. Recall that Ref. [28] reports such a correlation for a concentric flow diffusion flame, but evidently no investigator has attempted a correlation along this line for premixed flames. Unfortunately this idea cannot be verified from published data because flame lengths generally have not been reported. However, the foregoing discussion makes it clear that, in addition to the stoichiometry of the flame (which gives $v_\ell$ and V), flame length as a function of burner design and operating parameters should also be documented in any experimental program aimed at increased understanding of combustion noise generation.

It is easy to imagine a situation in which the wrinkled laminar flame of Fig. 1(a) becomes pierced and shredded and eventually broken into a collection of randomly-sized isolated remnants as it is subjected to more and more violent turbulent action. Such a turbulent flame could then be regarded as a collection of individual cells of mixture imbedded in the hot products of combustion. The sizes of these cells at a given cross-section normal to the flame axis would then be statistically distributed about some mean value which diminishes with downstream distance. The cells of unburned mixture, which characterize the distributed reaction model of Fig. 1(b), are convected along the length of the flame until they have been consumed. Thus the flame length in this model is given by

$$L_{DR} = UR_o/v_\ell \quad , \tag{3}$$

where $R_o$, the average radius of the cells entering the flame front, is defined by this relation. The peak frequency in this case should be given by

$$f_p R_o/v_\ell \propto f_p L_{DR}/V = \text{constant} \quad , \tag{4}$$

where V is once again a physical velocity, such as that of the mixture at the burner face, which characterizes the convective velocity in the flame. In the case of the distributed reaction model there exists at least the possibility of characterizing the abstract length scale $R_o$ associated with the model independent of the defining relation, Eq. (3). That is, there is every reason to expect that it correlate with the turbulent length scale in the flame, which can be obtained independently. This would mean that the peak frequency depends fundamentally on both the reactivity of the fuel (through $v_\ell$) and the fluid mechanics of the flame (through $R_o$) as suggested in Ref. [28]. Therefore it is important that some measure of the turbulence size scale be obtained and correlated with $R_o$ computed using Eq. (3).

Figure 1(c) represents the as yet unnamed turbulent diffusion flame model favored by several investigators [16,21,30,31,33] in which noise generation is attributed to the unsteady motion of the flame front itself as the turbulently fluctuating mixture flow enters the reaction zone. In this model the flame front is represented by an isothermal surface which is displaced slightly downstream when the local mixture flow velocity exceeds the mean value and is displaced slightly upstream when the local mixture flow velocity is less than the mean value. If the combustion process is considered to occur at constant pressure (as established by

Ref. [8]), then this motion of an isothermal surface translates, through the ideal gas equation of state, to a density fluctuation or volume displacement which propagates to the farfield as sound.

Figure 2 shows the effect that an individual turbulent eddy might have upon impact with the flame front. In this simplistic interpretation the resulting source would be a lateral quadrupole rather than a monopole. Indeed, monopole source behavior can be recovered from the model of Fig. 1(c) only if the unsteady component of mixture flow is predominantly irrotational, in which case streamwise fluctuations will dominate. If on the other hand the unsteadiness of the mixture flow is predominantly vortical (as in the case of true turbulence), Fig. 2 demonstrates that the model of Fig. 1(c) cannot explain observed monopole sound production. In order for turbulent eddies to exhibit monopole source behavior they must penetrate into the reaction zone as indicated in the sequence shown in Fig. 3. This new model, combining as it does aspects of the laminar flame model (there are alternating lamina of unburned mixture and hot products of combustion) and the distributed reaction model (there are individual cells of mixture distributed throughout the flame), seems well suited for explaining the wide range of experimental trends reported in the literature for thermoacoustic efficiency and peak frequency. This model would lead to higher thermoacoustic efficiencies than the distributed reaction model of Fig. 1(b) because ignition of the cell is initiated throughout its volume rather than only at its outer surface.* Thus any future experimental study of noise production by turbulent flames should sample all variables relevant to such a model.

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*Recall that Thomas and Williams [8] demonstrate that central ignition of a bubble of combustible mixture produces nearly on order of magnitude higher thermoacoustic efficiency than surface ignition.

## Recommendations for Further Research

A reasonable goal for future combustion noise research would be to predict the sound pressure spectrum in the acoustic farfield of a simple ducted, premixed, hydrogen-fueled burner such as the one shown in Fig. 4. This type of burner is recommended for further study because it offers the compromise between simplicity and practicality required of a useful benchmark experiment. Many practical combustion systems are of this general type, and accurate analytical techniques already exist for treating acoustic propagation from them. Although still quite complex, the combustion kinetics and fluid mechanics for this type of burner are much simpler than for, say, diffusion-flame burners or burners utilizing gaseous hydrocarbon or liquid fuels.

An analytical model for describing the generation and propagation of combustion noise in a burner similar to that of Fig. 4 has already been formulated and used in conjunction with farfield sound pressure autospectra to predict burner thermoacoustic efficiency spectra [39-41]. Unfortunately, the burner actually used in the cited studies was somewhat two-dimensional in the reaction zone and thus was not accurately represented by the one-dimensional model. However, this model could easily be adapted to the one-dimensional burner of Fig. 4 and used to establish a benchmark-quality data base for its thermoacoustic efficiency. Source models based on the physical turbulent mixing model of Fig. 3 could then be postulated and specialized to the burner of Fig. 4 and their predicted thermoacoustic efficiency spectra compared with the measured spectra.

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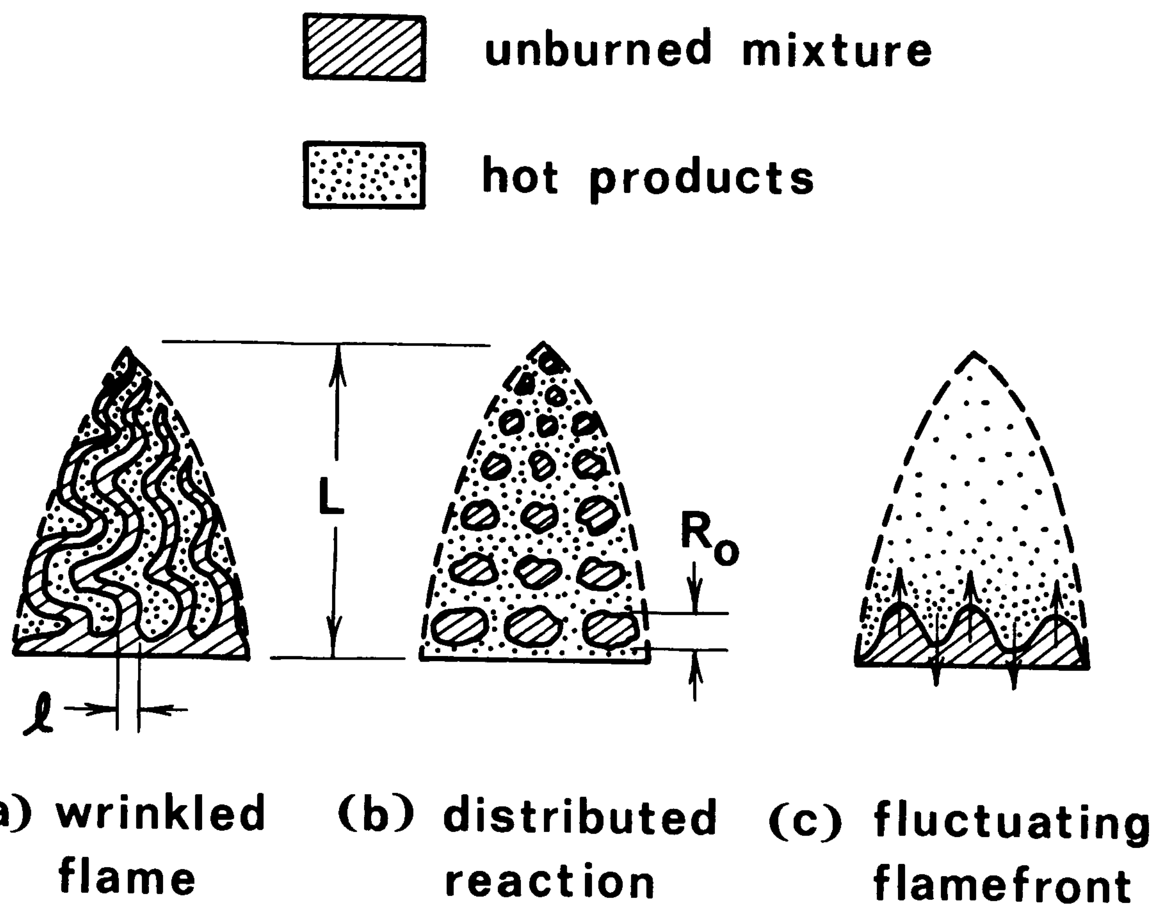


Fig. 1. Various Turbulent Flame Models From the Literature.

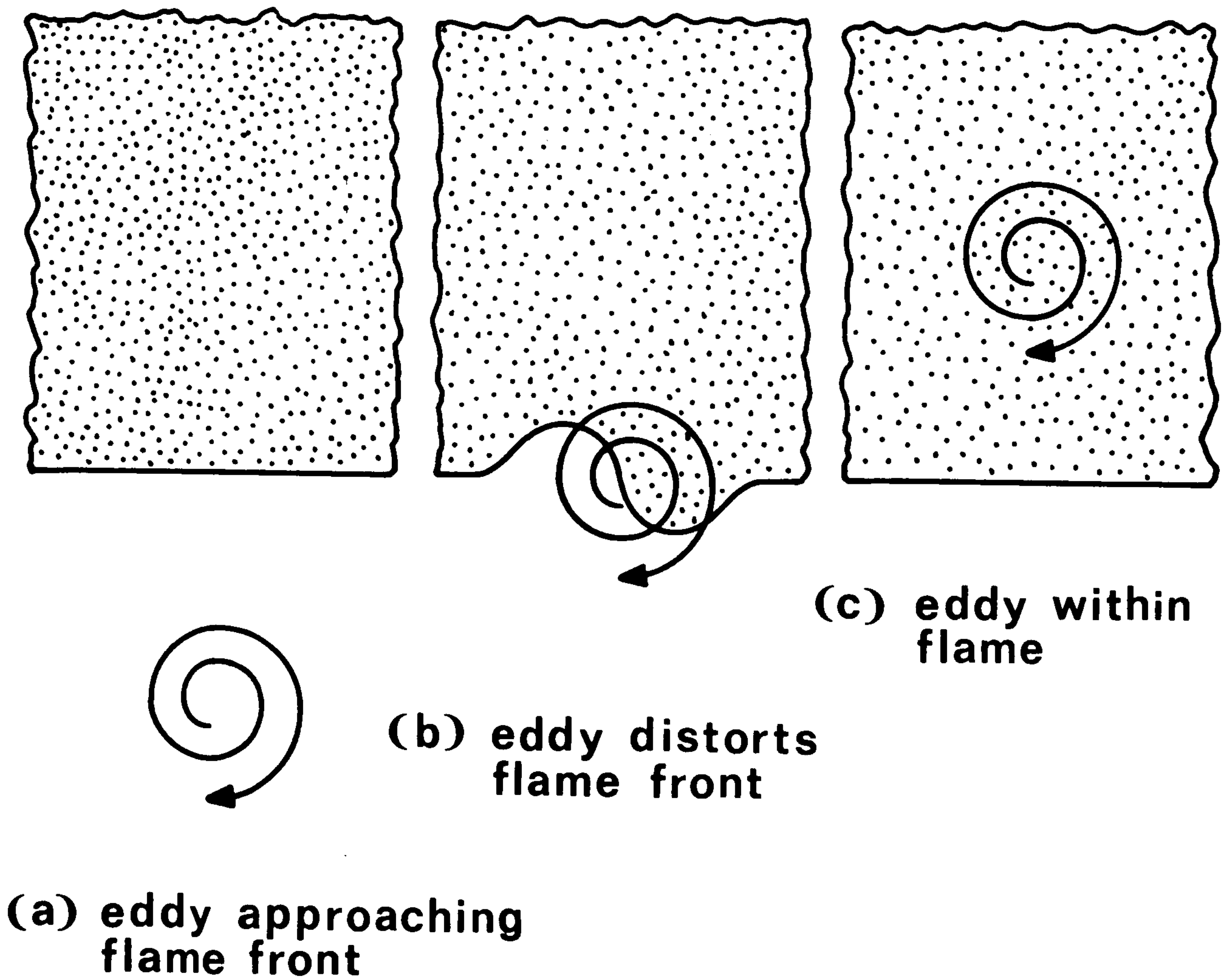


Fig. 2. Turbulent Eddy Impacting the Flame Front
Acts as a Lateral Quadrupole Source.

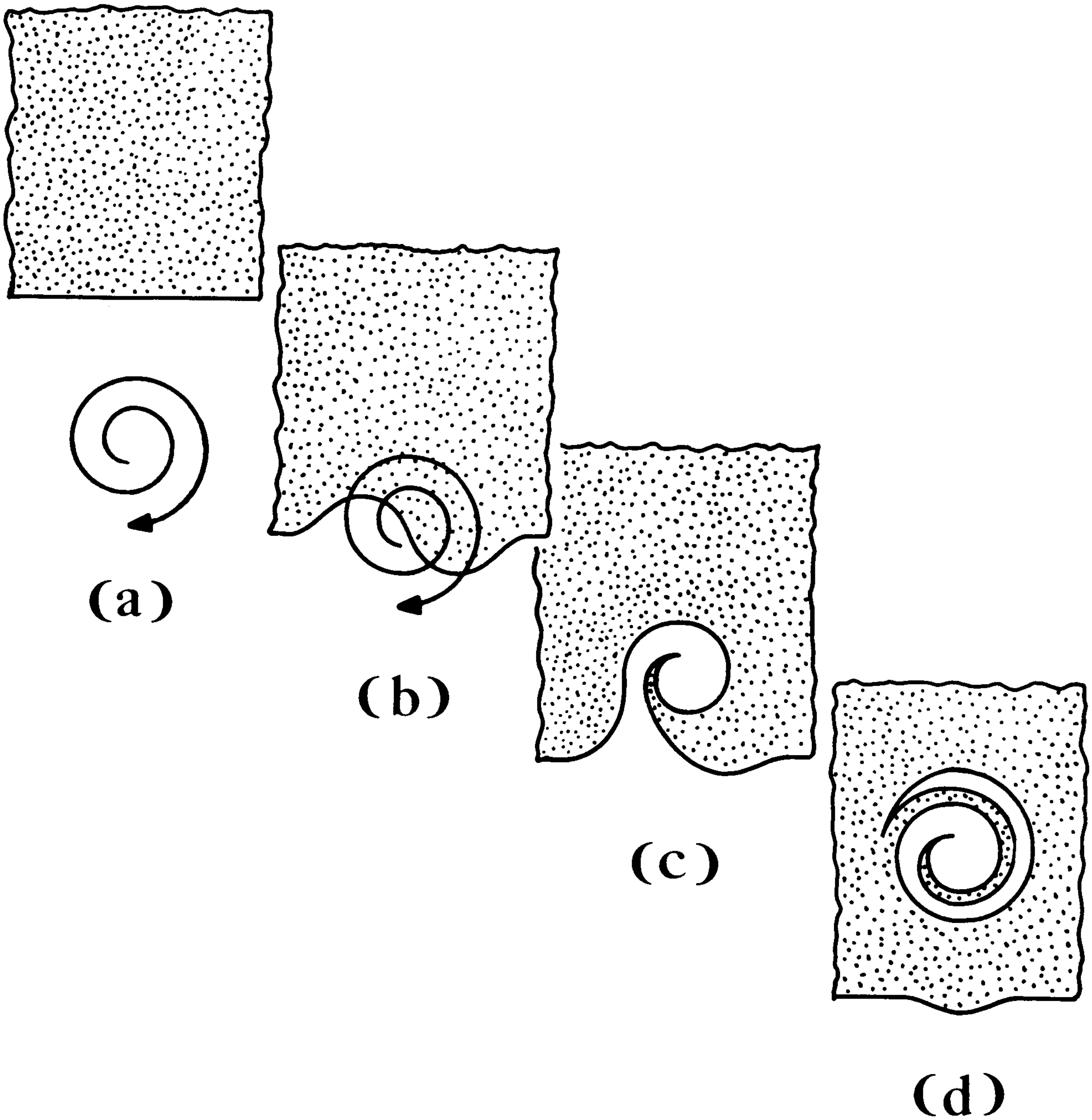


Fig. 3. Turbulent Eddy Entraining Unburned Mixture in the Hot Products of Combustion Can Act as a Monopole Source.

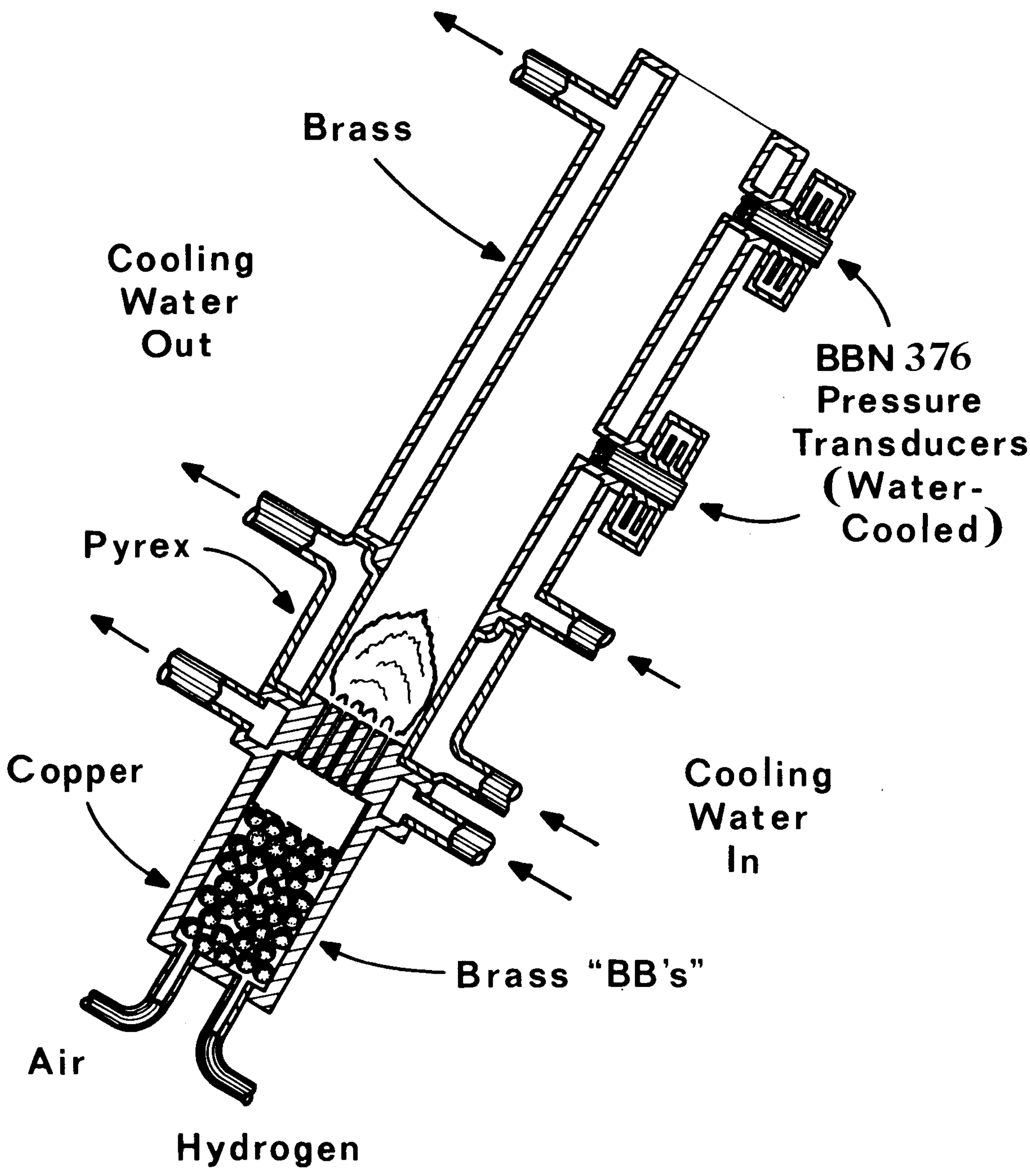


Fig. 4. Recommended Experimental Apparatus.

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15. Supplementary Notes

Final report. Project Manager, Eugene A. Krejsa, Fluid Mechanics and Instrumentation Division, NASA Lewis Research Center, Cleveland, Ohio 44135.


16. Abstract


A critical review of the combustion noise literature is presented for the period between 1952 and early 1984. The extensive body of literature dealing with feedback-supported combustion oscillations is excluded, as are papers treating all forms of indirect combustion noise, such as entropy noise. Primary emphasis is placed on past theoretical and semi-empirical attempts to predict or explain observed direct combustion noise characteristics of turbulent, gas-fueled burners; works invloving liquid-fueled burners are reviewed only when ideas equally applicable to gas-fueled burners are presented. The historical development of the most important contemporary direct combustion noise theories is traced, and the theories themselves are compared and criticized. While most theories explain combustion noise production by turbulent flames in terms of randomly distributed acoustic monopoles produced by turbulent mixing of products and reactants, none are able to predict the sound pressure in the acoustic farfield of a practical burner. The main reason for this failure is the lack of a proven model which relates the combustion noise source strength at a given frequency to the design and operating parameters of the burner. Specific recommendations are given for establishing a benchmark-quality data base needed to support the development of such a model.



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