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Title: INVESTIGATION OF THE MECHANISM IN RIJKE PULSE COMBUSTORS WITH TANGENTIAL AIR

PROJECT ADMINISTRATION DATA

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MUST HAVE PRIOR APPROVAL FOR ACQUISITION OF EQUIP COSTING MORE THAN $1000.
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MOD #M015 PROVIDES A NO-COST EXTENSION TO 3/15/93 FOR RESEARCH EFFORT AND
6/15/93 FOR THE FINAL REPORT.
GEORGIA INSTITUTE OF TECHNOLOGY
OFFICE OF CONTRACT ADMINISTRATION

NOTICE OF PROJECT CLOSEOUT

Closeout Notice Date: 08/04/94

Project No. E-16-615

Center No. R5997-0A0

Project Director: ZINN B T

School/Lab: AERO ENGR

Sponsor: US DEPT OF ENERGY/DOE ALBUQUERQUE - NM

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Contract Entity: GTRC

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Title: INVESTIGATION OF THE MECHANISM IN RIJKE PULSE COMBUSTORS WITH TANGENTIAL

Effective Completion Date: (Performance) 930315 (Reports) 930615

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NOTE: Final Patent Questionnaire sent to PDPI.
INVESTIGATION OF THE MECHANISM IN RIJKE PULSE COMBUSTORS WITH TANGENTIAL AIR AND FUEL INJECTION

Annual Report for the Period August 1, 1989 - July 31, 1990


September, 1990

Work Performed Under Contract No. DE-AS04-85AL31881

For

U.S. Department of Energy
Albuquerque Operations Office
P.O. Box 5400
Albuquerque, New Mexico 87115

By

School of Aerospace Engineering
Georgia Tech Research Corporation
Georgia Institute of Technology
Atlanta, Georgia 30332

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UNITED STATES DEPARTMENT OF ENERGY
Introduction

This report describes work performed under DOE Contract No. DE-AS04-85AL31881 during the period August 1, 1989 to July 31, 1990 which covers the first year of the contract. The objective of this investigation is to elucidate the mechanisms which control the driving of the pulsations in the liquid fuel burning, Rijke type, pulse combustor which had been developed under a preceding DOE contract\(^1\).

The Rijke type pulse combustor developed under the preceding DOE program is shown in Fig. 1. It consists of a vertical tube, with a decoupling chamber at either end and an air/fuel injection system. Approximately twenty percent of the total combustion air enters through the top decoupler. The remainder is injected with the fuel through the air/fuel injection system which is located at a distance of L/4 from the combustor entrance at the top of the tube. The air/fuel injection system generates a combustible mixture which is injected tangentially into the combustor in order to stabilize the combustion process near the injection location. It had been experimentally shown that the swirling flow generated by the tangential injection near the injection point helped to stabilize the combustion process. This configuration readily produced satisfactory pulse combustion of a variety of liquid fuels including fuel oils Nos. 5 and 6.

Pulse combustor operation is generally controlled by a feedback mechanism involving an interaction between several processes. For example, a periodic air/fuel ratio may produce periodic reaction and heat release processes. The periodic expansion which is associated with the periodic heat release may excite acoustic pressure oscillations which can lead to a periodic reactants injection rates and, consequently, a periodic air/fuel ratio, which completes the proposed feedback mechanism. Some of the candidate processes which could affect the mechanism which controls the operation of the pulse combustor shown in Fig. 1 and will be investigated under this program are: (1) periodic combustion processes inside periodically shed vortices, (2) periodic flow oscillations caused by oscillations of a recirculation vortex core which may be produced by
tangentially injected reactants, and (3) periodic modulation of the fuel and/or air injection rates.

Initial efforts under this contract were concerned with the development of a pulse combustor setup which will be suitable for the proposed investigations. The latter involve the performance of detailed diagnostics of the pulsating combustion process to elucidate the driving mechanism. Gaseous fuels have been used initially because the absence of liquid drops and combustion generated particulates in the combustion region significantly simplifies the optical diagnostics. The results obtained in these studies will then be used to guide follow up studies which will utilize liquid fuels. To satisfy the objectives of this program, the developed pulse combustor must be similar to the Rijke pulse combustor shown in Fig. 1. In addition, it requires optical access for visualization studies and capabilities for measuring radical radiation, velocities, temperatures and pressures. Although gaseous fuels have been used in the initial studies, it is believed that the developed pulse combustor possesses many of the features of the previously developed liquid fuel burning pulse combustor which is of primary interest to this program.

Efforts conducted during the first six months of this contract year focused on (1) development of a new pulse combustor setup for the proposed investigations, (2) investigation of various air/fuel injection systems to identify the one which produced best simulation of the characteristics of the previously developed liquid fuel burning Rijke pulse combustor, see fig. 1, and (3) determination of the characteristics of the gaseous fuel burning pulse combustor which will be used in the initial investigation of the driving mechanisms. Efforts conducted during the second half of this contract year included: (1) the design, fabrication and installation of a new pulse combustor which was utilized in the investigation of the driving mechanisms in the developed pulse combustor, (2) a series of check out tests to assure that the performance of the developed pulse combustor simulated the performance of the previously developed liquid fuel burning pulse combustors, (3) visualization studies which used the recently acquired intensified imaging system were conducted, and (4) measurements of time and space dependences of
radiation intensities to determine the characteristics of the investigated combustion process and heat release rates. These activities are briefly described in the following sections.

**Investigation of The Air/Fuel Injection System For Gas Burning Pulse Combustors**

During the initial part of this program, the existing, liquid fuel burning Rijke pulse combustor was modified to operate on propane. Various air/fuel injector configurations were tested in order to determine not only which configuration would produce good pulse combustion operation over a wide range of operating conditions, but also to establish which would best simulate the characteristics of the liquid fuel burning Rijke pulse combustor. The results were used to guide the design and development of the new pulse combustor setup which is described in the next section. In addition, the systematic study of different injector configurations resulted in a better understanding of the driving mechanisms in this propane burning combustor, which will be discussed later.

In the pulse combustor shown in Fig. 1, the liquid fuel is entrained by the atomizing air stream which moves through the central tube. The resulting flow mixes with two swirling air streams inside a short rectangular duct section which connects the injector to the vertical combustor. Since the combustion process in the original pulse combustor could not be observed, it was speculated that some of the liquid fuel drops evaporated and premixed with the air prior to combustion, while the remaining drops burned in diffusion flames as they were convected by the flow through the injection duct and into the combustor. Premixed type combustion most likely dominated in the injection duct while some of the combustion occurred in diffusion flames inside the combustor. The incandescent appearance of the injection duct and combustor walls near the injection system soon after the initiation of combustion support the above hypothesis regarding the extent of the combustion process. It is one of the goals of this study to confirm this hypothesis by direct observation of the combustion process.
Since gas generally burns faster than liquid fuel, it was anticipated that in order to simulate the above described burning of liquid fuel drops in the injection duct and combustor sections by a gaseous flame, a diffusion type gas flame will most likely have to be used. An appropriate injection system would have to be designed which would allow the gas to burn in a diffusion flame anchored inside the injection system and extending from there into the combustor section. It had been conjectured that such a flame could simulate some of the important attributes of the injection system of the liquid burning pulse combustor, see Fig. 1, such as combustion in shed vortices, an oscillating recirculating region, and periodic fuel and air injection rates. This section briefly describes the performance of some of the experimental setups which were investigated in the course of this study.

Initially, the performance of the pulse combustor with injection systems which produced premixed and diffusion flames were investigated. A typical setup consisted of the liquid burning pulse combustor system retrofitted with various propane and air injection systems. More than twenty different fuel and air injection system configurations which produced premixed and diffusion type flames were investigated, see Fig. 2.

In the premixed fuel injection system, see Fig. 2a, two fuel jets are injected normally into an air stream through openings in the side walls of a small mixing cavity. The resulting mixture enters a rectangular duct having width, height and length of 1.6", 3.6" and 6.0", respectively. Tests with this injection system produced the following results:

(1) For a given fuel injection rate, the amplitude of the pulsations strongly depends upon the air/fuel ratio. Large amplitude pulsations occur in two narrow regions on the rich and lean sides of stoichiometric operation, see Fig. 3. Maximum amplitudes in the vicinity of 168 dB were excited in the pulse combustor when operating with nondimensional air/fuel ratios \( \alpha \) of approximately .8 and 1.6. For some values of air/fuel ratios, the amplitudes of pulsations are extremely sensitive to the magnitude of the air/fuel ratio, with small changes in this ratio producing large changes in amplitude, see Fig. 3. Several acoustic modes are present in the combustor during pulse combustion operation, see Fig. 3. The dominating
mode depends upon the air/fuel ratio. Figure 3 shows that the pulsations were dominated by the fundamental mode of the combustor when the operation was fuel rich (i.e., \( \alpha = 0.8 \)) and by the first harmonic of the fundamental mode of the combustor under fuel lean operating conditions (i.e., \( \alpha = 1.6 \)). This behavior is most likely connected to the relationship between the characteristic combustion times at different air/fuel ratios and the period of the excited mode.

(2) Chemical analysis of the combustion products was performed with this injection system to obtain some data about pollutant formation in this pulse combustor. Typical results showing the dependence of CO$_2$, CO, O$_2$ and NO$_X$ concentration in the exhaust flow of the pulse combustor upon the nondimensional air/fuel ratio is presented in Fig. 4. The data show extremely low NO$_X$ emissions at both fuel rich and fuel lean operating conditions with a maximum in NO$_X$ emissions of nearly 60 ppm at \( \alpha \) slightly less than one. Significantly, the NOx emissions drop rapidly reaching values of just several ppm both at \( \alpha \) values of 0.6 and 1.7. It should be noted that low NO$_X$ emissions occurred at air/fuel ratios \( \alpha \) where the amplitudes of the pulsations were high (i.e., see Fig. 3), suggesting that for this specific pulse combustor design there might be a connection between the low NO$_X$ emissions and the amplitude of pulsations. Furthermore, the low NO$_X$ emissions may be, in part, related to the lower combustion zone temperatures at the \( \alpha \) regions where the low NO$_X$ emissions occurred. These low NO$_X$ emissions were obtained without using any NO$_X$ reduction methods, and they appear to be an inherent property of this pulse combustor configuration. These low NO$_X$ emissions strongly suggest that this combustor design should be further investigated.

In the diffusion flame injection system, see Fig. 2b, the fuel and air are injected into the rectangular injection duct through two concentric tubes with the fuel tube located inside the larger air tube. This injection system was expected to produce a diffusion flame anchored inside the injection duct and extending into the combustor section. Extensive tests with this injection system were conducted and produced the following results:
(1) For a given fuel injection rate, high amplitude (~165 dB) pulse combustion operation was attained over a wide range of $\alpha$; that is, $0.5<\alpha<1.7$, see Fig. 5. It should be pointed out that this range of $\alpha$ nearly covers the entire range of flammability of this fuel. This combustor configuration should, therefore, be useful for practical applications. Several acoustic modes are present in the combustor during pulse combustion operation, see Fig. 5. The amplitude of the fundamental mode of the combustor is considerably larger than that of its harmonics for the whole range of investigated air/fuel ratios. This result is consistent with the results obtained in the previous investigations of this pulse combustor using liquid fuels.

(2) Chemical analysis of the combustion products was performed with this injection system to obtain some data about pollutant formation in this pulse combustor. Typical data showing the dependence of the CO$_2$, CO, O$_2$ and NO$_x$ concentration in the exhaust flow of the pulse combustor upon the nondimensional air/fuel ratio is presented in Fig. 6. It shows that the lowest NO$_x$ emissions of 17 and 15 ppm occurred at values of $\alpha$ equal to 0.6 and 1.8, respectively, while the NO$_x$ concentration was 88 ppm at $\alpha=1.0$. A comparison of the NO$_x$ emissions produced by the premixed and diffusion types injection systems reveals that the former produced slightly lower NO$_x$ emissions, see Figs. 4 and 6. This difference is believed to be due to the higher temperatures associated with the diffusion flames.

A comparison of the performance of the pulse combustor with the premixed and diffusion flame injection systems, see Figs 2, with the results obtained during the pulse combustion of liquid fuels indicates that the pulse combustion of gas (propane) with the diffusion flame injection system better simulates the pulse combustion of liquid fuels. Specifically, in both cases combustion took place inside the injection system and combustor; both produced large amplitude pulse combustor operation over a wide range of air/fuel ratios; in both cases the amplitude of pulsations was insensitive to the air/fuel ratio; and both produced similar dependence of the exhaust flow NO$_x$ concentration upon the air/fuel ratio. Considerations of the slow evaporation and mixing which control the combustion of liquid fuels with the flames which are most likely produced by the injection
systems shown in Fig. 2 also suggest that the diffusion flame injection system should provide a better simulation of the combustion of liquid fuels.

Additional investigations aimed at obtaining a better understanding of the performance of the Rijke tube pulse combustor were conducted during the periods when various components of the new pulse combustor were being designed and/or fabricated. These efforts investigated the effects of changing the combustor length, closing the upper end of the combustor (i.e., eliminating the axial air flow and establishing a "solid wall" acoustic boundary condition at the upper end of the combustor), changing the location of the fuel injection system relative to the combustor tube, and changing the manner in which the air/fuel mixture enters the combustor. Examples of some of the investigated configurations are presented in Figs. 7-10.

Some of the results obtained in these studies are summarized below.

1. Pulse combustor operation was obtained with different fuel injection systems located at different positions on the combustor tube; that is, at distances of L/4, L/2 and 3L/4 from the combustor entrance (L is the combustor length). The performance of the combustor depended, however, upon the location of the injection system. This result is contrary to the expected behavior of Rijke type pulse combustors where pulse combustion operation can be only attained when the combustion heat release occurs at L/4. The results reported herein strongly suggest that for some operating conditions there must be a different mechanism, such as the suggested periodic combustion in shed vortices, which controls the driving of pulsations in the developed pulse combustor. This driving may indeed occur in the rectangular injection duct with the "Rijke tube" serving only as a resonating tail-pipe.

2. As expected, changing the combustor length merely affected the frequency of the excited oscillations. Good pulse combustor operation was attained with combustor tube lengths which varied between 60 and 120 inches, see Fig. 7.
3. The pulse combustor configuration with the upper tube end closed (see Fig 8) operated satisfactorily with amplitudes higher than 165 dB. This observation further supports the statement made under item 1 above that there must be another mechanism which controls the operation of the investigated pulse combustors. This mechanism is believed to be related to the manner in which the air and fuel are injected into the combustor.

4. Both radial and tangential injection of the reactants into the pulse combustor produced satisfactory pulse combustor operation. It appears, however, that tangential injection of the reactants produced a more stable operation. The latter is important in practical applications because past experience has shown that an unstable pulse combustion operation often results in a transition to steady burning

**Development of The New Pulse Combustor Setup**

This combustor setup will be used to investigate the mechanisms which drive the pulsations in the previously developed, liquid fuel burning, Rijke pulse combustor. A schematic of the developed pulse combustor is shown in Fig. 11. Initial tests will be conducted with propane which will be supplied with air through the tangential air/fuel injection system. The dimensions of this pulse combustor represent a compromise between those used in the previously developed pulse combustor (see Fig. 1) and those suggested by the results obtained in the tests conducted during last report period. In parallel efforts, a control panel, an ignition system, reactants supply systems and a safety system were developed, see Fig. 12.

**Pulse Combustor Setup.** A schematic and a photograph of the pulse combustor and its two supports are presented in Figs. 11 and 12, respectively. The developed pulse combustor is operated in a horizontal rather than the vertical orientation which was used with the original pulse combustor shown in Fig. 1. This facilitates mounting and traversing of the pulse combustor in the optical diagnostic station without affecting its performance characteristics. The pulse combustor consists of several steel pipe sections, a water cooled reactants injection and a combustion section
which is equipped with quartz windows to permit optical diagnostics, and two decoupling chambers. Each decoupler is resting on a support and translation system (Fig. 13) which can move the combustor along three, mutually perpendicular axes. Using this support arrangement, any combustor section can be moved onto the probe volume of the measurement system. The operation of the developed pulse combustor setup is controlled by the reactants supply system, ignition system, safety system and control panel shown in Fig. 14.

Since most of the planned measurements require optical access to the injection and combustion section. This section is fitted with strategically placed, flat windows, see Figs. 11 and 15. The rectangular injection duct section which supplies the reactants into the combustor tube has optical windows on two of its walls, and it is attached to the combustor tube in a manner which forces the reactants to be injected tangentially into the combustor. One of the optical windows is longer than the other to provide optical access into the combustor tube. Those windows provide capabilities for investigating the characteristics of the combustion process both inside the injection duct and the combustor tube. Two additional round windows whose diameter equals that of the combustor tube are installed at the end walls of the two decouplers to allow viewing the combustion process along the axis of the tube. These windows will be used for combustion process and flow visualizations, chemiluminescence radiation measurements, LDV velocity measurements, and possibly optical temperature and density measurements. The combustor is also equipped with 21 measurement ports along its axis. Twelve of them are evenly spaced along its entire length and the rest are evenly spaced around the combustor section which is equipped with quartz windows. Finally, the developed combustor will permit the employment of different fuel injection systems and different fuels.

This combustor is operated at average energy input rate of 400,000 BTU/HR. Since most of this energy is expected to be released in the vicinity of the injection point, this section of the combustor is cooled with six water jackets, see Fig. 16, which are connected into two groups of pipes with approximately equal flow resistance to keep the same cooling water flow rates through the two groups of water jackets. This design is expected
to provide an approximately even combustor wall temperature distribution and avoid overheating.

The combustor is ignited with an oxygen/propane ignition flame generated by an ignitor specifically designed for this system. The ignitor is installed immediately downstream of the reactants injection port. It is mounted on the side wall of the rectangular duct and it is constructed of a stainless steel cylindrical combustion chamber with a spark plug threaded into its end wall, see Fig. 6. Ignition is attained by turning the spark plug on and feeding small flow rates of oxygen and propane into the cylindrical chamber. These streams mix and they are ignited by the spark plug. The resulting flame enters the rectangular injection duct through a 1/4" diameter hole. Once this flame is established, a stream of reactants is injected into the rectangular duct where it is ignited by the oxygen/propane flame.

To avoid an unexpected explosion, a rupture disc has been installed on the upstream decoupler. This rupture disc is designed to break and vent the system once the pressure inside exceeds a certain prespecified magnitude. The safety system also employs a UV detector which monitors the UV radiation from the combustion zone and is programmed to cutoff the fuel flow to the combustor as soon as combustion there stops. This prevents the accumulation of an explosive mixture inside the combustor after an accidental flame extinguishment.

**Instrumentation.** The acoustic pressures inside the combustor are measured with Kistler model 211B5 piezoelectric pressure transducers. Each transducer has been mounted on a "semi-infinite" tube to prevent heat damage to the pressure transducer from the hot gases and flames inside the combustor, and to provide a measuring probe with a flat frequency response. In this arrangement, the pressure transducer is mounted at the end of a 2 feet long .25" diameter stainless steel tube which is attached at one end to the combustor wall and to a plastic tube which simulates a "semi-infinite" tube at its other end. The latter provides a flat frequency response because a pressure signal which enters the "semi-infinite" tube is (in theory) not reflected back. Since no reflection occurs at all frequencies, the pressure transducer is only exposed to travelling pressure waves which

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arrive from the measurement location on the combustor wall. The pressure transducers are calibrated before a test together with their "semi-infinite" probes. A high-level, low impedance output signal with the resolution on the order of one part per 20,000 of full scale range is generated by the utilized pressure transducers with a sensitivity independent of cable length or capacitance. The measured signals are amplified by a Kistler model 504E Dual Mode Amplifier, and the variable gain output of this amplifier ensures voltage levels adequate for computer based data acquisition.

Both global and local reaction rates are determined from flame radiation measurements. Measured radiation can be used to determine reaction and heat release rates because it has been established\(^2\) that a linear relationship exists between the heat release rate and a narrow spectral band or broad band flame radiation. A photomultiplier tube, Hamamatsu model R-268, is used to measure the radiation emitted from the flame because of its high frequency response and broad band spectral response. The photomultiplier views the combustor section which has quartz windows through an optical arrangement which could observes a local area of 0.7" x 0.7". The radiation measurement system is mounted on a translation mechanism which can move in two direction and permits measurements of the X- and Y- dependences of the flame radiation. By choice of appropriate filters, C-C, C-H and O-H radiation can be measured.

During this reporting period, the intensified imaging system has been used to obtain intensified, gated images for radiation measurements and flow visualization. The spatial resolution of the camera is 128 x 128 pixels with an adjustable temporal resolution down to 50 nanoseconds. In addition, up to four channels of analog data (e.g., pressure measurements) can be acquired simultaneously with the images.

A technique has been developed in which the pressure signal recorded simultaneously with the images is used as a clock. This permits recording of images at the same phase during successive cycles in order to determine the cycle to cycle repeatability of the combustion process. In addition, images obtained at different instants of many cycles can be ensemble averaged and sorted into chronologically sequential events.
describing the location of re-ignition and the flame spread. All of these
techniques have been thoroughly tested on a gas fired, Helmholtz type,
pulse combustor during the previous reporting period and some of them
have been applied during this reporting period.

Parallel to the imaging system, an additional computer data
acquisition system based upon a Hewlett Packard 1000A700 computer is
employed to obtain the acoustic pressure and radiation data. The electrical
signals provided by the transducers are amplified to a level at which the
background noise is a small fraction of the output signal. These signals are
then digitized by a computer controlled 16-channel Preston
multiplexer/converter. The signals are then analyzed by a FFT algorithm to
obtain their spectra. This signal analysis provides the pressure frequency
and amplitude, the radiation amplitude at the frequency of pulsations and
the phase difference between radiation and pressure oscillations.

Performance of the Developed Pulse Combustor

The performance of the new experimental setup has been studied
during this reporting period by using a premixed air/fuel injection system,
see Fig. 2. Typical results showing the dependence of the pulsations
amplitude upon the air/fuel ratio are presented in Fig. 17. Since all the
dimensions of all major components, including the injection system, the
injection duct and the inside diameter of the combustor, were kept
unchanged, it was expected that the performance of the developed
experimental setup would be qualitatively similar to the performance of the
combustor which was developed under the previous DOE research
program. This expectation is supported by the data presented in Figs. 3 and
17. For example, in both combustors fundamental mode oscillations
dominated the excited pulsations at low air/fuel ratios \( \alpha \) between
approximately 0.5 and 0.9. For values of \( \alpha \) higher than .9 the amplitude of
the fundamental mode decreases rapidly and the amplitude of the first
harmonic starts growing until it dominates the pressure oscillations when
\( 1.1 < \alpha < 1.3 \). Similar agreements between various parameters which describe
the performance of these combustors were also observed. These similarities
in performance characteristics suggest that the few design changes in the
newly developed combustor, involving geometrical differences due to the addition of optical windows and differences in wall temperatures due to water cooling, did not significantly affect the combustor performance. In view of the similarities in the performances of the two combustors, it is expected that the findings of the current program will be also applicable to the previously investigated pulse combustor.

**Investigation of the Driving Mechanism**

**Flow Visualization by Shadowgraphy.** The shadowgraph system shown in Fig. 18 was developed in an attempt to visualize the motion of the interfaces between hot and cold gases inside the combustion zone of the developed pulse combustor. It used a laser beam emitted from a Lexel model 65 ion laser as a light source and a conventional system of lenses. Since the conditions inside the combustion region were expected to change periodically with time, a mechanical chopper was installed a short distance downstream of the ion laser. By operating the shutter at an appropriate frequency and phase, it should permit viewing of events at different phases of the cycle. The generated images were projected on a screen and a video camera was used to record the images.

Experiments with this shadowgraph system failed to produce clear images. Further analysis of the flow conditions inside the injection duct of the combustor indicated that in the center of the injection duct the mean flow speed is around 100 m/s under normal operating conditions. The mechanical chopper's speed of rotation is around 90 revolution per second depending upon its setting. Since the small aperture on the chopper can view approximately 10 degrees, the exposure time of the chopper aperture is approximately \( \frac{10}{360} \times \frac{1}{90} = 0.000309 \) second. During this viewing period the gas molecules move about 31 mm which must be responsible for the blurred images obtained by the system. This result indicated that in order to obtain clear views of the conditions inside the combustion zone, a high speed shadowgraph system must be employed. Consequently, these studies will be repeated with a high speed movie camera during the next reporting period.
Radiation Measurements. A measurement system for measuring C-C, C-H or O-H radiation from the combustion zone was set up. To measure the spatial distribution of the radiation, the optical windows were blocked with the exception of one 0.7" x 0.7" square hole which was left open. Radiation from the combustion zone passed through this hole and through a 40 inch long, 1" x 1", square tube made of black card board material before reaching the focus lens. From there, the radiation passed through a C-C, C-H or O-H filter before reaching the photomultiplier. Precautions were taken to assure that surrounding light did not interfere with the measurements.

The characteristics of the C-H radiation measured in tests with the premixed air/fuel injection system, a propane input rate of 1.6 SCFM and nondimensional air/fuel ratio of 0.97 are presented in Fig. 19 and Tables 1 and 2. These data represent averages of results obtained in two tests which were highly repeatable. The measured data were analyzed with a FFT software to obtain the amplitudes and phases (with respect to the local pressure oscillations) of the radiation signals. Under this operating condition, the combustor pulsations were dominated by the first harmonic mode which was characterized by a frequency of 218 Hz and a pressure amplitude of 166 dB.

An examination of the data in Table 1 and Fig. 19 indicates that the amplitude of the C-H radiation along the centerline of the injection system (i.e., the Y direction in Fig. 19) increases from nearly zero along an initial distance of 2D, where D is the injection port diameter, to a maximum value at a distance of 7D downstream of the injection point. After reaching a maximum value at Y=7D, the amplitude of the radiation decreases as Y further increases. Figure 19 also shows that for each Y location the amplitude of radiation is a maximum at the centerline. On the other hand, the amplitudes of the radiation in the vicinity of the side walls of the injection duct are always low. These results clearly indicate that combustion begins at a distance of about 3D from the injection port and that the highest heat release rate occurs in a region between approximately 3D and 7D; that is, in a region located between 2.1 and 4.9 inches downstream of the injector.
Table 2 presents phase differences between the local radiation and pressure oscillations measured in the above discussed tests. Since the magnitudes of the radiation signals measured close to the injection point were in the range of the background noise, the phases of these signals (i.e., the data in the first row of Table 2) are not reliable. An examination of the phase difference data in Table 2 indicates that the phase difference between the radiation and pressure oscillations along the injection duct centerline increases monotonically from \(-56.3\) to \(+60.3\) as \(Y\) increases. These phase data together with the frequency of the oscillations can be employed to approximately determine the flame propagation speed\(^4\). Such a calculation was conducted and it showed that the average flame speed at \(Y=1.4\) inch, which is estimated to be located in the potential core of the jet, is about 44 m/s, see Fig. 20. Under this operating condition the mean flow velocity of the jet is 71 m/s. Thus, the data indicate that the flame propagation speed is approximately 62 percent of the jet velocity. Interestingly, Smith\(^5\) in a related study has concluded that burning vortices shed from a rear-facing step are convected by the flow at a speed which equals 40 to 60 percent of the local flow velocity. Examination of the phase variations along the side walls of the injection duct shows that the phase there decreases as \(Y\) increases when \(2D<Y<5D\), reaching a minimum value at \(Y=5D\), and it increases thereafter. These trends indicate that combustion first occurs near the walls at the \(Y=5D\) location and it propagates from there simultaneously upstream and downstream towards the injection port and the combustor, respectively. Considering the physics of the flow in the injection duct (see Fig. 20), it is suggested that the flame propagation in the upstream direction is controlled by the recirculating flows in the two corners of the injection duct while its propagation in the downstream direction is controlled by the local flow velocity. This description of the flame propagation suggests that a flow direction reversal occurs near \(Y=5D\). This conjecture will have to be further investigated in the future. Finally, the radiation data indicate that the flame and flow variations inside the injection duct are periodic and it is believed that they are closely related to the driving mechanism which drives the pulsations in the investigated pulse combustion.
Flow Visualization by the Intensified Imaging System.
During this reporting period, the computer based intensified imaging system has been used to obtain C-H radical radiation and broad band visible radiation data, and to visualize the reacting flow field inside the reactants injection duct. The utilized setup is shown in Figs. 21 and 22. The imaging system basically consists of a intensified CCD camera and a computer system. The CCD camera was supported by a tripod at a distance of approximately two feet from the quartz window. A Nikon 28 mm wide angle lens was used to focus the observed object onto the image plane, the CCD array plane. During the tests, the amplified acoustic pressure signal measured in the duct was sent into the computer through one of four analog signal input ports. This pressure signal was used as a clock to determine the phase of the image relative to the pressure oscillation. In most of the tests, the sampling rate of the imaging system was set at 503 frames per second and for each frame the exposure time was 50 microsecond. These tests were used to obtain distributions of the broad band visible radiation intensity when the combustor oscillated at its fundamental mode pulsating operation, distributions of C-H radiation intensity when the combustor oscillated at its fundamental mode, distributions of broad band visible radiation intensity when the combustor was operated under non-pulsating condition and distributions of broad band visible radiation intensity when the combustor oscillated at the first harmonic of the fundamental mode.

The broad band visible radiation intensity distributions were measured when the 99 Hz fundamental mode oscillation was excited in the combustor which was operated with a fuel input rate of 0.94 SCFM and nondimensional air/fuel ratio $\alpha$ of 1.35. Therefore, the system sampling rate was approximately 5 frames per cycle.

Sequences of images obtained in different cycles are presented in Figs. 23 through 27 where the last four sequences describe the conditions inside the combustor during four successive cycles. These images show the instantaneous distributions of the combustion intensity (where the highest intensity is white and lowest black) and their changes during a cycle. An examination of the images in Figs. 23-27 suggests that during a given cycle
combustion begins inside two small structures which grow in size as they are convected downstream. These structures impinge upon each other at approximately $Y = 7D$, resulting in intensification of the rate of combustion to its maximum level. The intensity of the combustion process decreases during the remainder of the cycle to the point where only very low radiation is present at the end of the cycle. This process repeats itself from one cycle to another, see Figs. 24 through 27. Schadow et al. observed similar structures in their investigations of vortex shedding in an acoustically excited free reacting jet. These structures were subsequently identified to be vortices which were shed from the jet shear layer. In view of the similarities between the images observed in this study and those reported by Schadow et al., it is conjectured that the structures observed in the current study are vortices which are periodically formed in the region where the jet shear layer starts.

The instants at which the radiation intensity distribution images were obtained during a pressure cycle are presented in the Fig. 28. Letting the instant of maximum pressure represent zero phase, the images shown in Fig. 28 show that the vortex was shed during the period when the phase changed from 0 to 180 degrees. Figure 28 also reveals that maximum heat release occurs at approximately 352 degree, or 8 degrees ahead of the pressure peak, which indicates that the heat release occurs in phase with the pressure oscillation. This, in turn, satisfies Rayleigh's criterion which states that in order to drive pulsations the heat release and pressure oscillations need to be in phase. The intensified imaging system can also provide instantaneous distributions of the radiation intensity on a three dimensional coordinate system, see Figs. 29 through 33. These clearly show the formation of two vortices early in the cycle and their subsequent coalescence and the resulting increase in the intensity of the combustion process.

More detailed information about the evolution of the vortex and the periodic combustion process in the air/fuel injection duct was obtained by using the imaging system in a stroboscopic mode. This technique was developed earlier under this program and is discussed in the "Instrumentation" section of this report. The images obtained using this
technique under the same operating conditions as those discussed above are presented in Fig. 34. It provides 25 views for one cycle. An analysis of these images supports the conclusions derived from the above discussed images; that is, maximum heat release occurs when the pressure perturbation is positive and it lasts approximately 20 percent of the cycle duration.

Measurements of the C-H radiation from the combustion process inside the air/fuel injection duct were conducted under the above discussed operating conditions using the same setting for the imaging system. A C-H filter which only allows the C-H radiation of 431.5 nm to pass was placed immediately in front of the CCD array. However, because of the presence of the filter and relatively short time exposure of 50 microsecond, the collected signal was weak and the images were not as sharp as the images obtained when the broad band visible radiation was measured. Figure 35 presents typical images obtained with this technique during two cycles of the oscillations.

An examination of Fig. 35 reveals that the C-H radiation intensity distributions are similar to the measured broad band visible radiation intensity distributions. In both cases, the radiation is periodic indicating the presence of a periodic combustion process with a very short intensive heat release period. Similar results were reported by other investigators\textsuperscript{5,7,8}.

Broad band visible radiation measurements were also conducted when the combustor was operated in a steady mode (i.e., no pulsations were present in the system). The images sampled, at 503 frames per second, under this operating condition are presented in Fig. 36. An examination of these images indicates that no coherent flow structures are present in the combustion zone and that the combustion process has the characteristics of a turbulent steady jet flame. Furthermore, similar radiation intensity distributions appear in all the images, suggesting the lack of any periodic phenomenon.

When the combustor operated at the first harmonic of its fundamental acoustic mode, its frequency of oscillations equaled 216 Hz. At
this frequency, the imaging system could only "observe" two events during a given cycle. Views obtained in this manner are shown in Fig. 37. An examination of this figure indicates that in spite of the fact that only two views at any given cycle were observed, the observed radiation intensity patterns appear to be periodic, as expected. Additional instants during the cycle could be obtained when the system is operated under stroboscopic mode. Additional visualizations need, however, to be performed to obtain more details about the process.

Conclusions

In summary, efforts conducted during the first year of this research program focused on the identification of gas burning pulse combustor configurations which best simulate the previously developed liquid fuel burning pulse combustor, the development of new combustor setup with access for optical diagnostics, the installation of the experimental setup, checkout of the performance of the developed setup, and the conduct of preliminary radiation and flow visualization studies. These efforts produced the following results:

1. A new air/fuel injection system for gaseous fuels has been developed and employed in the new pulse combustor to investigate the driving mechanisms in the liquid fuel burning pulse combustor. The new pulse combustor setup has been fabricated, installed and checked out. These tests revealed that the performance of this pulse combustor was similar to the performance of the previously developed liquid fuel burning Rijke type combustor.

2. A newly acquired intensified imaging system has been assembled, installed and used to visualize the reacting flow in the air/fuel injection duct and investigate the characteristics of the combustion process. Satisfactory images have been obtained for different combustor operating conditions.

3. Broad band visible and C-H radiation measurements and flow visualizations have shown that large coherent structures are formed
periodically inside the air/fuel injection duct during pulse combustion operation. These results strongly suggest that combustion is initiated inside shed vortices which are convected by the flow. The intensity of the combustion process increases as the vortices are convected downstream and it reaches a maximum value when the vortices coalesce. The maximum in the reaction rate occurs when the combustor pressure is near its maximum amplitude, suggesting that the heat release rate and pressure oscillations are in phase. This, in turn, indicates that the resulting combustion process satisfies Rayleigh's criterion for the driving of pulsations.

4. Additional investigations aimed at obtaining a better understanding of the performance of the Rijke type pulse combustor were conducted. Tests have shown that some of the developed air/fuel injection systems can excite pulsations even when they are attached to the combustor tube at a distance other than L/4 from the combustor entrance, as required by the principles of the Rijke tube. This finding suggests that there exist additional mechanisms which drive the pulsations. It is noteworthy that one of the air/fuel injection systems investigated under this program produced remarkably low NOx emissions (e.g., several ppm concentration at nondimensional air/fuel ratio of 1.7) which suggests that this system be further investigated.

References


Fig. 1 A Schematic of the Developed Liquid Fuel Burning Rijke Type Pulse Combustor with Tangential Fuel and Air Injection System.
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Combustor Tube

Fuel and Air Mixture

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Fig. 24 Images of Visible Radiation Intensity Distributions inside the Air/Fuel Injection Duct Obtained with the Imaging System in an Experiment Conducted with a Propane Input Rate of 0.94 SCFM and a Nondimensional Air/Fuel Ratio of 1.35. All Five Frames, from the Left to Right, Were Taken in the Same Cycle at Equal Time Intervals.
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INVESTIGATION OF THE MECHANISM IN RIJKE PULSE COMBUSTORS WITH TANGENTIAL AIR AND FUEL INJECTION

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Introduction

This report describes work performed under DOE Contract No. DE-AS04-85AL31881 during the period August 1, 1990 to July 31, 1991 which covers the second year of the contract. The objective of this investigation is to elucidate the mechanisms that control the driving of pulsations in the liquid fuel burning, Rijke type, pulse combustor developed under the DOE contract which preceded this one.

The Rijke type pulse combustor developed under the preceding DOE program is shown in Figure 1. It consists of a vertical tube with a decoupling chamber at either end and an air/fuel injection system. Approximately twenty percent of the total combustion air enters the combustor through the top decoupler. The remainder is injected with the fuel through the air/fuel injection system which is located at a distance of L/4 from the combustor entrance at the top of the tube. The air/fuel injection system generates a combustible mixture which is injected tangentially into the combustor in order to stabilize the combustion process near the injection location. This pulse combustor produced satisfactory pulse combustion of a variety of liquid fuels including fuel oil Nos. 5 and 6.

Pulse combustor operation is generally controlled by a feedback mechanism involving interactions between several processes. For example, a combustor whose air/fuel ratio varies periodically with time may produce periodic reaction and heat release processes. The periodic expansion which is associated with the periodic heat release may excite acoustic pressure oscillations which can lead to a periodic reactants injection rates and, consequently, the generation of a periodic air/fuel ratio, which completes the proposed feedback mechanism. An additional feedback process which could control the operation of the pulse combustor shown in Figure 1 is the occurrence of periodic combustion inside periodically shed vortices. The research conducted under this program is concerned, in part, with the determination of the feedback mechanism that controls the operation of developed Rijke pulse combustor.
Initial efforts under this contract have been concerned with the development of a pulse combustor setup suitable for the proposed investigations. Gaseous fuels were used initially because the absence of liquid droplets and combustion generated particulates in the combustion region was expected to significantly simplify the utilized optical diagnostics. However, to satisfy the objectives of this program, the developed pulse combustor had to be similar to the Rijke type pulse combustor shown in Figure 1. These initial efforts have led to the development of the new pulse combustor setup. The design of this new pulse combustor was based upon data obtained in a large number of experiments specifically conducted for this purpose during previous report periods and data obtained under our previous DOE program. Series of checkout and performance tests have demonstrated that the newly developed pulse combustor operated properly and it simulated the performance of the previously developed liquid fuel burning Rijke pulse combustor.

The above described efforts were followed by visualization studies that used an intensified imaging system. Radiation patterns having the appearance of large coherent vortex structures were observed immediately downstream of the air/fuel injection plane. The visualization studies were complemented by measurements of the time and space dependences of radiation intensities, which were used to determine the characteristics of the investigated combustion process and heat release rates. It was found that the heat release process was periodic and in phase with the pressure oscillation. Thus, according to Rayleigh criterion, this periodic heat release process was responsible for driving the pressure oscillations.

During the second year of this research, attention was focused on the investigation of the mechanisms which control the driving process. Specifically, the occurrence of periodic combustion in shed vortices and/or due to periodic modulation of the fuel and/or air injection rates was studied. Efforts conducted during the first half of this contract year focused on (1) combustor flow visualizations, which included shadowgraph and Schlieren measurements and flow visualizations by the intensified imaging systems, and (2) investigations of air/fuel flow rate modulations as
driving mechanism. Efforts conducted during the second half of this year included: (1) continuation of the shadowgraph and Schlieren measurements, (2) development of a seeding system for the LDV velocity measurements, and (3) development of a design criterion for similar pulse combustors.

These activities are briefly described in the following sections.

**Experimental Setups**

A schematic of the pulse combustor which was developed for this study is shown in Figure 2. The dimensions of the important components of this pulse combustor are the same as those of the previously developed pulse combustor. As shown in Figure 2, this pulse combustor was operated in a horizontal rather than the vertical orientation which was used with the original pulse combustor, see Figure 1. This facilitated mounting and traversing the combustor in the optical diagnostic station without affecting its performance characteristics. The pulse combustor consisted of several steel pipe sections, a water cooled reactants injection/combustion section which was equipped with quartz windows to permit optical diagnostics, and two decoupling chambers. Each decoupler rested on a support and translation system which can move the combustor along three, mutually perpendicular, axes. Using this support arrangement, any combustor section can be moved onto the probe volume of the measurement system. The operation of the developed pulse combustor is controlled by the reactants supply system, ignition system, safety system and control panel.

Since most of the needed measurements required optical access to the combustor section where the reactants were injected, the combustor was fitted with strategically placed, flat, windows. The rectangular injection duct which supplied the reactants into the combustor tube had optical windows on two of its walls, and it was attached to the combustor tube in a manner which forced the reactants to be injected into the combustor tangentially. Two additional round windows whose diameter equals that of the combustor tube were installed at the end walls of the two decouplers to allow viewing the combustion process along the axis of the combustor. Those windows provided capabilities for investigating the characteristics of the combustion process both inside the injection duct and the combustor
tube by flow visualizations, chemiluminescence radiation measurements, LDV velocity measurements, and optical temperature and density measurements.

This combustor was operated at an average energy input rate of 400,000 BTU/HR. Since most of the energy was expected to be released in the vicinity of the injection point, this section of the combustor was cooled with six water jackets. This design was expected to produce a uniform combustor wall temperature distribution and avoid overheating at any wall location.

The combustor was ignited with an oxygen/propane pilot flame generated by an ignitor specifically designed for this purpose. Ignition was attained by first igniting an oxygen/propane flame which entered the rectangular injection duct through a 1/4" diameter hole. This flame then ignited a stream of reactants which was subsequently injected into the rectangular duct. The oxygen/propane pilot flame was extinguished as soon as the combustor reached a steady operating condition.

To avoid possible instrument damage and mechanical failure due to an unexpected explosion, a rupture disc was installed on the upstream decoupler. This rupture disc was designed to break and vent the system once the pressure inside the combustor exceeded a prespecified magnitude. The safety system also employed a UV detector which monitored the UV radiation from the combustion zone and was programmed to cutoff the fuel flow to the combustor as soon as combustion there stopped. This prevented the formation of an explosive mixture inside the combustor after an unexpected flame extinguishment.

Kistler model 211B5 piezoelectric pressure transducers were used to measure the amplitudes and phases of the excited pressure oscillations at various locations inside the pulse combustor. These transducers have been mounted on "semi-infinite" tubes to prevent heat damage to the pressure transducer from the hot gases and flames inside the combustor, and to provide a measuring probe with a flat frequency response. The pressure transducers were calibrated before tests together with their "semi-infinite" probes. A high-level, low impedance, output signal was generated by the
utilized pressure transducers with a sensitivity independent of cable length or capacitance. The measured signals were amplified by a Kistler model 504E Dual Mode Amplifier, and the variable gain output of this amplifier ensured voltage levels adequate for the utilized computer based data acquisition system.

An intensified imaging system has been used to obtain intensified, gated, images for radiation measurements and flow visualization. Since it has previously been shown that the intensity of broad band radiation or that at a specific wavelength is directly proportional to the rate of combustion\(^4\), the radiation information obtained was used to determine the spatial distribution and time dependence of the heat release rate inside the combustor. To determine the phase of the imaged data, they were correlated with a pressure signal which was acquired simultaneously with the images. This, in turn, permitted recording of images at the same phase during successive cycles in order to determine the cycle to cycle repeatability of the combustion process. In addition, images obtained at different instances over many cycles could be ensemble averaged and sorted into chronologically sequential events.

To obtain the pressure frequency and amplitude, the radiation amplitude at the frequency of pulsations and the phase difference between radiation and pressure oscillations, a computer data acquisition system based upon a Hewlett Packard 1000/A700 computer was employed. The pressure and radiation signals were digitized by a computer controlled 16-channel Preston multiplexer/converter and then analyzed by a FFT algorithm to obtain their spectra and needed phase angles.

**Combustor Flow Visualization Studies**

**Combustor Flow Visualization by Shadowgraphy**

A classical high speed shadowgraphy system has been set up to take shadowgraph movies of the reacting flow field. It used a laser beam emitted from a Lexel model 65 ion laser as a light source and a conventional system of lenses. The generated images were recorded by a high speed HYCAM II camera on black and white Eastman 7277 4-X Reversal Film. By recording the density variations in the reacting flow
field, the high speed shadowgraph movies describe the main features of the reacting flow field and its time evolution. At the outset of these efforts, it was expected that the shadowgraph movies will reveal the presence of vortex structures in the flow field similar to those that characterized the radiation patterns measured by the imaging system. It was also expected that the high speed shadowgraph movies will provide better descriptions of the temporal variations of these vortical structures.

Unfortunately, efforts to date failed to produce satisfactory shadow images of the reacting field, due to the image distortion caused by nonuniform deformation of the quartz windows due to the large temperature gradients that were established between their internal and external surfaces. The 6" long injection duct has a rectangular cross-section of 3.50" x 1.75". It is enclosed by two 1.75" x 6" water cooled metal surfaces and two walls that include one 3.50" x 6" and one 3.5" x 11" quartz glass windows that are 1.00" thick. Visual observation and radiation measurement have indicated that the quartz windows come in contact with the flame and that the combustion process is nearly completed within the short injection duct. Under normal operating conditions the combustor is operated with energy inputs ranging at up to 400,000 Btu/Hr. At the maximum energy input rate, the combustion process inside the injection duct has a high mean combustion intensity that equals 3.0 Btu/inch$^3$ sec or 184,534 Btu/m$^3$ sec. The presence of a high combustion intensity and the direct contact between the quartz windows and the flame produced high temperature gradients across the thickness of the windows whose properties varied from one point to another. This, in turn, produced uneven thermal expansion of the quartz glass windows, which resulted in their nonuniform deformation. Consequently, the light beam produced by the shadowgraph system were refracted differently as they passed through different window locations. When this nonuniform window refraction was superimposed upon the refraction produced by the flow density gradients, the generated shadow images did not convey any useful information about the flow characteristics.

Considerations of the problem suggested several possible solution approaches. One involved cooling the quartz windows to reduce the
severity of the temperature gradients; another focused on restoring the fidelity of the images by optically "subtracting" the image distortion caused by the windows; and the last required that the shadow images be obtained immediately after combustor ignition during the period before the quartz windows were deformed by heat transfer form the reacting gases. These various solution approaches were attempted during the report period and the results are summarized below.

**Film Cooling the Windows** The first investigation focused on cooling the windows with flowing films of nitrogen. Such cooling methods have been used in rocket motors and jet engines. The application of the method in the investigated Rijke combustor required that a rapidly moving film of cool nitrogen be established between the reacting gases inside the injection duct and the quartz windows. The moving nitrogen film was expected to remove some of the heat transferred towards the windows and provide an insulating layer between the quartz windows and the reacting gases. The cooling provided by the nitrogen films was expected to reduce the heat fluxes to the windows and the nonuniformity of their deformations.

To introduce the cooling nitrogen films into the mixing duct, new mounting plate for the injector was designed and installed. This plate contained .5 mm slots that were used to inject nitrogen films along the inner surfaces of the quartz windows, see Figure 3. Room temperature nitrogen was chosen because it is inert and it was not expected to affect the reaction process. It has been estimated that the injected nitrogen velocity could be increased up to 200 m/sec by controlling the upstream nitrogen cylinder pressure.

Unfortunately, this nitrogen cooling failed to produce satisfactory results. With low nitrogen injection rates, which produced film velocities below 30 m/sec, the cooling was inadequate and no significant reduction in window deformation was observed. When the nitrogen flow rate was increased to produce film velocities of 100 m/sec, the deformation of the quartz glass was significantly reduced. However, when the film velocities increased to these magnitudes, the nitrogen flow apparently interfered with the flow and combustion processes inside the injection duct, resulting in
unstable pulsations with constantly varying amplitudes and frequencies. Consequently, this cooling technique could not be used to improve the quality of the shadow movies.

**Obtaining Shadow Images Immediately After Ignition** Since it generally takes several seconds after ignition for the quartz windows to heat up and deform, one could attempt to obtain the needed shadow images immediately after ignition during this time period before significant window deformation occurred. The length of this time period depends upon the combustor fuel flow rate and it varies from about 8 seconds at 140,000 Btu/Hr to about 3 seconds at 400,000 Btu/Hr. The biggest problem encountered with this approach is that the combustor and high speed camera must be also brought to desired steady operating conditions during the available time period after ignition. Generally, the combustor is ignited with a very small fuel flow rate and it operates in a steady mode. After ignition, the fuel and air flow rates are increased to the desired levels and stable pulse combustion operation is obtained. This procedure requires about 1 to 2 minutes. In addition, it takes about 1 to 2 seconds to bring the high speed camera to the desired speed. The desired high speed shadowgraph movies can be taken only after these two steps are completed.

In order to reduce the time required to bring the pulse combustor to test operating condition before the windows are deformed, the following procedure was followed. First, the combustor was brought to the desired operating condition following the normal operating procedure. At this point operation was stopped by cutting off the fuel and air flow using manual cut-off valves. This shut off procedure allowed all the the regulating valves to remain at the setting of the test conditions. Consequently, the openings of these valves were effectively pre-set for this operating condition. After permitting the combustor to cool off, it was re-ignited and pulse combustion operation was obtained almost instantaneously and the high speed shadow movies were then taken. This procedure assured the movie was taken within 3 seconds after ignition.

Undistorted, shadowgraph movies were obtained by this approach for a limited range of operating conditions. These movies did not reveal the presence of any large coherent structures. However, due to the
limitations of this method, useful data could be only obtained for low fuel
flow rate, which produced low amplitude pulse combustion operation.
Another draw back of this approach is that it is quite possible that the
combustor operation did not reach a steady operating condition before the
movie was shot.

**Modified Schlieren Method** In another attempt to visualize
the flow field, the classical Schlieren photography technique was
modified. The optical arrangement for the modified system is basically the
same as for the classical Schlieren system with the exception of the choice
of the "knife-edge" at the focal point before the image plane, see Figure 4.
In the modified system, the "knife-edge" is made of a black cardboard
whose shape is determined by the method described below.

To obtain the shape of the knife-edge, the combustor is operated at
the test operating conditions. After a few seconds, the focal point begins to
grow in size due to the deformation of the quartz windows (in the absence
of window deformation, the focal point will be a pin-point). The
combustor is then stopped and the focal point shape is monitored until it no
longer changes. Since there is no flame in the combustor any more, the
final focal point shape is purely due to the deformation of the quartz
windows. A piece of black card board having the same shape as the final
focal shape is then formed and used as the "knife-edge" for the modified
Schlieren system. Since the deformation of the quartz windows is different
under different operating conditions, a new "knife-edge" must be made for
each investigated combustor operating condition.

When the above described "knife-edge" is used, no light can pass
through the "knife-edge" and reach the image plane when there is no
burning inside the combustor. Thus, it is expected that only the light beam
refracted by the combustion process will pass the "knife-edge" and change
the illumination on the image plane when burning occurs inside the
combustor. The resulting variation of the illumination intensity will form
an image that will contain a description of the combustion process
characteristics.
The development of the above described optical setup has been completed. The new system uses a more powerful 6.25 watt laser as a light source instead of the previously used 5 mw laser. The applicability of the modified Schlieren technique is currently under investigation and the results will be described in next semi-annual report.

**Combustor Flow Visualization by the Intensified Imaging System**

During this reporting period, the computer based intensified imaging system was used to obtain broad band visible radiation data, and to visualize the reacting flow field inside the combustor tube. The imaging system basically consists of an intensified CCD camera and a computer system. The CCD camera was attached to a tripod at a distance of approximately one feet from the round quartz window, which views the combustor axis, see Figure 2. A Nikon 50 mm lens was used to focus the observed object onto the image plane, the CCD array plane. During the tests, the measured acoustic pressure signal was sent into the computer through one of four analog signal input ports. This pressure signal was used as a clock to determine the phase of the images relative to the pressure oscillation. In most of the tests, the exposure time of each frame was 50 microseconds. These tests were used to obtain distributions of the broad band visible radiation intensity when the combustor oscillated at its fundamental and first harmonic longitudinal acoustic modes.

Sequences of such images obtained when the imaging system was operated in a stroboscopic mode and the pulse combustor operated with 0.94 SCFM of propane and nondimensional air/fuel ratio of 1.35 are presented in Figure 5. It provides 12 frames for one pressure oscillation cycle. These images show the instantaneous distributions of the combustion intensity (where the highest intensity is white and lowest black) and their variation during the cycle. An examination of the images in Figure 5 indicates that intensive heat release occurs during approximately 20 percent of the cycle duration, and that the high reaction rate region extends only a very short distance into the combustor tube. Furthermore, very small fraction of the intensive combustion existed inside the combustor tube during the cycle, suggesting that the combustion process is nearly completed inside the reactants injection duct. The images obtained in six
completed inside the reactants injection duct. The images obtained in six successive cycles are presented in Figure 6. Seven frames, from the left to right, describe the sequence of events during one cycle. Figure 6 shows excellent repeatability of the periodic heat release process from cycle to cycle.

**Driving Mechanisms Studies**

**Existence of Traveling Waves in the Air/Fuel Feed Lines**

Acoustic pressure measurements revealed the presence of traveling pressure waves inside the air and fuel feed lines. Since the fuel and air velocities inside the feed lines were subsonic, the combustor pressure oscillation produced disturbance which propagated with the speed of sound in the upstream direction along the fuel and air feed lines. To investigate the phenomena, the measured pressures were Fourier analyzed to obtain the amplitudes, frequencies and the phases. These data are presented in Figures 7 through 10.

Figure 7 presents data obtained in a test when the combustor oscillated at its fundamental acoustic mode. It shows that the amplitudes of the traveling pressure wave decayed with distance away from the opening of the 0.75 inch inside diameter air feed line. Furthermore, the phase delay increased linearly with the distance from the air injection point. The data obtained when the combustor was operating at its first harmonic mode are shown in Figure 8. The trend is similar to that exhibited in the fundamental mode case, see Figure 7. Data obtained for fuel feed line are presented in Figures 9 and 10. It should be noted that the phase delay varies linearly with distance along the feed lines, suggesting that travelling pressure waves, propagating at a constant speed, occur inside both the air and fuel feed lines. The propagation speeds of these waves should equal the local speed of sound less the average velocity of the air or the fuel inside their respective feed lines. Calculations of the speeds of sound in air and propane and the average velocities (based upon measured volume flow rates and cross-sectional areas of the feed lines) have supported the above statement. They predict that travelling wave propagation speeds when the fundamental combustor mode is excited are 254.0 m/sec in the air line and 208.0 m/sec in the fuel line. These velocities are 254.0 m/sec in the air line
and 172.6 m/sec in the fuel line when the first harmonic mode of the combustor is excited. Corresponding measurements showed that under fundamental mode operation the propagation speeds in the air and fuel feed lines were 249.0 m/sec and 217.0 m/sec, respectively. The errors between the predicted and measured velocities in the air and fuel feed lines are 1.97% and 4.15%, respectively, during fundamental mode operation. Similar measurements during first harmonic mode operation revealed speeds of 259.0 m/sec and 164.0 m/sec in the air and fuel feed lines, respectively. These correspond to errors of 1.93% and 4.98% for the air and fuel feed lines, respectively. The excellent agreement between the predictions which were based upon the travelling wave assumption and the experimental data strongly supports the existence of travelling waves in the air and fuel feed lines.

**Air/Fuel Injection Rate Modulation and Periodic Combustion**

The pressure oscillations immediately inside the fuel and air injector orifices were practically in phase with the pressure oscillations in the combustor. The changes in the combustor pressure were transmitted upstream into the air and fuel feed lines as travelling waves. Hence, the fluctuating components of the particle velocities near the fuel and air orifices were directed into the combustor when its pressure was below average and away from the combustor when its pressure was above average. Using calculated impedance values of air and propane, the acoustic velocities in the fuel and air lines were calculated using the measured pressure oscillations. Figure 11 shows the dependence of the acoustic velocity amplitude of air and propane upon the amplitude of pressure oscillation in dB. It shows that when the amplitude of the pressure oscillation is around 170 dB, the amplitudes of the acoustic velocity oscillations are 19 m/sec and 23 m/sec in the propane and air lines, respectively.

By superposition of the acoustic velocities induced by these traveling pressure waves with the mean flow velocities the fluctuating fuel and air feed rates into the combustor were calculated. They showed that the fuel feed rate was high when the combustor pressure was below average and vice versa. Consequently, fuel and air injection rates into the combustor
vary periodically during a cycle. Since the fuel and air injection velocities are lower than their mean values during the first half of the pressure oscillation cycle and higher during the second half of the cycle, the relative amounts of fuel and air injected into the combustor during the second half of the cycle are always larger. The relative amount of fuel and air flow rates injected during the first and second halves of the cycle is determined by the ratio of the amplitude of acoustic velocities to the mean injection velocities of the air and fuel. The dependence of the relative amounts of fuel and air injected during each half cycle upon the ratio of the acoustic velocity amplitude to the mean injection velocity is shown in Figure 12. Examination of this figure shows that as the ratio of the acoustic velocity to the mean injection velocity increases, the relative amounts of air and fuel injected during the first and second half cycles of the oscillations decrease and increase, respectively. It should be noticed that when the amplitude of the acoustic velocity equals to the mean injection velocity, more than 82% of the total air or fuel is injected into the combustor in the second half of the pressure oscillation cycle.

As discussed above, the relative amounts of the fuel or air injected during each half cycle of the oscillation are determined by the ratio of the acoustic velocity amplitude to the mean injection velocity. The acoustic velocity amplitude depends upon the amplitude of the pressure oscillation, see Figure 11. However the mean injection velocities of the air and propane depend upon the air and fuel injection configurations, the propane flow rate and the nondimensional air/fuel ratio. The dependence of the mean air/fuel injection velocities of the investigated combustor upon the propane flow rate and nondimensional air/fuel ratio was calculated, see Figure 13. It shows that for the investigated operating conditions (i.e., propane flow rate from 2 to 4 SCFM, air/fuel ratio from 0.75 to 1.5), the propane injection velocity is lower than 30 m/sec while the air injection velocity varies between 100 and 340 m/sec.

Using the acoustic velocity amplitudes calculated from pressure amplitude (see Figure 11) and the mean air and propane injection velocities (see Figure 13), the dependence of the relative amounts of propane and air flow rates injected during the second half of the cycle upon the amplitude
of pressure oscillation (in dB) was calculated, see Figures 14 and 15. These figures indicate that these flow rates strongly depend upon the mean combustor air and fuel flow rates. For example, when the pressure amplitude is 170 dB, 70% to 90% of the total propane and 53% to 61% of total air flow rates during a cycle are injected during the second half of the cycle.

In summary, travelling pressure waves excited inside the air and fuel feed lines induce fluctuations of the fuel and air injection velocities, which, in turn, produce oscillatory propane and air injection rates. As a result, the majority of the fuel is always injected into the combustor in the second half of the cycle. This periodic variation of the fuel injection results in a periodic combustion and heat release processes. However, whether this periodic heat release process can drive the pressure oscillation will depend upon the phase of the heat release process relative to the pressure oscillation. According to Rayleigh's criterion, if they are in phase, the pressure oscillation will be driven. Otherwise, pulse combustion will not occur.

**Driving Due to Air and Fuel Injection Rates Modulation**

It will be shown in this section that under certain operating conditions the above discussed periodic variation of the air and fuel injection rates can result in a periodic heat release process which is in phase with the pressure oscillation, and thus, drive the pressure oscillation.

In order to understand the manner in which the fundamental and first harmonic longitudinal acoustic modes of the combustor can be excited by the combustion process it might be useful to consider the time variations of the pressure oscillations, see Figure 16. According to Rayleigh's criterion, an acoustic mode can be driven by a periodic heat addition process only if its pressure oscillation is in phase with the heat addition oscillation. Therefore, it follows from Figure 16 that if the periodic heat release is "positive" in range I, where $0<\phi<90$, then it will drive both modes. When the heat release is "positive" in range II, where $90<\phi<180$, it will drive the fundamental mode and damp its first harmonic. When the heat release is "positive" in range III, where $180<\phi<270$, the first harmonic will be driven and the fundamental will be damped. Finally, if
the heat release is "positive" in range IV, where $270<\phi<360$, both modes will be damped. Consequently, the driving or damping of these modes will depend upon the phase of the periodic heat release process.

The phase of the periodic heat release process depends upon the time delay between the instant at which the "excess" fuel is injected into the combustor and the instant at which most of its energy is released. The characteristic time that controls the combustion process can be approximately expressed in the following form:

$$\tau_{\text{combustion}} = \tau_{\text{species}} + \tau_{\text{convection}} + \tau_{\text{mixing}} + \tau_{\text{kinetics}}$$

where $\tau_{\text{species}}$ is the time required to mix the cold reactants to form a combustible mixture; $\tau_{\text{convection}}$ is the convection time of the combustible mixture from the injection point to combustion region; $\tau_{\text{mixing}}$ is the mixing time between the cold mixture and the hot combustion product left in the combustor, which is determined by the injection velocity and the flow structure; and $\tau_{\text{kinetics}}$ is the chemical delay time, which is determined by the fuel type and mixture air/fuel ratio.

For a premixed type injector, it can be estimated that $\tau_{\text{species}} = 0$.

The convection time is controlled by the injection velocity of the reactive mixture and the location where most of the burning occurs. Since the orifice of the reactive mixture injector is 0.7" in diameter, which is close to the diameter of the orifice of the air feed line, the mean mixture injection velocity is roughly the same as the mean air injection velocity. This velocity, as shown in Figure 13, is higher than 100 m/sec. Since it is several times larger than the amplitude of the acoustic velocity induced by the pressure oscillation, the variation of the reactive mixture injection velocity during a cycle is small. Therefore, the convection time does not change significantly during a cycle. As a result, it can be estimated that $\tau_{\text{convection}} = \text{constant}$.
$\tau_{\text{mixing}}$ is determined by the injection velocity and the flow structure. At present time, its variation can not be determined in a simple way.

The chemical delay time strongly depends upon the air/fuel ratio. Since the variations of the air and propane injection velocities do not match each other, the air/fuel ratio inside the reactants injection duct varies periodically with time. As a result, the chemical delay time varies periodically with time during a pressure oscillation cycle.

As mentioned previously, the phase of the maximum heat release occurs when the "excess" fuel energy is released. "Excess" fuel is always injected into the combustor during half the cycle when the acoustic pressure is negative. The time when the "excess" fuel energy is released relative to the pressure oscillation depends upon the delay time. As discussed above, for the developed premixed type injection system under normal operating conditions, the variation of the delay time is largely determined by the chemical time, which is dependent upon the air/fuel ratio. Consequently, the air/fuel ratio when the "excess" fuel is injected into the combustor will determine the phase of the maximum heat release and, thus, determine if driving will occur.

In summary, the air/fuel ratio when "excess" fuel is injected into the combustor determines the the chemical delay time of the mixture which, in turn, determines the phase of maximum heat release. Driving occurs when this maximum heat release is in phase with the maximum pressure amplitude. The excited pressure oscillation affects the air and fuel injection rates which, in turn, controls the air/fuel ratio modulation and, thus, the phase of maximum heat release, which completes the feedback loop.

Since the driving mechanism depends upon the specific operating condition, each case needs to be analyzed separately. To demonstrate this point the behavior of the pulse combustor under fuel rich and lean operating conditions are discussed below. This will be used to demonstrate that the change of the delay time due to changes in the air/fuel ratio may be
the cause of the "mode shifting" exhibited by the developed pulse combustor.

**Investigation of the Mode-Shifting Phenomenon**

The occurrence of mode shifting in the pulse combustor has been reported in previous report. It was found that when the premixed injector is used, the operating mode of the combustor shifts from the fundamental acoustic mode to its first harmonic as the nondimensional air/fuel ratio $\alpha$ is increased from fuel rich to fuel lean operation, see Figure 17.

The excitation of different mode oscillations at different values of $\alpha$, with the premixed type injector, may be explained by considering the characteristic times which control the combustion process and the characteristics of the excited combustor modes. According to Rayleigh's criterion, an unsteady heat release process will drive a given combustor mode if it has a component in phase with the mode's pressure oscillation, and if the heat is released in a region where the pressure amplitude of this mode is significant. It can be also shown qualitatively that in order to drive a given mode, the combustion time, which depends upon the convection, mixing and reaction times, must approximately equal half the period of the oscillation of the excited mode. Thus, a given combustion process will drive those modes for which the above stated conditions are satisfied. The observation that the pulse combustor operates at its fundamental and first harmonic modes at fuel rich and fuel lean conditions, respectively, strongly suggests that the characteristic combustion time decreased as the value of $\alpha$ increased.

The above described mode shifting was explained by the following conjecture, see Figure 18. In the reported tests, $\alpha$ was increased by increasing the air flow rate. This, in turn, increased the velocity of the reactants entering the injection duct. This velocity increase reduced the time required for the reactants to reach the combustion region. In addition, the high flow velocities accelerated the mixing between the fresh reactants, the combustion products and reacting pockets left over from the previous cycle. These effects were expected to decrease the characteristic combustion time. As the combustion time decreased, its magnitude became
considerably smaller than half the period of the fundamental combustor mode and it approached the magnitude of half the period of the first harmonic of the combustor. Since the above stated time condition requires that the combustion time approximately equal half the period of the oscillation, the first harmonic of the combustor was excited as the air/fuel increased because of the decrease in the combustion time produced by the increase in the air/fuel ratio.

Figures 19 and 20 present typical time dependences of the pressure oscillation, the air/fuel ratio, the convection time, and the chemical time calculated from data measured in two experiments. The convection time was defined as the time needed for the reactive mixture to reach a point 5 inches downstream from the injection port. A distance of 5 inches was chosen because the measured data showed that highest reaction rates occurred approximately at that location. The chemical times (i.e., the time required to complete the reaction process) were obtained from Zukoski who used flame blow-off data to obtain chemical times. Zukoski, using a heavy hydrocarbon fuel having a molecular weight of about 100, found that changing the air/fuel ratio can markedly change the time required to consume the combustible mixture. Since the molecular weight of propane, which was used in this study, is 44 or about half that of the fuel used in Zukoski's studies, it is possible that the chemical time dependence upon air/fuel ratio for propane/air mixtures is slightly different from those shown in Figures 19 and 20. Nevertheless, it is believed that these data can be used to assess the impact of the mixture air/fuel ratio variations upon the chemical time delay.

Typical results calculated for a fuel rich operating condition are presented in Figure 19. These calculations are based upon data measured in a test with $\alpha=0.84$ and propane flow rate of 2.8 SCFM. Under these conditions, the fundamental acoustic mode of the combustor whose frequency equals to 99 Hz and its period equals to 10 ms was excited. To simplify the calculation, it has been assumed that all the fuel injected in the second half of the cycle was injected at the instant when the acoustic pressure is minimum. Using this assumption, it follows from Figure 19 that when the "excess" fuel was injected into the combustor the air/fuel
ratio of the mixture was 0.69. Under this operating condition the convection time was about 1.1 ms and the chemical time around 1.3 ms. The sum of the two time delays is about 2.4 ms, which means the heat release of this "excess" fuel was delayed by about a quarter of the cycle. Consequently, the heat release process will be in range I. Thus this heat release process will drive the fundamental mode pressure oscillation.

The heat release process must be further delayed by $\tau_{\text{mixing}}$. Flow visualization studies indicated that the heat release occurred between 2.77 ms to 4.77 ms after the occurrence of pressure minimum. If the average of 3.77 ms is taken as the total time delay, this total time delay is 1.37 ms longer than the sum of the chemical time and the convection time calculated above. This difference may be considered as the mixing delay time.

Typical results calculated for a fuel lean operating condition are shown in Figure 20 which is based upon data measured in a test with $\alpha=1.56$ and propane flow rate of 2.8 SCFM. Under these conditions, first harmonic of the acoustic mode of the combustor with a frequency and period of 210 Hz and 4.76 ms, respectively, was excited. It follows from the curves that when the "excess" fuel was injected into the combustor in the second half of the cycle, the air/fuel ratio was around 1.1. The convection time was about 0.65 ms and the chemical time around 0.45 ms. The sum of the time delays was about 1.1 ms, which is only 45% of the time delay in the above discussed fuel rich case. Assuming that the time delay due to mixing was roughly the same as in the above discussed fuel rich case, (i.e., 1.37 ms), then the total time delay including the mixing time delay would be 2.47 ms. The heat release of the "excess" fuel delayed by 2.47 ms would occur almost exactly at the instant of the pressure peak of the first harmonic pressure oscillation. Therefore, under this operating condition, the heat release of the "excess" fuel was almost perfectly in phase with the first harmonic pressure oscillation, which according to Rayleigh's criterion should drive this mode.

The above discussed conjecture regarding the mechanism that control the mode shifting was further investigated experimentally during the report period. The key point in the conjecture is that the combustion process is
shortened and/or it starts earlier as the air/fuel ratio increases, thus becoming more in phase with the first harmonic mode oscillations. If this conjecture is true, it is expected that when the combustor is operated at its fundamental mode, the phase lead between the radiation and pressure oscillations would increase as the air/fuel ratio is increased.

Figure 21 describes the dependence of the amplitudes of the fundamental and first harmonic of the combustor pressure oscillations upon the nondimensional air/fuel ratio of the injected reactant mixture. In these tests, \( \alpha \) was varied by changing the air flow rate while keeping the fuel (i.e., propane) flow rate constant at a value of 2.4 SCFM. Figure 21 shows that the pulsations were dominated by the fundamental (i.e., 90 Hz) and first harmonic (i.e., 180 Hz) modes of oscillations which attained peaks of 166 and 165 dB at \( \alpha = 0.85 \) and \( \alpha = 1.55 \), respectively. The fundamental mode oscillations dominated the pressure spectra for \( 0.5 \leq \alpha \leq 1.1 \). The amplitude of the fundamental mode reached a minimum of approximately 131 dB at \( \alpha = 1.4 \) and it started increasing thereafter reaching a second peak of approximately 155 dB at \( \alpha = 1.7 \). The first harmonic mode exhibited a small peak of 142 dB at \( \alpha = 0.85 \) and a large peak of 165 dB at \( \alpha = 1.55 \), rapidly decreasing thereafter.

Figure 22 shows that the phase difference decreases monotonically from positive to negative values, where negative phase implies that the combustion process is leading, as the air/fuel ratio increases. Furthermore, the amplitude of pulsations becomes very small when the phase difference is smaller than -60 degrees. In summary, these results provide additional proof regarding the applicability of the conjectured explanation for the cause for mode shifting.

**LDV Velocity Measurements**

As is reported earlier in this report, combustion process radiation measurements obtained with the intensified imaging system suggested that coherent vortex structures are periodically formed in the combustion region. However, since the measured radiation data only provided qualitative information about the flow field, additional quantitative data is needed to determine the mechanism that drives the pulsations. Such
quantitative data must include an accurate description of the combustion zone flow field including its steady and fluctuating components. Preparation for obtaining such velocity data, using a Laser-Doppler Velocimeter (LDV) system, started during the report period.

A laser-Doppler velocimeter determines the velocity of a moving object (e.g., a particle) by measuring the Doppler frequency of light scattered from the object. If the object is sufficiently small, it moves with the velocity of the fluid and the fluid velocity can be determined by measuring the object's velocity. Small particles that scatter light are generally available in fluids, but must be added in gas phase measurements to achieve sufficiently high data rates. The choice of the seeding material is based upon its physical properties as it is required to ensure that the seed particles can follow the fluctuations of the flow with sufficient accuracy. In this program, titanium dioxide particles having an average size of 0.19 micro-meter will be used. Such particles are fully entrained by a highly turbulent flow with flow fluctuation frequencies up to 1000 Hz.

The arrangement developed during the report period to introduce the seed particles into the air flow is shown in Figure 23. A small amount of the tangential air is diverted from the main air line to the injector and passed through the seeding system where it mixes with the particles. The seeder flow with the suspended particles is then injected into the tangential air line where it mixes with the tangential air flow before the flow is injected into the mixing chamber. The seeder flow with the suspended particles is transported through copper tubing and previously utilized plastic tubing was replaced by metal tubing to reduce the electrostatic charge of the titanium dioxide particles, which probably also reduced the tendency of the particles to stick to the combustor section windows. Since the seeding is accomplished by recirculating a fraction of the tangential air flow, the seeding system does not introduce any additional air and no corrections for the measured air flow rate are needed.

The seeding system consists of an auger feed system, a seed hopper, a drive motor and a tachometer, see Figure 24. The titanium dioxide particles are stored in the seed hopper. Particles are continuously fed to the throat area by the motor driven auger. The seeding air passes through
the nozzle and transports the particles downstream. To keep an even seed flow, the auger speed and the seeding air flow rate have to be adjusted. In addition, periodic light mechanical shocks (5 Hz) are applied to the seed hopper by an electric solenoid to prevent particle coagulation in the hopper and, thus assist the feeding process.

An opto-electronic tachometer was installed on the feeding system in order to measure the instantaneous auger speed (RPM), see Figure 25. A slotted disk was attached to the auger shaft between a LED light source and a photodiode as shown in Figure 25. As the disk rotates, it periodically interrupts the light beam. This, in turn, provides the a pulsed output which is read by a frequency meter. The disk has 60 slots, which yields the auger speed directly in RPM. By calibrating the system under certain seeding air flow rates, the seed flow rate can be also determined by the auger speed (RPM).

A Proposed Design Procedure for the Developed Rijke Pulse Combustors

This section outlines a developed design procedure for the investigated Rijke pulse combustor that is based upon current understanding of the pulse combustor driving mechanism, which was described in the previous semi-annual report. Specifically, this design procedure is based upon a driving mechanism that consist of periodic supply rates of fuel and air that produce periodic combustion and heat release processes that drive the pulsations. These periodic fuel and air supply rates are caused by the response of the flows within the feed line to the combustor pressure oscillations.

Generally, the fuel and air feed rates in the developed combustor vary periodically with time with their maximum injection rates occurring during that part of the cycle when the combustor pressure is lower than the mean combustor pressure. As stated by Rayleigh's criterion, heat release oscillations drive pressure oscillations when they are in phase with one another. This implies that the maximum heat release must occur "near" the maximum pressure oscillations. Therefore, to drive pulsations, the "excess" fuel injected when the combustor pressure is below its mean value
must release its energy when the combustor pressure is near its maximum. Furthermore, enough air for burning this "excess" fuel at the "right" time must be available. Since the instantaneous air/fuel ratio changes with time during a cycle, it is not guaranteed that the "excess" fuel will be completely burned when needed (to drive the pulsations) if the mean combustor air/fuel ratio is near one.

The time dependence of the air/fuel ratio of the injected mixture is determined by the mean air/fuel ratio, the characteristics of the air and fuel feed systems and the combustor pressure oscillations. Most practical combustors generally operate with a sufficient amount of excess air to assure that all the fuel is burned. Furthermore, since operating with large air/fuel ratios increases the thermal losses through the exhaust stack, the mean air/fuel ratios utilized by practical combustor are generally confined to a narrow range. It follows that the only practical way to obtain the desired, instantaneous, air/fuel ratio when "excess" fuel is injected into the combustor is by "tailoring" the time dependence of the air/fuel ratio modulation. The goal is to obtain periodic air and fuel injection rates that will assure that sufficient air is available for burning the varying quantities of fuel shortly after their injection at various instants during the cycle, and especially under the conditions when "excess" fuel is injected into the combustor.

Possible periodic air/fuel injection rates were investigated during the report period using an approach similar to the one discussed in the previous semi-annual report. These revealed that three different types of air/fuel ratio modulation can be obtained, depending upon the combustor operating conditions, the air and fuel injection systems designs and the amplitude of pressure oscillations. These are described below and in Figs. 10 to 12.

(a) Figure 26 describes the first type of air/fuel ratio modulation, which will be referred to as Type (a) modulation. For this modulation, "excess" fuel is injected into the combustor when the mixture air/fuel ratio is lower than its mean value. Therefore, in order to assure that this "excess" fuel is burned, the mean combustor air/fuel ratio has to be much higher than one to assure that the air/fuel ratio of the mixture with the
"excess" fuel is not smaller than one. Consequently, the combustor will have to operate with too much excess air which is undesirable as it will result in high thermal losses.

(b) Figure 27 describes the Type (b) air/fuel ratio modulation that represents the "opposite" of the Type (a) modulation. For this modulation, "excess" fuel is injected into the combustor when the mixture air/fuel ratio is higher than its mean value. Therefore, since the mean combustor air/fuel ratio is higher than one, the air/fuel ratio of the mixture which contains the "excess" fuel will be considerably higher than one. Consequently, the excess fuel will burn at a lower temperature and, therefore, at lower reaction at heat release rates. This will reduce the magnitude of the heat release peak and, therefore, the driving provided by the heat release oscillation. Therefore, this type of modulation is also not desirable for a pulse combustor.

(c) The Type (c) air/fuel ratio modulation is shown in Figure 28. For this modulation, the air and fuel injection rates vary periodically with time but the air/fuel ratio remains constant throughout the pressure oscillation cycle. This type of air/fuel ratio modulation is desirable because by choosing an appropriate mean air/fuel ratio one is assured that sufficient air is available for burning the varying quantities of fuel that are injected at various instances during the cycle.

According to Rayleigh's criterion, pulsations can be driven by a periodic combustion process, if the latter produces an oscillatory heat addition process that is in phase with the pressure oscillation. This means that the "excess" fuel injected when the combustor pressure is below its mean value must release its energy when the combustor pressure is near its maximum. Consequently, it is desired that the time delay between the injection and reaction of the "excess" fuel approximately equal half the oscillation period.

The above discussion indicates that in order to design a pulse combustor similar to the Rijke pulse combustor that was developed under this program it is necessary to assure that (1) the fuel and air injection rates produce a Type (c) air/fuel ratio modulation, and (2) the time delay for the
combustion process of the "excess" fuel approximately equals half the oscillation period.

For the premixed type air/fuel injection that was developed under this program, a Type (c) air/fuel modulation can be obtained by proper selection of the sizes of the air and fuel injectors. On the other hand, the attainment of the needed time delay can be assured by proper choice of the combustor length that controls the frequency and, thus, the period of the oscillation. The manner in which these goals can be met is discussed in the remainder of this section.

(I) **Determination of the air and fuel injectors sizes**

**Needed Combustor Design Data:**

- Fuel type
- Mean air/fuel ratio
- Combustor capacity in Btu/Hr
- Amplitude of pressure oscillations
- Mean air injection velocity

**Proposed Design Procedure:**

Step 1. Determine the stoichiometric air/fuel ratio for the given fuel.

Step 2. Calculate the mean fuel flow rate assuming 100 percent combustion efficiency.

Step 3. Calculate the acoustic velocity amplitudes in the air and fuel injection systems using the physical properties of the fuel and assuming that the pressure amplitudes inside the air and fuel injection systems equal the design combustor pressure amplitude in dB (this assumption has been verified by measurements).

Step 4. Determine the size of the air injector from the specified design mean air injection velocity
Step 5. Determine the size of the fuel injector that will produce a Type (c) air/fuel modulation using the following procedure:

Letting $B$, $\omega_a$ and $\omega_f$ be the stoichiometric air/fuel ratio and the air and fuel flow rates, respectively, then the instantaneous nondimensional air/fuel ratio of the mixture is given by:

$$\alpha(t) = \left(\frac{\omega_a}{\omega_f}\right) / B = \left(\frac{(V_a+V'_a)}{(V_f+V'_f)} \frac{A_a}{A_f}\right) / B$$  \hspace{1cm} (1)

where $A_a$, $A_f$, $V_a$, $V_f$, $V'_a$ and $V'_f$ are the cross sectional areas of the air and fuel injectors, the mean air and fuel injection velocities and the acoustic velocities in the air and fuel lines, respectively. These variables, with the exception of $A_f$, are known from the calculations performed under Steps 1-4 above. The unknown $A_f$ can be determined from Eq. (1) if its left hand side is specified. Since the Type (c) air/fuel modulation requires that the nondimensional air/fuel ratio equal a prespecified constant value at all times, Eq. (1) can be rewritten in the following form:

$$\left(\frac{V_a+V'_a}{V_f+V'_f}\right) \frac{A_a}{A_f} = C B$$  \hspace{1cm} (2)

where $C$ is the specified value of $\alpha$. Solving Eq. (2) for $A_f$, one obtains:

$$A_f = \left(\frac{(V_a+V'_a) A_a}{(CB)} - \frac{\omega_f}{\rho_f}\right) / V'_f$$  \hspace{1cm} (3)

where $\rho_f$ is the fuel density.

The above solution for $A_f$ is a function of time because $V'_a$ and $V'_f$ vary periodically with time. Therefore, the mean value of $A_f$ will be chosen as the cross sectional area of the fuel injector, as it is expected that the chosen area will produce air/fuel ratio modulation that will be close to the desired Type (c) modulation.
(II) **Determination of the combustor length**

In this section the determination of the combustor length that produces a combustor design that satisfies the condition that the combustion time delay approximately equal one half of the period of the oscillations is discussed. The combustion time delay is approximately given by:

$$\tau_{\text{combustion}} = \tau_{\text{species}} + \tau_{\text{convection}} + \tau_{\text{mixing}} + \tau_{\text{kinetics}} \quad (4)$$

where $\tau_{\text{species}}$, $\tau_{\text{convection}}$, $\tau_{\text{mixing}}$ and $\tau_{\text{kinetics}}$ are the fuel and air mixing time, the time required to "convect" the mixture from the injection location to the reaction zone, the mixing time between the reactive mixture, flamelets and/or combustion products and the chemical reaction time, respectively. The species mixing time, $\tau_{\text{species}}$, depends upon the fuel and air injection system design and it may be assumed to equal zero for a premixed type air/fuel injection system. The convection time, $\tau_{\text{convection}}$, depends upon the injection velocity of the mixture and it approximately equals the ratio of the distance from the injection plane to the combustion zone and the injection velocity. The mixing time, $\tau_{\text{mixing}}$, depends upon the mixture injection velocity and the characteristics of the flow in the combustion zone. Finally, the chemical reaction time, $\tau_{\text{kinetics}}$, depends upon the fuel type and nondimensional air/fuel ratio of the mixture and it can be estimated from kinetics calculations or determined experimentally.

Considerations of the characteristics of the various processes that affect the combustion time, $\tau_{\text{combustion}}$, suggest that it is strongly dependent upon the fuel type, the mixture injection velocity and the nondimensional air/fuel ratio, which are input combustor design parameters. Therefore, the initial design specifications essentially fix the the magnitude of the combustion delay time. This, in turn, requires that the length of the combustor be chosen to produce pulsations frequency that will satisfy the time condition that the combustion time approximately equal half the period of the oscillations.
Letting $T$ and $L$ be the period of the pressure oscillation and the combustor length, the frequency of the fundamental acoustic mode of the Rijke combustor is approximately given by:

$$f = \frac{1}{T} = 0.5 \frac{a}{L}$$  \hspace{1cm} (5)$$

where $a$ is the speed of sound. Using Eq. (5) and the above stated time condition (i.e., $\tau_{\text{combustion}} = T/2$) for the attainment of pulse combustion operation, it follows that the combustor length that will satisfy this condition is given by

$$L = a \tau_{\text{combustion}}$$  \hspace{1cm} (6)$$

This combustor tube length will assure that the maximum heat release rate occurs in the positive half cycle of the pressure oscillation, which satisfies Rayleigh's criterion for the driving of pulsations by a heat addition process.

In summary, this section provides an initial design procedure that could be used to guide the design of a Rijke pulse combustor that utilizes a premixed air/fuel injection system. This procedure requires that the fuel, air/fuel ratio, the air/fuel ratio modulation and the air injection system diameter be specified. Using this design data, the characteristics of the combustion time needs to be obtained from an external source such as kinetic calculations and/or experimental data. Once the combustion time is determined, the size of the fuel injection line and the combustor length that will produce pulse combustion operation are determined by following Steps 1 to 5 and using Eqs. (3) and (6).

**A Pulse Combustor Model**

Work has been initiated on the development of a model capable of describing the operation of the developed Rijke pulse combustor. This model assumes that the combustion process can be described by a distributed mass addition process, see Figure 29. This simplification is based upon the fact that the combustion process is almost completed in the injection duct and that the driving of pulsations in the combustor tube is
controlled by the periodic mass (i.e., combustion products) addition to the combustor tube by the periodic combustion process at the L/4 location. Work on this model will continue during the next report period and the results will be presented in the next semi-annual report.

**Summary and Conclusions**

In summary, efforts conducted during the previous six months of this research program focused on the investigation of the driving mechanisms of the developed pulse combustor. These efforts produced the following results:

1. Flow visualization studies have shown that the combustion process is periodic under pulsating operating conditions. Large coherent structures or vortices are formed periodically inside the reactants injection duct and are convected downstream. The intensity of the combustion process reaches a maximum value when the vortices coalesce, resulting a heat release process which drives the pulsations. This intensive heat release lasts a very short period of time, occupying approximately 20 percents of the cycle. During the remainder of the cycle, the heat release rate remains low. In addition, the vortices coalesce before they enter the combustor tube. As a result, the majority of the combustion process occurs within the reactants injection duct.

2. Acoustic pressure measurements along the fuel and air feed lines revealed that the combustor pressure oscillation excites travelling waves inside the fuel and air feed lines. These travelling waves, in turn, produce periodic air and fuel injection rates into the combustor. The periodic modulation of the reactants flow rates results in periodic variation of the air/fuel ratio. The latter produces a periodic heat release process which drives the pressure oscillations.

3. It is shown that the previously observed "mode shifting" is caused by the changes in the delay time between the instants of reactants injection and heat release, respectively. These changes in the delay
time have been related to changes in the chemical time which are associated with the changes in the air/fuel ratio.

4. A seeding system for the LDV measurements has been developed. Preliminary tests have shown that the developed seeding system met the requirements of the LDV measurements.

5. A design procedure for similar pulse combustors, which is based upon the air and fuel flow rate modulation driving mechanism, has been proposed.

References


Fig. 1  A Schematic of the Developed Liquid Fuel Burning Rijke Type Pulse Combustor with Tangential Air and Fuel Injection System.
Fig. 2 A Schematic of the Developed Experimental Setup which Utilizes a Tangential Air/Fuel Injection System Equipped with Quartz Windows.
Figure 3. A schematic of the developed air and fuel injector with Nitrogen film injection arrangement.
Figure 4. A schematic of the modified Schlieren system.
Fig. 5  
Images of Visible Radiation Intensity Distributions inside the Combustor tube Obtained with the Imaging System Operated on the Stroboscopic Mode in an Experiment Conducted with a Propane Input Rate of 0.94 SCFM and Nondimensional Air/Fuel Ratio of 1.35. Note that It provides 12 Frames for One Cycle.
Fig. 6 Images of Visible Radiation Intensity Distributions inside the Combustor tube Obtained with the Imaging System in an Experiment Conducted with a Propane Input Rate of 0.94 SCFM and a Nondimensional Air/Fuel Ratio of 1.35. All Seven Frames, from the Left to Right, Were Taken in the Same Cycle at Equal Time Intervals, and It Shows Six Successive Cycles.
Fig. 7 Dependence of the Amplitude of Acoustic Pressure (in dB) and the Phase Delay upon the Locations along the Air Feed Line Measured in Tests when the Combustor Was Operating on Fundamental Mode of 104 Hz.

Fig. 8 Dependence of the Amplitude of Acoustic Pressure (in dB) and the Phase Delay upon the Locations along the Air Feed Line Measured in Tests when the Combustor Was Operating on First Harmonic Mode of 230 Hz.
Dependence of the Phase Delay upon the Locations along the Fuel Feed Line Measured in Tests when the Combustor Was Operating on Fundamental and First Harmonic Modes, respectively.

Dependence of the Amplitude of Acoustic Pressure (in dB) upon the Locations along the Fuel Feed Line Measured in Tests when the Combustor Was Operating on First Harmonic Mode of 230 Hz.
Fig. 11 Dependence of the Amplitude of the Acoustic Velocity upon the Amplitude of Acoustic Pressure Oscillation Calculated for Air and Propane.
Fig. 12 Dependence of the Relative Percentages of Fuel or Air Inputs in the First and Second Half Pressure Cycles upon the Ratio of Acoustic Velocity Amplitude to the Mean Injection Velocity.
Dependence of the Mean Injection Velocities of Propane and Air upon the Propane Input Rate and the Nondimensional Air/Fuel Ratios.
Fig. 14 Dependence of the Relative Amount of Propane Input in the Second Half Pressure Cycle upon the Amplitude of Pressure Oscillation.
Fig. 15  Dependence of the Relative Amount of Air Input in the Second Half Pressure Cycle upon the Amplitude of Pressure Oscillation.
**Fig. 16** Schematic of the Time Dependence of the Pressure Amplitudes of Fundamental Mode and Its First Harmonic Mode. Note the Four Different Regions for Driving and Damping.
Fig. 17  Dependence of the Amplitude of Pulsations in Different Acoustic Modes (in dB) Upon the Nondimensional Air/Fuel Ratio Measured with a Propane Input Rate of 2.8 SCFM and the Premixed Flame Injection System.
Premixed Type:

\[ \tau_{\text{species}} = 0 \]

Figure 18. A schematic of the conjecture for the mode shifting phenomenon.
Fig. 19

Fig. 20  Time Dependence of Nondimensional Air/Fuel Ratio, Pressure Amplitude, Chemical Time and Physical Time Calculated for Fuel Lean Operation from Pressure Measurement and Travelling Wave Assumption.
Figure 21. The dependence of the acoustic pressure amplitude upon the nondimensional air/fuel ratio measured in tests with 2.4 SCFM propane input rate.
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Figure 23. A schematic of the seeding arrangement prepared for LDV measurement.
Figure 24. A schematic of the seeding system prepared for LDV measurement.
Figure 25. A Schematic of the developed opto-electronic tachometer for the seeding system.
Figure 26. A schematic of the Type (a) nondimensional air/fuel ratio modulations.
Figure 27. A schematic of the Type (b) nondimensional air/fuel ratio modulations.
Figure 28. A schematic of the Type (c) nondimensional air/fuel ratio modulations.
Figure 29. A schematic of the combustor and the simplified model.
This synopsis summarizes the accomplishments of DOE Contract NO. DE-AS04-85AL31881, which investigated the combustion of different liquid fuels in Rijke type pulse combustors. Interest in the development of a Rijke pulse combustor capable of burning liquid fuels was stimulated by earlier studies by the investigators of this program which had demonstrated that various coals can be burned efficiently and with low pollutant emissions in Rijke type pulse combustors. This research program consisted of three tasks. Task A was concerned with the development of a Rijke pulse combustor design capable of burning different liquid fuels, and determination of the performances of uninsulated and insulated versions of the developed Rijke pulse combustor when burning different liquid fuels under different operating conditions. Task B was concerned with the elucidation of the mechanisms responsible for driving the pulsations in the developed combustors, and Task C was concerned with the determination of the dependence of the combustor performance upon the amplitude of pulsations. The results of these studies are briefly discussed in the remainder of this document.

ACCOMPLISHMENTS

Spontaneous excitation of pulsations in a Rijke pulse combustor requires that the majority of the combustion process energy be released near the middle of the first half of the combustor tube, see Fig. 1. Consequently, the first phase of this study investigated the stabilization of the combustion process of various liquid fuels at the desired location by
means of different combustion process stabilization schemes. These included direct injection of a liquid fuel spray at various axial locations along the combustor center line; injection of liquid fuel sprays in combination with the use of various flame holding devices; the establishment of a two phase, liquid-gas, flow in the fuel feed line; and the use of tangential injection of the liquid fuel and most of the combustion air. Among these, only the last two approaches produced satisfactory results.

When a two phase flow is present in the fuel feed line, oscillations having the same frequency are excited in the combustor and the fuel feed line. This, in turn, produces a periodic fuel feed rate into the combustor, which produces an oscillatory combustion process. In addition, the presence of a gas in fuel the feed line enhances the liquid fuel atomization. Finally, when the gas phase in the fuel feed line is fuel or air (as was the case in these experiments) the combustion process is stabilized next the fuel injector at the desired combustor location. Two approaches were developed to establish a two phase flow in the fuel feed line. In the first approach, the fuel feed line is passed through the flame region and some of the fuel is evaporated by heat transfer from the adjacent gases. In the second approach the fuel is premixed with air or methane prior to its entrance into the fuel feed line. Problems were encountered with the first approach when burning heavy fuel oils. These involved clogging of the fuel feed line by deposits of heavy hydrocarbons on the feed line walls.

The problems which were encountered with the two phase injection system lead to the development of the tangential injection system which provided "aerodynamic" stabilization of the combustion process in the vicinity of the fuel and air injection point. This stabilization is attained by the establishment of flow recirculation near the tangential injection location. The tangential injection system, for a patent application has been filed, is shown in Fig. 2. It consists of three enclosed parallel air lines and a fuel feed line which injects the fuel into an annular space around the central air line. The central air line, referred to as the atomizing stream, entrains the liquid fuel through holes in its wall. After mixing with the fuel, the central air stream and the air supplied by the other two lines enter a small
rectangular plenum, located just upstream of the combustor wall, where the three streams mix. From there, the resulting air/fuel mixture enters the combustor with its velocity directed around the inner combustor wall. The swirling motion of the injected mixture apparently forms a flow recirculation region near the injection location. The remainder of the combustion air was injected axially through the combustor inlet.

Once the development of a satisfactory liquid fuel burning Rijke pulse combustor had been completed satisfactorily, the efforts of this program turned to the evaluation of the combustion of fuel oils Nos. 2, 5 and 6 in the developed Rijke pulse combustor. The combustion of each of these fuels was evaluated over wide ranges of fuel input rates, air/fuel ratios, and different ratios of the tangential and axial air flow rates. Measured data included the amplitudes, frequencies, waveforms, and spectra of the excited pressure oscillations, temperature distributions along the combustor, and chemical analysis of the combustion products. The measured amplitudes provided information about the degree of driving provided by the combustion process; the measured frequencies identified the excited acoustic modes; the waveforms and spectra provided information about the presence of higher harmonics in the excited pulsations; the temperature distributions provided information about the location of the heat release region; and the chemical composition data were used to determine the combustion efficiencies and pollutant emissions.

These tests revealed that the developed Rijke pulse combustor can burn a variety of liquid fuels with high combustion efficiencies with low excess air values. Furthermore, it produced low concentrations of CO and soot in its exhaust flow. Of special significance is the fact that all of the measured NO\textsubscript{X} concentrations were below the NSPS limits. The measured temperature distributions showed that maximum temperatures occurred near the tangential injection location indicating that a substantial fraction of the combustion energy was released in this region. Finally, the investigation of the dependence of the combustor performance upon the ratio of the tangential to axial air flow rates ratio revealed that maximum pulsations amplitudes are attained when this ratio Besides, the influence of the relative ratio of the axial air to when the tangential air flow rate equals
65-75% of the total air flow rate. Furthermore, these studies in conjunction with axial temperature distribution measurements revealed that this air flows ratio affected the location of the combustion zone and, thus, the efficiency of driving of pulsations by the combustion process.

Upon completion of the of the above described investigations, which were carried out in an uninsulated combustor tube, a refractory lined Rijke combustor having the same design and dimensions as the uninsulated combustor was developed. This combustor was designed for the purpose of evaluating the effect of insulation upon the combustor performance. In addition, this combustor was used to investigate the mechanisms which control the operation of the developed Rijke combustor. These investigations consisted of extensive series of tests with fuel oils Nos. 2 and 5 which investigated the characteristics of the reaction rate by measuring C-C radiation emitted by the combustion process; the characteristics of the excited pulsations by measuring the pulsation pressure amplitude distribution along the combustor axis; the rich and lean limits of pulsating and steady operation of the combustor; and the temperature distribution in one cross-section. A comparison of the measured data with similar data (for the same fuel) obtained in the uninsulated combustor revealed that, as expected, the refractory insulation decreased the heat losses through the combustor walls and increased the gas temperature inside the combustor. Furthermore, the presence of refractory material increased the acoustic losses of the system which, in turn, decreased the amplitudes of the excited pulsations. It appears that any potential increase in driving of the pulsations, due to higher reaction rates inside the insulated combustor, could not compensate for the increased damping provided by the refractory liner.

The C-C radiation measurement showed the the reaction rate was oscillatory, indicating the presence of a periodic heat release process which supplies the energy required to drive the pulsations. The measured radiation and pressure signals were fourier analyzed and their spectra were compared. This comparison revealed strong similarities between the two spectra. Specifically, large amplitude resonant pulsations are excited
in the combustor when the radiation spectrum contains peaks at frequencies corresponding to acoustic resonances of the combustor. However, peaks in the radiation spectrum at nonresonant frequencies of the combustor do not drive flow oscillations at these frequencies because they do not possess the energy required for driving nonresonant pressure oscillations in the combustor. Finally, the measured radiation and pressure data were used to evaluate the magnitude of Rayleigh's integral which provides a measure of the driving provided by the combustion process. This integral consists of an integral of the product of the instantaneous pressure and instantaneous total radiation signals over a period of the oscillation. The Rayleigh integral was evaluated for a wide range of combustor operating conditions and its magnitude was compared with the measured pulsations pressure amplitudes. This comparison showed that the amplitude of the excited pulsations increased as the magnitude of the Rayleigh's integral increased and vice versa. Furthermore, the amplitude of the excited pulsations increased as the phase difference between the pressure and heat addition oscillations decreased. Finally, the measured data suggest that the amplitude of the excited oscillations increases as the maximum gas temperature inside the combustor increases.
Fig. 1 A schematic of a general Rijke type pulse combustor.
Fig. 2  A Schematic of the Developed Liquid Fuel Burning Rijke Type Pulse Combustor with Tangential Fuel and Air Inlelction System.
INVESTIGATION OF THE CHARACTERISTICS OF LIQUID FUEL BURNING, RIJKE TYPE, PULSE COMBUSTORS

Final Report

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ABSTRACT

This report summarizes results obtained under a DOE program in which a Rijke type pulse combustor (i.e., LRPC) capable of burning low quality liquid fuels was developed. In the initial phase of this program two methods for stabilizing the combustion process at the required location were developed. The first method requires the establishment of a two phase flow in the fuel feed line and the second uses a newly developed feed system which injects all of the fuel and most of the combustion air tangentially into the combustor. An investigation of the performance of the two stabilization methods showed that the tangential flow injection system is superior. Consequently, follow up studies investigated the performance of an uninsulated and an insulated LRPC which had identical dimensions and utilized the same tangential injection system. This study showed that pulse combustion operation is possible over a wide range of fuel loadings and fuel/air ratios, including fuel rich conditions. Combustion efficiencies higher than 99% can be obtained with only 5% excess air when burning light fuel oils. Also, the addition of insulation increases the combustor gas temperatures and reduces the amplitude of the excited pulsations. Finally, no soot was visible in the exhaust flow, the CO concentrations were negligible, and all of the measured NOX concentrations were below 180 ppm which is considerably below the U.S. federal limit for NOX emissions.

The mechanisms responsible for driving the pulsations in the developed LRPC were investigated. This study showed that the reaction rate, determined from C-C and C-H radiation measurements, oscillates with the same frequency as the pressure and that with the exception of a few low frequency peaks in the radiation spectrum the spectra of the radiation and pressure signals are similar. This result indicates that an understanding of the driving mechanism will require the elucidation of the processes responsible for the appearance of the various peaks in both spectra. It has also been shown that the amplitude of the pulsations depends upon the location of the heat release region and the phase difference between the pressure and heat release oscillations. Finally, it was demonstrated that the Rayleigh integral, which provides a measure of the combustion driving, and pressure amplitude exhibit similar qualitative dependence upon independent combustor operating parameters.
INTRODUCTION

This report summarizes the accomplishments of DOE Contract No. DE-AS04-85AL31881 which has been concerned with the development of a liquid fuel burning, Rijke type, pulse combustor (to be denoted henceforth as LRPC). This three year investigation was inspired by earlier studies by the principal investigators of this program in which a highly efficient, coal burning, Rijke type, pulse combustor was developed\(^1\)-\(^3\). These studies have demonstrated that various unpulverized coals having mean particle diameters in the .25 - .5 inch range can be burned with high combustion efficiencies while utilizing low amounts of excess air. For example, subbituminous coals were burned in the Rijke combustor with combustion efficiencies around 99 percent with only 5 percent excess air. In addition, the developed coal burning Rijke pulse combustor exhibited high combustion intensities and low NO\(_X\) concentrations in the exhaust flow. Most significantly, this outstanding performance was achieved in a simple combustor which consisted of a 9 foot long, 5 inch inside diameter uninsulated carbon steel tube.

The investigations of the coal burning Rijke combustor revealed that pulse combustion operation over a wide range of operating conditions can be attained if means for stabilizing the combustion process at a distance of \(L/4\) (where \(L\) is the combustor length) from the combustor entrance could be found. These findings strongly suggested that other low and high quality fuels could be burned efficiently and with low levels of pollutant formation in Rijke type pulse combustors if the combustion process could be stabilized at a distance of \(L/4\) from the combustor entrance. The research described in this report was undertaken with the objective of determining whether the advantages exhibited by the coal burning Rijke pulse combustor can be also attained when burning various liquid fuels.

This research program has been divided into three tasks. The objectives of Task A were: (1) to develop a Rijke type pulse combustor design capable of burning various liquid fuels stably over a wide range of operating conditions, and (2) determine the performance characteristics of insulated and uninsulated versions of the developed combustor while burning different liquid fuels under different operating condition. The objective of Task B was to investigate the
mechanisms responsible for driving the pulsations in the developed combustors, and Task C investigated the dependence of the combustor performance upon the amplitude of pulsations.

RESULTS

Development of a Liquid Fuel Burning Rijke Type Pulse Combustor

The majority of the efforts expended under Task A during the first year of this investigation focused on the development of an efficient, liquid fuel burning, Rijke type, pulse combustor. The first Rijke pulse combustor configuration investigated under this program is shown in Fig. 1. The combustor consisted of a nine feet long, 5.76 inch inside diameter carbon steel pipe. It was attached to decoupling chambers at both ends. They were included in the design to assure that the acoustic pressures are negligibly small at both ends of the combustor. Combustion air was supplied axially through the upper decoupler and the fuel was injected radially into the surrounding air flow through a "home made" liquid injector that was located at a distance of L/4 from the combustor entrance plane, see Fig. 1. This pulse combustor design failed to achieve satisfactory operation because its flame and heat release were distributed over a large fraction of the combustor length.

The failure of the combustor design shown in Fig. 1 to operate properly pointed out the need to develop a flame stabilization method that will assure that of the majority of the combustion heat is released in the vicinity of the X=L/4 location as dictated by the principles of operation of Rijke combustors\(^1,2\). Consequently, the majority of efforts during the remainder of the first year of this study focused on the determination of the effectiveness of various flame holding methods. Specifically, the liquid fuel injection and flame holding schemes shown in Fig. 2 were investigated. Configuration 2-a consisted of a commercial injector which was located at the X = L/4 position and produced a full cone spray. Configuration 2-b used V-shaped flame holders located several inches downstream of the injector shown in Fig. 2-a, Configuration 2-c used two metal grid flame holders, which were placed on top of one another and installed several inches downstream of the injector shown in Fig. 2-a. The configuration shown in Fig. 2-d utilized two fuel injectors. The primary "home made" injector was attached to a coiled fuel line which was placed inside the hot gases
Spatial Dependence of Excited Acoustic Pressure and velocity Oscillations.

Figure 1   A Schematic of the Developed Liquid Fuel Burning Rijke Type Pulse Combustor.
Figure 2  Investigated Flame Holding Methods.
downstream of the fuel injection point. The coiled section was added to the fuel feed line to promote fuel evaporation as the presence of fuel vapor inside the fuel line was expected to increase the potential for "coupling" between the combustor and fuel line oscillations. This coupling was expected to provide a mechanism for driving the combustor pulsations. The secondary fuel injector, located near the combustor entrance plane, was used to preheat the combustor walls to a prespecified temperature before starting the fuel flow into the primary injector.

The effect of the flame holding methods shown in Fig. 2 and those utilized in subsequent studies upon the combustor performance are described in detail in Refs. 4 through 8. For convenience, Ref. 4 is included in Appendix A of this report. Briefly, Configuration 2-a which used a commercial injector to inject a spray of liquid fuel into the combustor without using any flame holding method failed to produce pulse combustion operation. The resulting combustion process was steady and it extended over a significant distance along the combustor. The V-shaped flame holders shown in Fig. 2-b were inserted into the combustor in order to stabilize the combustion and heat release processes near the $X=L/4$ position. This configuration also failed to produce pulse combustion operation. The configuration shown in Fig. 2-c was the first which produced pulse combustion operation with pressure amplitudes of the order of 155 dB. Observations of the resulting flame indicated that it was shorter and considerably more "intense" than the steady flames produced by the steady combustion process which occurred with Configurations 2-a,b.

The characteristics of the configuration shown in Fig. 2-d were investigated in an effort to determine whether pulse combustion operation with amplitudes higher than those produced by Configuration 2-c could be attained. Initial tests with this configuration operated with pressure amplitudes in the 160-170 dB range. Furthermore, this configuration produced pulse combustion operation over a wider range of operating condition than was attained with the other investigated configurations. Consequently, it was decided to proceed with a systematic investigation of the combustion characteristics of several different light and heavy fuel oils in a Rijke pulse combustor which utilized fuel injection schemes similar or identical to the one shown in Fig. 2-d.

When the injection scheme shown in Fig. 2-d produced satisfactory pulse combustion operation, a fraction of the liquid fuel usually evaporated and
produced a two phase gas-liquid flow inside the injector feed line. The evaporation of the liquid fuel increased the pressure in the feed line which undoubtedly contributed to the production of a "better" spray inside the combustor. In addition, acoustic oscillations could be readily sustained by the two phase flow inside the injector feed line.

The injection configuration shown in Fig. 2-d produced highly satisfactory combustor performance in tests with light fuel oils such as kerosene or fuel oil No. 2. Difficulties were encountered, however, when heavy liquid fuels such as fuel oil Nos. 5 and 6 were burned in this configuration. In these tests, the combustor performance would start deteriorating after operating properly for a period of time. This manifested itself by a gradual drop in the amplitude of pulsations until pulse combustion operation eventually stopped. An investigation of the problem revealed that the pulsations stopped when the coiled evaporator line got clogged by deposits of tar and solid matter. This clogging occurred because of the differential evaporation of the various hydrocarbons which make up the heavy fuel oils. When a heavy fuel flows through the heated evaporator coil, the lighter molecular weight hydrocarbons evaporate first and "leave behind" the heavier molecular weight hydrocarbons which start depositing on the inner walls of the evaporator coil. In time, this deposition process results in clogging of the fuel line. When this occurs, the fuel flow rate into the combustor is either drastically reduced or stopped, which either stops the pulsations or the operation of the combustor.

An investigation of the mechanism controlling the driving of pulsations in the configuration shown in Fig. 2-d revealed that acoustic oscillations having the same frequency as the oscillations inside the pulse combustor exist inside the fuel feed line during pulse combustor operation. Such fuel feed line oscillations can produce an oscillatory fuel flow rate into the combustor which can produce an oscillatory combustion process. If such a combustion process releases heat in phase with the combustor pressure oscillations, it can (according to Rayleigh's criterion) provide the energy needed for sustaining the combustor pulsations. The phase difference between the heat release and pressure oscillations depends upon the phase difference between the fuel feed rate and the combustor pressure oscillations. This phase difference depends on whether standing or traveling acoustic pressure oscillations occur inside the fuel feed line. Since the
Characteristics of a standing acoustic wave depend upon the length of the fuel feed line, it was decided to investigate this question by changing the length of the evaporator coil (see Fig. 2-d) and determine its effect upon the pulse combustor operation. In these tests, the length of the evaporator coil was varied between \(0.5\lambda\) to \(1.75\lambda\), where \(\lambda\) was the wavelength of pulsations inside the Rijke combustor. Pulse combustion operation was obtained with all of the tested lengths of the fuel feed line. These results suggest that no appreciable standing wave component was present in the fuel feed line. Otherwise, any change in the fuel feed line length would have changed the natural frequency of the feed line and one would expect a range (or ranges) of feed line lengths for which significant fuel system oscillations and, thus, combustor pulsations could not exist.

The results described above suggested that the fuel feed line oscillations consisted primarily of travelling acoustic waves. Jones\(^9\) proposed a theory which explains how a travelling acoustic wave could be responsible for a feedback mechanism which can maintain the operation of a pulse combustor. In this case the pressure oscillations just inside and outside (i.e. in the combustor) the fuel injector orifice are practically in phase. The changes in the combustor pressure are transmitted upstream in the fuel line as a travelling wave. Hence, the fluctuating component of the particle velocity near the fuel orifice is directed into the combustor when the pressure is high and away from the combustor when the pressure is low. Under these conditions the fuel flow rate out of the orifice is near its maximum when the pressure in the combustor is low and vice versa. Thus, if the phase difference between the fuel feed rate and combustion oscillations equals half the period of the oscillation of the pulsation, heat would be supplied in phase with the combustor pressure oscillations, satisfying Rayleigh's criterion\(^10\).

Some efforts were also expended during this program on finding a solution to the clogging problem encountered during the combustion of heavy fuel oils. The objective of these efforts was to eliminate the clogging in the fuel line caused by the evaporation of the lighter hydrocarbons while maintaining the needed two phase flow in the feed line. The developed solution consisted of mixing the heavy fuel oil with gas, either air or methane, upstream of the fuel feed line, and shortening the length of the coiled evaporator line immersed
inside the hot gases. The injection of a gas into the liquid fuel produced the needed two phase flow and the shortening the fuel feed line minimized the evaporation of light hydrocarbons which caused the above described clogging problem. A typical injector configuration in which fuel oil No. 5 is mixed with air at the upstream end of the fuel feed line is shown in Fig. 3.

Extensive tests with the injector configuration shown in Fig. 3 and related configurations revealed that they can produce satisfactory pulse combustion of both light and heavy fuel oils over wide ranges of combustor operating conditions. The characteristics of the resulting combustion process strongly depend, however, upon the relative amounts of injected gas and liquid fuel flow rates, the length of the evaporator coil, and the characteristics of the injector. Furthermore, the attainment of optimum performance requires that the characteristics of the fuel injection system be modified when the range of operating conditions (e.g., fuel feed rate) or the utilized fuel are changed.

While the above described investigations have resulted in the development of several different fuel injection and flame holding configurations which produced excellent performance of the Rijke combustor, it was decided to proceed with a search for other flame stabilization methods which would be less sensitive to the properties of the liquid fuel and combustor operating conditions. Since it has been previously established\(^\text{11}\) that swirling flows can be utilized to stabilize combustion processes in various combustors, it was decided to investigate the use of a swirling flow to stabilize the combustion process at the \(X = L/4\) location in the Rijke combustor. It was conjectured that an "appropriate" tangential injection of fuel and combustion air into the combustor would create a recirculating flow region which could stabilize the combustion process aerodynamically in the vicinity of \(X = L/4\) position. To investigate this conjecture, the effect of different fuel and combustion air injection schemes, which produced a swirling flow in the vicinity of \(X = L/4\) position, upon the Rijke pulse combustor performance were investigated. Some of these configurations are shown in Fig. 4. In these configurations a fraction of the combustion air was injected axially through the top decoupler and the remainder through one or two injection nozzles which produced clockwise or counter clockwise air flow movement inside the combustor. The tested fuel was injected
Figure 3  A Schematic of One of the Initially Developed Fuel Oil No.5 Injection System.
(a) Configuration with Direction of Swirling Air Injection Parallel to Tangential Fuel Injection.

(b) Configuration with Direction of Swirling Air Injection Opposite to Tangential Fuel Injection.

(c) Configuration with Radial Fuel Injection.

Figure 4 Investigated Combustor Configurations with Tangential or Radial Fuel Injection and Parallel Primary and Secondary Swirling Air Injection.
either axially, radially, or tangentially through injectors similar to those shown in Fig. 4.

Tests conducted with the configurations shown in Fig. 4 revealed that they are capable of producing large amplitude pulse combustion operation. Furthermore, examination of the combustor walls after the tests revealed no carbon or tar accumulations and no smoke was visible in the exhaust flow during the tests, suggesting that these configurations produce complete combustion of heavy and light fuel oils. Also, these tests showed that the performance of the pulse combustor was independent of the direction of the swirling air flow. In view of these findings, it was decided to proceed with the investigation of the performance of the Rijke pulse combustor when all of the fuel and some of the air are injected with swirl into the combustor. To perform this study, it was first necessary to replace the injector configurations shown in Fig. 4 with a new, permanent, injection system which would be easy to operate and capable of handling wide ranges of air and fuel flow rates. Such an injection system was developed and tested extensively, and some of the results are described below.

Schematics of the tested Rijke combustor and the new swirling fuel and air injection system are provided in Figs. 5 and 6, respectively. An examination of Fig. 5 reveals that the combustion air is divided into axial and tangential streams with the axial air flow entering the combustor through the upper decoupling chamber and the tangential air stream through the new injection system. The air entering the developed injection system, see Fig. 6, is divided into two streams. The function of the central, atomizing, air stream (denoted by $W_{af}$) is to supply the fuel into the combustor. This air stream entrains fuel (denoted by $W_f$) which is injected radially through orifices around the periphery of the central fuel injection tube just upstream of a small mixing chamber. The main swirling air stream (denoted by $W_{sw}$) is supplied to the mixing chamber through two lines located on both sides of the atomizing air line. The two swirling air streams mix with the fuel-air mixture inside the mixing chamber and the resulting mixture enters the combustor tangentially through a large, nearly square, injection port.

The newly developed fuel and air injection system possesses capabilities for independent control of the atomizing and swirling air flow rates, and the fuel flow rate. This, in turn, provides capabilities for controlling the air/fuel ratio in the fuel injector, the ratio of the atomizing air and the swirling air flow rates.
Figure 5 A Schematic of the Rijke Combustor with the Swirling Air/Fuel Injection System.
Figure 6  A Schematic of the Air/Fuel Injection System Attached to a Section of the Rijke Combustor.
and the ratio of the swirling air and axial air flow rates. In addition, it is believed that the modified fuel injection system provides better atomization of the fuel than the injection systems shown in Fig. 4. Finally, the modified injection system supplies the air with low velocity which proved to be desirable in earlier tests under this program.

In addition to the above described fuel injection system, the Rijke pulse combustor also includes a kerosene fuel injector which is located a short distance downstream of the combustor's entrance plane, see Fig. 5. This fuel injector is used to ignite and preheat the combustor prior to the activation of the main fuel injector. In addition, the upper decoupler is fitted with a viewing window and a mirror which are located on top of the combustor and used to view the combustion process. A pressure transducer is attached to the midpoint of the combustor and is used to measure the amplitude and frequency of pulsations. Finally, a sampling line is inserted into the exhaust decoupler and used to continuously sample the combustion products. The removed gases are pumped into a chemical analysis system which determines the concentrations of CO, O₂, CO₂, NOₓ, SO₂ and hydrocarbons in the combustion products. The measured concentrations are then used to determine the combustion efficiency and pollutant formation of the combustor under the investigated test conditions.

Developed LRPC Performance

The combustor and injector configurations shown in Figs. 5 and 6 were tested extensively to determine the dependence of the combustor performance upon the characteristics of the utilized fuel and operating conditions. The results of these test are described in Refs. 12-14. The developed Rijke combustor with the swirling injection system was capable of burning both light and heavy fuel oils with high combustion efficiencies over wide ranges of combustor operating conditions. For example, Fig. 7 describes the limits of pulse combustion operation for two different fuel oil No. 2 injection rates. This figure shows that the developed combustor can be operated with fairly large amplitudes of pulsations (i.e., higher than 160 dB) over wide ranges of air/fuel ratios which include both fuel rich and fuel lean conditions. Similar results were also obtained in tests conducted with heavy fuel oils. In contrast, other pulse combustor designs (e.g., the Lennox pulse furnace) are known to possess considerably narrower ranges of operating conditions.
Air/Fuel Ratio Limits of Pulse Combustion Operation Measured in Tests with Fuel Oil No. 2 Supplied at Rates of 3.68 and 4.27 g/sec. Note that Steady Operation of the Combustor is Possible over a Narrow Range of $\alpha$ Below the Rich Limit of Pulse Combustion Operation.
The investigations of the performance of the combustor shown in Fig. 5 have also revealed that the amplitude of pulsation generally increases as the fuel input rate increases, see Fig. 8. The indicated increase in the amplitude of pulsation with fuel input rate is similar to the behavior exhibited by other pulse combustor designs. The dependence of the combustion efficiency upon the fuel input rate and the nondimensional air/fuel ratio $\alpha$ is described in Fig. 9. These data show that at the lower fuel input rates nearly 100 percent combustion efficiency is attained with only two to three percent excess air while at the higher fuel input rate around seven percent excess air is required to burn all of the fuel. These combustion efficiencies are higher than those attained with the previously investigated Rijke pulse combustor configurations which prevaporized some of the fuel prior to injection into the combustor.

The dependence of the $\text{NO}_x$ concentration in the combustion products upon the fuel input rate and nondimensional air/fuel ratio $\alpha$, measured during the tests described in Fig. 9, is described in Fig. 10. These data show that the $\text{NO}_x$ concentration increases as the fuel flow rate increases and that for a given fuel flow rate a maximum $\text{NO}_x$ concentration occurs at some value of $\alpha$. This maximum is hardly noticeable at low fuel flow rates and it is more pronounced at the maximum fuel flow rate (i.e., $W_f = 4.1 \text{ g/sec}$). All of the measured $\text{NO}_x$ concentrations were below 180 ppm which is considerably below the U.S. federal limit for $\text{NO}_x$ emissions. It should be also pointed out that the magnitude of the $\text{NO}_x$ concentrations produced during the combustion of No. 2 fuel oil are considerably lower than those generated when fuel oil No. 6 was burned in the same combustor.

A comparison of the $\text{NO}_x$ concentrations in the combustion products measured in tests with the same fuel input rates but different amplitudes of pulsations are presented in Fig. 11. An examination of this figure shows that the $\text{NO}_x$ concentration increases as the amplitude of pulsations increases. Also, as shown in Fig. 10, these data indicate that for given test conditions the $\text{NO}_x$ concentration attains a maximum at a specific value of $\alpha$ which is generally near stoichiometric conditions.

In order to determine the effect of thermal conditions inside the developed Rijke combustor upon its performance, a second, insulated, Rijke pulse combustor having design characteristics similar to those of the uninsulated
Figure 8  Dependence of the Amplitude of Pulsations Upon the Nondimensional Air/Fuel Ratio $\alpha$ for Different Input Rates, $W_f$, of No. 2 Fuel Oil.
Figure 9  Dependence of the Combustion Efficiency Upon the Nondimensional Air/Fuel Ratio $\alpha$ for Different Fuel Input Rates, $W_f$ of No. 2 Fuel Oil.
Figure 10  Dependence of the Exhaust Flow NOx Concentration Upon the Nondimensional Air/fuel Ratio $\alpha$ for Different Input Rates, $W_f$, of No. 2 Fuel Oil.
Figure 11  Dependence of the Exhaust Flow NO\textsubscript{x} Concentration Upon $\alpha$, the Fuel Feed Rates, $W_f$, and the Amplitude of Pulsations $p'$ Determined in Tests with No. 2 Fuel Oil.
Figure 12  A Schematic of the Insulated Rijke Type Pulse Combustor.
combustor shown in Fig. 5 was also developed and tested under this program. This combustor is shown in Fig. 12. It has the same internal diameter and length, the same ignition and fuel and air injection systems as the uninsulated combustor shown in Fig. 5.

The insulated combustor has been tested extensively and the results are discussed in Refs. 14 and 15. As in the case of the uninsulated Rijke combustor, the insulated combustor demonstrated a capacity for burning both light and heavy fuel oil over wide ranges of fuel input rates and air/fuel ratios. The addition of ceramic insulation was expected to decrease the heat losses through the combustor walls and possibly decrease the pulsations amplitudes due to increased acoustic damping by the porous ceramic walls. Therefore, it was decided to compare the amplitudes and temperature distributions measured in the insulated and uninsulated combustors when operated under similar conditions. Figure 13 compares dependence of the amplitudes measured in both combustors upon the nondimensional air/fuel ratios. This comparison shows that the amplitudes of pulsations in the insulated combustor are lower than those in the uninsulated combustor. The data presented in Fig. 13 suggests that the damping introduced by the refractory wall insulation dominates any additional driving which might have been introduced due to the higher temperatures and, thus, higher reaction rates in the insulated combustor. The temperature distributions in the insulated and uninsulated combustors are compared in Fig. 14. As expected, these data clearly show that the insulation increases the maximum temperature and decreases the heat losses in the Rijke combustor. It should also be pointed out that the temperature distributions plotted in Fig. 14 were obtained in tests with nearly identical amplitudes of pulsations.

In order to get a better understanding of the characteristics of the developed LRPC, tests were performed with fuel oils Nos. 2 and 5 to determine the dependence of the excited pulsations amplitude and combustor stability upon the relative flow rates of the axial, swirling and atomizing air flow rates. These tests have been conducted by keeping two of the three air flow rates constant and varying the overall air/fuel ratio $\alpha$ by varying the flow rate of the third combustion air stream. Some of these results are presented in Figs. 15 and 16.
Figure 13 A comparison of the Dependence of the Amplitude of Pulsation $P'$ Upon the Nonsimentional Air/Fuel Ratio $\alpha$ Measured in Tests Conducted with a 4.20 gm/sec Fuel Oil No. 2 Input Rate in the Insulated and Uninsulated Combustors.
Comparison of the Steady Temperature Distributions Measured Inside the Insulated and Uninsulated Rijke Combustors in Tests Conducted with Fuel Oil No. 2 and $W_f = 4.2$ g/sec.
Figure 15  Dependence of the Amplitude of Pulsations $P'$ Upon the Nondimensional Air/Fuel Ratio $\alpha$ Measured in Test Conducted with a 3.68 gm/sec Fuel Oil No. 5 Input Rate. Note that the Atomizing and Swirling Combustion Air Flow Rates Were Kept Fixed while the Axial Combustion Air Flow Rate was Increased.
Figure 16  Dependence of the Amplitude of Pulsations $P'$ Upon the Nondimensional Air/Fuel Ratio $\alpha$ Measured in Tests Conducted with a 3.68 gm/sec Fuel Oil No.5 Input Rate. Note that the Axial and Swirling Combustion Air Flow Rates Were Kept Fixed while the Atomizing Combustion Air Flow Rate Was Increased.
Figure 15 describes the dependence of the excited combustor pulsations amplitude upon the axial combustion air flow rate. Data are presented for a series of tests in which the axial air flow rate was increased from 7 to 30 grams/second while the atomizing and swirling combustion air flow rates were kept fixed. For clarity, the relative percentages of the axial, atomizing and swirling combustion air flow rates utilized in each test are presented as the elements of column matrices next to each data point. Examination of these matrices shows that for the reported tests the relative percentages of the axial air flow rates increased from 22 to 51 percent. These changes in the axial air flow rates resulted in an increase of the overall nondimensional air/fuel ratio $\alpha$ from .8 to 1.3. Figure 15 shows that as the axial combustion air flow rate increases the amplitude of pulsations decreases. Stable pulse combustion operation could only be attained for the indicated range of $\alpha$. For values of $\alpha$ beyond this range the pulsations become unstable and they are characterized by constantly changing frequencies and amplitudes. The results presented in Fig. 15 indicate that the highest amplitude was attained at the lowest axial combustion air flow rate. Since for this test condition the sum of the swirling and atomizing air flow rates is relatively high, this result suggest that high amplitude pulsations are obtained when the swirling air flow streams establish a recirculating flow region which stabilizes the combustion zone near the injection point.

Figure 16 describes the dependence of the amplitude of pulsations of the LRPC upon the atomizing combustion air flow rate. The latter was varied between 10 to 18 grams/second while the axial and swirling air flow rates were kept fixed. An examination of the results shows that the amplitude of pulsations increases slowly as $\alpha$ increases until it reaches a maximum of 157 dB at $\alpha = 1.0$. Thereafter, the amplitude decreases rapidly as $\alpha$ increases. For these tests stable pulse combustion operation could only be attained for $.92 \leq \alpha \leq 1.09$, which is much narrower than the $0.8 \leq \alpha \leq 1.3$ range for which stable pulse combustion operation was attained while changing the axial air flow rate.

Consideration of the physics of the problem suggest that the atomizing air flow affects the behavior of the pulse combustor in two ways. First, it affects the characteristics of the generated droplet spray and, second, it changes the overall air/fuel ratio of the burned mixture. It is believed that for a certain fuel input rate there exists an optimum range of atomizing air flow rates for which good
atomization of the liquid fuel and good mixing of the fuel and air is attained. If
the atomizing air flow rate is too low, adequate atomization of the fuel is not
attained which adversely affects the quality of the combustion process. On the
other hand, when the atomizing air flow rate is too high, it produces a conical
spray with a large angle. As the spray cone angle is increases, a larger fraction of
the injected fuel strikes the combustor walls. This results in fuel accumulation on
the walls and incomplete combustion. It should be also pointed out that for the
data presented in Fig. 16 the flow rate of the atomizing air flow is nearly doubled
while the overall nondimensional fuel/air ratio \( \alpha \) only changes between 0.92 and
1.09. It is anticipated that for a fixed fuel input rate such significant changes in
the atomizing air flow rate will produce large changes in the characteristics of the
generated spray.

The effect of the swirling air flow rate upon the amplitude of pulsations
was also investigated. Figure 17 describes the variations of the pulsation's
amplitude in tests with fuel oil No 2 in which the swirling air flow rate was
varied while the atomizing and axial air flow rates were kept fixed. An
examination of the data presented in Fig. 17 shows that the amplitude of
pulsations increases with \( \alpha \) when the air/fuel ratio is less than 1.0, it reaches a
maximum at \( \alpha = 1.0 \), and it subsequently decreases as \( \alpha \) increases beyond 1.0.
For these tests, stable pulse combustion operation was attained for 0.79 < \( \alpha \) <
1.17.

Analysis of measured data and considerations of the physics of the problem
suggest that the tangential injection of air and fuel results in the formation of a
recirculation flow region in the vicinity of the injection point. This recirculation
zone plays an important role in stabilizing the flame. The formation of this
recirculation zone depends, however, upon the ratio of the angular momentum
to the axial momentum of the flow. The data presented in Fig. 17 indicates that
for a given fuel flow rate and fixed axial and atomizing air flow rates, there is an
optimum swirling air flow rate which maximizes the amplitude of pulsations
when \( \alpha \) in near 1.0. The data presented in Fig. 17 suggest that for the
investigated test conditions the majority of the combustion heat release occurred
near the \( x = L/4 \) position when the overall air/fuel ratio was near stoichiometric.
In this case the relative percentages of the axial, atomizing and swirling
combustion air flow rates were 29, 17 and 54, respectively.
Figure 17 Dependence of the Amplitude of Pulsations \( P' \) Upon the Nondimensional Air/Fuel Ratio \( \alpha \) Measured in Tests Conducted with a 4.20 gm/sec Fuel Oil No.2 Input Rate. Note that the Axial and Atomizing Combustion Air Flow Rates Were Kept Fixed while the Swirling Combustion Air Flow Rate Was Increased.
The dependence of the axial temperature distribution along the combustor upon the test conditions was also investigated. These data were obtained by using use of thermocouples which were placed at different axial positions along the combustor center line. Typical results are presented in Figs. 18-20. Fig. 18 describes axial temperature distributions measured under the test conditions described in Fig. 15. In these tests the atomizing and swirling air flow rates were kept fixed while the nondimensional air/fuel ratio $\alpha$ was increased by increasing the axial air flow rate. The temperature distributions presented in Fig. 18 indicate that as the axial air flow rate increases, the location of the maximum temperature (and presumably the combustion zone) moves downstream away from the $X=L/4$ position.

Axial temperature distributions measured in tests in which the axial and swirling air flow rates were kept constant and $\alpha$ was increased by increasing the atomizing air flow rate are presented in Fig. 19. These temperature distributions were measured under the test conditions described in Fig. 16 and they show that varying the atomizing air flow rate over the indicated range has little effect upon the temperature distribution within the combustor. Apparently the effect that changing the atomizing air flow rate has upon the generated spray is not sufficient to significantly affect the temperature distribution within the combustor.

Temperature distributions measured in tests in which the axial and atomizing air flow rates were kept constant and $\alpha$ was increased by increasing the swirling air flow rate are presented in Fig. 20. An examination of the results shows that the axial temperature distribution along the combustor axis changes very little as the swirling flow rate increases.

One of the objectives of this study was to evaluate the combustion characteristics of light and heavy fuel oils in the developed Rijke combustor. Figure 21 compares the dependence of the excited amplitudes of pulsation upon $\alpha$ at the same input rates of fuel oils Nos. 2 and 5. These results indicate that the combustion of fuel oil No. 2 excites higher amplitudes over the whole range of air/fuel ratios. The data presented in Fig. 22 show that the combustion of fuel oil No. 2 produces considerably higher maximum temperatures than the
Figure 18 Axial Distribution of the Steady Temperature within the Insulated Rijke Combustor Measured in Tests with a 3.68 gm/sec Fuel Oil No.5 Input Rate and Different Values of $\alpha$. 
Figure 19  Axial Distribution of the Steady Temperature within the Insulated Rijke Combustor Measured in Tests with a 3.68 gm/sec Fuel Oil No.5 Input Rate and Different Values of $\alpha$. Note that the Axial and Swirling Combustion Air Flow Rates Were Kept Fixed while the Atomizing Combustion Air Flow Rate Was Increased.
Figure 20  Axial Distribution of the Steady Temperature within the Insulated Rijke Combustor Measured in Tests with a 3.68 gm/sec Fuel Oil No.5 Input Rate and Different Values of $\alpha$. Note that the Axial and Atomizing Combustion Air Flow Rates Were Kept Fixed while the Swirling Combustion Air Flow Rate Was Increased.
Figure 21  Comparison of the Dependence of the Amplitude of Pulsations $P'$ Upon the Nondimensional Air/Fuel Ratio $\alpha$ Measured in Tests Conducted in the Insulated Combustor and 4.20 gm/sec Input Rate of Fuel Oil Nos. 2 and 5.
Figure 22  Comparison of the Dependence of the Maximum Temperature Inside the Insulated Rijke Combustor Upon the Nondimensional Air/Fuel Ratio $\alpha$ Measured in Tests Conducted with a 4.2 gm/sec Input Rate of Fuel Oil Nos. 2 and 5.
combustion of the same input rate of fuel oil No. 5, at various nondimensional air/fuel ratios $\alpha$. A comparison of measured axial temperature distributions in tests conducted with fuel oil Nos. 2 and 5 is presented in Fig. 23. Again, the maximum temperature measured with fuel oil No. 2 was higher than that measured with fuel oil No. 5. Also, the temperature drop which occurred in the combustor was higher with fuel oil No. 2. It should be also noted that the maximum temperature in the test with fuel oil No. 5 occurred downstream of the location of the maximum temperature in the test with fuel oil No. 2.

The higher maximum temperatures measured in tests with fuel oil No. 2 were probably due to the fact that fuel oil No. 2 has a higher heating value than fuel oil No. 5. The shift in the location of the maximum temperatures measured in tests with these two fuels, see Fig. 23, was probably due to the fact that fuel oil No. 2 burns faster than fuel oil No. 5. The higher heating value and the closer proximity of its heat release region to $X = L/4$ must be the reasons that the combustion of fuel oil No. 2 in the Rijke combustor produced higher pulsation amplitudes than the combustion of fuel oil No. 5, see Fig. 21. Finally, the larger temperature drop downstream of the combustion region observed in the tests with fuel oil No. 2, see Fig. 23, was probably caused by the higher heat losses to the combustor walls caused by the larger amplitudes of pulsations which were excited in the tests with this fuel.

In summary, efforts conducted to date under Task A of this program resulted in the development of two different designs of liquid fuel burning, Rijke type, pulse combustors. The first design requires the existence of a two phase flow in the liquid fuel feed system which can support acoustic oscillations. These acoustic oscillations produce an oscillatory fuel feed rate which results in a periodic combustion and heat addition processes which provide the energy required for supporting pulse combustion operation. While producing excellent combustion characteristics, the performance of this system is sensitive to the type of fuel used and the combustor operating conditions. The second LRPC design developed under this program utilizes swirling injection of all the fuel and most of the combustion air to (apparently) establish a recirculating region near the injection point which stabilizes the combustion process at the desired $X = L/4$ location. This combustor exhibits excellent performance characteristics over wide ranges of operating conditions while burning both light and heavy fuel oils.
Figure 23  A Comparison of the Spatial distribution of the Steady Temperature Measured Inside the Insulated Rijke Combustor in Tests Conducted with a 4.20 gm/sec Input Rate of Fuel Oils Nos.2 and 5.
Furthermore, it is easy to operate and is relatively insensitive to changes in fuel properties or combustor operating conditions.

The basic design features of the LRPC which utilizes tangential injection of the fuel and combustion air appear to be new and a patent application covering the design of this injector-Rijke combustor system is currently in preparation.

Investigation of the LRPC Driving Mechanism

The investigation of the mechanism responsible for driving the pulsations in the developed Rijke combustor was divided into studies of the location of the heat release region, the determination of the pressure and radiation spectra, and the investigation of the phase relationship between the pressure and heat release oscillations. The investigation of the location of the heat release region focused upon the determination of the steady state temperature distributions within the combustion region, see, for example, Figs. 24-25. These results show that the combustion region temperature distribution is highly nonuniform and it strongly depends upon the relative amounts of axial and tangential (i.e., the sum of atomizing and swirling flow rates) combustion air flow rates. The relative amounts of the various air flow rates strongly affect the tangential and radial temperature distributions while exerting little influence upon the axial temperature distribution. Maximum temperatures were generally attained 12 to 25 inches downstream of the fuel injection location.

Since it is well known that pulse combustion processes are generally driven by energy supplied by the combustion process, an understanding of the mechanism(s) which drive the pulsations in the developed LRPC required an investigation of the time and spatial dependences of the reaction rate and their relationships with the pressure oscillations under different operating conditions. Since it has been established\textsuperscript{16,17} that the characteristics of the reaction rate can be determined from measurements of the intensity of O-H, C-C and C-H species radiation from the combustion zone, it has been decided to use this technique in the present study. The optical system developed under this program to measure the radiation intensity has been described elsewhere\textsuperscript{13} and only some of the results obtained in this study are briefly described herein.
Figure 24  Dependences of Temperatures at Three Different Tangential Locations of a Given Axial Cross Sectional Area Upon the Nondimensional Air/Fuel Ratio $\alpha$ Measured in Tests with Fuel Oil No. 2 and $W_f=3.29$ g/sec.
Figure 25 Variations of Steady Temperatures with Tangential Direction Measured 1" From the Inside Wall at Two Different Axial Locations in Tests with Fuel Oil No. 2, \( W_f = 3.29 \text{ g/sec} \) and \( \alpha = 1.18 \) (Upper Half of the Figure) and \( \alpha = 0.80 \) (lower Half of the Figure).
Typical dependences of the measured C-C radiation intensity and acoustic pressure are presented in Fig. 26. An examination of the radiation and pressure spectra shows that they have pronounced peaks at 98, 196 and 294 Hz. In addition, the pressure spectrum contains two distinct, small amplitude peaks at lower frequencies. While the radiation spectrum does not exhibit corresponding low frequency peaks, it is possible that these peaks are masked by the high levels of radiation noise at low frequencies. It is also noteworthy that the radiation spectrum possesses peaks at other frequencies which do not have counterparts in the pressure spectrum. At present, the mechanisms which produce the peaks in the radiation spectrum are not understood. It is also believed that some of the peaks in the radiation spectrum do not have counterparts in the pressure spectrum because they occur at frequencies which do not correspond to acoustic resonances of the combustor. Consequently, considerable driving (i.e., radiation intensity) would be required to drive pressure oscillations in the combustor at the frequencies of these peaks. Finally, an examination of the time variations of the pressure and C-C radiation signals presented at the bottom of Fig. 26 shows that while the shape of the pressure signal is fairly repetitive from cycle to cycle, the shape of the radiation signal may vary considerably from one cycle to another. The latter observation may be the cause for the "ruggedness" exhibited by the radiation spectrum (as compared the pressure spectrum) on the top of Fig. 26.

Another investigated subject is the relationship between the amplitude of the excited pulsations and the phase difference between the pressure and radiation oscillations. According to Rayleigh's criterion, driving of pulsations occurs when

$$\int_V \int_T P' \cdot Q' \, dV \, dt > 0$$

where, $P'$, $Q'$, $V$, $t$ and $T$ describe the acoustic pressure, unsteady heat release, volume occupied by the combustion process, time and period of pulsations, respectively. It can be readily shown that driving occurs when the magnitude of the phase difference between the pressure and heat release (or radiation) oscillations is smaller than 90 degrees. Thus, since the amplitude of pulsations is expected to be proportional to the magnitude of the driving provided by the combustion process, one would expect that the amplitude of pulsations would
Figure 26  Autospectra and Time Dependences C-C Radiation and Pressure Oscillations Measured in a Test with Fuel Oil No. 2, $W_f=4.2$ g/sec, $\alpha=0.86$ and $p'=169.3$ dB. Note that the Fundamental Mode Occurs at 98 Hz.
increase as the above mentioned phase difference between the heat release and pressure oscillations decreases. This would imply that a larger fraction of the combustion energy is released in phase with the pressure oscillations.

The double integration in Eq.(1) is performed over the volume \( V \) of the combustion region and the period of the oscillation \( T \). Ideally, an evaluation of the above integral requires detailed knowledge of the spatial and temporal distributions of all the quantities which appear inside the integral. However, since detailed determination of the quantities which affect the Rayleigh integral was beyond the capabilities of the experimental setup utilized in the present study, the magnitude of the Rayleigh integral was estimated in the present study by use of the following relationship:

\[
\int_V \int_T P' \cdot Q' \, dV \, dt = \int_V \int_T |P'| \cdot |R'| \cos \phi \, dV \, dt = P'_{\text{max}} \cdot R'_{\text{max}} \cos \phi = E \quad (2)
\]

where \( P'_{\text{max}} \) and \( R'_{\text{max}} \) denote the pressure amplitude measured at the combustor midpoint and the total (i.e. integrated) radiation amplitude was measured through the mirror at the top of the combustor, respectively. The angle \( \phi \) is the phase difference between the measured pressure and global radiation oscillations.

Since the approximate magnitude of the Rayleigh integral \( E \) (see Eq. (2)) describes the magnitude of the driving of the pulsations by the combustion process, one would expect that the \( \alpha \) dependence of the measured maximum pulsations amplitude will qualitatively follow the \( \alpha \) dependence of the approximate value of the Rayleigh Integral \( E \). An examination of Figs. 27 through 31 shows that this is indeed the case. Figures. 27 and 28 describe the dependence of pulsations amplitude, C-C radiation amplitude, phase difference between the pressure and radiation oscillations and the approximate value of the Rayleigh integral \( E \) upon the nondimensional air/fuel ratio \( \alpha \) for fuel oils No. 2 and 5, respectively. The data presented in these figures were obtained in tests which were conducted by only increasing the axial air flow rate. These results show that the phase difference between the pressure and radiation oscillations increases monotonically when the axial air flow rate increases. Simultaneously, the amplitude of pressure oscillation and the Rayleigh integral \( E \) decrease. A comparison of the data presented in Figs. 27 and 28 shows that the phase
Figure 27  Dependence of the Amplitude of Pulsations $P'$, the Amplitude of the C-Alpha C Radiation Oscillations $R$, the Phase Difference Between the Pressure and the Radiation Oscillation $\phi$ and the Rayleigh Integral $E$ Upon the Nondimensional Air/Fuel Ratio $\alpha$ Measured in tests With 3.68 gm/sec Fuel Oil No. 2 Input Rate. Note that the Atomizing and Swirling Combustion Air Flow Rates Were Kept fixed while the Axial Combustion Air Flow Rate Was Increased.
Figure 28 Dependence of the Amplitude of Pulsations $P'$, the Amplitude of the C-Radiation Oscillations $R$, the Phase Difference Between the Pressure and the Radiation Oscillations $\phi$, and the Rayleigh Integral $E$ Upon the Nondimensional Air/Fuel Ratio $\alpha$ Measured in tests With 3.68 gm/sec Fuel Oil No. 5 Input Rate. Note that the Atomizing and Swirling Combustion Air Flow Rates Were Kept fixed while the Axial Combustion Air Flow Rate Was Increased.
difference measured with fuel oil No. 5 is larger than that measured with fuel oil No. 2. For example, the minimum phase difference for both fuels is nearly the same. However, the maximum phase difference for fuel oil No. 2 is 22.67 degree while that for fuel oil No. 5 is 69.66 degree.

The dependence of pulsations magnitude, C-C radiation amplitude, the phase difference between the pressure and the radiation oscillations and the Rayleigh integral \( E \) upon the nondimensional air/fuel ratio \( \alpha \) for fuel oil No. 5 measured in tests in which \( \alpha \) was increased by only increasing the atomizing air flow rate is presented in Fig. 29. Again, the behavior of the pulsations amplitude is qualitatively similar to the behavior of the Rayleigh integral \( E \). Furthermore, the phase difference between the pressure and radiation oscillations decreases when the amplitude of the pressure oscillation increases and vice versa. Finally, Figs. 30 and 31 describe the variations of the same quantities in tests conducted with fuel oils Nos. 2 and 5 in which the phase difference between the radiation and pressure oscillations and the nondimensional air/fuel ratio \( \alpha \) was increased by increasing the swirling air flow rate. The trends exhibited by the data presented in Figs. 30 and 31 are qualitative similar to those exhibited by the data in Figs. 28 and 29; that is, the amplitude of the pressure oscillations increases when the phase difference between the pressure and radiation oscillations decreases and the magnitude of the Rayleigh integral \( E \) increases. It should be noted, however, that while the amplitude of the radiation oscillation generally varies in a manner similar to the variations of the pressure amplitude, an exception to this behavior is exhibited by the data presented in Fig. 31, obtained with fuel oil No. 5, where the radiation amplitude remains nearly constant over a fairly wide range of \( \alpha \). While the specific mechanisms responsible for the observed behavior are yet to be determined, it is satisfactory to note that the trends exhibited by the measured pressure amplitudes, phase differences and Rayleigh integrals behave as expected.

Figure 32 presents axial temperature distributions measured along the combustor in tests with a fixed fuel oil No. 2 input rate of 4.2 g/s, and different air/fuel ratios. All the tests described in Fig. 32 were conducted with 15% axial air flow rate, 17% atomizing air flow rate, and 53% swirling air flow rate. The data in Fig. 32 show that the highest temperature was obtained when \( \alpha=1 \).
Figure 29 Dependence of the Amplitude of Pulsations $P'$, the Amplitude of the C-C Radiation Oscillations $R$, the Phase Difference Between the Pressure and the Radiation Oscillation $\phi$ and the Rayleigh Integral $E$ Upon the Nondimensional Air/Fuel Ratio $\alpha$ Measured in tests With 3.68 gm/sec Fuel Oil No. 5 Input Rate. Note that the Axial and Swirling Combustion Air Flow Rates Were Kept fixed while the Atomizing Combustion Air Flow Rate Was Increased.
Figure 30  Dependence of the Amplitude of Pulsations $P'$, the Amplitude of the C-C Radiation Oscillations $R$, the Phase Difference Between the Pressure and the Radiation Oscillation $\phi$ and the Rayleigh Integral $E$ Upon the Nondimensional Air/Fuel Ratio $\alpha$ Measured in tests With 4.20 gm/sec Fuel Oil No. 2 Input Rate. Note that the Atomizing and Axial Combustion Air Flow Rates Were Kept fixed while the Swirling Combustion Air Flow Rate Was Increased.
Figure 31 Dependence of the Amplitude of Pulsations $P'$, the Amplitude of the Combustion C Radiation Oscillations $R$, the Phase Difference Between the Pressure and the Radiation Oscillation $\phi$ and the Rayleigh Integral $E$ Upon the Nondimensional Air/Fuel Ratio $\phi$ Measured in tests With 3.68 gm/sec Fuel Oil No. 5 Input Rate. Note that the Atomizing and Axial Combustion Air Flow Rates Were Kept fixed while the Swirling Combustion Air Flow Rate Was Increased.
Figure 32  Axial Distributions of the Steady Temperature Within the Insulated Rijke Combustor Measured in Tests Conducted with a 4.20 gm/sec Fuel Oil No.2 Input Rate and Different Values of $\alpha$. 
Furthermore, the results presented in Fig. 32 indicate that in all tests the maximum temperature occurred near X=48.5 inches. To determine whether a correlation exists between the maximum temperature and the excited pulsations amplitude, the $\alpha$ dependences of these two quantities upon are presented in Fig. 33. The data show that the amplitude of pulsations increases as the the maximum temperature increases and vice versa. While no final conclusions can be drawn from the data presented in Fig. 33, they suggest the existence of a relationship between the magnitude of the attained maximum temperature and the driving of pulsations.
Figure 33 Dependence of the Amplitude of Pulsation $P'$ and the Steady State Temperature Measured at $Z=48.5''$ Upon the Nondimensional Air/Fuel Ratio $\alpha$ Measured in Tests Conducted at fixed Relative Amount of the Combustion Air Streams and a 4.20gm/sec Fuel Oil No.2 Input Rate.
SUMMARY

This study has demonstrated that Rijke type pulse combustor can burn both light and heavy liquid fuels efficiently with low excess air values and low concentrations of pollutants in the combustion products. Successful performance of the developed LRPC requires that most of the combustion process energy be released at a distance of L/4 from the combustor entrance, where L is the combustor length. Two practical combustion stabilization methods have been developed. The first requires the establishment of a two phase gas-liquid flow in the fuel feed line by either pre-vaporizing some of the liquid fuel or premixing the liquid fuel with air or methane. The second stabilization method involves tangential injection of most of the combustion air and all of the fuel into the combustor in order to establish a recirculation region which stabilizes the combustion process near the injection point. The second method is superior to the first one and it produces satisfactory combustor operation over wide ranges of fuel input rates and air/fuel ratios. The performance of the combustor is, however, sensitive to the relative amounts of axial and tangential combustion air flow rates.

The effect of insulating the combustor walls with a refractory material was also investigated. A comparison of the performances of identical insulated and uninsulated LRPC revealed that the addition of refractory material decreased the heat losses through the combustor walls and increased the gas temperature inside the combustor. The presence of refractory material increased, however, the acoustic losses of the system which, in turn, decreased the amplitudes of the excited pulsations. It appears that any potential increase in driving of the pulsations, due to higher reaction rates inside the insulated combustor, could not compensate for the increased damping provided by the refractory material.

An investigation of the driving mechanisms in the developed combustor has shown that there exists a strong correlation between the spectra of the radiation and pressure oscillations. Large amplitude resonant pulsations are excited in the combustor when the radiation spectrum contains peaks (not necessarily of large amplitudes) at frequencies corresponding to acoustic resonances of the combustor. On the other hand, peaks in the radiation spectrum at nonresonant frequencies of the combustor do not drive pressure at these frequencies because they do not possess the energy required for driving nonresonant pressure oscillations.
oscillations in the combustor. The applicability of Rayleigh's criterion has been investigated extensively using fuel oils Nos. 2 and 5 over wide ranges of fuel input rates and air/fuel ratios. Rayleigh's criterion was satisfied in every one of these tests; that is, the amplitude of the excited pulsations increased as the magnitude of Rayleigh's integral increased and vice versa. Furthermore, the amplitude of the excited pulsations increased as the phase difference between the pressure and heat addition oscillations decreased. Finally, the measured data suggest that the amplitude of the excited oscillations increases as the maximum gas temperature inside the combustor increases.

The results described in the above paragraph indicate that the driving mechanisms in the developed LRPC are strongly dependent upon the processes which are responsible for the formation of the various peaks in the radiation spectrum. The latter may depend upon a feedback mechanism between the reaction rate and combustor flow oscillations. Since the scale up of the developed combustor, its application in the combustion of solid and gaseous fuels, and its application in special processes (e.g., gasification) will require that the mechanisms which control its operation be understood, it is strongly recommended that these mechanisms be investigated in a follow up research program.

Considerations of the flow field inside the developed Rijke combustor and previous experience with other pulse combustors and unstable ramjet combustors\textsuperscript{18,19} suggest that the driving of the pulsations inside the developed LRPC is produced by unsteady combustion inside vortical structures which produces a periodic expansion process. Such vortical structures generally occur inside a shear layer when the unstable Strouhal numbers of the shear layer occur over a range of frequencies which includes the frequencies of some natural acoustic modes of the combustor. It is conjectured that such reacting vortical structures could occur inside the developed LRPC in the shear layers which form in the vicinity of the recirculation region. Since the proposed mechanism is quite complex, and since it is believed that the driving mechanisms in the developed combustor during the combustion of different fuels are similar, it would be reasonable to simplify the investigation of the driving mechanism by investigating initially the combustion of gaseous fuels in a Rijke pulse combustor having design characteristics similar to those of the
developed combustor. This will permit the determination of the characteristics of the combustor flow field and driving mechanism without having to deal with any problems resulting from the interference of liquid drops with the measurements. Once an understanding of the characteristics of the flow field and driving processes in the gas burning Rijke pulse combustor will have been developed, the investigation could proceed with the investigation of the flow field in the LRPC during the combustion of light and heavy liquid fuels.
REFERENCES


INVESTIGATION OF THE MECHANISM IN RIJKE PULSE COMBUSTORS WITH TANGENTIAL AIR AND FUEL INJECTION

Final Report

By B. T. Zinn, J. I. Jagoda, B. R. Daniel, and T. Bai

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For

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Project Summary

The three year's research, under DOE Contract No. DE-AS04-85AL31881, focuses on the investigation of the mechanisms that control the driving of pulsations in the liquid fuel burning, Rijke type, pulse combustor developed under a preceding DOE contract.

The combustor consists of a vertical steel tube with two decouplers at both ends. Most of the combustion air and all the fuel enter the combustor through a developed air/fuel injection system, which is attached to the combustor tangentially and generates a swirling flow inside the combustor tube.

To study the mechanisms that control the operation of this combustor, an experimental setup is developed with access for detailed optical measurements. Propane is employed as fuel because the absence of liquid drops and combustion generated particulates in the combustion region significantly simplifies the optical diagnostics. The experimental techniques utilized include acoustic pressure measurements, space and time resolved radiation measurements, steady temperature measurements, exhaust flow chemical analysis, high speed video and intensified images of the reacting flow field by a computer based CCD camera imaging system.

Flow visualization by the imaging system and the results from radiation intensity distribution measurements suggest that the periodic combustion processes caused by periodic vortex shedding and impingement provide the energy required to sustain the pressure oscillations. High radiation intensity occurs during a relatively short period of time and is in phase with the pressure oscillations, indicating that Rayleigh's criterion is satisfied.

Periodic variations of the air and fuel flow rates and, consequently, the air/fuel ratio of the reacting mixture inside the combustor appear to be another mechanism that contributes to the occurrence of periodic combustion and heat release processes. The presence of this mechanism has been uncovered by acoustic pressure measurements that revealed the presence of travelling pressure waves inside the air and fuel feed lines. These travelling waves produce periodic fuel and air feed rates which, in turn, result in periodic combustion and heat release processes within the combustor.
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INTRODUCTION

This report summarizes the accomplishments of DOE Contract No. DE-AS04-85AL31881. This three year investigation started in August 1989 and its objective was to elucidate the mechanisms that control the driving of pulsations in the liquid fuel burning, Rijke type, pulse combustor developed under a preceding DOE contract\(^1\), see Fig. 1. It was demonstrated in that contract that the developed Rijke type pulse combustor can burn a variety of light and heavy liquid fuel oils with high combustion efficiencies while using low excess air, which produces high thermal efficiencies.

Since the elucidation of the driving mechanism in the Rijke pulse combustor required the use of optical diagnostics (e.g., radiation measurements), it was decided to perform these investigations in a Rijke pulse combustor that burned propane instead of a liquid fuel in order to avoid difficulties that are often encountered due to the presence of liquid droplets in the combustion region. Consequently, an effort was made to develop a Rijke pulse combustor that is similar to the one developed in the preceding program and demonstrated similar performance characteristics. Such a pulse combustor was developed in the early phases of this program, and it is shown in Fig. 2. The developed experimental setup was provided with capabilities for measuring steady combustor temperature distributions, the characteristics of the excited pressure oscillations, the exhaust flow composition, the characteristics of the flow field and the reaction rates. This pulse combustor consists of a cylindrical tube that is attached to a decoupling chamber at each end. Fuel and air are supplied via a tangential air/fuel injection system that is located at a distance of L/4 from the combustor entrance, where L is the combustor length. Part of the combustor tube, where combustion occurs, is water cooled. This section is also equipped with flat quartz windows to permit optical diagnostics. Two windows are installed on the walls of the rectangular injection duct that supplies the reactants into the combustor tube and additional windows are installed on the walls of the combustor tube section, in the immediate vicinity of the reactants injection system.

This setup was first used to investigate the characteristics of the combustion region and the unsteady heat release process. The former was investigated with the aid of an intensified imaging system that measured the spatial distribution of emitted radiation. It revealed the presence of radiation patterns having the
appearance of large coherent vortex structures immediately downstream of the air/fuel injection plane. The visualization studies were complemented by measurements of the time and space dependencies of radiation intensities, which were used to determine the characteristics of the investigated combustion process and heat release rates. These showed that the reaction and heat release processes were periodic and in phase with the pressure oscillation, which satisfied Rayleigh's criterion for driving the pressure oscillations by a combustion process.

The setup was then used to investigate the mechanisms responsible for the driving of the pulsations. This study revealed the presence of traveling acoustic waves in both the fuel and air feed lines during pulse combustor operation. These traveling waves are induced by the pressure oscillation in the combustor and they propagate in a direction opposite to that of the air and fuel flows. Calculations based upon measured data showed that these traveling waves produce oscillatory fuel and air injection rates that, in turn, produce periodic variations of the air/fuel ratio and reaction rate inside the combustor. Pulse combustion operation occurred when the oscillatory heat release process had a component in phase with the pressure oscillation.

To verify that the modulation of the fuel and air supply rates by the combustor pressure oscillations was an important element of the driving mechanism, the combustor performance was investigated under operating conditions that prevented wave propagation in the fuel and air supply systems. This was accomplished by choking the flow leaving either the fuel or the air supply line, or both. These tests provided improved understanding of the driving mechanism.

Finally, an investigation of the velocity field in the combustion zone was initiated, and is currently in progress. This study uses a Laser-Doppler Velocimeter (LDV) system to determine the characteristics of the steady, acoustic and turbulent velocity components in specific regions of the combustion zone. The objective of these measurements is to obtain velocity data that could be used to improve the understanding of pulsating combustion processes, and verify a previously advanced hypothesis regarding the characteristics of the flow in the combustion region, which is needed to complete the description of the driving mechanism.

This research program has been divided into the following five tasks: (I) development of a Rijke pulse combustor setup suitable for detailed investigation of combustor performance and driving mechanism, (II) determination of the
combustion zone structure and reaction rates characteristics by use of an intensified imaging system, (III) determination of the flow characteristics of the combustion zone by use of various visualization techniques, (IV) determination of reaction rates by radiation measurement, and (V) determination of the combustion zone velocities by use of LDV. The accomplishments of the four tasks are briefly discussed in the remainder of this report while the results of the fifth task will be discussed in a following report after this task is completed.

ACCOMPLISHMENTS

Task I: Development of the Rijke Pulse Combustor

1. Determination of Combustor Design Parameters and Configuration

Initial efforts under this contract were concerned with the development of a pulse combustor setup that was suitable for the proposed investigations of the performance driving mechanisms of the previously developed liquid fuel burning Rijke pulse combustor, see Fig. 1. These objectives required that the developed pulse combustor be geometrically similar to the previously developed Rijke pulse combustor, that it possess optical access for visualization studies, and capabilities for measuring radical radiation, velocities, temperatures and pressures. Finally, the developed Rijke pulse combustor was designed to burn gaseous fuels in order to eliminate interference from liquid drops and combustion generated particulates in the combustion region with the proposed optical diagnostics.

First, to determine whether the previously developed pulse combustor could burn propane and whether its performance while burning propane was similar to its performance while burning liquid fuels, the liquid fuel burning Rijke pulse combustor was modified to operate on propane. Various gas/air injection systems were tested, and the results were used to guide the design and development of the new pulse combustor setup. In addition, the systematic study of different injector configurations resulted in a better understanding of the driving mechanisms in this pulse combustor.

This study also investigated the performance of the pulse combustor when it was retrofitted with various injection systems that burned the reactants in premixed or diffusion type flames, see Figs 3 and 4. In addition, tests were carried out with the reactants injected tangentially or radially into the combustor tube.
In the premixed fuel injection system, see Fig. 3, two fuel jets are injected normally into an air stream through openings in the side walls of a small mixing cavity. The resulting mixture enters a rectangular duct of width, height and length of 1.6", 3.6" and 6.0", respectively. Combustion generally started in the mixing duct and it was completed in the combustor tube. Tests were conducted with the reactants entering the combustor tube either tangentially or radially, with different air/fuel ratios. The results are discussed in Ref. 2.

In the diffusion flame injection system, see Fig. 4, the mixing cavity was removed and the fuel and air were injected into the rectangular duct through two concentric tubes with the fuel tube located inside the larger air tube. This injection system was tested with the reactants entering the combustor tube either tangentially or radially. The results are presented in Ref. 2.

Additional tests investigated the dependence of the combustor performance upon the combustor length (which was varied between 60 and 120 inches), the boundary conditions (e.g., the effect of closing the upper end of the combustor, which eliminated the axial air flow and established a "solid wall" acoustic boundary condition at the upper end of the combustor, see Fig. 5), the location of air and the fuel injection system (e.g., see Fig. 6), and the manner in which the air/fuel mixture enters the combustor (e.g., see Fig. 7).

2. Development of the Pulse Combustor Setup

A schematic and a photograph of the pulse combustor and its two supports are presented in Figs. 8 and 9, respectively. The developed pulse combustor is operated in a horizontal rather than the vertical orientation in which the original pulse combustor, see Fig. 1, was operated. This facilitates mounting and traversing of the pulse combustor in the optical diagnostic station without affecting its performance characteristics. The pulse combustor consists of several steel pipe sections, a water cooled reactants injection and a combustion section that is equipped with quartz windows to permit optical diagnostics, and two decoupling chambers. Each decoupler is resting on a support and translation system that can move the combustor along three, mutually perpendicular, axes, see Fig. 10. Using this support arrangement, any combustor section can be moved onto the probe volume of the measurement system. The operation of the developed pulse combustor setup is controlled by the reactants supply systems, ignition system, safety system and the control panel shown in Fig. 11.
Since most of the planned measurements required optical access into the injection and combustion section, this section was fitted with strategically placed, flat windows, see Figs. 8 and 12. The rectangular injection duct that supplies the reactants into the combustor tube has optical windows on two of its walls, and it is attached to the combustor tube in a manner that forces the reactants to be injected tangentially into the combustor. Two additional round windows whose diameter equals that of the combustor tube are installed at the end walls of the two decouplers to allow viewing the combustion process along the axis of the combustor tube. The combustor is also equipped with 21 measurement ports along its axis, which are used for steady temperature and dynamic pressure measurements. Finally, the developed combustor permits the employment of different fuel injection systems and different fuels.

This combustor can be operated with energy input rates up to 400,000 Btu/Hr. Since most of this energy is released in the vicinity of the injection point, this section of the combustor is cooled by six water jackets, see Fig. 13. Those water jackets are connected into two groups of pipes with approximately equal flow resistance to keep the same cooling water flow rates through the two groups of water jackets.

The combustor is ignited with an oxygen/propane pilot flame generated by an ignitor specifically designed for this system. The ignitor is mounted on the side wall of the rectangular duct and it is constructed of a stainless steel cylindrical combustion chamber with a spark plug threaded into its end wall, see Fig. 12. Ignition is attained by turning the spark plug on and feeding small flow rates of oxygen and propane into the cylindrical chamber. These streams mix and the resulting mixture is ignited by the spark plug. The resulting flame enters the rectangular injection duct through a 1/4" diameter hole. Once this flame is established, a stream of reactants is injected into the rectangular duct where it is ignited by the oxygen/propane flame.

To avoid an explosion, a rupture disc has been installed on the upstream decoupler. This rupture disc is designed to break and vent the system once the pressure inside exceeds a certain threshold. The safety system also employs a detector which monitors the UV radiation from the combustion zone and is programmed to cutoff the fuel flow to the combustor as soon as combustion there stops. This prevents the formation of an explosive mixture inside the combustor after an accidental flame extinguishment.
Generally, the mode of operation of the combustor were determined from measured acoustic pressures, which were measured with Kistler model 211B5 piezoelectric pressure transducers. Each transducer has been mounted on a "semi-infinite" tube to prevent heat damage to the pressure transducer from the hot gases and flames inside the combustor, and to provide a measuring probe with a flat frequency response. In this arrangement, the pressure transducer is mounted at the end of a 2 feet long .25" diameter stainless steel tube which is attached at one end to the combustor wall and to a plastic tube which simulates a "semi-infinite" tube at its other end. The pressure transducers are calibrated before a test together with their "semi-infinite" probes. A high-level, low impedance output signal with the resolution on the order of one part per 20,000 of full scale range is generated by the utilized pressure transducers with a sensitivity independent of cable length or capacitance. The measured signals are amplified by a Kistler model 504E Dual Mode Amplifier, and the variable gain output of this amplifier ensures voltage levels adequate for computer based data acquisition.

**Task II: Development of the Intensified Imaging System**

1. **System Description**

The intensified imaging system was used to obtain intensified, gated, images of flame radiation measurements and for flow visualization. The imaging system basically consists of a intensified CCD camera and a computer system. The CCD camera was supported by a tripod at a distance of approximately two feet from the quartz window. A Nikon 28 mm wide angle lens was used to focus the observed object onto the image plane, the CCD array plane. The spatial resolution of the camera is 128 x 128 pixels with an adjustable temporal resolution down to 50 nanoseconds. In addition, up to four channels of analog data can be acquired simultaneously with the images.

A technique has been developed in which the pressure signal recorded simultaneously with the images is used as a clock. This permits recording of images at the same phase in the cycle during successive cycles in order to determine the cycle to cycle repeatability of the combustion process. In addition, images obtained at different instances over many cycle can be ensemble averaged and sorted into chronologically sequential events describing the location of re-ignition and the shape of the flame spread in order to quantify the local flame
speed at different instances during the cycle by calculating the phase angle between the local radiation and pressure fluctuations.

2. Measurements

The intensified imaging system has been used to obtain C-H radical radiation and broad band visible radiation data, which are proportional to the reaction rates at the measurement locations. The utilized setup is shown in Figs. 14 and 15. During the tests, an acoustic pressure signal measured in the duct was amplified and sent into the computer through one of four analog signal input ports. This pressure signal was used as a clock to determine the phase of the image relative to the pressure oscillation. In most of the tests, the sampling rate of the imaging system was set at 503 frames per second and for each frame the exposure time was 50 microsecond. These tests were used to obtain distributions of the C-H and the broad band visible radiation intensity when the combustor oscillated at its fundamental mode and its first harmonic, and when the combustor was operated in a steady mode. In the following, some of the results are briefly discussed. More details can be found in Ref. 2 and 3.

Sequences of the broad band visible radiation intensity distribution images obtained in different cycles are presented in Figs. 16 through 20. These images were obtained when the 99 Hz fundamental mode oscillation was excited in the combustor. The combustor was operated with a fuel input rate of 0.94 SCFM and nondimensional air/fuel ratio $\alpha$ of 1.35. The system sampling rate was approximately 5 frames per cycle. These images show the instantaneous distributions of the radiation intensity and their changes during a cycle. An examination of the images in Figs. 16-20 suggests that during a given cycle combustion begins inside two small, vortex-like, structures that grow in size as they are convected downstream. These structures merge with each other at a distance (approximately) $Y=7D$, where $D$ is the injection duct diameter, downstream of the entrance to the injection duct, resulting in intensification of the rate of combustion to its maximum level. The reaction rate decreases during the remainder of the cycle to the point where only very low radiation is present at the end of the cycle. This process repeats itself from one cycle to another, see Figs. 16 through 20.

More detailed information about the evolution of the vortex-like structures and the periodic combustion process in the air/fuel injection duct was obtained by using the imaging system in a stroboscopic mode. This technique was developed
earlier under this program. The images obtained using this technique under the same operating conditions as those discussed above are presented in Fig. 21. It provides 25 views for one cycle. An analysis of these images supports the conclusions derived from the above discussed images.

Broad band visible radiation measurements were also conducted when the combustor was operated in a steady mode (i.e., no pulsations were present in the system). The images obtained under this operating conditions, using a 503 frames per second sampling rate, are presented in Fig. 22. An examination of these images indicates that no coherent flow structures are present in the combustion zone and that the combustion process has the characteristics similar to those of a turbulent, steady, jet flame. Furthermore, similar radiation intensity distributions appear in all the images, suggesting the lack of any periodic phenomenon.

Task III: Radiation Measurements

1. Development of the Radiation Measurement System

An optical system for measuring the total radiation emitted by the combustion zone (i.e., global), and that emitted from specific regions was developed, see Figure 23. These data were then used to determine the reaction rates under various operating conditions. A photomultiplier tube, Hamamatsu model R-268, is used to measure the radiation emitted from the flame because of its high frequency response and broad band spectral response. The photomultiplier views the combustor section that has quartz windows through an optical arrangement that permit measurement of the radiation passing through a local area of 0.7" x 0.7". The radiation measurement system is mounted on a translation mechanism that can move in two direction and permits measurements of the X- and Y- dependencies of the flame radiation. By choice of appropriate filters, C-C, C-H and O-H radiation can be measured.

2. Measurements

In this section typical measured C-H radiation data is discussed; detailed discussions of all the measurements can be found in Refs. 1 and 2. The data discussed in this section was obtained in tests with the premixed air/fuel injection system, a propane input rate of 1.6 SCFM and nondimensional air/fuel ratio $\alpha$ of 0.97. The results are presented in Figures 24 and 25. These data represent averages of results obtained in two tests which were highly repeatable. The
measured signal were periodic indicating that the reaction rate in the pulse combustor is periodic. The measured data were analyzed with a FFT software to obtain the amplitudes and phases (with respect to the local pressure oscillations) of the radiation signals. Under this operating condition, the combustor pulsations were dominated by the first harmonic of the combustor tube which whose frequency and pressure amplitude equaled 218 Hz and 166 dB, respectively.

An examination of the data in Fig. 24 indicates that the amplitude of the C-H radiation along the centerline of the injection system increases from nearly zero along an initial distance of 2D, where D is the injection port diameter, to a maximum value at a distance of 7D downstream of the injection point. After reaching a maximum value at Y=7D, the amplitude of the radiation decreases as Y further increases. On the other hand, the amplitudes of the radiation in the vicinity of the side walls of the injection duct are always low. These results indicate that combustion begins at a distance of about 3D from the injection port and that the highest heat release rate occurs in a region between approximately 3D and 7D; that is, in a region located between 2.1 and 4.9 inches downstream of the injector.

Figure 25 presents phase differences between the local radiation and pressure oscillations measured in the above discussed tests. Since the magnitudes of the radiation signals measured close to the injection point were in the range of the background noise, the phases of these signals (i.e., the data in the first row of Fig. 25) are not meaningful. An examination of the phase difference data in Fig. 25 indicates that the phase difference between the radiation and pressure oscillations along the injection duct centerline increases monotonically from -56.3 to +60.3 as Y increases. Examination of the phase variations along the side walls of the injection duct shows that the phase there decreases as Y increases when 2D<Y<5D, reaching a minimum value at Y=5D, and it increases thereafter. These trends suggest that combustion may first occur near the walls in the vicinity of the Y=5D location and it propagate from there simultaneously upstream and downstream towards the injection port and the combustor, respectively.
Task IV: Visualization Studies

1. Schlieren Method Tests

A Schlieren system was set up to take high speed Schlieren movies of the reacting flow field, see Fig. 26. By recording the density variations in the reacting flow field, the high speed Schlieren movies provide descriptions of the main features of the reacting flow field and their time evolution.

At the outset of these efforts, it was expected that the Schlieren movies would reveal the presence of vortex structures similar to those that characterized the radiation patterns measured by the imaging system. It was also expected that the high speed Schlieren movies would provide better descriptions of the temporal variations of these vortical structures. However, the classical Schlieren setup failed to produce satisfactory images of the reacting flow field, because the intense heat transfer from the combustion process caused the quartz windows to deform, unfocusing the Schlieren beam.

To resolve this problem, an attempt was made to cool the windows with flowing nitrogen films. These films were expected to increase the resistance to convective heating of the windows by the hot gases while simultaneously cooling the hot windows. The cooling films were injected via a new .5 mm slots in drilled in a new injector mounting plate, see Fig. 27. Room temperature nitrogen was chosen because it is inert and was not expected to affect the reaction process.

Unfortunately, the nitrogen cooling failed to produce satisfactory results. With low nitrogen injection rates, which produced film velocities below 30 m/sec, the cooling was inadequate and no significant reduction in window deformation was observed. When the nitrogen flow rate was increased to produce film velocities of 100 m/sec, the deformation of the quartz glass was significantly reduced. However, when the film velocities increased to these magnitudes, the nitrogen flow apparently interfered with the combustion processes inside the injection duct, resulting in unstable pulsations with constantly varying amplitudes and frequencies.

Another effort was made to resolve this problem. A modified Schlieren, which attempted to restore the fidelity of the images by optically "subtracting" the image distortion caused by the windows\(^2,3\), was developed. Tests using the modified Schlieren system were performed for a large number of different combustor operation conditions. A conventional high speed movie camera and a
high speed video motion analyzer with a short exposure time were used to record the Schlieren images. The resulting images showed the presence of a reaction zone similar to that of a turbulent flame and the absence of any periodic phenomena, such as vortex structures. These observations are in contrast with the radiation intensity measurements that strongly suggested the periodic formation of reacting vortices within the combustion region played a key role in the driving of the pulsations.

2. Flow Visualization with a High Speed Video System

Another effort to visualize the flow field and combustion process was made by directly recording images of the combustion zone with a high speed video camera. The high speed video camera utilized in this study was a Kodak EktaPro EM Motion Analyzer, see Fig. 28. The system consists of an intensified imager, an intensified imager controller, a processor, a video cassette recorder and a video monitor. The Kodak EktaPro Intensified Imager has a spatial resolution of 192 x 239 pixels and a spectral response from 440 nm to 700 nm. It can be operated at speeds ranging from 30 to 6000 frames per second and exposure times of 10 microseconds to 5 milliseconds. The processor, Kodak EktaPro EM Process Model 1012, can store 1000 full frame images and up to 12,000 split frame images. Images obtained by the intensified imager are first stored in the processor and then played back at a desired rate. The playback rate can vary from 0 to 960 frames per second. A video monitor, Kodak EktaPro 1000 Monitor, was used to display the video images and a video cassette recorder was used to down load the images to a video tape for further analysis.

The video images obtained in these tests were similar to those obtained by the imaging system earlier under this program. In order to obtain more information about the flow field, images were obtained by seeding the flow field with aluminum oxide particles. The objective of this method was to obtain a description of the flow field by tracking the radiation from the heated particles. Images obtained by this method suggested that two vortex-like structures are formed early in the cycle. These structures expand as they are convected downstream until they merge and occupy most of the flow region. Simultaneously, the intensity of the radiation from the flow increases in magnitude and it reaches a maximum value as the structures coalesce. After that, the structures decrease in size and their radiation intensity diminishes.
Driving Mechanism Studies

1. Existence of Traveling Waves in the Air/Fuel Feed Lines

This study investigated the possibility that pressure oscillations inside the air and fuel feed line produced periodic air and fuel supply rates into the combustor that were responsible for the formation of a periodic heat release process that drove the combustor pulsations. Acoustic pressure measurements revealed the presence of traveling pressure waves inside the air and fuel feed lines. Since the fuel and air velocities inside the feed lines were subsonic, the combustor pressure oscillation produced disturbance that propagated with the speed of sound in the upstream direction along the fuel and air feed lines. To investigate this phenomenon, the measured pressures were Fourier analyzed to obtain their amplitudes, frequencies and the phases. In the following, some of the results are briefly discussed in an effort to explain how these traveling pressure waves contribute to the driving of the oscillations in the developed combustor; additional results are presented in Refs. 2 and 3.

Figure 29 presents data obtained in a test in which the fundamental acoustic mode of the combustor tube was excited. It shows that the amplitudes of the traveling pressure wave decayed with distance away from the opening of the 0.75 inch inside diameter air feed line. Furthermore, the phase of the traveling waves increased linearly with the distance from the air injection point. The data obtained when first harmonic of the combustor was excited is presented in Fig. 30. The trend is similar to that exhibited in the fundamental mode case. Similar data measured in fuel feed line are presented in Figs. 31 and 32. The observation that the phase varies linearly with distance along the feed lines suggests that the measured oscillations are traveling pressure waves that propagate at a constant speed inside both the air and fuel feed lines. Calculations of the speeds of sound in air and propane and the average velocities (based upon measured volume flow rates and cross-sectional areas of the feed lines) have supported the above conclusion. The predicted traveling wave propagation speeds were in excellent agreement with the experimental data.

2. Air and Fuel Injection Rate Modulation and Periodic Combustion

The changes in the combustor pressure were transmitted upstream into the air and fuel feed lines as traveling waves through the fuel and air injection ports. Hence, the fluctuating components of the particle velocities near the fuel and air
injector were directed into the combustor when its pressure was below average and away from the combustor when its pressure was above average. Using calculated impedances of air and propane and measured acoustic pressure amplitudes, the acoustic velocities in the fuel and air lines were calculated. Figure 33 shows the dependencies of the acoustic velocity amplitudes in air and propane upon the amplitude of pressure oscillation in dB. It shows that when the amplitude of the pressure oscillation is around 170 dB, the amplitudes of the acoustic velocity oscillations in the propane and air lines are 19 m/sec and 23 m/sec, respectively.

By superposition of the acoustic velocities upon the mean flow velocities the fluctuating fuel and air feed rates into the combustor were calculated. They showed that fuel and air injection rates into the combustor varied periodically during a cycle. The relative amounts of fuel and air flow rates injected into the combustor during the first (i.e., when the combustor pressure was "positive") and second (when the combustor pressure was "negative") halves of the pressure oscillation cycle were determined by the ratio of the amplitudes of acoustic velocities to the mean injection velocities of the air and fuel. Some of the calculated results are shown in Fig. 34. This figure indicates that as the ratio of the acoustic velocity to the mean injection velocity increases, the relative amounts of air and fuel injected during the “positive” and “negative” half cycles of the oscillations decrease and increase, respectively. For example, when the amplitude of the acoustic velocity equals to the mean injection velocity, more than 82% of the total air or fuel is injected into the combustor in the “negative” half of the pressure oscillation cycle.

In summary, traveling pressure waves excited inside the air and fuel feed lines induce fluctuations of the fuel and air injection velocities, which, in turn, produce oscillatory propane and air injection rates. As a result, the majority of the fuel is always injected into the combustor in the “negative” half of the cycle. This periodic variation of the fuel injection results in a periodic variations of the combustion region air/fuel ratio, the reaction and heat release rates. However, whether this periodic heat release process can drive combustor pressure oscillation depends upon the phase difference between the heat release and pressure oscillations. According to Rayleigh's criterion, driving of pressure oscillations occurs when the magnitude of this phase is smaller than ninety degrees.
3. Driving Due to Air and Fuel Injection Rates Modulation

As mentioned previously, the phase of the maximum heat release occurs during the phase when the "maximum" injected amount of fuel is burned. This "Excess" fuel is always injected into the combustor during half the cycle when the acoustic pressure is negative. The time when the "excess" fuel energy is released relative to the pressure oscillation depends upon the delay time between fuel and air injection and the instant of energy release. For the developed premixed type injection system, the characteristics of this delay time are largely determined by the characteristics of the chemical time, which is dependent upon the air/fuel ratio. Consequently, the air/fuel ratio when the "excess" fuel is injected into the combustor will determine the phase of the maximum heat release and, thus, determine if driving will occur. Driving occurs when this maximum heat release is in phase with the maximum pressure amplitude. The excited pressure oscillation affects the air and fuel injection rates which, in turn, controls the air/fuel ratio modulation and, thus, the phase of maximum heat release, which completes the feedback loop.

4. Investigation of the Mode-Shifting Phenomenon

It was found that, when the premixed injector is used, fundamental modes oscillations are excited in the combustor at low air/fuel ratios and they are replaced by first harmonic oscillations as the air/fuel ratio α is increased, see Fig. 35.

The excitation of different mode oscillations at different values of α with the premixed type injector may be explained by considering the characteristic times that control the combustion process and the characteristics of the excited combustor modes. According to Rayleigh's criterion, an unsteady heat release process will drive a given combustor mode if it has a component in phase with the mode's pressure oscillation, and if the heat is released in a region of the combustor where the pressure amplitude of this mode is significant. It can be also shown qualitatively that in order to drive a given mode, the combustion time, which depends upon the convection, mixing and reaction times, must approximately equal half the period of the oscillation of the excited mode. Thus, a given combustion process will drive those modes for which the above stated conditions are satisfied. The observation that the pulse combustor operates at its fundamental and first harmonic modes at fuel rich and fuel lean conditions,
respectively, strongly suggests that the characteristic combustion time decreased as the value of $\alpha$ increased.

The above described mode shifting can be explained by the following conjecture. In the reported tests, $\alpha$ was increased by increasing the air flow rate. This, in turn, increased the velocity of the reactants entering the injection duct, which reduced the time required for the reactants to reach the combustion region. In addition, the high flow velocities increased mixing rates between fresh reactants, combustion products and reacting pockets left over from the previous cycle. These effects are expected to decrease the characteristic combustion time. As the combustion time decreased, its magnitude became considerably smaller than half the period of the fundamental combustor mode and it approached the magnitude of half the period of the first harmonic of the combustor. Since the above stated time condition requires that the combustion time approximately equal half the period of the oscillation, the first harmonic of the combustor was excited as the air/fuel increased because of the decrease in the combustion time produced by the increase in the air/fuel ratio. This conjecture is schematically described in Figure 36. This conjecture was supported by calculations of the characteristic times for two test conditions in which the fundamental and first harmonic modes were excited\textsuperscript{2,3}. The characteristic time calculated for each of these test conditions approximately equaled half the period of the excited oscillations.

5. The Role of Traveling Waves in the Reactants Feed Lines.

Modulation of the air and fuel injection rates into the combustor and vortex shedding were identified as two important components of the driving mechanisms. It was not clear, however, whether these processes depend upon one another or whether they can drive pulsations independently. To resolve this question, tests were conducted in which the modulation of the air and/or fuel injection rates was eliminated by installing sonic orifices in the air and/or fuel feed lines, see Figure 37(a). It was, thus, possible to determine whether pulse combustion operation is possible in the absence of such modulations. If this was the case, then it would follow that the pulsations could be driven by some other mechanisms, such as vortex shedding. Furthermore, the effect of modulations in the reactants flow rates upon the combustor performance was investigated by comparing the combustor performance in the presence and absence of such modulations.
This study consisted of four series of tests in which different combustor configurations were utilized, see Table 1. In each of these tests one or both reactant injection rates were choked by use of sonic orifices, and the choking of the line was verified by pressure measurements that showed that no disturbances were present in the feed line upstream of the orifice.

The first series of tests investigated the effect of choking the fuel line with a sonic orifice upon the combustor performance. These tests investigated the dependence of the amplitudes of the excited combustor modes upon the nondimensional air/fuel ratio at a fixed propane input rate of 1.5 SCFM. The effect of choking the fuel line was determined by comparing the resulting combustor performance with its performance under normal operating conditions. This comparison showed that choking the fuel lines significantly changed the combustor performance, see Figures 38 through 41. In the absence of fuel line choking, both the fundamental and first harmonic longitudinal modes of the combustor were excited with the former attaining its maximum amplitude at $\alpha=1.5$ and the latter at $\alpha=1$. When sonic orifices were installed in the fuel lines, the maximum amplitude of the fundamental and first harmonic of the longitudinal modes of the combustor were excited at $\alpha=0.7-0.8$ and $\alpha=1.0-1.1$, respectively, and pulse combustor operation was not attained beyond $\alpha=1.45$.

The second series of tests investigated the effect of choking the air line and choking both the fuel and the air lines upon the combustor performance. Table 2 summarizes the results of these tests. It was found that when only the air feed line was choked, unstable pulse combustion operation was possible in a very narrow range of $\alpha$. However, when both the air and fuel lines were choked, pulse combustion operation was not possible.

In the third series of tests, the performance of the combustor was studied by moving the sonic orifice in the air feed line 12 inches upstream of its original position. This modification changed the acoustic characteristics of the air supply system and the performance of the pulse combustor. The results of these tests are presented in Figs. 42 and 43. They show that when both the air and fuel sonic orifices were installed at the end of the feed lines, pulsations were not excited. However, when the sonic orifice was installed 12 inches upstream of its original position, the fundamental and first harmonic modes of the combustor were excited at various ranges of $\alpha$.

In the last series of tests, an attempt was made to eliminate the air and fuel flow rate modulations without significantly changing the flow field in the
its original position, the fundamental and first harmonic modes of the combustor were excited at various ranges of $\alpha$.

In the last series of tests, an attempt was made to eliminate the air and fuel flow rate modulations without significantly changing the flow field in the injection duct. When the air line was choked, the 0.28 inches diameter sonic orifice was installed approximately 1.5 inches above the mixture injection orifice whose diameter equaled 0.7 inches, see Figure 37(a). Therefore, the sonic air jet could pass through the mixture injection orifice undisturbed. In the modified design, an impingement plate was installed in the reactants mixing chamber 0.35 inches downstream of the air line orifice, see Figure 37(b). The impingement plate consisted of a round metal sheet of 0.4 inches in diameter and it was attached to the air injector by three legs. In this configuration the sonic air jet was forced to impinge upon the plate before mixing with the fuel, which should have prevented the air jet from passing through the mixture injection orifice undisturbed. Four comparable tests were conducted, and the configuration of Figure 37(b) was used in two of these tests. The results are presented in Table 3 and Figures 44 through 47. A comparison of these results with the observations from Test No. 3 in Table 2 reveals that the impingement plate significantly changed the combustor performance. When the plate was absent and the air line was choked, no stable pulsations were obtained, see Test No. 3 in Table 2. In contrast, when the plate was installed, high amplitude stable pulsations were obtained for both the fundamental and first harmonic modes, see Figure 46. These results indicate that the characteristics of the flow fields in the mixing chamber and in the injection duct play an important role in the driving of the pulsations. Finally, it should be noted, see Figure 47 and Table 3, that no pulsations were excited when both the air and fuel lines were choked, even when impingement plate was present in the injection system, indicating that the air and fuel feed rates modulations are an essential element of the driving mechanisms.

**Laser Doppler Velocity Measurements**

A limited number of laser Doppler velocimeter measurements were carried out in the tangential injection duct in order to gain additional insight into the flow field in that part of the pulse combustor. These measurements were carried out because the radiation images shown in Figs. 16-22 strongly suggest
that the processes that occur in the tangential injection duct are responsible for driving the pulsations in the pulse combustor.

Two components of velocity were measured simultaneously using an Aerometrics, two channel, phase Doppler anemometer powered by a seven watt argon ion laser. This velocimeter includes a pair of Bragg cells that permit the detection of back flow. This is critical in this application. The signal processor of the system uses an FFT routine to determine velocities and their distributions. Aluminum Oxide particles were used to seed the flow.

Velocity distributions in the injection duct in selected planes parallel to the injection plate (see Fig. 2) were measured in cold flow as well as in flow with combustion. The reactants flow rate was kept constant at 47.9 SCFM during these runs. Velocities measured at planes located 2.5 and 3.5 inches downstream of the fuel/air injector are shown in Figs. 48 and 49. In both cases, the flow is dominated by large, downward injection velocity at the center of the duct. At the same time the presence of significant back flow near the wall of the duct indicates the that a large toroidal vortex has been formed around the central jet. This type of flow field is commonly found in sudden expansion dump combustors.

Comparisons of the hot and cold flow data in Figs. 48 and 49 indicate that the pulse combustion process slightly increases the magnitude of both the incoming jet velocity of the reverse flow. In addition, it was observed that presence of combustion reduced the level of turbulence in the flow. A similar observation had been made in measurements behind a backward facing step as part of a different investigation. Given the limited resources, it was not possible to obtain enough velocity data to determine whether vortex shedding occured during any phase of the cycle.
PUBLICATIONS


REFERENCES


Table 1 - Summary of the Test Program

<table>
<thead>
<tr>
<th>Test Sequence</th>
<th>Fuel Flow Rate SCFM</th>
<th>Air Feed Line</th>
<th>Fuel Feed Line</th>
<th>References</th>
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<td>Figure 46</td>
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<td>Figure 49</td>
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<tr>
<td></td>
<td></td>
<td>3</td>
<td>1</td>
<td>Figure 50</td>
</tr>
</tbody>
</table>

0 ---- Regular configuration
1 ---- Sonic orifice installed at the line outlet
2 ---- Sonic orifice installed 12 inches upstream of the line outlet
3 ---- Sonic orifice with impingement plate installed at the line outlet
Table 2 - Summary of Test Sequence No. 2

Fuel: Propane
Fuel Flow Rate: 1.11-1.17 SCFM

<table>
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<tr>
<th>Test No.</th>
<th>Air Line</th>
<th>Fuel Line</th>
<th>Observations</th>
</tr>
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<tr>
<td>1</td>
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<td>0</td>
<td>Stable fundamental and harmonic pulsations. Fund. mode not excited under fuel rich conditions.</td>
</tr>
<tr>
<td>2</td>
<td>0</td>
<td>1</td>
<td>Stable fundamental and harmonic pulsations. Fund. mode readily excited under fuel rich conditions.</td>
</tr>
<tr>
<td>3</td>
<td>1</td>
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<td>Pulsations could only be obtained within an extremely narrow $\alpha$ range and were very unstable.</td>
</tr>
<tr>
<td>4</td>
<td>1</td>
<td>1</td>
<td>No pulsations could be excited over a wide range of combustor operating conditions.</td>
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0 ---- Regular Orifice Installed at the Line Outlet.
1 ---- Sonic Orifice Installed at the Line Outlet.
Table 3 - Summary of Test Sequence No. 4

Fuel: Propane  
Fuel Flow Rate: 1.1 SCFM

<table>
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<th>Observations</th>
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<tr>
<td>1</td>
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<td>0</td>
<td>Stable fundamental and first harmonic pulsations. Fundamental mode at fuel rich was not excited, see Figure 47.</td>
</tr>
<tr>
<td>2</td>
<td>0</td>
<td>1</td>
<td>Stable fundamental and first harmonic pulsations. Fund. mode at fuel rich was easy to excite, see Figure 48.</td>
</tr>
<tr>
<td>3</td>
<td>3</td>
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<td>High amplitude stable pulsations can be obtained for both the fundamental and harmonic modes, see Figure 49.</td>
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<tr>
<td>4</td>
<td>3</td>
<td>1</td>
<td>No pulsations could be excited. Fuel and air flow rates were searched in the widest possible range by changing the upstream pressure, see Figure 50.</td>
</tr>
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</table>

0 ---- Regular Orifice Installed at the Line Outlet.  
1 ---- Sonic Orifice Installed at the Line Outlet.  
3 ---- Sonic Orifice with the Impingement Plate Installed at the Line Outlet.
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Combustor Tube

Fuel and Air Mixture

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Fig. 19 Images of Visible Radiation Intensity Distributions inside the Air/Fuel Injection Duct Obtained with the Imaging System in an Experiment Conducted with a Propane Input Rate of 0.94 SCFM and a Nondimensional Air/Fuel Ratio of 1.35. These Five Frames, from the Left to Right, Were Taken at Equal Time Intervals in a Pressure Cycle next to the One Shown in Fig. 18.
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\[ \tau_{\text{combustion}} = \tau_{\text{species}} + \tau_{\text{convection}} + \tau_{\text{mixing}} + \tau_{\text{kinetics}} \]

**Premixed Type:**

\[ \tau_{\text{species}} = 0 \]

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**Fig. 36**

A schematic of the conjecture for the mode shifting phenomenon.
Fig. 37  Schematics of the injection system configurations utilized in the investigation:
(a) Sonic orifices are installed in the air and fuel feed lines.
(b) Sonic orifices are installed in the air and fuel feed lines. The air injector is modified by the addition of an impingement plate.
Dependence of the amplitude of pulsations of the combustor fundamental and first harmonic mode oscillations upon the nondimensional air/fuel ratio measured in tests with 1.5 SCFM propane input rate and the regular injection configuration.
Fig. 39  Dependence of the amplitude of pulsations of the combustor fundamental and first harmonic mode oscillations and the pressure oscillations in the fuel and air feed lines upon the nondimensional air/fuel ratio measured in tests with 1.5 SCFM propane input rate and the regular injection configuration.
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Fig. 41  
Dependence of the amplitude of pulsations of the combustor fundamental and first harmonic mode oscillations and the pressure oscillations in the fuel and air feed lines upon the nondimensional air/fuel ratio measured in tests with 1.5 SCFM propane input rate and the fuel feed line chocked.
Dependence of the amplitude of pulsations of the combustor fundamental and first harmonic mode oscillations upon the nondimensional air/fuel ratio measured in tests with 1.198 SCFM propane input rate and the air and fuel feed lines chocked.
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Fig. 45 Dependence of the amplitude of pulsations of the combustor fundamental and first harmonic mode oscillations upon the nondimensional air/fuel ratio measured in tests with 1.1 SCFM propane input rate and the fuel feed line chocked.
Dependence of the amplitude of pulsations of the combustor fundamental and first harmonic mode oscillations upon the nondimensional air/fuel ratio measured in tests with 1.1 SCFM propane input rate and the air feed lines choked by the modified impingement plate air injector.

Dependence of the amplitude of pulsations of the combustor fundamental and first harmonic mode oscillations upon the nondimensional air/fuel ratio measured in tests with 1.1 SCFM propane input rate and the air and fuel feed lines choked. The air feed line was choked by the modified impingement plate air injector.
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Fig. 49  Vertical velocity distribution across the injection duct at 3.5 inches from the injection plate. Positive velocities towards the combustor pipe, negative velocities back towards the injector plate.
| ACTIVITY/MONTH          | 1  | 2  | 3  | 4  | 5  | 6  | 7  | 8  | 9  | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 | 25 | 26 | 27 | 28 | 29 | 30 | 31 | 32 | 33 | 34 | 35 | 36 | 37 | 38 | 39 | 40 | 41 | 42 | 43 | 44 | 45 | 46 | 47 | 48 |
|------------------------|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|
| Task I:                |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
| Combustor Development  |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
| Design                 |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
| Fabrication           |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
| Installation          |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
| Checkout              |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
| Task II:              |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
| Imaging System        |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
| Task III:             |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
| Particle Tracking     |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
| Imaging System        |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
| Schlieren Cinematography |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
| Task IV:              |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
| Radiation Measurements|    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
| Imaging System        |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
| Task V:               |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
| Velocity Measurements |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |

Projected          |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
Actual             |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
Continuing         |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |