EXPERIMENTAL MEASUREMENT OF COMBUSTION NOISE
AND COMPARISON TO A PREDICTIVE MODEL

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(ABSTRACT)

The acoustic emission from the combustion of turbulent mixtures of several gaseous fuels and oxygen was measured to determine the effect of burner diameters, flow velocities and reactant chemistries. The data are presented in the form of acoustic pressure spectra and over-all sound pressure levels.

The experiment consisted of a geometrically simple pre-mixed burner with five interchangeable nozzles whose diameters varied from 0.117 cm to 0.541 cm. The fuels examined in the experiment were acetylene, methane and propane. Three flow velocities were tested for each fuel. Methane was tested within a velocity range of 10 m/s to 25 m/s while propane was examined within a range of 20 m/s to 40 m/s. Acetylene was tested at somewhat higher velocities ranging from 50 m/s to 100 m/s.

The resulting data base consisted of 23 unique test conditions. The data were evaluated based on peak frequency and overall sound pressure level. The experimental data are also compared to a predictive model.
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List of Symbols

\( a, b, c, d \)  
Constants in the transition burning expression

\( c \)  
Velocity of sound in air (m/s)

\( d \)  
Distance of the field point from source (m)

\( D \)  
Burner Diameter (m)

\( E \)  
Expansion ratio (-)

\( f \)  
Frequency (Hz)

\( f_c \)  
Frequency of the maximum radiated sound power (Hz)

\( F \)  
Fuel mass fraction (-)

\( H \)  
Heat release rate (kJ/s)

\( n \)  
The effective number of noise sources

OASPL  
Over-All Sound Pressure Level (dB)

OAPWL  
Over-All Sound Power Level (dB)

\( P \)  
Acoustic pressure (N/m\(^2\))

\( p \)  
Nondimensional acoustic pressure (-)

\( Q \)  
Volumetric flow rate (m\(^3\)/s)

\( R \)  
Radius of the spherical cell (m)
\( r \)  
Instantaneous radius of the spherical cell (m)

\( S_L \)  
Laminar flame speed of the fuel (m/s)

\( S_p \)  
Sound Power (W)

\( t \)  
time (s)

\( t_i \)  
Fuel injection time (s)

\( U \)  
Convective velocity of the fuel (m/s)

\( V \)  
Volume (m³)

\textbf{Greek Letters}

\( \beta \)  
Quantity used to nondimensionalize \( \frac{d^2V}{dt^2} \) (m³/s²)

\( \gamma \)  
Quantity used to nondimensionalize acoustic pressure (N/m³), Eq. (4.34)

\( \rho \)  
Density of air (kg/m³)

\( \tau \)  
Nondimensional time (-)

\textbf{Subscripts}

\( b \)  
Order of the frequency band

\( bl \)  
Quantities associated with the lower frequency of the "b" band
\( bu \)  
Refers to the quantities associated with the upper frequency of the "b" band

\( i \)  
Refers to the initial value of the corresponding quantities

\( n \)  
Refers to the order of frequency

\( s \)  
Refers to the surface burning process

\( tr \)  
Refers to the transition burning process

\( tt \)  
Refers to the complete process of burning
1.0 Introduction

In many practical industrial and commercial systems, turbulent combustion is used as an energy source. In all cases, these flow systems become noisy due to the combustion process. In turbopropulsion applications, combustion noise has been recognized as a potential contributor to core engine noise. In the interest of minimizing the noise from these combustion processes, much research has been devoted to measuring and describing the acoustic emission of such systems.

An understanding of the noise production mechanism of turbulent combustion can suggest ways of reducing such noise. Recently, studies have been conducted to control combustion noise by introducing cancelling sound waves via a feedback control system.

However, perhaps the most important use of combustion noise may be as a diagnostic tool to determine operating conditions of a process. Evidence strongly suggests that the acoustic noise of a flame is a strong indicator of stability characteristics in the reacting flow system. Under extreme conditions, combustion noise can be extensive enough to be destructive to the combustion chamber.

Despite the research into combustion noise in the past twenty-five years, the details of the noise production are still unclear. From an experimental standpoint, only a
limited amount of work has been devoted to measuring the sound emission from turbulent combustion systems. Such data have indicated that several parameters strongly influence the noise from combustion. It has been shown that burner geometry, reactant flow velocity, flame speed, and flame temperature affect the sound spectra and overall sound pressure levels in a turbulent combustion process [2,3]. However, the available experimental data do not lend well to understanding the noise production mechanism due to either overly complicated burner configurations or, simply, too few test conditions to determine the effects of varying relevant experimental parameters. This also makes it difficult to evaluate theoretical explanations of combustion noise.

The goal of this study is to obtain an experimental data base of combustion noise measurements for a variety of relevant experimental inputs. In addition, it is desirable to utilize a simple experimental apparatus to allow the data to have a wide range of application for the evaluation of theoretical models. Yet to design such an experiment, it seemed necessary to consider the requirements of evaluating such models.

Because of its availability and its recent development, the theoretical model of Mahan-Nathani [1] was selected as a guide to designing the experiment and also to test the usefulness of the data base for modellers in general. This model addresses the physics of the noise generation process and relies, not in correlation to existing data, but in a simple explanation of the noise generation in turbulent flames. The model, which attempts to predict the sound spectrum and over-all sound pressure level of a reacting flow, appears to exhibit spectral trends which are in general agreement with existing data. However, the lack of a general data base of sound spectra prevents the merit of the theoretical model from being fully evaluated. This study also attempts to perform such an evaluation.
2.0 Literature Review

Past experimental efforts into the acoustic emission of turbulent flames concentrate on a particular aspect of some practical application. These results, however, are not applicable to a wide range of combustion situations. This lack of an experimental data base as a reference for theoretical comparison is the primary motivation for the work presented here. The greatest concern with most theoretical exercises in explaining the mechanisms of combustion noise is the lack of experimental evidence to support or dismiss such models. The experimental work which has been conducted is limited in scope and consistency between individual efforts. Overviews on the experimental and theoretical efforts of the past are presented in References 2 and 3. It is evident in more recent studies that the field of combustion acoustics is tending toward the use of sound emission as a diagnostic tool.

The relationship between combustion and acoustics has been recognized and reported since as early as 1802 in a technical note on singing flames [4]. In 1896, Lord Rayleigh [5] gave the first satisfactory theoretical explanation of such noise. He suggested that periodic heat supply from the flame induces upstream gases in a burner to vibrate at its characteristic organ-pipe frequency.
As noise pollution became exceedingly more important in the 1950’s (with the
dawn of jet propulsion), a renewed interest was taken in understanding and reducing the
noise emission of combustion processes in commercial burners and jet engines. The
foundation of much of this modern theory is based on Lighthill’s theoretical treatment
of sound radiated from a non-reacting fluid flow as a result of turbulence [6,7]. This work
is the first to model the sound emission from a turbulent flow as a static distribution of
fundamental acoustic noise sources. Lighthill showed that the fluctuating shear in the
turbulence acts a quadrupole sound source.

Following Lighthill’s treatment of sound radiated from turbulent flow, Gaydon
and Wolfhard [8] reasoned that the noise from turbulent diffusion flames might be a re-
result of continuous ignitions of “turbulent balls” of mixed air and fuel. This view appears
to be consistent with research that soon followed.

A decade after Lighthill’s turbulent flow noise model, Bragg (in 1963) [9] ex-
tended this rudimentary theory to apply to a combusting flow. He suggested that a small
element of combusting fuel, burning at constant pressure, would displace surrounding
gases due to the increased volume of products as a result of heat evolution. This sphera-
ical pressure wave would be followed by an expansion wave at the end of combustion,
thereby bringing the surroundings to rest again. Bragg’s example illustrated the charac-
teristics of a simple monopole source. In this instance, the total sound energy radiated
by the combustion process and the intensity at any point would depend on both the rate
of change of volume evolution \( \frac{dV}{dT^2} \) and the rate of volume evolution itself \( \frac{dV}{dT} \). In
addition, Bragg concluded that the noise produced directly by the non-reacting flow is
negligible in comparison to the combustion source noise resulting from unsteadiness in
local heat release rates. This direct acoustic noise of combustion was estimated to be
about one millionth \( (10^{-4}) \) of the total energy release of the combustion. It is important
to note that this theory insists that a laminar flame would emit no combustion noise due to the steadiness of the reaction.

The theory of combustion noise as represented by a series of reacting monopole sources was reinforced by the work of Smith and Kilham [10] in 1963. Experimental observations allowed them to relate sound pressure to various geometrical and flow parameters using scaling laws. For premixed flames of propane, ethylene, and methane with air, they found that the acoustic power was proportional to $U D S_L$ for various fuel-air mixtures; where $U$ is the convective velocity of the mixture, $D$ is the diameter of the nozzle, and $S_L$ is the laminar flame speed. They concluded by showing that this relationship is similar to that of the acoustic output of a statistical distribution of simple monopole sources throughout the combustion zone.

In 1966, Thomas and Williams [11] performed an experimental study of the noise produced by the combustion of a spherical volume of homogeneous premixed gas contained in a soap bubble and ignited by a spark. The study considered both surface ignition and central ignition of the spherical volume. This experimental approach was chosen in an attempt to study the basic relationship between flame structure and sound radiation for a simple combustion system. They found that this combustion process acted as a simple monopole source whose strength is a function of the rate of volume variation ($\frac{dV}{dT}$). In addition, Thomas and Williams found a strong relationship between sound emission and flame speed. A thorough physical examination of the propagating flame was made using high speed motion picture photography and is presented in the paper. This experimental evidence indicated that the centrally ignited bubble does in fact act as a monopole source and the flame expansion ratio directly affects the noise output.

Giammar and Putnam [12] examined the acoustic output of two commercial turbulent diffusion burners, combusting natural gas. Both burners were impinging gas jet types. The first configuration consisted of two axially impinging jets, the second
burner being an “octopus” burner configuration with eight impinging jets pointed from eight corners of a geometric cube towards a common center. The effects of flow rate and burner diameter were examined. They identified various sources of combustion noise and, based on the acoustic pressure spectra, showed that this noise was dominant in the 160 to 1000 Hz range.

An extensive analysis of non-premixed flames was performed by Knott [13] in 1971. In particular, Knott considered non-resonating flames of hydrogen and ethylene with oxidizers of oxygen and air. The effects of burner diameter, equivalence ratio and flow rate on acoustic power were examined. It was determined that acoustic power is proportional to $U_{fuel}^4$. Finally, based on experimental results, Knott proposed a model comprised of monopole noise sources.

In 1975, Kumar [14] reviewed Knott’s work and although he commends Knott on the bulk of his work, he questioned the method of premixing the fuel and oxidizer in Knott’s apparatus and did not feel that fully developed pipe flow was achieved for the tests. However, Kumar does not cite why he believes this fault renders the data unreliable. In his own experiments, Kumar measured the sound spectra of premixed and nonpremixed methane and enriched air flames. He found “profound differences” between the two configurations with the sound power of the premixed flame proportional to $U^3$ and the nonpremixed flame output proportional to $U^4$. For the experimental tests performed, Kumar presents acoustic pressure spectra, time domain pressures and data relating to the directionality of the sound emitted from the flames.

Chiu and Summerfield [15] offered correlations between acoustic power and turbulence scales and intensities for open flames and liquid spray combustors. Furthermore, they examined the sound emission and resonance in ducted combustors. Data is presented in the form of acoustic pressure spectra for the combustion processes examined. Of particular interest was the comparison between near field and far field spectra which
showed identical frequency distributions. They concluded that the noise generation was attributed to various non-steady phenomena including turbulent fluctuations and acoustic instabilities inherent in the burner design.

Perhaps the most widely cited research of the 1970's belongs to Strahle [3,16,17,18]. He based his theory of combustion noise on Lighthill's [6,7] aeroacoustic model. Strahle proposed that the sound emitted from a turbulent flame is proportional to the reaction rate time derivative. In addition, he offered further evidence that the sound source possesses monopole behavior. Strahle was able to derive meaningful scaling rules, based on his own experimental evidence, to correlate the acoustic output of turbulent flames. Acoustic pressure spectra presented by Strahle indicate that most of the noise occurs in the range of 200 to 2000 Hz. Based on experimental data, Strahle developed a scaling law to predict the sound pressure levels to be

\[ S_p = 0.625 \times 10^{-5} U^{2.67} D^{2.81} S_L^{1.83} F^{-0.26}, \]  

where the convective velocity \((U)\) and flame speed \((S_L)\) are in feet per second, burner diameter \((D)\) is in feet, and fuel mass fraction \((F)\) is unitless. The standard deviation of these results was determined to be 37 percent.

Shivashankara et al. [19,20] considered flames with flow velocities to 600 fps and burner sizes ranging up to one inch in diameter. The data is presented in the form of pressure spectra in the time domain and frequency domain. Based on this experimental data and other published results, scaling laws were developed to predict acoustic output of turbulent flames. These scaling laws consider the fuel mass fraction to be independent of flame speed. In addition, the study notes that the directivity in the combustion noise source varies by less than 4 dB with the peak pressure recorded axially downstream of the flow. It should be emphasized that these scaling laws only predict the total sound
power output of the turbulent flame and do not address the spectral distribution of the combustion noise.

Mathews and Rekos [21] attempted to apply the analytical relationship of Strahle to several burner configurations and to a full-scale turbofan engine. Frequency spectra were examined for peak frequencies and over-all sound pressure levels. The predictions of Strahle for sound pressure level proved to be in good agreement with noise data obtained from the tested combustors. They conclude by discussing a number of relationships between experimental variables and measured acoustic data.

The work of Lighthill and Strahle was further advanced by Dowling [22] in 1978 to include the effect of variation of mean temperature and flow velocity at the flame front. In particular, he examined the refraction of sound waves as they pass through the combustion zone. His work offered an explanation of why Strahle's theory failed to predict the observed non-uniformities in the sound field of a turbulent flame.

In 1979, Ramohalli [23] considered the possibility of inferring information regarding the operating conditions of a flame through examination of the acoustic emission of the combustion system. Based on photographic observations and the frequency spectra of the tested flames, a simple model was developed to extract information regarding the acoustic field. The photographs of the flame explicitly show that large eddies form first and then break down into smaller and smaller eddies. This was an important step in using the sound spectra of a flame as a diagnostic tool to determine combustion details such as turbulence and reaction rates. In addition, the effect of air-fuel ratio on frequency spectra is presented.

Ho and Doyle [24] presented a parametric expression for the prediction of sound power levels. By applying the effective combustor discharge temperature, they found good agreement between their model and experimental data. Furthermore, the experimental data is presented as frequency spectra which show peak frequencies to be about
450 Hz for the experimental tests performed. The model was found to apply to a broad range of applications including gas turbine engines.

Ramachandra and Strahle [25] developed a nonintrusive acoustic technique to determine heat release rates and turbulent properties in an open premixed turbulent flame. This technique reinforces the importance of utilizing the acoustic emission of the flame as a diagnostic tool for determining operating conditions of the combustion system. Utilizing the optical emission of $C_2$ radicals as an indicator of heat release, they concluded that the fluctuating heat release rate can be deduced from the sound spectrum of the flame.

A thorough study of the effects of burner size and shape on over-all sound pressure levels and frequency spectra was conducted by Kotake and Takamoto [26]. The performance of rectangular, square and circular burner nozzles of various sizes was studied over a range of equivalence ratios. It was found that nozzle shape had little effect on the noise spectra for fuel rich flames; however an appreciable effect was observed for fuel lean flames. Correlations of the acoustic output were determined for flow velocity and effective burner diameter.

The acoustic emission of open turbulent diffusion flames was examined by Seshan [27] in 1986. The performance of two different diameter burners was examined as were two industrial furnaces. The two burners studied were tested for the combustion of methane. Upon examining the data, Seshan found a common spectral shape for a wide range of operating and burner configurations. Peak frequency ranges correlated well with the cold flow Reynolds number as predicted by theoretical estimations. He concluded by suggesting that an algorithm might be developed to monitor and control industrial burners through the acoustic output of the flame.

In 1987, Mahan [28] reconsidered the work of Thomas and Williams [11] and their examination of the surface ignition of combustible bubbles. His model assumed
that a stream of turbulent eddies, of initial diameters distributed about a specific mean value and standard deviation, enter the combustion zone and are burned via surface ignition. A Fourier analysis of the pressure-time series resulting from a continuous stream of these reacting eddies produced a line spectrum. When converted to a third-octave band pressure spectrum, the results closely resembled those obtained experimentally by Thomas and Williams. This study was perhaps one of the first successful attempts at predicting an acoustic spectrum of a turbulent combustion process.

In 1988, Mahan and Nathani [29] improved upon Mahan's original model. The previous model had not considered the convective velocity of the eddy while entering the flame front. Experimental evidence had shown that this is an important parameter in the noise production process. The improvement included a transition burning period during which the eddy enters the combustion zone. In a second phase, the eddy is assumed to burn uniformly as described in the original model.

Based on Mahan's work, Nathani [1], developed a model which more closely approximates reality. The model predicts a third-octave pressure spectra and over-all sound pressure levels based on burner diameter, flow velocity, laminar flame speed, flame temperature, and several parameters applying to the acoustic environment. From available data at the time, the model appeared to yield good results. Yet, to determine its validity, the model needs to be thoroughly exercised using consistent experimental data.

In general, past studies have concentrated on a particular application of combustion noise production; a complete and consistent data base which utilizes a simple burner and considers relevant variables does not exist. In addition, the theoretical studies cited consider, at best, the total sound output of the turbulent combustion process and do not attempt to predict the spectral distribution of this noise. The development of noise production theory has reached a stage where a consistent data base is necessary to aid in evaluation.
3.0 Experimental Design

To allow the data to be as useful as possible to theorists, the Mahan-Nathani model [1] was obtained as a guide in designing the experiment. The model then suggested the parameters to be examined. From the theory, discussed in Appendix A, relevant inputs were then determined to be burner diameter, flow velocity, and fuel chemistries.

3.1 Burner design

In keeping with the simplicity of the theoretical model, it was important to utilize a geometrically simple burner. For this reason, a Harris Model #85 (Serial number 0688) standard commercial type oxy-acetylene welding torch was chosen for mixing and regulating the fuel and oxygen flows. The torch was modified to accept a range of burner nozzles which threaded onto the torch handle, replacing the standard welding tips. Because the objective of the study was to exercise the theoretical model, it was necessary to be able to systematically adjust each theoretical variable independent of the other
model variables. This configuration allowed easy alteration of fuel type, flow velocities, and burner diameters thereby addressing all model parameters. The burner allowed for safety and portability which was also a fundamental requirement for the experiment.

The oxygen and fuel are mixed in a small chamber in the welding torch. From there, the flow is directed through a small orifice past which the passage diameter gradually increases until the mixture reaches the torch head. The small orifice acts as a flame arrester should the flame front propagate upstream to the mixing chamber. Nassau Rockmount resettable flashback arresters were also provided at the base of the torch for both fuel and oxidizer. From the torch head, the flow then passes through the chosen burner nozzle.

Five nozzles were constructed to thread into the torch head. The available nozzle inside diameters were 0.117 cm, 0.165 cm, 0.356 cm, 0.414 cm, and 0.541 cm. Each nozzle was 13.34 cm in length. For acetylene and propane, the three smallest burners were tested, and for methane, the three largest burners were used. For the fuels tested, the burners used were selected based on the limits of flashback and blow-off. The nozzles were constructed of ASTM 4140 steel tubing and a 3/8 inch bolt. The head of the bolt was drilled to match the outside diameter of the given tubing. After inserting the tubing into the machined bolt, the two pieces were silver soldered. A smoothly converging nozzle shape was machined into the base of each burner to aid in achieving developed flow. The burner construction allowed a range of nozzle diameters to be conveniently threaded into the torch head which accepted the 3/8 inch 28 thread.
3.2 Oxidizer Selection

Oxygen was selected as an oxidizer for the fuels tested although many past experimental efforts utilized air. The reason for this was that oxygen offers wider flammability limits for a given fuel. This allowed a wider range of conditions to be tested experimentally. In addition, oxygen allowed a more stable flame with the desired simple burner configuration without the need of external flame holders as air (as an oxidizer) would dictate.

Mixture ratios were based on the neutral flame concept (Appendix B) which provides for complete combustion via premixed oxygen and entrained atmospheric air. This was an important step in determining an overall stoichiometric fuel and oxidizer mixture.

3.3 Flow Control

Supply pressures for the various gases were controlled by two-stage regulators. The oxygen cylinder pressure was regulated by an Industrial Gas and Supply regulator (Model number 25-100). For acetylene and methane, an Industrial Gas and Supply regulator (Model number 25-15) was used. For the considerably lower pressure propane, a Matheson regulator (Model number 9) was used.

Gas flow was controlled and measured using three different flow meters: Brooks Instrument Division Model No. 1112CH11E2AA; Cole Parmer Instrument Co. Model No. FM034-39; Cole Parmer Instrument Co. Model No. FM044-40. The Cole Parmer
Model FM044-40 was used exclusively for oxygen flow while the other two flow meters were used for fuel flows depending on the required flow rates.

The flow meters were calibrated using a Singer American Meter Division 802 (serial number K871130) gas meter. To allow for any pressure drop that may have occurred through the burner configuration, the flow from the burner exit was measured by the gas meter for a range of flow meter scale readings and the time was recorded for the given flow volume using a stop watch. This allowed calibration charts to be created for each meter with respect to the particular gas flow/pressure drop conditions.

3.4 Data Acquisition

A microphone was used in conjunction with a real-time analyzer to measure the acoustic signal. Sixteen samples of the acoustic emission were collected and averaged using a Spectrascope Model SD330A-7 Real-Time Analyzer (Serial Number 251) to produce a spectral distribution for each test point. The spectra were then digitized and stored on an IBM PC. A block diagram of the instrumentation is shown in Figure 1.

A Bruel and Kjaer 4133 microphone and Bruel and Kjaer Type 2801 power supply were used to convert the acoustical pressure output of the burner into an electrical signal. The signal was then amplified by a Realistic Pre-amplifier (Model 42-2101A) rated at 1.5 Watts. The output of the amplifier provided the required input signal for the spectrum analyzer.

The acoustical signal from the amplifier was converted into a frequency spectrum by the real-time analyzer. The analyzer utilizes a series of frequency-tuned bandpass filters to convert the input electrical signal from the time domain to the frequency domain.
Instrumentation

Figure 1. Block diagram of acoustic instrumentation
To achieve minimum analysis time, the analyzer employs time compression techniques. Following the compression, the input signal is frequency analyzed using 250 synthesized filter locations that are tuned by a built-in sweep generator. The analyzer range could be varied from 25 Hz to 20,000 Hz and a wide range of input bands and output gains could be selected to achieve maximum sensitivity. The analyzer also allowed for averaging to condition a noisy signal. In keeping with past experimental efforts, a frequency range of 0 to 10,000 Hz was used for experimental measurement. In addition, the signal was sampled and averaged 16 times to minimize time domain randomness encountered during testing.

The analyzer can store an averaged spectrum which may later be plotted via a 1 to 5 Volt output signal for both the X-axis (frequency) and Y-axis (pressure). These output signals were instead transformed to digital signals using a Data Translation Series DT2811 analog and digital I/O board. The board was configured for an analog to digital conversion and was installed in an IBM PC. This allowed the data to be stored digitally on 5 1/4 inch floppy diskettes. The signal board was controlled by a BASIC program written specifically for this application. The digital data were later converted from voltages to frequency and pressure and reduced for inspection and plotting. Calibration of the data acquisition system is discussed in the Procedure section.

3.5 Acoustic Environment

Although it was desirable to conduct the acoustic tests in an anechoic chamber, it was infeasible due to the possible fire hazard of running an open flame in a small room with walls of raw insulation. In addition, the soot generated by the acetylene flame
during initial start-up made running the tests in a confined area impractical. Because of these problems, it was decided to run the tests outside. This is a common method of running acoustic tests on large equipment that cannot be tested in an anechoic chamber. This method only requires an open space free of standing structures which might reflect generated sound waves. Generally, a microphone is placed at ground level, in accordance with ANSI standard S1.34-1980 (ASA 14-1980) and the true sound pressure is then half of the pressure measured by the microphone.

After considering several alternatives, it was decided to conduct the tests at Virginia Polytechnic Institute and State University’s Prices Fork Research Center. The Mechanical Engineering Department’s Rocket Testing Laboratory offered an instrumentation building at the base of a steep hill adjacent to a large flat field. The height of the roof of the building was just even with the field surface. This allowed the tests to be run on top of the building while the instrumentation was kept secure within the building. The nearest standing structure was another small building approximately 200 yards away.

A four-foot-square testing pad was constructed to allow the microphone to be mounted at ground level. The stage was constructed of two-by-fours and half-inch plywood such that the height of the platform was about four inches. The platform with the mounted microphone was placed flat on the roof of the test building with the burner placed upon the platform. The microphone was placed one meter below the burner exit and one meter away from the point where the burner axis intersected the platform. This gave the microphone a total distance of just over 1.4 meters from the noise source, as shown in Figure 2, such that far-field sound waves could be assumed down to approximately 350 Hz.

It was readily observed in preliminary testing that a breeze could cause instabilities in the reacting flow. Since this did not reflect the true noise of the combustion process,
Microphone Placement

Figure 2. Microphone placement relative to the burner
it was desirable to conduct the tests under very calm weather conditions. During daylight hours, a breeze was consistently blowing off the barren field next to the test site. However, a few hours after sunset each day, much calmer conditions generally prevailed. In addition, at night fewer disturbances from Prices Fork Road, approximately a quarter of a mile away, were evident. It was therefore obvious that the most reliable data could be collected on very calm nights.

Acetylene data was collected in the early morning of July 4, 1990; Propane data was collected late night on July 5, 1990; Methane data was collected late night on July 23, 1990.

Once the experimental apparatus was obtained, the experimental procedure was next designed. The next chapter discusses the determination of test points to be examined, the calibration of the instrumentation and the experimental method which was followed.
4.0 Experimental Procedure

4.1 Determination of Test Matrix

4.1.1 Equivalence Ratio

Initially, the possible range of burner diameters, flow velocities and mixture ratios for each fuel had to be determined. It was noticed at preliminary stages of the experimental work that a premixed stoichiometric flow of fuel and oxygen caused high-frequency instabilities. It was theorized that the flame might in fact be over-oxidized due to entrained atmospheric air. These instabilities had to be avoided if the true direct noise of the combustion process was to be measured. This necessitated the use of a different criterion for determining fuel-oxygen mixtures.

Mixture ratios were chosen based on the neutral flame concept (Appendix B) which provides for complete combustion of the fuel via premixed oxygen and entrained atmospheric air using visual inspection. The mixture for each fuel was adjusted until
only two flames zones were visible and this ratio was applied to all tests for that fuel. This was an important step in determining an overall stoichiometric fuel and oxidizer mixture.

4.1.2 Burner Diameter and Flow Velocity

To determine the range of flow velocities to be tested, each burner was examined for a given fuel. The flow velocity of the reacting mixture was decreased until flash-back occurred. This velocity was the lower limit for the fuel and burner combination. Next, the flow velocity of the reacting mixture was gradually increased until blow-off occurred. This velocity was the upper limit for the fuel and burner combination. Another such limiting factor for the fuels tested was the limited flow rate that could be generated using the given pressure regulators and flow meters. For acetylene and propane, this limiting factor dictated the use of only the smallest three burner nozzles. Conversely, stable methane flames were not attainable for the smallest two diameters and only the three largest burner nozzles were tested.

Once the stability limits for the given fuels were determined, a range of three flow velocities was selected, the highest and lowest being slightly within the indicated velocity limits. It is not surprising that all burner sizes tested for a given fuel exhibited very similar flash-back and blow-off flow velocities as these are directly related by the laminar flame speed of a given mixture.
4.2 Acoustic Calibration

The acoustical instrumentation was calibrated using a General Radio Company Type 1567 Sound Level Calibrator (Serial number 15480) with an output of 114 dB at 1000 Hz. The sound level calibrator output was confirmed using a Columbia Model SPL-103 Sound Level Meter (Serial number E2223). The microphone was placed in the calibrator with the proper adaptor and the resulting pressure-frequency spectrum was determined by the spectrum analyzer. This spectrum was then routed to the x-axis and y-axis pen plotter outputs, converted to two digital signals by the A/D board, and recorded as a single data set of voltages representing coordinates of the pressure-frequency spectrum. This was repeated for all possible analyzer input range and output gain combinations. The calibration procedure was performed a total of 22 times for the different input range/output gain combinations and a 95 percent confidence interval showed an uncertainty of +/- 0.289 percent for the pressure amplitude output. With the known analog microphone pressure and frequency inputs and the recorded digital output, the output voltage signal from the microphone could be determined for the known input sound source. This allowed for the raw voltages to be converted to the corresponding frequency and pressure data by applying the calibration results when experimental measurements were later taken.

The integrity of the analyzer was tested using a Bruel and Kjaer Sweep/Function Generator (Serial number 89-09556) in conjunction with a Hewlett Packard 5314A Universal Counter (Serial number 2204A09094). Various periodic signals were applied to the analyzer at known frequencies and the frequency spectra were verified.

A white noise generator was used to assure a flat response for the microphone.
4.3 Test Procedure

The test matrices used for the experiments are shown in Tables 1-3. These tables indicate the flow velocities for the fuel and oxygen and the indicated flow meter scale readings to obtain the desired flows for the given burners.

The experimental procedure consisted of connecting the test fuel to the flow meters and selecting the desired burner nozzle. An initial flow of fuel only was ignited and the two flow meters were then adjusted until the proper flow velocities of the fuel and oxygen were achieved. Next, the input range and output gain of the real time analyzer were adjusted to achieve maximum resolution without overloading the analyzer input. The acoustic signal was then averaged 16 times and the resulting spectral distribution was stored in the analyzer memory.

The analog-to-digital (A/D) board control program was prepared to begin receiving data from the analyzer by selecting the plotting function on the analyzer. The analyzer's X and Y plotter outputs were in fact connected to the A/D board. The analyzer transferred the stored averaged frequency spectrum to the digital A/D board over a period of about one minute. Because the pen plotter outputs are intentionally rate-controlled to limit pen speed, a high sampling rate was chosen on the A/D board to ensure faithful replication of the spectrum. Essentially, then, the acquisition of the spectral data can be interpreted as the determination of 250 pressure-frequency data points by the analyzer, the fitting of an analog curve to form a spectral shape, the transmission of this analog function to an A/D board, and the conversion to discrete points again. The sampling rate chosen produced about 2000 coordinate points for each spectrum. The data was stored on disk under a file name unique to the given test condition. This procedure was repeated for all experimental test points. The background
Table 1. Acetylene Test Matrix

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<tr>
<th>Fuel and Burner Parameters</th>
<th>Volumetric Flow Rate</th>
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</thead>
<tbody>
<tr>
<td>D (cm)</td>
<td>$U_{mix}$ (m/s)</td>
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<tr>
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<td>50</td>
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<tr>
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<td>75</td>
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<tr>
<td>Fuel and Burner Parameters</td>
<td>Volumetric Flow Rate</td>
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<tr>
<td>---------------------------</td>
<td>----------------------</td>
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<td>20</td>
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<tr>
<td>0.356</td>
<td>30</td>
</tr>
</tbody>
</table>

4.0 Experimental Procedure
noise was measured on each date of testing as a reference for any possible variation that might have existed. In addition, the spectra for several non-reacting flows were measured for reference.

### 4.4 Data Reduction

#### 4.4.1 Constant Bandwidth Spectra

Each file of raw data consisted of up to 2,000 spectral samples due to the high sampling rate of the A/D board. The analyzer, however, generated only 250 discrete frequency coordinates with its band-pass filters. The raw data did not perfectly reveal these discrete points. The closest coordinates to the center frequencies measured by the analyzer were then selected for the reduced data file. At frequencies below 2000 Hz, where the spectrum was rather complicated and the analyzer transferred data at a relatively slow rate, the raw data files contained a high density of frequency-pressure coordinates. For these lower frequencies, the analyzer center frequencies could generally be matched within 0.5 percent by the raw data frequencies. At frequencies above 5000 Hz, where the spectrum was relatively flat, the analyzer center frequency could be matched within 3 percent. A BASIC program was written to perform this reduction and is shown in Appendix C.
4.4.2 Overall Sound Pressure Level

The overall sound pressure level was generated from the constant percentage bandwidth data. Because each of the 250 points generated in this data represents a RMS pressure value, the overall sound pressure level was calculated by also taking an RMS pressure of all of the constant bandwidth pressure components. This reduction was performed by a BASIC program shown in Appendix C.

4.4.3 Third Octave Band Spectra

The constant percentage bandwidth data was reduced to third octave band spectra by applying an RMS summation of the pressures within each third octave band. These pressures were then matched to the appropriate central frequency of the respective band. This reduced the constant bandwidth spectrum to 19 third-octave bands. A BASIC program was written to perform this reduction procedure and is presented in Appendix C.
5.0 Results and Discussion

An experimental data base of combustion noise was collected to aid in the development and appraisal of predictive models. Specifically, the theoretical model of Mahan-Nathani (Appendix A) was chosen to examine trends found in the experimental data. The model was evaluated by addressing all inherent input parameters including burner diameter, flow velocity and chemical inputs. The acoustic emission from the combustion of turbulent mixtures of several gaseous fuels and oxygen was recorded. Oxygen was selected as an oxidizer to allow wider stability limits than could be achieved with air as an oxidizer. Acetylene, methane and propane were each examined with three burner diameters and three flow velocities as shown in Tables 1, 2 and 3. The fuel-oxygen mixture ratios were determined based on the concept of a “neutral flame” (Appendix B). This is the condition upon which the fuel is completely oxidized by the pre-mixed oxygen and entrained air from the surroundings. Upon applying this criterion, the following fuel-oxygen ratios (volumetric) were obtained for the three fuels:

- acetylene: 1:1
- methane: 2:3
- propane: 1:2
Section 5.1 discusses the constant-bandwidth frequency spectra that were measured experimentally. This data can be seen in Appendix D. The peak frequencies and overall sound pressure levels for all spectra were identified and are tabulated in Table 4. These two parameters were chosen as useful characteristics to allow quantitative comparisons to be made regarding input variable effects. In addition, these parameters will be used for the comparison of experimental data to model predictions.

In Section 5.2, model predictions are compared to the experimental results. For constant-bandwidth spectra, the model predicts spectra that show an unrealistic peak frequency of 0 Hz. For increasing frequencies, the predictions show a series of harmonics. To allow a more reliable comparison, the experimental data is converted from constant-bandwidth spectra to third-octave-bandwidth spectra. The converted experimental data is presented in Appendix E. The peak frequency and overall sound pressure level for this data is shown in Table 5.

### 5.1 Experimental Results

All acoustic spectra were measured using a frequency scale of 0 to 10,000 Hz while pressure scales were adjusted to allow maximum resolution. The operation of the spectrum analyzer using the 10 kHz band allows a useful frequency range above 120 Hz; lower frequencies are limited by the uncertainty in the analyzers' first measurement step. The spectral plots which follow typically show a low frequency content (below 120 Hz) which is an artifact of the spectral analysis procedure and does not represent the true frequency content in this range. Therefore, the peak frequencies reported in Table 4 consider the first identifiable peak above this range. Preliminary measurements on the
Table 4. OASPL and Peak Frequency for Constant-Bandwidth Data

<table>
<thead>
<tr>
<th>Fuel and Burner Parameters</th>
<th>Experimental Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel (-)</td>
<td>D (cm)</td>
</tr>
<tr>
<td>Acetylene</td>
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</tr>
</tbody>
</table>
250 Hz band indicated no significant spectral content below this limiting 120 Hz associated with the 10 kHz band.

The effects of each input variable are described in the following discussion. Comparison spectral plots show the effects of a single variable while holding others constant. The constant parameters represent the median values.

1. Burner Diameter: Figures 3, 4, and 5 show the effect of burner diameter on the frequency spectra of methane, propane and acetylene respectively while holding all other experimental parameters constant. In general, the data presented in the figures and in Table 4 reveal that the peak frequency is not significantly affected by changing diameter. The slight effects that are seen appear to be random.

The tabulated data show an interesting exception to this trend which supports past theoretical efforts. For propane flowing at 20 m/s through the 0.117 cm burner, a peak frequency was measured which is much lower than those found for the 0.165 cm and 0.356 cm burner diameters tested at the same flow velocity. It is apparent that this is caused by a low turbulence condition. The calculated Reynolds number for this case is about 1600 and is the only test point considered which might not be turbulent. This finding supports Braggs' [9] theory which predicts no noise for laminar flames. Although the reaction was clearly audible, it is suspected that the acoustic mechanism at this point was in a transitory phase between a noiseless laminar flame and a steady turbulent reaction. Because the noise mechanism in this reaction is likely different than that found in the rest of the data, this test condition will not be considered in the discussion which follows.

Other inconsistencies in the spectral trends for diameter might be wrongly assumed by only considering the data in Table 4. In several cases, the peak frequency occurs in a region where the spectrum is somewhat flat and does not contain a

5.0 Results and Discussion
Figure 3. Spectra for Methane with varying burner diameter: $U = 20 \text{ m/s}$
Figure 4. Spectra for Propane with varying burner diameter: \( U = 30 \text{ m/s} \)
Figure 5. Spectra for Acetylene with varying burner diameter: \[ U = 75 \text{ m/s} \]
dominant peak. Upon considering the spectral shapes in these cases, the spectral content of the data show the general trends seen in the rest of the data set.

Finally, the data from Table 4 clearly show that the overall sound pressure levels increase with increasing burner diameters.

As discussed previously, the model predicts decreasing peak frequencies with increasing burner diameters. However, this trend is not exhibited in the experimental data. Perhaps the range of experimental burner diameters examined is not wide enough to expose an underlying trend. The model would also predict increasing overall sound pressure levels with increasing burner diameters, simply due to the larger sound sources associated with larger burner diameters. This predicted trend is supported by the experimental data.

2. Flow Velocity: Figures 6, 7 and 8 show the effect of flow velocity on frequency spectra with burner diameter and chemistry held constant. These figures show velocity to have little effect on peak frequency. Yet, examination of the data in Table 4 shows peak frequency to increase for eleven out of the possible fifteen direct comparisons allowed by the experimental data. This general trend would then be in agreement with the theoretical model which predicts increasing peak frequencies with increasing flow velocities. The data presented in Table 4 also shows that overall sound pressure level increases with increasing flow velocity. This trend is also predicted by the theoretical model.

3. Chemical Inputs: Only one direct comparison could be made regarding the reactant chemistry. Figure 9 shows a spectral comparison of propane and methane for flow through a burner diameter of 0.356 cm at a velocity of 20 m/s. The figure shows that the two spectra are remarkably similar. The theoretical model only considers two parameters which would differentiate between fuels; namely, flame speed and flame temperature. Flame speed and flame temperature data as presented by Gaydon and
Figure 6. Spectra for Acetylene with varying flow velocity: $D = 0.165$ cm
Figure 7. Spectra for Methane with varying flow velocity: $D = 0.414 \text{ cm}$

5.0 Results and Discussion
Figure 8. Spectra for Propane with varying flow velocity: $D = 0.165$ cm
Figure 9. Spectra for Methane and Propane: $D = 0.356$ cm, $U = 20$ m/s
Wolfhard [8] show methane and propane to be comparable regarding these two parameters. Hence, the model would also predict very similar acoustic spectra.

The noise attributed to the experimental surroundings is shown in Figure 10. The reader should note the pressure scale is less than 10 percent of scales used to show reacting flows. It is clear that the background noise present during experimental testing is insignificant when compared to the sound emission from the combusting fuel-oxygen mixtures.

Figure 11 shows the spectra of a non-reacting methane flow of 20 m/s through the 0.414 cm burner. The figure clearly demonstrates that the non-reaction flow noise contributes less than 10 percent to the overall sound pressure level of the reacting flow case. This result is also consistent with the theory of Bragg [9]. In addition, it should be remembered that this noise also includes the background noise present during testing.

Data points in the test matrix were found to be quite repeatable as shown in Figures 11 and 12. Figure 12 shows three spectra of reacting acetylene at 75 m/s through a 0.165 cm diameter nozzle. Initial experimental tests were conducted to determine if successive measurements for a given condition were repeatable. It was shown that in fact they were. Yet to quantify a confidence level, one test point for each of the fuels was repeated three times. This allowed a T-test to be performed with nine degrees of freedom. This analysis yielded a 95 percent confidence level of +/- 18 percent for the peak frequency and +/- 12 percent for the overall sound pressure level.

5.0 Results and Discussion
Figure 10. Spectrum of Background Noise
Figure 11. Spectrum of non-reacting Methane flow: $U = 20$ m/s, $D = 0.414$ cm
Figure 12. Spectra for Acetylene: $U = 75 \text{ m/s}, D = 0.165 \text{ cm}$
5.2 Comparison To Theoretical Model

The study has now reached a point where the performance of the Mahan-Nathani theoretical model may be considered. As with the experimental data just presented, peak frequency and overall sound pressure level will be used as criteria for evaluating the model. As discussed previously, the model predicts an unrealistic peak frequency of 0 Hz for constant-bandwidth spectra. To allow a more meaningful comparison between the model predictions of peak frequency and those determined experimentally, the experimental constant-bandwidth data is converted to third-octave-bandwidth spectra. Upon applying this conversion to the theory, the model will then predict non-zero peak frequencies, and a direct comparison can be made to the peak frequencies determined experimentally. Also, since third-octave-bandwidth spectra reduce the data to seventeen center frequencies in a 10 kHz frequency range, more general insight into the frequency content of the acoustic spectra is allowed. This conversion then avoids the mundane task of evaluating the intricacies of the experimental data when compared to the relatively simple third-octave-bandwidth data as predicted by the model. The converted experimental data appears in Appendix E. The tabulated peak frequencies and overall sound pressure levels appear in Table 5.

5.2.1 Determining Model Input Requirements

Recall that the model requires input parameters which include burner diameter, flow velocity, flame speed and flame temperature. Since flame speeds and flame temperatures were not measured experimentally, their values must be estimated. However,
the two stage reaction of the neutral flame (Appendix B) dictates two different reactions with unique flame speeds and flame temperatures to each stage. To further complicate matters, the true reaction encountered experimentally is certainly more complicated than this assumed two-step reaction. In light of these uncertainties, estimating these chemical parameters becomes necessary.

As a first approximation, an attempt was made to run the model for flame speeds and flame temperatures as obtained from literature [8,29]. These values were obtained for the fuel-oxygen ratios used experimentally. Arguably, these values were measured for a complete reaction with oxygen and ignore the entrained air encountered experimentally. The model predictions based on these inputs provided poor results when compared to the experimental results.

Upon considering the flame speed data from Gaydon and Wolfhard [8], it was seen that flame speed is very sensitive to the fuel-oxygen ratio in the combustible mixture. For example, the flame speeds for methane were found to vary from approximately 25 cm/s for the fuel-rich, stage one reaction of the neutral flame (1:1 fuel-oxygen ratio) to 330 cm/s for the combustion of a stoichiometric mixture of methane and oxygen (1:2 fuel-oxygen ratio). These flame speeds apply to the complete combustion of the fuel-oxygen mixture, yet the neutral flame reaction (which determined the experimental mixtures) considers the partial reaction of a methane molecule in oxygen followed by continuing reaction with entrained air.

The model clearly failed to predict the experimental data under these conditions. A close examination of these data revealed that the model may produce useful results however, if the flame speed and flame temperature are adjusted from the data of Gaydon and Wolfhard [8] (which were measured under completely different conditions), to those which might realistically exist in these experiments.
The model was next examined to determine its sensitivity to flame speed and flame temperature. It was noted that flame temperature only affects amplitude, and consequently overall sound pressure level, and not the frequency distribution of the predicted acoustic spectra. Higher flame temperatures resulted in higher acoustic pressures at all frequencies. It was revealed, though, that flame speed affects the frequency distribution, with higher flame speeds resulting in higher-frequency spectral distributions.

This evidence suggested that the model might be forced to match the frequency content of the experimental data by adjusting the flame speed. Flame temperature inputs could then be adjusted to match the overall sound pressure levels measured in the experimental tests. Because the model predicts a non-zero peak frequency in a third-octave-band spectrum, a force fit of the model could be made with two distinct and necessary requirements; a match of both peak frequency and overall sound pressure level.

This exercise in forcing the data might then lend some insight into what flame speeds and flame temperatures might actually be occurring experimentally. In addition, if the required force fit data appeared to be unrealistic, this flaw could then be addressed.

The resulting flame speeds and flame temperatures required to force fit the model to the experimental data are shown in Table 6. The data for flame speeds is fairly consistent for all three fuels. However, the necessary flame temperatures required to match the overall sound pressure levels vary considerably throughout the range of test conditions. In fact, the true flame speeds and flame temperatures for a given fuel should be similar as the chemistry (mixture) is constant for all cases. The data presented in Table 6 reveal no obvious trends for required flame speeds and flame temperatures yet it does suggest what flame speeds and flame temperatures might be used to model a given fuel. In addition, if the theoretical model is correct, the data suggest what the true flame speeds and flame temperatures encountered in the experimental tests might be.
### Table 5. Third-Octave Band Results for Experimental Data

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<tr>
<th>Fuel and Burner Parameters</th>
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</thead>
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<td>D (cm)</td>
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5.0 Results and Discussion
Table 6. Requirements to Force Fit the Model to Experimental Results

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<tr>
<th>Fuel and Burner Parameters</th>
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5.2.2 Estimating Flame Speed and Flame Temperature

Based on the flame speed and flame temperature data of Gaydon and Wolfhard [8], the values of these parameters required to match the model prediction to the experimental results do not appear to be unrealistic. It seems that a reasonable estimate of flame speed and flame temperature might be made by considering both the force fit requirements and the published values.

It is likely that the true flame speeds for the fuel-oxygen mixtures examined experimentally must fall between the flame speed indicated for the fuel lean mixture in the primary stage reaction of the neutral flame and that for a stoichiometric fuel-oxygen mixture. From Gaydon and Wolfhard, the range of possible flame speeds for the fuels tested are then:

- Acetylene: \(300 < S_L < 1100 \text{ cm/s}\)
- Methane: \(30 < S_L < 330 \text{ cm/s}\)
- Propane: \(60 < S_L < 400 \text{ cm/s}\)

These respective flame speeds set limits on what the true values can be in the experimental tests.

The adiabatic flame temperatures were calculated for the experimental fuel-oxidizer mixtures to suggest a limit on the possible flame temperature which might be present in the experimental tests. The calculated adiabatic flame temperatures for each fuel were determined to be:

- Acetylene: \(T = 4637 \text{ K}\)
- Methane: \(T = 2873 \text{ K}\)
- Propane: \(T = 2827 \text{ K}\)
Due to convective heat transfer and radiative heat transfer, the true flame temperature is expected to be lower than the calculated adiabatic flame temperature.

From the possible flame speeds and flame temperatures presented for experimental fuels, and based on the flame speeds and flame temperatures necessary to force the model (Table 6), specific flame speeds and flame temperatures were assumed for each fuel. These estimates are as follows:

- **Acetylene:** \( T = 4000 \text{ K} \), \( S_L = 500 \text{ cm/s} \)
- **Methane:** \( T = 2400 \text{ K} \), \( S_L = 240 \text{ cm/s} \)
- **Propane:** \( T = 2750 \text{ K} \), \( S_L = 260 \text{ cm/s} \)

The outcome of the assumed flame speed and flame temperatures as applied to the theoretical model yielded some interesting results, yet also exposed some possible weaknesses in the theory. Table 7 shows the predicted peak frequency and the overall sound pressure level for each experimental test point. The model proved to match methane the most accurately and acetylene the least accurately of the three fuels tested. This is partially an artifact of the method of estimating the flame speed and flame temperature parameters. Furthermore, several anomalies in the model code results were noted and will be discussed in Section 6.2.3.

Figure 13 shows the model prediction for the third octave band spectrum of a 10 m/s methane flow through a 0.414 cm burner diameter. The similarity in the results through the first frequency peak is because the assumed flame speed is very close to the force fit required flame speed. However, the spectral shape of the model closely approximates the experimental results. In particular, the second frequency spike at approximately 2000 Hz is almost the same in both spectra and is not directly an artifact of the model being forced. A comparison of a higher flow velocity (25 m/s) through the same burner is shown in Figure 14. In this case, the model fails to predict even the shape of the experimental spectra.

5.0 Results and Discussion
Table 7. Model Results for Assumed Chemical Parameters

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<th>Fuel and Burner Parameters</th>
<th>Model Results</th>
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Figure 13. 1/3-Octave Spectrum for Methane: $U = 10$ m/s, $D = 0.414$ cm
Figure 14. 1/3-Octave Spectrum for Methane: $U = 25\, m/s, D = 0.414\, cm$
Figure 15 shows a prediction for acetylene with the largest tested burner diameter of 0.356 cm. The results clearly show that the predicted spectrum shape closely resembles that determined experimentally. However, the overall sound pressure level predicted is much higher than the experimental data indicates.

Some apparently anomalous behavior was observed in the results obtained from the computer model. These are detailed and discussed in Appendix A.
Figure 15. 1/3-Octave Spectrum for Acetylene: $U = 75 \text{ m/s}, D = 0.356 \text{ cm}$
6.0 Conclusions and Recommendations

6.1 Conclusions

An experimental data base of acoustic spectra was collected for the noise emission of turbulent combustion process. Unlike the limited number of past experimental efforts, the experiment utilizes a geometrically simple burner configuration and uses a consistent method of addressing known relevant input parameters.

Increasing burner diameters and flow velocities were found to have little effect on frequency content yet caused increasing overall sound pressure levels. The effects of alternate fuels and consequently, flame speed and flame temperature, could only be examined for one case between methane and propane. The overall sound pressure level and the acoustic spectra were very similar, as might be expected due to similar laminar flame speeds and adiabatic flame temperatures. For all cases, the peak frequency was determined to fall between 80 Hz and 2000 Hz. Overall sound pressure levels fell between 61 dB and 93 dB.
To test the usefulness of the data base to theories in general, the data was compared to the turbulent combustion noise model of Mahan-Nathani [1]. Initially, the model code was run using flame speed and flame temperature data as published in combustion literature. Upon application of these values, the model predicted acoustic spectra which were inconsistent with experimental data. Because of the complex nature of the reaction present in the experimental tests it was probable that these published values did not accurately represent the physical process encountered experimentally. Therefore, flame speed and flame temperature data were assumed based on the likely range of these variables and the required values to approximate the experimental results. In general, when applied to the model code, the assumed flame speeds and flame temperatures yielded acoustic spectra which closely resembled the spectral shapes found experimentally. Several discrepancies in the code were identified including the calculation of the number of sound sources (Appendix A). Also, limitations in the model were apparent for high velocities and high flame speeds as found with acetylene.

The study indicates that the model results for low velocity, low flame speed conditions in some cases closely approximate the experimental results. In addition, it reveals that combustion noise may have a wide range of diagnostic applications. These applications include the possibility of using acoustic emission of a flame as a means as a means of determining fuel-oxidizer mixture ratios, flame speeds and flame temperatures as well as methods for combustion noise reduction. With refinement, the model might be used to more practically determine flame speeds and flame temperatures of fuel-oxidizer mixtures under atmospheric pressures.
6.2 Recommendations

The present study reveals the need for further examination in both experimental noise measurement and theoretical predictive methods. The experimental data and the model predictions show tremendous potential for a clear understanding of the true noise mechanism of combustion.

The following recommendations are made for future experimental work.

1. Additions to the existing data base of acoustic spectra might offer more insight into the effects of the four input variables. A wider range of burner diameters and flow velocities could show slight trends not apparent in the present study. However, this would require a burner design with flame holders to overcome stability limits. This type of experimental configuration would add further complications which the model does not provide for. In addition, more fuels should be examined to offer insight into chemical effects (flame speed and flame temperature) on the acoustic spectra; as the present study only allows one direct comparison. The effect of equivalence ratio might also be examined.

2. To address the uncertainty in overall fuel-oxidizer ratios, a burner might be utilized which includes a coflow of non-reacting gas around the reacting mixture. This would eliminate the possibility of entrained air as occurred with the present experimental design. The true mixture of fuel and oxygen would then be assured and a better estimate of flame speed and flame temperature data could be made. However, this method will still allow for some energy loss to the non-reacting gas, resulting in lower temperatures than the adiabatic flame temperature.
The following recommendations are made for further study of Nathani’s theoretical model.

1. The possibility of incomplete combustion should be addressed in the model.

2. A more plausible reaction should be modelled to include more than one reaction step. Simply considering a two step reaction may lead to considerably better model results.

3. A statistical distribution of cell sizes, rather than the constant diameter employed in the present model, might favorably affect the models' predicted frequency distribution. As the model stands, the spectral content is determined simply by the combustion of one reacting cell.

4. The discontinuities in input variable trends should be addressed. It is suspected that the problem lies not in the supporting theory, but in the numerical integrations which occur in the model code.

5. The calculation of the number of sound sources in the model code should be corrected to properly follow the theory. Presently, this error is slight (about 9 percent) and only affects the calculation of overall sound pressure levels.
References


References


Appendix A. The Mahan-Nathani Model
A1. The Mahan-Nathani Model

Based on the work of Mahan [28], Nathani [1] proposed a new model which addresses the physics of the noise generation process, allowing the prediction of the acoustic emission from a turbulent flame. The model simplifies the combustion process by assuming that the flow of combustibles from the burner breaks down into small spherical cells of reactants whose initial diameter is dependent on the diameter of the burner. The subsequent combustion of one of these cells produces a sound pressure wave which is sensed in the form of combustion noise. By methodically adding up the effects of a continuous stream of these cells, the total noise generation of a turbulent combustion system can be predicted. The model considers the following parameters to predict the overall sound pressure level and the frequency spectrum of the flames' sound emission:

Burner \( U = \text{Mixture Convective Velocity} \)

\( D = \text{Burner Diameter} \)

Fuel \( S_L = \text{Laminar Flame Speed} \)

\( E = \text{Expansion Ratio (Volumetric)} \)

A1.1 Modeling the Noise Sources

For a turbulent jet of combusting fuel-oxidizer mixture, turbulent eddies of reactants and hot products are formed which are subsequently burned upon entering the flame zone. Nathani reasons that the flow of these complex eddies might be modeled as
a single continuous stream of spherical cells whose initial diameters were fixed at a constant value with no deviation.

Given a pre-mixed flow of fuel-oxidizer through a burner of diameter $D$, the volumetric flow rate of the mixture is given by

$$Q = \frac{\pi}{4} D^2 U,$$  \hspace{1cm} (A1.1)\]

where $U$ is the reactant mixtures' convective velocity. If $R_i$ is the initial radius of a combustible cell, then the initial volume of a single cell is

$$V_i = \frac{4}{3} \pi R_i^3.$$  \hspace{1cm} (A1.2)\]

Assuming the continuous stream of injected mixture breaks up uniformly into a single stream of the theoretical noise sources, then the injection time, in which a single cell is formed is given by

$$t_i = \frac{2R_i}{U}.$$  \hspace{1cm} (A1.3)\]

Because the model considers only a single stream of reacting cells, the volumetric flow rate, $Q$, can be written as

$$Q = \frac{V_i}{t_i}.$$  \hspace{1cm} (A1.4)\]

Substituting Eq. (A1.2) and Eq. (A1.3) into Eq. (A1.4) yields

$$Q = \frac{2}{3} \pi R_i^2 U.$$  \hspace{1cm} (A1.5)\]

Finally, equating Eqs. (A1.1) and (A1.5) gives
\[ R_i = \sqrt{\frac{3}{8}} D. \]  \hspace{1cm} (A1.6)

It is of particular interest to note that the above result was derived without any reference to turbulence scales. The correctness of this result awaits the scrutiny of the experimental data.

### A1.2 The Burning Process

The model hypothesizes that two distinct burning processes occur as the spherical cell of reactants propagates through the flame front boundary. The transition process begins at time zero when the cell initially comes in contact with the flame front, and ends when the cell has just completely entered the reaction zone. The transition time \( t_r \) is then determined to be

\[ t_r = \frac{2R_i}{U}. \]  \hspace{1cm} (A1.7)

The surface burning process begins when the cell has completely entered the reaction zone, and ends when the fuel in the cell has been completely consumed. Assuming a uniform combustion occurring radially toward the center of the cell, the surface burning time \( t_s \) is given by

\[ t_s = \frac{R_i}{S_L}. \]  \hspace{1cm} (A1.8)
where $R_i$ is the initial radius at the beginning of the surface burning process (the radius at the end of the transition process) and $S_L$ is the laminar flame speed of the mixture. Hence, the total burning time of one cell of reactants is determined to be

$$t_t = t_r + t_s .$$  \hspace{1cm} (A1.9)

### A1.3 The Acoustic Pressure Expression

The primary goal of the analysis is to evaluate an expression for $dV/dt$ as a function of time for both the surface and transition burning processes. This is necessary because the total acoustic energy radiated by the combustion process is dependent on the time rate of change of the volume evolution $d^2V/dt^2$, as shown by Bragg [10]. For the surface burning process, it can be shown that

$$\left. \frac{d^2V}{dt^2} \right|_s = 8\pi(E - 1)(t - t_0)S_L^3 .$$  \hspace{1cm} (A1.10)

where $E$ is the expansion ratio (volume occupied by the products of combustion divided by the volume occupied by the unburned mixture at the same pressure).

Determining $dV/dt^2$ for the transition burning process is somewhat more complicated than for the surface burning process. The following four boundary conditions have been identified for the process:

$$\left. \frac{dV}{dt} \right|_{r = 0} \text{ and } \left. \frac{d^2V}{dt^2} \right|_{r = 0} , \text{ at } t = 0 .$$  \hspace{1cm} (A1.11)

and
\[ \frac{dV}{dt} \bigg|_r = \frac{dV}{dt} \bigg|_s \text{ and } \frac{d^2V}{dt^2} \bigg|_r = \frac{d^2V}{dt^2} \bigg|_s, \text{ at } t = t_r. \quad (A1.12) \]

These four boundary conditions suggest that \(\frac{dV}{dt}\) might be represented by the following third-degree quadratic expression

\[ \frac{dV}{dt} \bigg|_r = at^3 + bt^2 + ct + d. \quad (A1.13) \]

Upon applying the boundary conditions, it can be shown that

\[ a = \frac{-8\pi(E - 1)t_rS_L^3}{t_r^3}. \quad (A1.14) \]

\[ b = \frac{4\pi(E - 1)t_rS_L^3}{t_r^2} (t_r + 2t_r). \quad (A1.15) \]

\[ c = d = 0. \quad (A1.16) \]

### A1.4 Evaluation of the Radius at the Beginning of Surface Burning

At this point the only unknown remaining is the radius of the cell at the beginning of the surface burning process \(R_s\). Since \(R_s\) is implicitly used in determining expressions for both transition and surface burning processes, it must be evaluated in terms of the four basic fuel and burner parameters. Following the logic of the model thus far, an expression containing \(R_s\) is determined as

\[ \frac{at_r^4}{4} + \frac{bt_r^3}{3} = \frac{4}{3} \pi(E - 1)(R_t^3 - R_s^3). \quad (A1.17) \]
Both expressions for a and b are nonlinear functions, therefore it is not possible to obtain an explicit expression for \( R_b \). However, equation (A1.17) may be solved iteratively with equations (A1.7), (A1.8), (A1.9), (A1.14) and (A1.15) to obtain \( R_b \).

### A1.5 Development of the Acoustic Pressure Expression

An expression for the acoustic pressure due to a single burning cell in terms of fundamental burner and fuel variables is now presented. Nathani shows that the non-dimensional acoustic pressure for surface burning is

\[
P_s = \tau - 1,
\]

(A1.18)

where \( \tau \) is the non-dimensional time

\[
\tau = \frac{1}{\mu}
\]

(A1.19)

\( P_s \) is defined as

\[
P_s = \frac{v_s}{\gamma},
\]

(A1.20)

\[
\gamma = \frac{\rho}{4\pi d} \beta,
\]

(A1.21)

\[
\beta = 8\pi \mu (E - 1) S_L^3,
\]

(A1.22)

where \( \rho \) is the density of air. The non-dimensional acoustic pressure for the transition period is found to be
\[ P_{\tau} = \frac{1}{\beta} (3at_{tt}^2 \tau^2 + 2bt_{t}\tau) . \]  

(A1.23)

The non-dimensional acoustic pressure as a function of time for the burning of one cell is given by equations (A1.18) and (A1.23). Nathani uses a Fourier series of the periodic function of period \( \tau = 1 \) to apply these equations to a continuous stream of combustible cells and to obtain the pressure spectra. The reader is referred to this work (Nathani [1]) for further explanation.

A1.6 Third-Octave Band Spectra

The Fourier series solution discussed in the previous section generates a line spectrum for the acoustic emission of a turbulent flame. The line spectrum is converted into a third-octave band spectrum by applying an RMS to the pressures within a given third-octave band.

The first 1/3-octave band extends from 0 to 45 Hz with a center frequency of 20 Hz

\[ 0 < f_1 < 45 \text{ Hz}, \text{ and } f_{1c} = 20 \text{ Hz} . \]  

(A1.24)

The lower frequencies of the remaining \( b^n \) bands are given by

\[ f_{bl} = 45 \times 2^{(b-2)/3} , \]  

(A1.25)

the upper frequencies of the \( b^n \) bands are given by

\[ f_{bu} = 45 \times 2^{(b-1)/3} , \]  

(A1.26)
and the center frequencies of these bands are given by

\[ f_{bc} = 45 \times 2^{(2b - 3)/6}. \]  \hspace{1cm} (A1.27)

The pressure amplitude in each band is calculated by applying an RMS sum of the pressures within each third-octave band

\[ |P_b| = \sqrt{\sum_{n = f_{b,low}}^{n = f_{b,high}} |P_n|^2}, \quad b = 1, 2, ..., \infty. \]  \hspace{1cm} (A1.28)

### A1.7 The Effective Number of the Noise Sources

The solution for the acoustic pressure developed thus far only reflects a single burning cell. Therefore, an expression for the number of such reacting cells at a given time is developed in terms of fundamental burner and fuel parameters.

Nathani shows that the number of effective noise sources at any given instant is

\[ n = \sqrt{\frac{2}{3}} \frac{U_{it}}{D}. \]  \hspace{1cm} (A1.29)

From this result, an expression for the total sound power can be obtained by multiplying the power expressions for the noise generated by a single cell by the instantaneous number of cells in the combustion zone.
A1.8 Evaluating Pressure and Power

A1.8.1 Sound Pressure

The total sound pressure amplitude generated by a single cell is obtained by taking the root-mean square of the sum of the pressure amplitudes in each band, that is,

\[ P_{st} = \sqrt{|P_1|^2 + |P_2|^2 + |P_3|^2 + \ldots + |P_b|^2 + \ldots + |P_\infty|^2}. \]  \hspace{1cm} (A1.30)

The overall sound pressure level (OASPL) is given by

\[ OASPL = 20 \log\left(\frac{P}{P_{ref}}\right), \]  \hspace{1cm} (A1.31)

where

\[ P_{ref} = 2 \times 10^{-5} \text{ N/m}^2. \]  \hspace{1cm} (A1.32)

A1.8.2 Sound Power

The sound power is shown to be the product of the pressure amplitude produced by a single cell and the instantaneous number of the combustible cells in the combustion zone:

\[ S_p = 4\pi d^2 n \left(\frac{P_{st}^2}{2\rho c}\right), \]  \hspace{1cm} (A1.33)
where $\rho$ is the density of air and $c$ is the velocity of sound. The overall sound power level (OAPWL) is expressed as

$$OAPWL = 10 \log \left( \frac{S_p}{S_{pref}} \right),$$

(A1.34)

where,

$$S_{pref} = 10^{-13} \text{ W}. \quad (A1.35)$$

### A1.9 Computer Code

All calculations cited in this section have been coded to be performed by a FORTRAN program. The program implements regression routines to determine the coefficients for the acoustic pressure expression during the transition burning process. Output options include third-octave band predictions and calculated overall sound pressure levels. The computer code is included in Appendix A2.
A2. Model FORTRAN Code
FORTRAN PROGRAM FOR
“A TURBULENT COMBUSTION NOISE MODEL”

(THESIS)

SUBMITTED TO

DEPARTMENT OF MECHANICAL ENGINEERING

VIRGINIA POLYTECHNIC INSTITUTE AND STATE UNIVERSITY

BLACKSBURG, VIRGINIA

BY

ARUN NATHANI

THE FOLLOWING PROGRAM EVALUATES CURVES FOR
DV/DT AND ACOUSTIC PRESSURE GENERATED BY A
SINGLE BURNING CELL IN THE COMBUSTION ZONE.
IT ALSO GENERATES LINE SPECTRA, 1/3 OCTAVE BAND
SPECTRA FOR THE TOTAL SOUND PRESSURE PRODUCED IN
THE COMBUSTION ZONE. IN ADDITION, THIS PROGRAM
GIVES THERMOACOUSTIC EFFICIENCY, SOUND POWER,
PEAK FREQUENCY AND OVER-ALL SOUND PRESSURE LEVEL.
FINALLY, THE PROGRAM DEVELOPS A EMPIRICAL
CORRELATION FOR THE SOUND POWER PRODUCED IN
TERMS OF FUNDAMENTAL BURNER AND FUEL PARAMETERS

INPUT BURNER PARAMETERS

U ...... CONVECTIVE VELOCITY OF FUEL INJECTION (M/S)
D ...... BURNER DIAMETER (M)

INPUT FUEL PARAMETERS

SL ...... LAMINAR FLAME SPEED (M/S)
E ...... EXPANSION RATIO (RATIO BETWEEN THE VOLUME
       OCCUPIED BY BURNT GASES TO UNBURNT GASES
QQ ...... CALORIFIC VALUE OF THE FUEL (J/M**3)
FR ...... AIR-FUEL VOLUMETRIC RATION
FLTP...... FLAME TEMPERATURE (KELVINS)

EXPERIMENTAL PARAMETERS
C DOP,DP... DISTANCE OF OBSERVATION POINT FROM SOURCE (M)
C RHO ..... DENSITY OF AIR (KG/M**3)
C CSOU..... VELOCITY OF SOUND IN AIR (M/S)
C FLIN..... PREIGNITION REACTANT TEMPERATURE

PARAMETERS EVALUATED

C DVT .... DV/DT (M**3/S), (RATE OF CHANGE OF VOLUME
C FOR A SINGLE BURNING CELL AS A FUNCTION
C OF TIME)
C D2VT .... D**2V/DT**2 (M**3/S**2), (DERIVATIVE OF
C DV/DT AS A FUNCTION OF TIME)
C PST...... ACOUSTIC PRESSURE (N/M**2) AS A FUNCTION
C OF TIME FOR A SINGLE BURNING CELL
C SPL...... SOUND PRESSURE LEVEL SPECTRUM, (NONDIMEN
C -SIONAL LINE SPECTRUM AS A FUNCTION
C OF FREQUENCY)
C OASPL ... OVER-ALL SOUND PRESSURE LEVEL, (NONDIMEN
C SIONAL)
C ETA ..... THERMOACOUSTIC EFFICIENCY
C POWW ... ACOUSTIC POWER (WATTS)

INTERMEDIATE PARAMETERS

C R1 ...... INITIAL RADIUS OF THE CELL (M)
C RS ...... CELL RADIUS AT THE BEGINNING OF
C SURFACE BURNING (M)
C NI ...... INSTANTANEOUS NUMBER OF CELLS
C A,B ..... CONSTANTS IN THE DV/DT EXPRESSION
C TTR ..... TRANSITION TIME (S)
C TS ...... SURFACE BURNING TIME (S)
C TTT ..... TOTAL BURNING TIME (S)
C AN,BN ... FREQUENCY DEPENDENT VARIABLES USED TO
C EVALUATE SPL SPECTRUM
C H ...... HEAT PRODUCTION RATE

INDEPENDENT PARAMETERS

C CF ...... CENTRAL FREQUENCIES IN 1/3 OCTAVE BAND (HZ)
C F ...... FREQUENCY (HZ)
C T ...... TIME (S)
C PR ...... REFERENCE ACOUSTIC PRESSURE (N/M**2)
C BF ...... FREQUENCIES ENVELOPING THE 1/3 OCTAVE BANDS
C PI ...... 22.7/
C NN ...... NUMBER OF HARMONICS WHERE CALCULATIONS STOP
C IA,IB,IC,ID,IE...... INTEGERS TO IDENTIFY THE USER PROMTS
REGRESSION ARRAYS INVOLVED

UUU, UU... ARRAYS FOR CONVECTIVE VELOCITY
DDD, DD... ARRAYS FOR BURNER DIAMETER
EEE, EE... ARRAYS FOR EXPANSION RATIO
SLL, SLL... ARRAYS FOR FLAME SPEED
PPP... ARRAY OF PREDICTED POWER
PRWW... ARRAY OF REGRESSION POWER
BB... SOLUTION OF REGRESSION
X, DBD, R, SCPE, XMAX, XMIN... EXTERNAL ARRAYS FOR RGIVN

THIS PART OF THE PROGRAM WILL GIVE DIMENSIONS TO ALL ARRAYS INVOLVED IN THE SOLUTION

DIMENSION DV(500), PST(500)
DIMENSION FN(900), AN(900), BN(900)
DIMENSION PF(900), PSF(900), PAF(900)
DIMENSION BF(900), CF(900), CFPK(900), PBAND(900), DB(900)
DIMENSION POWER(200), BCF(200), UN(200), UA(200)
DIMENSION POGIL(200)
DIMENSION DDD(6, 6, 6, 6), UUU(6, 6, 6, 6), SLLL(6, 6, 6, 6), EEE(6, 6, 6, 6)
DIMENSION PPP(6, 6, 6, 6), FFP(6, 6, 6, 6), POWR(6, 6, 6, 6)
DIMENSION UU(4), EE(4), SLL(4), DD(4)
DIMENSION X(81, 5), BB(5, 1), DBD(5), R(5, 5), SCPE(1, 1), XMAX(5), XMIN(5)

FOLLOWING STEP DEFINES THE EXTERNAL SUBROUTINES WHICH SUBSEQUENTLY WILL BE USED TO EVALUATE THE REGRESSION FIT FOR SOUND POWER

EXTERNAL AMACH, RGIVN, UMACH, WRRRN

FOLLOWING STEPS PROMPT THE USER TO FEED IN THE INFORMATION FOR WHICH THE PROGRAM IS DESIRED TO RUN. ACCORDING TO THE INFORMATION FED IN, THESE STEPS TAKE AN EXIT TO EXECUTE THE DESIRED ACTIONS OR FURTHER THE USER FOR MORE INFORMATION.

CONTINUE
STDE = 0.
CFFP = 0.
WRITE(6, *)
WRITE(6, *)
WRITE(6, *)
WRITE(6, *)
WRITE(6, *)
READ(5, *) JA
RHO = 1.21
FR = 9.47
DP = 1.
CSOU = 343.
QQ = 3.58*10.**7
WRITE(6,*)
IF (IA.EQ. 1) GO TO 11
WRITE(6,*)'  DO YOU WANT TO...
WRITE(6,*)'  EVALUATE POWER, THERMOACOUSTIC EFFICIENCY'
WRITE(6,*)'  PEAK FREQUENCY AND OASPL FOR A SINGLE CASE'
WRITE(6,*)
WRITE(6,*)'  ENTER: < 1 > FOR YES, < 2 > FOR NO'
READ(5,*)IB
WRITE(6,*)
WRITE(6,*)'  DO YOU WANT TO...
WRITE(6,*)'  OBTAIN LINE SPECTRUM FOR A SINGLE'
WRITE(6,*)'  BURNING CELL?'
WRITE(6,*)
WRITE(6,*)'  ENTER: < 1 > FOR YES, < 2 > FOR NO'
READ(5,*)IC
WRITE(6,*)
WRITE(6,*)'  DO YOU WANT TO...
WRITE(6,*)'  OBTAIN 1/3 OCTAVE BAND FOR A SINGLE'
WRITE(6,*)'  BURNING CELL?'
WRITE(6,*)
WRITE(6,*)'  ENTER: < 1 > FOR YES, < 2 > FOR NO'
READ(5,*)ID
WRITE(6,*)
WRITE(6,*)'  DO YOU WANT TO...
WRITE(6,*)'  OBTAIN DV/DT VS. TIME, AND PRESSURE'
WRITE(6,*)'  VS. TIME PLOTS FOR A SINGLE BURNING CELL?'
WRITE(6,*)
WRITE(6,*)'  ENTER: < 1 > FOR YES, < 2 > FOR NO'
READ(5,*)IE
WRITE(6,*)
IF (IA.EQ. 2) GO TO 12
11 CONTINUE
WRITE(6,*)'  PLEASE ENTER U(MIN),U(MAX) '
WRITE(6,*)'  (BOUNDARY VALUES OF CONVECTIVE VELOCITY (IN M/S))'
READ(5,*)UMIN,UMAX
WRITE(6,*)
UU(1) = UMIN
UU(2) = (UMIN + UMAX)/2.
UU(3) = UMAX
DO 13 K = 1,3
DO 14 L = 1,3
DO 15 M = 1,3
DO 16 N = 1,3
UUU(K,N,M,L) = UU(N)
16 CONTINUE
15 CONTINUE
14 CONTINUE
13 CONTINUE
WRITE(6,*)'  PLEASE ENTER D(MIN),D(MAX)'

Appendix A. The Mahan-Nathani Model 79
WRITE(6,*) (BOUNDARY VALUES OF BURNER DIAMETER, (IN CM))
READ(5,*)DMIN,DMAX
WRITE(6,*)
DD(1) = DMIN/100.
DD(2) = (DMIN + DMAX)/(2.*100.)
DD(3) = DMAX/100.
DO 17 K = 1,3
DO 18 L = 1,3
DO 19 N = 1,3
DO 20 M = 1,3
DDD(K,N,M,L) = DD(M)
20 CONTINUE
19 CONTINUE
18 CONTINUE
17 CONTINUE

WRITE(6,*) PLEASE ENTER SL(MIN),SL(MAX)
WRITE(6,*) (BOUNDARY VALUES OF FLAME SPEED (IN CM/S))
READ(5,*)SLMIN,SLMAX
WRITE(6,*)
SLL(1) = SLMIN/100.
SLL(2) = (SLMIN + SLMAX)/(2.*100.)
SLL(3) = SLMAX/100.
DO 21 K = 1,3
DO 22 M = 1,3
DO 23 N = 1,3
DO 24 L = 1,3
SLLL(K,N,M,L) = SLL(L)
24 CONTINUE
23 CONTINUE
22 CONTINUE
21 CONTINUE

WRITE(6,*) PLEASE ENTER E(MIN),E(MAX)
WRITE(6,*) (BOUNDARY VALUES OF EXPANSION RATIO)
READ(5,*)EMIN,EMAX
WRITE(6,*)
EE(1) = EMIN
EE(2) = (EMIN + EMAX)/2.
EE(3) = EMAX
DO 25 M = 1,3
DO 26 N = 1,3
DO 27 L = 1,3
DO 28 K = 1,3
EEE(K,N,M,L) = EE(K)
28 CONTINUE
27 CONTINUE
26 CONTINUE
25 CONTINUE

WRITE(6,*) UD E SL SP ETA OSSPL FREQP
WRITE(6,*)

MM = 1
DO 29 L = 1,3
DO 30 M = 1,3
DO 31 K = 1,3
DO 32 J = 1,3

C THIS PART OF THE PROGRAM WILL GIVE VALUES TO ALL
C THE EXPERIMENTAL PARAMETERS USED
C
U = UUU(K,L,M,J)
D = DDD(K,L,M,J)
SL = SLLL(K,L,M,J)
E = EEE(K,L,M,J)

C THIS PART OF THE PROGRAM WILL GIVE INPUT VALUES OF
C THE BURNER AND FUEL PARAMETERS

IF (IA .EQ. 1) THEN
GO TO 33
ENDIF

12 WRITE(6,*)' ENTER CONVECTIVE VELOCITY U (M/S)'
READ(5,*)U
WRITE(6,*)
WRITE(6,*)' ENTER BURNER DIAMETER D (CM)'
READ(5,*)D
D = D/100.
WRITE(6,*)
WRITE(6,*)' PLEASE ENTER INITIAL REACTANT TEMP. IN KELVINS' (ENTER < 1> FOR DEFAULT (298 K))'
WRITE(6,*)
READ(5,*)GG
WRITE(6,*)

IF (GG .EQ. 1) THEN
FLIN = 298.
ELSE
FLIN = GG
ENDIF

WRITE(6,*)' PLEASE ENTER SOUND VELOCITY IN MEDIUM'
WRITE(6,*)' (ENTER < 1> FOR DEFAULT (343 M/S))'
READ(5,*)HH
WRITE(6,*)

IF (HH .EQ. 1) THEN
CSOU = 343.
ELSE
CSOU = HH
ENDIF
WRITE(6,*)  PLEASE ENTER MEDIUM DENSITY'
WRITE(6,*)  (ENTER <1> FOR DEFAULT (1.21 KG/M**3))'
READ(5,*)RR
WRITE(6,*)

IF (RR .EQ. 1.) THEN
RHO = 1.21
ELSE
RHO = RR
ENDIF

WRITE(6,*)  PLEASE ENTER DISTANCE OF OBSERVATION POINT'
WRITE(6,*)  (ENTER <1> FOR DEFAULT (1 M))'
READ(5,*)DOP
WRITE(6,*)

IF (DOP .EQ. 1.) THEN
DP = 1.
ELSE
DP = DOP
ENDIF

WRITE(6,*)  ENTER FUEL TYPE FROM THE FOLLOWING OPTIONS...'
WRITE(6,*)  ENTER <1> FOR METHANE'
WRITE(6,*)  ENTER <2> FOR CARBON MONOXIDE'
WRITE(6,*)  ENTER <3> FOR HYDROGEN'
WRITE(6,*)  ENTER <4> FOR ACETYLENE'
WRITE(6,*)  ENTER <5> FOR OTHER THAN ABOVE'
READ(5,*)IF
IF (IF .EQ. 1) THEN
SL = .5
FR = 9.47
FLTP = 2210.
QQ = 3.58*10.**7
ENDIF

IF (IF .EQ. 2) THEN
SL = .4
FR = 2.38
FLTP = 2400.
QQ = 5.86*10.**6
ENDIF

IF (IF .EQ. 3) THEN
SL = 2.5
FR = 2.88
FLTP = 2400.
QQ = 1.08*10.**7
ENDIF
IF (IF .EQ. 4) THEN
SL = 1.4
FR = 11.9
FLTP = 2600.
QQ = 5.61*10.**7
ENDIF

IF (IF .EQ. 5) THEN
WRITE(6,*), PLEASE ENTER THE FOLLOWING INFORMATION ABOUT THE
WRITE(6,*), LAMINAR FLAME SPEED? (IN CM/S)
READ(5,*), SL
SL = SL/100.
WRITE(6,*), STOCHIOMETRIC AIR-FUEL RATIO (VOLUMETRIC)?
WRITE(6,*), FLAME TEMPERATURE? (IN KELVINS)
READ(5,*), FRT
WRITE(6,*), HEAT OF REACTION (IN J/M**3) X 10 ** -7 ?
READ(5,*), QQ
QQ = QQ*10.**7
WRITE(6,*)
ENDIF

E = FLTP/FLIN

WRITE(6,*)
WRITE(6,*), OUTPUT.....
WRITE(6,*)
33 CONTINUE

NN = 500
NNN = 50.
PI = 22./7.

C THIS PART OF THE PROGRAM EVALUATES THE INTERMEDIATE
C PARAMETERS WHICH ARE DIRECTLY RELATED TO
C BURNER AND FUEL VARIABLES

RI = SQRT(3./8.)*D
TTR = 2.*SQRT(3./8.)*D/U
H = (PI/4.)*U*D**2*QQ/FR
CN = U/(2.*SL)

C 1. IN THIS FIRST PHASE OF PROGRAMMING, THE
C RADIUS "RS" AT THE BEGINNING OF SURFACE
C BURNING IS EVALUATED.
1.1 In the first step the initial values of highest possible RS (RSH) and lowest possible RS (RSL) are given. Also a initial value of RS (RSG) is guessed.

RSH = R1
RSL = 0
RSG = R1

1.2 Loop for the calculation of "RS" begins in this step. The first step is to check the convergence of guessed value of "RS".

34 IF RSG.GT. R1 .OR. RSG.LT. 0.1*R1 THEN
WRITE(6,*') PROGRAM NOT CONVERGING. INPUT DATA
GO TO 35
ENDIF

1.3 Surface burning time and total burning time are evaluated in terms of the guessed value of radius at the beginning of surface burning.

TS = RSG/SL
TTT = TTR + TS
EPS = TTR/TTT

1.4 Constants A and B are evaluated.

A = -8.*PI*(E-1.)*TS*TTT*SL**(3/(TTR**3)
B = 4.*PI*(E-1.)*TS*SL**(3*(TS + 2.*TTT))/(TTR**2)

1.5 The difference "RSD" between the guessed value of RS and the calculated value of RS (from the guess) is evaluated. This difference is changed into percentage deviation from the guess. If the change, then mesh size taken from the loop and the current guess of "RS" is accepted as the final value of "RS".

RSD = RSG - (R1**3 - 3.*TTR**3*(A*TTR/4. + B/3.)/(4.*(E-1.)*PI))**.333
PD = RSD/RSG
IF (PD .LT. 0.) THEN
PD = -1.*PD
ENDIF
IF (PD .LE. .01) THEN
RS = RSG
GO TO 36
ENDIF

1.6 If the guessed value of "RS" is less than the calculated value, then

Appendix A. The Mahan-Nathani Model
C 1.6.1 LOWEST POSSIBLE VALUE OF “RS” IS EQUATED TO
C     THE GUESS.
C 1.6.2 A NEW GUESS IS MADE AS A MEAN OF PREVIOUS
C     GUESS AND THE HIGHEST ACCEPTABLE VALUE OF “RS”.

IF (RSD .LT. .0) THEN
  RSL = RSG
  RSG = (RSG + RSH)/2.
ENDIF

C 1.7 IF THE GUESSED VALUE OF “RS” IS GREATER THAN THE
C     CALCULATED VALUE, THEN
C 1.7.1 HIGHEST POSSIBLE VALUE OF “RS” IS EQUATED TO
C     THE GUESS,
C 1.7.2 A NEW GUESS IS MADE AS A MEAN OF PREVIOUS
C     GUESS AND THE LOWEST POSSIBLE VALUE OF “RS”.
C 1.7.3 GO BACK TO THE START OF LOOP

IF (RSD .GT. .0) THEN
  RSH = RSG
  RSG = (RSG + RSL)/2.
ENDIF

GOTO 34

36 CONTINUE

BETA = 8.*PI*TTT*(E-1.)*SL**3

C THE FOLLOWING STEPS EVALUATE DV/DT AND RATE
C OF CHANGE OF DV/DT AS A FUNCTION OF TIME
C FOR A SINGLE BURNING EDDY

IF (IA .EQ. 1) GO TO 37
IF (IE .EQ. 2) GO TO 37
GB = RHO/(4.*PI*DP)
IF (IE .EQ. 1) THEN
  WRITE(6,*) 'DV/DT AND PRESSURE VS TIME FOR A SINGLE BURNING
  WRITE(6,*)
  WRITE(6,*) 'NONDIMEN. TIME DV/DT (M**3/S) PRESS. (N/M**2)
  WRITE(6,*)
ENDIF
DO 38 I = 1, NNN
  TAU = FLOAT(I-1)/(NNN-1)
  T = TAU*TTT
  IF(TAU.LT.EPS)THEN
    DV(I) = A*T**3 + B*T**2
    PST(I) = GB*(3.*A*T**2 + 2.*B*T)
  ENDIF
  IF(TAU.GT.EPS)THEN
    DV(I) = 4.*PI*(E-1.)*(TTT-T)**2*SL**3
    PST(I) = GB*8.*PI*(E-1.)*(T-TTT)*SL**3
  ENDIF
III = 1

Appendix A. The Mahan-Nathani Model
IF (1A .EQ. 1) GO TO 39
IF (1E .EQ. 1) THEN
WRITE(6,1000) TAU,DV(I),PST(I)
WRITE(6,*)
1000 FORMAT(1X,3(F15.6,3X))
ENDIF
39 CONTINUE
38 CONTINUE
37 CONTINUE
IF (1A .EQ. 1) GO TO 40
IF (1B .EQ. 2 .AND. 1C .EQ. 2 .AND. 1D .EQ. 2 ) GO TO 35
IF (1C .EQ. 1) THEN
WRITE(6,*)
WRITE(6,*)' LINE SPECTRUM DUE TO A SINGLE BURNING EDDY'
WRITE(6,*)
WRITE(6,*)' FREQ. (KHZ) PRESS (N/M**2)'
WRITE(6,*)
ENDIF
40 CONTINUE

C 2. THIS PART OF THE PROGRAM OBTAINS LINE SPECTRUM
C PRODUCED BY A SINGLE CONTINUOUS TRAIN OF EDDIES.

C 2.1 A LOOP IS STARTED FOR THE ORDER N OF THE LINE
C SPECTRUM. ALL THE VARIABLES DEPENDENT ON "N"
C TO BE USED FOR THE EVALUATION OF CONSTANTS "AN"
C AND "BN" ARE EVALUATED.

41 CONTINUE
PSUM = 0.
DO 42 N = 1,NN
XX = N
Q = XX*PI
TH = Q*EPS
S = SIN(2.*TH)
C = COS(2.*TH)
FN(N) = N/TTT
IF (FN(N) .GT. 13000.) GO TO 43

C 2.2 "AN" AND "BN" FOR THE GIVEN VALUE OF
C N ARE EVALUATED.

AN(N) = 3.*A*TTT**2/BETA*((EPS**2/(2.*Q)-1./(4.*Q**3))*S
I + EPS/(2.*Q**2)*C)
I + 2.*B*TTT/BETA*(EPS/(2.*Q)*S-1./(4.*Q**2) + 1./(4.*Q**2)*C)
I + EPS/(2.*Q)*S
I/1.+I./(4.*Q**2)*C
I -1./I./(2.*Q)*S

BN(N) = 3.*A*TTT**2/BETA*>((EPS)**2/(2.*Q) + 1./(4.*Q**3))*C
I + EPS/(2.*Q**2)*S-1./(4.*Q**3))
I + 2.*B*TTT/BETA*(-EPS/(2.*Q)*C + 1./(4.*Q**2)*S)

Appendix A. The Mahan-Nathani Model  86
1 + EPS/(2.*Q)**C-1./((2.*Q)-1.)/(4.*Q**2)**S
1 -1./((2.*Q)**2) + 1./((2.*Q)**C)

C THIS STEP CALCULATES ACOUSTIC PRESSURE
C AMPLITUDE AT EACH OF THE FREQUENCIES
C ORDER "N" FOR A SINGLE BURNING CELL. THESE
C PRESSURE AMPLITUDES ARE THEN MULTIPLIED BY
C THE NUMBER OF COMPACT NOISE SOURCE REGIONS
C TO OBTAIN THE TOTAL ACOUSTIC PRESSURE AT EACH
C HARMONIC FREQUENCY. FINALLY THE LINE SPECTRUM FOR THE
C SOUND PRESSURE VERSUS FREQUENCY IS PLOTTED.

PF(N) = 2.*SQRT(AN(N)**2 + BN(N)**2)
PSF(N) = RHO*PF(N)*BETA/(4.*PI*DP)
YYY = 0.00
ZZZ = FN(N)/1000.
IF (IA .EQ. 1) GO TO 44
IF (IC .EQ. 1) THEN
WRITE(6,2000)ZZZ,PSF(N)
2000 FORMAT(2X,F7.3,10X,F8.6)
ENDIF
44 CONTINUE

C SUM OF THE SQUARES OF THE PRESSURE AMPLITUDES
C AT EACH FREQUENCY

PSUM = PSUM + PSF(N)**2
42 CONTINUE
43 CONTINUE
IF (IB .EQ. 2 .AND. ID .EQ. 2 .AND. IA .EQ. 2) GO TO 35

C THE FOLLOWING STEPS EVALUATE PRESSURE AMPLITUDE
C OVERALL SOUND PRESSURE LEVEL, SOUND POWER
C PRODUCED, AND THERMOACOUSTIC EFFICIENCY

PAMP = SQRT(PSUM)
PDB = 20.*LOG10(PAMP/.00002)
ASPL = 20.*LOG10(PAMP*SQRT(CN)/.00002)
PRW = 4.*PI*DP**2*PAMP*PAMP*CN/(2.*RHO*CSOU)
TAE = PRW/H
IF (IA .EQ. 1) GO TO 45
IF (IB .EQ. 1 .OR. ID .EQ. 1) GO TO 46
45 CONTINUE

C THIS SECTION CONVERTS THE ARRAYS OF PREDICTED POWER
C AND INPUT PARAMETERS INTO CORRESPONDING ARRAYS TO
C BE USED LATER AS INPUT FOR IMSL SUBROUTINE RGIVN

PPP(K,L,M,J) = PRW
X(MM,1) = LOG10(UUU(K,L,M,J))
X(MM,2) = LOG10(DDD(K,L,M,J))
X(MM,3) = LOG10(SLL(L(K,L,M,J))
X(MM,4) = LOG10(EEE(K,L,M,J))
X(MM,5) = LOG10(PPP(K,L,M,J))
MM = MM + 1
NNNN = 1
46  CONTINUE

C THIS PART OF THE PROGRAM CONVERTS THE LINE SPECTRUM
C GIVEN EARLIER INTO 1/3 OCTAVE BANDS.

C IN THIS PART BOUNDARY FREQUENCIES OF THE
C 1/3 OCTAVE BANDS ARE DEFINED

BF(1) = 16.
BF(2) = 20.
DO 47 N = 3,32
   BF(N) = 45.*2.**(.33*(N-3))
47  CONTINUE

C EVALUATION OF CENTRAL FREQUENCIES OF 1/3 OCTAVE BANDS

CF(1) = 8.
DO 48 N = 2,32
   CF(N) = SQRT(BF(N-1)*BF(N))
48  CONTINUE

CFP = 0.
PMAX = 0.

C INITIALIZATION OF PRESSURE AMPLITUDES IN EACH BAND

DO 49 N = 1,32
   PBAND(N) = 0.
49  CONTINUE

C IN THIS SECTION NET PRESSURE AMPLITUDE IN EACH
C 1/3 OCTAVE IS EVALUATED AS THE MEAN SQUARE
C ROOT OF THE PRESSURES LYING INSIDE EACH OCTAVE
C ALSO THIS AMPLITUDE IS NONDIMENSIONALIZED
C EXPRESSED IN DECIBELS

DO 50 I = 1,31
DO 51 N = 1,500
IF(FN(N).GE.BF(I) .AND. FN(N).LE.BF(I + 1)) THEN
   PBAND(I) = PBAND(I) + PSF(N)**2
ENDIF
51  CONTINUE
50  CONTINUE

IF (IA .EQ. 1) GO TO 52
IF (ID .EQ. 1) THEN

C THIS SECTION GIVES HEADINGS TO THE 1/3 OCTAVE RESULTS

Appendix A. The Mahan-Nathani Model
WRITE(6,*)
WRITE(6,*), '1/3 OCTAVE.....'
WRITE(6,*)
WRITE(6,*), 'FREQ (KHZ) PRESS (DB) PRESS (N/M**2)'
WRITE(6,*)
ENDIF
52 CONTINUE
DO 53 N = 1, 13
PBAND(N) = SQRT(PBAND(N))
IF(PBAND(N),EQ.0.) THEN
GO TO 53
ENDIF
DB(N) = 20.*LOG10(PBAND(N)/.00002)
C THIS SECTION PLOTS THE 1/3 OCTAVE BAND
C FOR 1) PRESSURE AMPLITUDES 2) PRESSURE
C AMPLITUDES IN DECIBELS VERSUS THE
C CORRESPONDING CENTRAL FREQUENCIES
CFK(N) = CF(N)/1000.
IF (IA .EQ. 1) GO TO 54
IF (ID .EQ. 1) THEN
WRITE(6,3000) CFK(N), DB(N), PBAND(N)
WRITE(6,*)
3000 FORMAT(2X,F7.4,6X,F6.2,6X,F6.4)
ENDIF
54 CONTINUE
C THIS SECTION EVALUATES THE PEAK FREQUENCY AND
C THE CORRESPONDING PRESSURE AMPLITUDE
IF(PBAND(N),GE.PMAX) THEN
PMAX = PBAND(N)
C PCF = CF(N)
C CFP = 1./TTT
CFP = CF(N)
ENDIF
53 CONTINUE
C THIS SECTION WRITES DOWN THE OVERALL SOUND PRESSURE
C LEVEL, TOTAL SOUND PRESSURE, THE ACOUSTIC
C POWER AND PEAK FREQUENCY FOR A SINGLE RUN.
IF (IA .EQ. 1) GO TO 55
IF (IB .EQ. 1) THEN
WRITE(6,*)
WRITE(6,*), 'SOUND POWER = ', PRW, 'W'
WRITE(6,*)
WRITE(6,*), 'THERMOACOUSTIC EFFICIENCY = ', TAE
WRITE(6,*)
Appendix A. The Mahan-Nathani Model
WRITE(6,*) 'OVER-ALL SOUND PRESSURE LEVEL = ',ASPL,'DB'
WRITE(6,*)
WRITE(6,*) 'PEAK FREQUENCY = ',CFP,'HZ'
ENDIF
55 CONTINUE

C THIS SECTION WRITES DOWN THE OVERALL SOUND PRESSURE
C LEVEL, TOTAL SOUND PRESSURE, THE ACOUSTIC
C POWER AND PEAK FREQUENCY FOR MULTIPLE RUNS

IF (IA .EQ. 1) THEN
  TAE = TAE*10.**8
  D = D*10.**2 + .5
  SL = SL*10.**2 + .5
  CFFP = CFP + CFFP
  NU = U
  ND = D
  NSL = SL
  NE = E
  NC = CFP
  NA = ASPL
  NT = TAE
  NP = PRW
WRITE(6,4000)NU,ND,NE,NSL,PRW,NT,NA,NC
4000 FORMAT(2X,I2,4X,I11,4X,I2,4X,I2,4X,F6.4,4X,I3,4X,I3,4X,I4)
WRITE(6,*)
ENDIF
C FFP(K,L,M,J)=CFP
C X(MM,5)=LOG10(FFF(K,L,M,J))
C MM = MM + 1
IF (IA .EQ. 2) GO TO 35
PMAX = 0.
32 CONTINUE
31 CONTINUE
30 CONTINUE
29 CONTINUE

C THIS SECTION PERFORMS THE REGRESSION FOR THE
C SOUND POWER FOR 81 RUNNING SETS AS SPECIFIED
C IN THE INPUT. SUBROUTINE RGIVN FROM IMSL
C PERFORMS THE REGRESSION

IDO = 0
NROW = 81
NCOL = 5
LDX = 81
INTCEP = 1
IIND = -4
IDEP = -1
IFREQ = 0
IWT = 0
THIS SECTION COMPARES THE PREDICTED RESULTS WITH THE LITERATURE. IT ALSO GIVES THE MEAN PEAK FREQUENCY OF THE PREDICTED REGRESSION. FINALLY IT GIVES THE ACTUAL PREDICTED RESULTS AND THE CORRESPONDING REGRESSION RESULTS FOR SOUND POWER

BB(1,1) = 10.**BB(1,1)
WRITE(6,*)
WRITE(6,*) 'CONSTANT MULTIPLIER = ', BB(1,1)
WRITE(6,*)
WRITE(6,*) 'EXPONENT OF VELOCITY = ', BB(2,1)
IU = (BB(2,1)-2.3)*100./3.
IUL = (BB(2,1)-2.67)*100./2.67
WRITE(6,*) FROM LITER. FOR FUEL-LEAN PRE MIXED FLAME = ', IU
WRITE(6,*) FROM LITER. FOR FUEL-RICH PRE MIXED FLAME = ', IUL
WRITE(6,*)
WRITE(6,*) 'EXPONENT OF BURNER DIAMETER = ', BB(3,1)
IDR = (BB(3,1)-2.00)*100./2.00
IDL = (BB(3,1)-2.81)*100./2.81
WRITE(6,*) FROM LITER. FOR FUEL-LEAN PRE MIXED FLAME = ', IDR
WRITE(6,*) FROM LITER. FOR FUEL-RICH PRE MIXED FLAME = ', IDL
WRITE(6,*)
WRITE(6,*) 'EXPONENT OF FLAME SPEED = ', BB(4,1)
ISL = (BB(4,1)-1.83)*100./1.83
WRITE(6,*) FROM LITER. FOR FUEL-LEAN PRE MIXED FLAME = ', ISL
WRITE(6,*)
WRITE(6,*) 'EXPONENT OF EXPANSION RATIO = ', BB(5,1)
WRITE(6,*)
CFFP = (CFFP)/81.
WRITE(6,*) 'MEAN PEAK FREQUENCY = ', CFFP
WRITE(6,*)
WRITE(6,*) 'CALCULATED SP REGRESSION SP'
WRITE(6,*)
DO 56 L = 1, 3
DO 57 M = 1, 3
DO 58 K = 1, 3
DO 59 J = 1, 3
U = UUU(K,L,M,J)
D = DDD(K,L,M,J)
SL = SLLL(K,L,M,J)
E = EEE(K,L,M,J)
LI = 1
POWR(K,L,M,J) = BB(1,1)*U**BB(2,1)*D**BB(3,1)*SL**BB(4,1)*E**BB(5,1)
WRITE(6,5000)PPP(K,L,M,J),POWR(K,L,M,J)
WRITE(6,*)
5000 FORMAT(2X,F10.6,6X,F10.6)
STDE = (PPP(K,L,M,J)/POWR(K,L,M,J)-1.)*2 + STDE
59 CONTINUE
58 CONTINUE
57 CONTINUE
56 CONTINUE

C THIS SECTION GIVES THE STANDARD DEVIATION IN THE
C LITERATURE, AND THAT GIVEN BY THIS MODEL

STDE = SQRT(STDE/91.)*100.
WRITE(6,*),'STANDARD DEVIATION = ',STDE,' PERCENT'
WRITE(6,*)
WRITE(6,*),'STANDARD DEVIATION IN LITERATURE = 43 PERCENT'
35 WRITE(6,*)

C THIS SECTION PROMPTS THE USER FOR A SECOND RUN

WRITE(6,*),' DO YOU WANT TO RUN AGAIN'
WRITE(6,*)
WRITE(6,*),' ENTER <1> FOR YES, <2> FOR NO'
READ(5,*)IRUN
IF(IRUN.EQ.1) GO TO 10
STOP
END
A3. Anomalies In the Model Code

The results as presented in Table 7 expose a flaw in the model code. In particular, it is seen that for methane, the overall sound pressure level decreases in all cases when the velocity is increased from 10 m/s to 20 m/s. This is in sharp disagreement with the results that would be suggested by the actual Mahan-Nathani theory. However, the expected trend in overall sound pressure level is resumed when velocity is further increased to 25 m/s. Therefore, it appears that the results determined for a velocity of 10 m/s might be erroneous.

To investigate this discrepancy, the model code was run for all integer values of velocity between 5 m/s and 25 m/s for a fixed diameter of 0.356 cm. Figure 16 shows the response of overall sound pressure level as velocity is increased. The model shows that overall sound pressure levels decrease as velocity is increased from 5 m/s to 17 m/s. This is clearly in disagreement with the purely theoretical aspect of the model. Upon increasing velocity further, overall sound pressure levels increase as would be expected from the theory. These questionable results are apparently originating in the model code and are not due to the theory itself.

Another problem found was that the model code results for the smallest two burner diameters of acetylene yielded only two data points for the third-octave-band spectra. Hence, difficulty arose in trying to infer any conclusions regarding frequency content for acetylene. An examination of the model revealed that these results are due to a limitation in the fundamental theory. For very low burning times, as found with acetylene, the model will generate few data points. This indicates that the model should then be used only for low velocity, low flame speed cases.

With the assumed flame speed and flame temperature inputs, the shapes of the spectra predicted by the model are in general agreement with the experimental data.
Figure 16. Predicted Overall Sound Pressure Level vs. Velocity: Methane, $D = 0.356$ cm
However, the model responds inconsistently to flame speed input. In particular, the model will respond to increasing flame speed with incremental increases in predicted peak frequency. Yet, at certain input levels, the model will predict an inconsistently large peak frequency change in a discrete manner. Continuing with incremental flame speed increases will then result in peak frequencies which again follow the continuous increasing peak frequency trend exhibited by the data prior to the discontinuity. This inconsistency acts in a similar manner as the inconsistency noted for overall sound pressure level response to velocity. Yet, in those results, the inconsistency was noted for overall sound pressure and not peak frequency.

It should be stressed here that these discontinuities in the code behavior did not occur often, but once discovered were sought out. In particular, for all experimental test points, only the case of methane flowing at 10 m/s showed unexpected results and it is believed that the rest of the computer code results reflect the true theoretical model results. The noted discrepancies were primarily seen in peak frequencies and not in overall sound pressure levels. The only exception was seen for overall sound pressure level response to velocity for the specific case of methane. However, the relatively low velocity of 10 m/s makes these test points unique among the rest of the data. Perhaps the low velocity does not allow the model code to converge to a solution when iterations occur.

Any further study concerning this code should examine the convergence criteria and the numerical integration process. Perhaps a different integration routine would alleviate the problems. Another possible solution might be to include a warning flag if the number of iterations to convergence is either unreasonably high or low. The model results obtained could then be questioned as to their validity. An increase in the number of integration steps may also reduce the occurrence of the problem.

Finally, an inconsistency in the code was noted in the calculation of the number of sound sources. Recall that the number of sound sources is used only in calculating
sound pressure levels. Therefore, the shape of the acoustic spectra is not affected by this calculation. To determine the extent of the error, the correct calculation was introduced into the code along with the erroneous calculation. A comparison of the results revealed that the code consistently underestimates the number of sound sources by about 9 percent which in turn results in about a 3 percent under-prediction of overall sound pressure levels compared to the theoretical calculation. It is apparent that this error is not the source of the anomalies cited previously and only results in slight discrepancies. When discontinuities in the model results were noted, the number of sound sources calculated in the code remained continuous. However, it is suggested that any further study regarding this model should correct this error.
Appendix B. Neutral Flame
Difficulty arose when trying to determine acceptable experimental fuel-oxygen mixture ratios for the combustible gases examined. In particular, the possible entrainment of surrounding air into the mixture added considerable uncertainties. Initial experiments showed that stoichiometric and fuel lean mixtures exhibited (based on premixed reactant flows) high frequency instabilities which tended to mask the true combustion noise. In view of past experimental data, it seemed apparent that the initial mixture should be fuel rich to avoid the undesirable combustion instabilities.

Insight into the reactions that occur when a premixed fuel-oxygen mixture is combusted in air was necessary to determine experimental fuel-oxygen ratios. In addition, an understanding of the underlying chemistry would reveal how to properly apply the model to the experimental results. Because of its wide use in industrial applications, the extensive literature on acetylene as used in welding processes was examined.

The concept of a "neutral flame" [30,31,32] is widely used in welding and is the condition upon which the fuel is completely oxidized by premixed oxygen and diffused air. Thus, the complete reaction occurs in two distinct combustion zones. In the primary reaction zone, the fuel reacts with oxygen to form products of CO and H₂. For acetylene, the following chemical equation results for the primary reaction zone:

\[ C₂H₂ + O₂ \rightarrow 2CO + H₂ \]

In the secondary reaction zone, the carbon monoxide and the hydrogen produced in the first reaction are oxidized by atmospheric air being entrained into the turbulent flame. For acetylene, the following chemical equation results for the secondary reaction zone:

\[ 2CO + H₂ + 1.5O₂ + 5.64N₂ \rightarrow 2CO₂ + H₂O + 5.64N₂ \]
Therefore, the complete combustion of one mole of acetylene results from one mole of oxygen provided in the mixture and one-and-a-half moles of oxygen provided by the entrainment of surrounding atmosphere.

A neutral flame is characterized by two distinctly visible flame zones at the burner exit. The primary reaction zone consists of a brilliant blue inner cone which will generally be well defined. The secondary reaction zone consists of a roughly defined orange flame surrounding the inner cone.

The neutral flame can be obtained by visually inspecting the flame as the fuel and oxidizer flows are adjusted. If initially the flame is under-oxidized, three visible flame zones will be apparent. As more oxygen is bled into the mixture, the middle reaction zone will be reduced until just two flame zones are evident. This will be the neutral flame and for acetylene a fuel-oxygen ratio of about 1:1 will result. However, if oxygen flow is further increased, the primary reaction zone, characterized by the well defined inner cone, will "neck" down and an over-oxidized flame will result. Therefore, to obtain a neutral flame by visual inspection, it is desirable to begin with an under-oxidized mixture and increase oxygen flow until only two flame zones result.

For propane and methane, the chemical reactions are more complicated although it seems apparent that a fuel-rich pre-mixture is necessary for experimental tests. The visual process to determine a neutral flame for acetylene was applied to the flames of propane and methane. The fuel-oxygen mixture was adjusted until two distinct reaction zones were achieved. Using this approach, the following fuel-oxygen mixtures were achieved and were used for experimental tests:

<table>
<thead>
<tr>
<th>Fuel</th>
<th>Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acetylene</td>
<td>1:1</td>
</tr>
<tr>
<td>Methane</td>
<td>2:3</td>
</tr>
<tr>
<td>Propane</td>
<td>1:2</td>
</tr>
</tbody>
</table>
Appendix C. Reduction Programs
Program To Convert Raw Data To Constant-Bandwidth

10 REM ** THIS PROGRAM REDUCES THE RAW VOLTAGES FROM THE
20 REM ** INTO THE CORRESPONDING FREQUENCIES AND PRESSURES **
30 CLS : CLEAR
35 INPUT "INPUT ANALYZER VOLTAGE RANGE";A
40 DRS = "C:\RDATA\"
45 REM ** OPEN THE FILE TO BE REDUCED **
50 INPUT "DATA FILE TO BE REDUCED";DTS
60 FDS = DRS + DTS
70 OPEN FDS FOR INPUT AS #1
75 REM ** NAME THE REDUCED DATA FILE **
80 INPUT "REDUCED DATA FILE";REDDS
85 CCS = "C:\DATA\"
90 FR$ = CCS + REDDS
100 OPEN FR$ FOR OUTPUT AS #2
105 INPUT "NUMBER OF DATA POINTS";PT
110 FOR P = 1 TO PT
120 INPUT #1,X,Y
125 REM ** SELECT THE DATA POINTS AT 60 HZ INTERVALS **
130 IF X < 120 THEN 200
140 IF X < Z THEN 200
150 LET Z = X + 60
152 REM ** CALCULATE THE CORRESPONDING PRESSURE **
154 REM ** BASED ON 1 V INPUT TO ANALYZER = 1.4192 PA **
156 REM ** AND DIVIDE BY 2 TO CORRECT FOR THE REFLECTION AT MIC
160 PR = Y/S*A*1.4192/2
170 PRINT #2, USING"#####.##### ";X;PR
200 NEXT P
220 END
Program To Calculate Overall Sound Pressure Level

1 REM ** PROGRAM TO CALCULATE THE OASPL **
10 CLS : CLEAR
15 REM ** INDICATE FILE TO BE REDUCED **
17 REM ** FILE NAME CODED TO EXPERIMENTAL PARAMETERS **
20 DRS = "C:\DATA\R"
30 INPUT "BURNER NUMBER";BNS
40 INPUT "FLOW LETTER";FS
50 INPUT "FUEL LETTER";FLS
60 EXS = ".DAT"
70 FDS = DRS + BNS + FS + FLS + EXS
80 OPEN FDS FOR INPUT AS #1
100 GOSUB 500
130 INPUT "NUMBER OF DATA POINTS"; PT
140 FOR P = 1 TO PT
150 INPUT #1,X,Y
155 REM ** CALCULATE OASPL IN PASCALS **
160 XP = XP + Y**2
170 NEXT P
180 OP = XP**.5
185 REM ** CONVERT TO DB **
190 COG = LOG(OP/0.0002)/LOG(10)
200 DBOP = 20*COG
201 REM ** REPORT THE RESULTS FOR EXPERIMENTAL TEST POINTS **

Appendix C. Reduction Programs
203 LPRINT
206 LPRINT
208 LPRINT
210 LPRINT "FILE: \";BN$+FS+FL$"
220 LPRINT "FUEL: \";FUELS"
230 LPRINT USING"BURNER DIAMETER = #.#### cm";BD
240 LPRINT "FLOW VELOCITY = \";F" m/s"
250 LPRINT USING "OASPL = #.#### Pa";OP
260 LPRINT USING " = #.#### dB";DBOP
270 CLOSE 1
400 END

500 REM ** SUBROUTINE TO INTERPRET FILE NAME FOR FINAL REPORT **
505 IF FL$="A" THEN 600
510 IF FL$="P" THEN 700
520 REM SET MEHTANE PARAMETERS
530 IF BNS="3" THEN BD=.356
540 IF BNS="4" THEN BD=.414
550 IF BNS="5" THEN BD=.541
560 IF FS="A" THEN F=10
570 IF FS="B" THEN F=20
580 IF FS="C" THEN F=25
585 FUELS="METHANE"
590 GOTO 1000
600 REM SET ACETYLENE PARAMETERS
610 IF BNS="1" THEN BD=.117
620 IF BNS="2" THEN BD=.165
630 IF BNS = "3" THEN BD = .356
640 IF FS = "A" THEN F = 50
650 IF FS = "B" THEN F = 75
660 IF FS = "C" THEN F = 100
670 FUEL$ = "ACETYLENE"
680 GOTO 1000
700 REM SET PROPANE PARAMETERS
710 IF BNS = "1" THEN BD = .117
720 IF BNS = "2" THEN BD = .165
730 IF BNS = "3" THEN BD = .356
740 IF FS = "A" THEN F = 20
750 IF FS = "B" THEN F = 30
760 IF FS = "C" THEN F = 40
770 FUEL$ = "PROPANE"
1000 RETURN
Program To Convert To Third-Octave-Bandwidth

10 REM ** CONVERT PRESSURE SPECTRUM INTO 1/3 OCTAVE BANDS **
20 CLS : CLEAR
30 REM ** EVALUATE BOUNDARY FREQUENCIES OF 1/3 OCTAVE **
40 BF(1) = 14.1:BF(2) = 17.8:BF(3) = 22.4:BF(4) = 28.2:BF(5) = 35.5
50 FOR I = 6 TO 30
60 BF(I) = 45*2**(.33*(I-6))
70 NEXT I
90 REM ** EVALUATE CENTRAL FREQUENCIES OF 1/3 OCTAVE **
110 FOR I = 2 TO 30
120 CE(I-1) = (BF(I-1)*BF(I))
130 NEXT I
140 DR$ = "C:\DATA\"
150 DE$ = "_.DAT"
160 INPUT "DATA FILE TO BE REDUCED";DT$ 
170 FD$ = DR$ + DT$ + DE$
180 OPEN FD$ FOR INPUT AS #1
190 REM ** READ IN DATA FILE TO BE REDUCED **
200 INPUT "NUMBER OF DATA POINTS";PT
210 FOR P = 1 TO PT
220 INPUT #1,X,Y
230 X(P) = X:Y(P) = Y
240 NEXT P
250 INPUT "REDUCED DATA FILE";REDD$
260 CCS = "C:\TDATA\"
270 FR$ = CCS + REDDS + DES
280 OPEN FR$ FOR OUTPUT AS #2
290 REM ** CALCULATE THE RMS PRESSURE FOR EACH BAND **
300 FOR I = 1 TO 30
310 FOR P = 1 TO PT
320 IF X(P) > BF(I) AND X(P) < BF(I + 1) THEN 340
330 GOTO 350
340 P$UM(I) = P$UM(I) + Y(P)**2
350 NEXT P
360 NEXT I
370 FOR N = 1 TO 30
380 PBAND(N) = (P$UM(N))**.5
390 NEXT N
400 REM ** PRINT THE CENTRAL FREQUENCY VS PRESSURE TO FILE **
410 FOR N = 1 TO 30
420 IF CF(N) > 10000 THEN 460
430 IF CF(N) < 130 THEN 460
440 IF PBAND(N) = 0 THEN PBAND(N) = (PBAND(N-1) + PBAND(N + 1))/2
450 PRINT #2, USING"######.######", CF(N); PBAND(N)
460 NEXT N
480 END
Appendix D. Constant-Bandwidth Data
Figure 17. Spectrum for Methane: \( U = 10 \) m/s, \( D = 0.356 \) cm
Figure 18. Spectrum for Methane: $U = 20$ m/s, $D = 0.356$ cm
Figure 19. Spectrum for Methane: $U = 10 \text{ m/s}, D = 0.414 \text{ cm}$
Figure 20. Spectrum for Methane: \( U = 20 \text{ m/s}, D = 0.414 \text{ cm} \).
Figure 21. Spectrum for Methane: $U = 25 \text{ m/s}, D = 0.414 \text{ cm}$
Figure 22. Spectrum for Methane: \( U = 10 \text{ m/s}, D = 0.541 \text{ cm} \)
Figure 21. Spectrum for Methane: $U = 20 \text{ m/s, } D = 0.541 \text{ cm}$
Figure 24. Spectrum for Methane: $U = 25 \text{ m/s}, D = 0.541 \text{ cm}$
Figure 25. Spectrum for Propane: \( U = 20 \text{ m/s}, D = 0.117 \text{ cm} \)
Figure 26. Spectrum for Propane: $U = 30 \text{ m/s}, D = 0.117 \text{ cm}$
Figure 27. Spectrum for Propane: $U = 40 \text{ m/s}, D = 0.117 \text{ cm}$
Figure 28. Spectrum for Propane: $U = 20 \text{ m/s}$, $D = 0.165 \text{ cm}$
Figure 29. Spectrum for Propane: $U = 30 \text{ m/s}, D = 0.165 \text{ cm}$
Figure 30. Spectrum for Propane: $U = 30$ m/s, $D = 0.165$ cm
Figure 31. Spectrum for Propane: $U = 30 \text{ m/s}, D = 0.165 \text{ cm}$
Figure 32. Spectrum for Propane: $U = 40$ m/s, $D = 0.165$ cm
Figure 33. Spectrum for Propane: $U = 20\,\text{m/s}$, $D = 0.356\,\text{cm}$
Figure 34. Spectrum for Propane: \( U = 30 \text{ m/s}, D = 0.356 \text{ cm} \)
Figure 35. Spectrum for Acetylene: $U = 50 \text{ m/s}, D = 0.117 \text{ cm}$
Figure 36. Spectrum for Acetylene: $U = 75$ m/s, $D = 0.117$ cm
Figure 37. Spectrum for Acetylene: $U = 100$ m/s, $D = 0.117$ cm
Figure 38. Spectrum for Acetylene: $U = 50 \text{ m/s, } D = 0.165 \text{ cm}$
Figure 39. Spectrum for Acetylene: $U = 75 \text{ m/s}, D = 0.165 \text{ cm}$
Figure 40. Spectrum for Acetylene: $U = 100$ m/s, $D = 0.165$ cm
Figure 41. Spectrum for Acetylene: $U = 50 \text{ m/s}, D = 0.356 \text{ cm}$
Figure 42. Spectrum for Acetylene: $U = 75$ m/s, $D = 0.356$ cm
Appendix E. Third-Octave-Band Data
Figure 43. 1/3-Octave Spectrum for Methane: $U = 10 \text{ m/s}, D = 0.356 \text{ cm}$
Figure 44. 1/3-Octave Spectrum for Methane: $U = 20 \text{ m/s}, D = 0.356 \text{ cm}$
Figure 45. 1/3-Octave Spectrum for Methane: $U = 10 \text{ m/s}, D = 0.414 \text{ cm}$
Figure 46. 1/3-Octave Spectrum for Methane: $U = 20 \text{ m/s}, D = 0.414 \text{ cm}$
Figure 47. 1/3-Octave Spectrum for Methane: $U = 25 \, \text{m/s}, D = 0.414 \, \text{cm}$
Figure 48. 1/3-Octave Spectrum for Methane: $U = 10$ m/s, $D = 0.541$ cm
Figure 49. 1/3-Octave Spectrum for Methane: $U = 20 \text{ m/s}, \ D = 0.541 \text{ cm}$
Figure 50. $1/3$-Octave Spectrum for Methane: $U = 25 \text{ m/s}, D = 0.541 \text{ cm}$
Figure 51. 1/3-Octave Spectrum for Propane: $U = 20 \text{ m/s}, D = 0.117 \text{ cm}$
Figure 52. 1/3-Octave Spectrum for Propane: \( U = 30 \text{ m/s}, \ D = 0.117 \text{ cm} \)
Figure 53. 1/3-Octave Spectrum for Propane: $U = 40 \text{ m/s}, D = 0.117 \text{ cm}$
Figure 54. 1/3-Octave Spectrum for Propane: $U = 20$ m/s, $D = 0.165$ cm
Figure 55. 1/3-Octave Spectrum for Propane: $U = 30\text{ m/s}, D = 0.165\text{ cm}$
Figure 56. 1/3-Octave Spectrum for Propane: \( U = 30 \text{ m/s}, D = 0.165 \text{ cm} \)
Figure 57. 1/3-Octave Spectrum for Propane:  $U = 30 \text{ m/s}, D = 0.165 \text{ cm}$
Figure 58. 1/3-Octave Spectrum for Propane: $U = 40$ m/s, $D = 0.165$ cm
Figure 59. 1/3-Octave Spectrum for Propane: $U = 20$ m/s, $D = 0.356$ cm
Figure 60. 1/3-Octave Spectrum for Propane: $U = 30$ m/s, $D = 0.356$ cm.
Figure 61. 1/3-Octave Spectrum for Acetylene: $U = 50 \text{ m/s}, D = 0.117 \text{ cm}$
Figure 62. 1/3-Octave Spectrum for Acetylene: $U = 75\, \text{m/s}, D = 0.117\, \text{cm}$
Figure 63. 1/3-Octave Spectrum for Acetylene: \( U = 100 \, \text{m/s}, D = 0.117 \, \text{cm} \)
Figure 64. 1/3-Octave Spectrum for Acetylene: $U = 50 \text{ m/s}, D = 0.165 \text{ cm}$
Figure 65. 1/3-Octave Spectrum for Acetylene: $U = 75$ m/s, $D = 0.165$ cm

Appendix E. Third-Octave-Band Data
Figure 66. 1/3-Octave Spectrum for Acetylene: $U = 75 \text{ m/s}, D = 0.165 \text{ cm}$
Figure 67. 1/3-Octave Spectrum for Acetylene: \( U = 75 \text{ m/s}, D = 0.165 \text{ cm} \)
Figure 68. 1/3-Octave Spectrum for Acetylene: $U = 100$ m/s, $D = 0.165$ cm
Figure 69. 1/3-Octave Spectrum for Acetylene: $U = 50 \text{ m/s}, D = 0.356 \text{ cm}$
Figure 70. 1/3-Octave Spectrum for Acetylene: \( U = 75 \text{ m/s}, D = 0.356 \text{ cm} \)
Vita

The author was born in Winter Park, Florida on August 1, 1966 and graduated from Spring Valley High School, in Columbia South Carolina, in June of 1984. In September of that year, the author enrolled in the college of Engineering at the University of Miami and subsequently earned the degree of Bachelor of Science in Mechanical Engineering in May of 1988.

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