DEVELOPMENT OF COAL BURNING PULSATING COMBUSTOR FOR POWER GENERATION

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PITTSBURGH ENERGY TECHNOLOGY CENTER

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ABSTRACT

This report describes the progress made under DOE Contract DE-AS05-79ER 10068 that terminated on September 30, 1981. The research conducted under this program consisted of an investigation of the burning of coal in a pulsating mode of combustion in a combustor whose design is based upon the Rijke tube principles. The combustor consists of a vertical tube opened at both ends with a fuel burning bed located in the middle of its lower half. In this configuration, the heat released by the combustion process spontaneously excites the fundamental, longitudinal acoustic mode of the tube. This study demonstrated that the combustor constructed under this program can burn coal stably and continuously under either the self aspirating or the forced flow modes of operation. In the latter case, maximum amplitudes occur near stoichiometric air/fuel ratio operation, indicating that systems utilizing the developed combustor or a similar version should possess high thermal efficiencies. Additionally, it was verified that pulsating operation is possible for a variety of air/fuel ratios, including fuel rich conditions, which suggests that the developed combustor could be used as a coal gasifier. Finally, carbon monoxide, carbon dioxide, and particulates concentrations in the exhaust flow were measured. The determined carbon monoxide and carbon dioxide concentrations were used to evaluate combustion efficiencies which ranged between 89 and 98.5% for air/fuel ratios between 1.03 and 1.22, respectively.
INTRODUCTION

This report describes progress made under a research program entitled "Development of Coal Burning Pulsating Combustor for Power Generation" that was supported under DOE Contract DE-AS05-79ER 10068 during the period October 1, 1980 to September 30, 1981. The research activities undertaken under this contract have been concerned with the investigation of the feasibility of burning coal under a pulsating mode of combustion and the determination of the major operational characteristics of the developed, Rijke-like pulsating combustor.

As the name implies, the combustion process in a pulsating combustor takes place under pulsating (i.e., oscillatory) conditions, implying that the various flow properties (e.g., pressure, velocity, etc.) at different locations in the combustion oscillate with a given frequency that is a characteristic of the developed combustor. In contrast, the flow conditions are basically constant in conventional combustors. As it is discussed in more detail below, interest in the burning of coal under pulsating conditions stems from its potential advantages that include:

1. highly intense combustion process;
2. considerably improved convective heat transfer characteristics;
3. reduced pollutants formation;
4. ability to burn unpulverized coal;
5. self aspiration;
6. ability to reduce slagging and keep heat transfer surfaces clean; and
7. ability to burn coal with little excess air.
While various combinations of the above listed advantages have been demonstrated to date in applications involving pulsating combustion of gaseous (e.g., see Refs. 1-4) and liquid\(^1,5\) fuels, none of these advantages have been demonstrated consistently in applications of the pulsating combustion process in the burning of coal and/or other solid fuels\(^*\). Consequently, the investigation described in this report had been undertaken with the objective of determining whether a coal burning pulsating combustor that is capable of incorporating into its design as many of the above listed advantages as possibly could be developed.

Efforts conducted to date on the application of pulsating combustion in the burning of coal include the studies of Severyanin\(^6\) and Hanby\(^7\) that deal with the development of experimental combustors; Sommers\(^8\) that describe a full scale application in Germany in the 1950s; and Lyman\(^9\) who studies individual coal particles combustion under pulsating conditions. In addition, Ref. 1 contains several conceptual papers that discuss the development of coal burning pulsating combustors. All of the experimental efforts to date utilized pulverized coal and their design was either identical or representative of the well known Schmidt tube\(^1\) design that provided the foundation for the well known VI "Buzz Bomb" that was developed by the Germans during the second world war. Before proceeding with the discussion of the results of the coal studies\(^6-9\), a brief discussion of some of the

\* The principal investigator of this project has been told of such studies in the Soviet Union, but no written descriptions of such studies could be found in the English literature.
characteristics of the Schmidt Tube are in order. In this case it can be shown that in order to achieve a pulsating mode of combustion, the characteristic combustion time (that may include the characteristic times of vaporization, mixing, chemical kinetics and so on processes) must be of the order of half the period of oscillation of the combustor. Qualitatively, this requirement is due to the fact that in order to achieve a pulsating mode of combustion in a Schmidt tube, the heat release due to combustion needs to occur during the phase of maximum pressure in the combustor. Since in the Schmidt tube the fuel and oxidizer are injected into the combustor near the phase of pressure minimum (see Fig. 1), the time available for combustion between the injection instant and the instant of maximum pressure (when the combustion should occur) is approximately half the period of the oscillation, which explains the above stated criterion.

Satisfying the above stated time condition

\[ \tau_{\text{combustion}} \sim \frac{1}{2} T \]

(1)
does not appear to present any difficulties when gaseous fuels are involved and various pulsating combustors that utilize such fuels have been developed to date. However, as one changes from gaseous to liquid to solid fuels the combustion time becomes longer due to the "addition" of such processes as heating, vaporization, surface combustion and so on into the combustion process and satisfying Eq. (1) above becomes more difficult. In the case of pulverized coal combustors, attempts to resolve this difficulty usually involved various schemes for preheating the fuel in order to shorten the
Figure 1. Qualitative Description of "Required" Combustion Time for Pulsating Combustion in a Schmidt Tube.
combustion time\textsuperscript{6,7}. When the coal was not preheated, the developed combustors suffered from such problems as inability to stabilize the combustion process, incomplete combustion, and difficulties in maintaining pulsating combustion for different fuel/air ratios, and efforts to resolve these difficulties have resulted in cumbersome combustor design. Consideration of these problems at the initiation of this program had lead this group to the conclusion that burning coal in a Schmidt type pulsating combustor is bound to experience difficulties and the decision was made at the time to proceed with the development of a coal burning pulsating combustor that would be based upon the radically different Rijke tube oscillator\textsuperscript{12}. As is described in the next section, results obtained to date under this program indeed demonstrate that the Rijke-like combustor developed by this group is capable of successfully burning coal and other solid fuels under a pulsating mode of combustion over wide ranges of operating conditions.

Next, before proceeding with the discussion of the characteristics of the pulsating combustor that was developed under this program, it would be appropriate to provide evidence in justification of claimed advantages of the pulsating combustion process, as listed under items (1) through (7) earlier in this section.

1. **Highly Intense Combustion Process.** In Schmidt type pulsating combustors and in the one developed under this program the occurrence of pulsating combustion is associated with the presence of acoustic velocity oscillations in the combustor in addition to a steady flow velocity component. The acoustic velocity component changes directions at a rate
that equals the frequency of pulsations and it is believed to greatly enhance the rate of mixing of fuel and oxidizer in the combustor, resulting in a high rate of combustion.

Additional explanation that has been advanced in the literature\(^1\) for the high combustion rates of coal particles in pulsating combustors is the periodic stripping of the blanket of combustion products that surrounds the coal particle by the oscillating acoustic velocity. This action reduces the gas phase resistance (that is provided by the blanket of combustion products) to the migration of oxygen molecules toward the coal particle surface, resulting in the acceleration of the coal particle combustion. The above argument was based upon the notion that a coal particle is surrounded by a layer of combustion products after the initial phase of volatiles combustion. Recent combustion studies at Sandia\(^{13}\) seem to indicate, however, that the particle and the blanket of combustion products tend to "separate" before the coal particle is completely burned even in the absence of pulsations. While this may appear to contradict the argument advanced in this paragraph, it is nevertheless plausible that the presence of pulsations enhances the stripping of the combustion products layers from the coal particles.

While there may be some questions regarding the exact mechanism(s) responsible for the high rate of coal burning due to pulsations, evidence provided by Sommers\(^8\) and Lyman\(^9\) who studied pulverized coal combustion clearly supports this claim. Finally, as will be discussed in the next section, our own work to date in this area indicates that the pulsating combustion process is characterized by a very high combustion rate per unit area (i.e.,
Figure 2. The Effect of Oscillations on the Distribution of Heat Transfer Coefficient in the Combustor.
The implication of a high combustion rate is that the resulting combustor will be smaller in size requiring a smaller initial capital investment.

2. **Improved Heat Transfer Characteristics.** The presence of acoustic oscillations is apparently responsible for considerably increased convective heat transfer from the flow to the surrounding boundaries. This phenomenon is well known and it had been responsible in the past for the melting of the walls of liquid propellant rocket motors after the onset of combustion instability. A good discussion of this phenomenon is provided by Hanby¹⁴ and the resulting improvement in the convective heat transfer coefficient is described in Fig. 2 that was taken from Ref. 14. Figure 2 shows that the heat transfer coefficient depends upon the local flow conditions and that it reaches a maximum at a location of maximum acoustic velocity amplitude near the exit of the combustor. Comparing the plots provided in Fig. 2 for the heat transfer coefficients under pulsating and nonpulsating conditions clearly indicates the improved heat transfer processes that are associated with pulsating operation.

In practical terms, the improved heat transfer that is associated with the presence of acoustic velocity oscillations indicates that a given amount of heat can be transferred over a smaller heat transfer area, implying the need for a smaller heat exchanger and a smaller initial capital investment.

3. **Reduced Pollutants Formation.** This claim is supported by related studies conducted in the U. S. and the U. S. S. R. with pulsating combustors that utilized gaseous and liquid fuels. Reference 15 describes a Russian
investigation that specifically dealt with this problem. In this study, pollutants formation in two different combustor designs were compared under pulsating and nonpulsating (i.e., turbulent) operating conditions utilizing gaseous and liquid fuels. In all of the investigated cases, the results show reductions in the production of nitrogen oxides, carbon monoxide, hydrocarbons, sulfur dioxide and soot as a result of transition from nonpulsating to pulsating operation, with the reductions being significant (i.e., orders of magnitude) in most cases. In this case, the reduction in the production of carbon monoxide, hydrocarbons and soot also indicates that the presence of pulsations results in a more complete combustion process (i.e., higher combustion efficiency) which also supports some of the arguments advanced under item (1) above. Another point that needs to be emphasized is that pollutants reductions were observed while burning both gaseous and liquid fuels, suggesting that similar benefits might also occur during pulsating combustion of solid fuels.

Additional support for reduced nitrogen oxides formation during pulsating combustion is provided in the work of Belles\(^2\) that deals with pulsating combustion of gaseous fuels. The following is a quote from Ref. 2 that describes these results: "Fortunately, our measurements show that the \(\text{NO}_x\) emissions of pulse burners are considerably lower than those of conventional furnaces, both in absolute concentration and also in terms of mass emitted per unit of usable heat appear to be real and they are most encouraging".

While the above observations need to be further investigated, especially for coal combustion, they nevertheless indicate that the use of
pulsating combustion may reduce the production of pollutants to levels that will eliminate the need for complex combustor designs (e.g., combustion staging; see Ref. 16) and/or the incorporation of some expensive pollutants removal procedures or equipment into the system, resulting in reductions in both operational and/or capital investment costs.

4. **Ability to Burn Unpulverized Coal.** This is a characteristic of the Rijke-type pulsating combustor developed under this program and it is discussed in more detail in the next section. It's availability eliminates the need for investing in the acquisition of pulverizers and the continuous pulverizing cost, thus reducing both capital investment and operational costs. This feature should be particularly attractive to industries that are considering a switch to coal utilization and are considering the cost of such a move.

5. **Self Aspiration.** This feature implies that the combustor can "pump" its own oxidizer eliminating the need for auxiliary fans and/or pumps that are utilized in conventional combustors for moving the oxidizer (i.e., air) through the combustor. This unique feature of pulsating combustors offers the possibility of eliminating the costs associated with the purchase and operation of the needed air pumping equipment.

Before leaving this section, it should be pointed out that pulsating combustors can be operated under both self aspirating and forced oxidizer flow conditions.

6. **Reduced Slagging and Keeping that Heat Transfer Surfaces Clean.** The acoustic velocity oscillations that are associated with the pulsating combustion process result in back-and-forth motions (of different
amplitudes) of the gases along the various combustor and heat transfer surfaces. According to the Russian literature\textsuperscript{5,16} and physical intuition, this motion results in a scrubbing type action on the surface that reduces or prevents slagging and foreign material depositions along these surfaces. This scrubbing action of the acoustic velocity in pulsating combustors may provide an acceptable solution to this serious problem.

7. **Ability to Burn with Little Excess Air.** Conventional combustors operate with air/fuel mixtures that may contain up to forty percent more air than is required for stoichiometric combustion. The use of excess air results in a decrease in the thermal efficiency of the system due to the costs associated with the thermal losses in the exhaust products, the pumping the additional air and the energy lost in vaporizing the moisture content of the air. In addition, the excess air results in lower temperatures of the combustion products which may adversely affect heat transfer processes. Thus, it is desired to operate with as little excess air as possible. In studies conducted by this group and those described in Ref. 15 it has been found that maximum amplitude of pulsating combustors might be able to operate efficiently with little excess air, resulting in combustors having higher thermal efficiencies.

The above discussion describes the observed advantages of the pulsating combustion process that provided the impetus for this research program. It consisted of the development of the Rijke-like, coal burning, pulsating combustor and its testing under different operating conditions. The results of these efforts are described in the following section.
PROGRAM ACHIEVEMENTS

This section is divided into two parts with the first part providing the background for the Rijke tube combustor that has been utilized in this study and the second part briefly describing achievements under this program.

The Developed Rijke Type Combustor

One of the initial objectives of this program was the development of a coal burning pulsating combustor that would not suffer from the shortcomings of the earlier designs, as discussed in the Introduction Section. Considerations of the problems that needed to be resolved and a personal communication with Severyanin during a 1978 visit to the Soviet Union lead to the conclusion that a pulsating combustor based upon the Rijke Tube principles may offer an attractive alternative to the previously used Schmidt tube-like combustor designs.

The Rijke Tube, which was first developed in the 19th century, is shown schematically together with its associated acoustic wave structure in Fig. 3. In this configuration, the metal gauze is heated either apriori by a flame or concurrently by an electric current. In either case the wire acts as a heat source that induces an upward steady flow in the tube due to natural draft and periodic heating of the gas that results in the excitation of the natural mode of the tube, whose structure is also shown in Fig. 3. Theoretical investigations of the operation of the Rijke tube have been conducted by Carrier and Culick. In both cases it has been argued that the normalized heat transfer perturbation $Q'/\bar{Q}$ is related to the
Figure 3. Schematic of the Rijke Tube
normalized velocity oscillation \( (u' /a) \) via the relationship

\[
\frac{Q'}{Q} = qe^{-i\varphi} \left( \frac{u'}{a} \right)
\]

where \( Q \) is the heat transfer, \( q \) is a proportionality constant, \( \varphi \) is the phase difference between the heat addition and velocity perturbation and \( a \) the velocity of sound. The magnitude of the phase \( \varphi \) is of interest to the understanding of the physics of the problem. According to Ref. 17, \( \varphi = \frac{3\pi}{8} \) while according to Ref. 18 \( 0 \leq \varphi \leq \pi \).

Another point that needs to be emphasized is the importance of having a steady flow past the wire to the onset of an oscillation of the fundamental mode\(^{18} \). In the absence of such a flow, the frequency of any excited oscillation will be twice the frequency of the fundamental mode due to the fact that the heat transfer from the wire is proportional to the magnitude of the velocity and not its direction. On the other hand it can be shown that the presence of both a mean velocity and an oscillating velocity component may result in the excitation of the fundamental mode of the tube.

Additional experiments that influenced the present program were those conducted by Bosscha and Riess\(^{10} \) in which hot flow was introduced into the bottom of a vertical tube and heat was removed from the flow at a distance \( 3L/4 \) from the bottom of the tube as shown in Fig. 4. As in Rijke's experiments, the removal of the heat at the indicated location resulted in the excitation of the fundamental mode of the tube as shown in Fig. 4. While it will not be done here, it should be pointed out that the Bosscha and
Figure 4. A Schematic of the Base and Ring Experiments.
Riess experiments can be explained utilizing arguments similar to those used to explain the mechanisms responsible for the onset of the oscillation in the Rijke tube.

In summary, the Rijke, Bosscha and Riess experiments showed that the fundamental mode of a tube opened at both ends may be excited if heat is added at a distance of \( L/4 \) and/or removed at a distance of \( 3L/4 \) from the entrance of the tube. Keeping this in mind, a pulsating combustor could be designed by replacing the hot metal gauze by a coal burning bed at the \( L/4 \) position. While having a heat source at the \( L/4 \) position would be sufficient for obtaining a pulsating combustor, the pulsations would be amplified according to the Bosscha and Reiss experiments if heat is also removed from the hot combustion products at the \( 3L/4 \) position.

Summary of Accomplishments to Date

This section briefly summarizes the major accomplishments of this program to date. The objectives of this study were to (1) determine whether a coal burning pulsating combustor based upon the Rijke tube principles could be developed, and (2) determine the main operational characteristics of such combustor.

The developed Rijke tube pulsating combustor is shown in Fig. 5. It consists of cylindrical segments with internal diameter of 5.5" and wall thickness of 0.25". The total length is 108". Additional segments were built to permit variations in the combustor's length. Since the fuel remains in the bed over many cycles, this combustor does not suffer from the difficulties encountered in the previously discussed Schmidt type combustors in which
Figure 5. Schematic of the Developed Rijke Tube Pulsating Combustor.
preheating of the pulverized coal was required in order to satisfy the combustion time requirements. In this combustor configuration (see Fig. 5), coal is supplied to the combustion bed by means of a calibrated auger type feed system and pulsating combustion can be attained under either a self aspirating or a forced flow mode of operation. Under the forced flow mode, the decoupling chamber serves to guide the air into the combustor without altering the required open end boundary condition at the lower end. Coal was burned in a metal wire combustion bed located at L/4 and a water heating jacket was installed near the 3L/4 position. The lower decoupling chamber is disconnected from the tube when the combustor is operated under the self aspirating regime.

Developed measurement capabilities include thermocouple temperature measurements at different locations within the combustor, acoustic pressures using a condenser microphone, velocities using hot film, air flow rates during forced flow experiments using rotameters, high speed combustion zone photography utilizing specially designed viewing windows, coal feed rates utilizing a calibration curve of the auger type feed system, carbon monoxide and carbon dioxide gas concentrations at the exhaust flow using two Beckman model 864 infrared analyzers, and particulate emissions using a specially designed gas particulate sampling train. A sketch of the combined gas-particulate sampling train is shown in Fig. 6. The carbon monoxide and carbon dioxide gas concentration measurements in the exhaust flow provide data for the evaluation of the system's combustion efficiencies.
Figure 6. Schematic of the Combined Gas-Particulates Sampling Train. Legend on next page.
Legend (Fig. 6)

(1) Cylindrical shape sintered metal filter (60) - gas sampling
(2) Nozzle type ½" diameter probe - isokinetic particulate sampling
(3) Pressure regulator with valve - purge system
(4) Two way valves
(5) Four way valve
(6) Three way valves
(7) Filter - retention of 99.7% of particles greater than 0.3
(8) Ice bath
(9) Separators
(10) Protection filters
(11) Relief valve
(12) Dual head pump
(13) Vacuum gauge
(14) Thermocouple
(15) Flowmeter
(16) Needle point valves
(17) Flowmeters with valve
(18) Infrared analyzers
In what follows, the major results obtained to date utilizing the above described experimental set up are briefly discussed.

1. **Combustor Operation.** This program has established that a Rijke type pulsating combustor can be utilized to burn coal and other solid fuels stably and continuously under either self aspirating or forced flow conditions. Pulsating combustion operation has been obtained consistently with the developed combustor within minutes after the ignition of the combustion bed.

   Utilizing a nine foot length combustor, results obtained to date showed that the frequency of pulsation was in the range 74 to 84 Hertz and that the pressure amplitude varied between 140 and 160 dB for operations under the self aspirating mode and between 150 and 165 dB for operations under the forced flow mode.

2. **Characteristics of the Developed Pulsating Combustor.** One measure of the performance of the developed combustor is the amplitude of the excited acoustic oscillation. In this case an increase in the amplitude implies better coupling between the combustion process and the natural acoustic mode of the combustor that should result in "better" mixing and consequently more efficient combustion process. In addition, the increase in amplitude may result in better heat transfer processes and reduced pollutants formation. Thus, measured dependence of the amplitude of the oscillation upon different combustor operating parameters has been used as an indication of the performance of the system with a higher amplitude operation implying a more "efficient" operation.
Tests conducted to date showed that the amplitude of pulsations depends upon the location of the combustion zone within the lower half of the tube. For a given combustion bed configuration the amplitude is near maximum when the bed is located a distance of L/4 from the entrance to the tube. Also, moving the bed to different positions results in the excitation of higher harmonics of the fundamental combustor mode.

The amplitude also depends upon the degree of accumulation of coal in the bed. For low or zero accumulation, acoustic energy dissipation in the bed is minimized and the amplitude of the combustor pulsations increases. The amplitude of the oscillation decreased as the length of the combustor was decreased. As a matter of fact maximum amplitude was obtained with the maximum tested combustor length of 9 feet. This result indicates that the various processes responsible for wave excitation and wave losses are frequency dependent and that there is an optimum frequency of operation for Rijke Tube Combustors. It appears that for the present combustor a further (small) increase in length may result in further amplitude increase. These results also indicate that an investigation of the optimum frequency of operation is desirable.

3. Forced Flow Operation. Pulsating operation under forced flow conditions permitted testing under a variety of air/fuel ratios. A series of tests were conducted with coal and wood for different air/fuel ratios and the results, plotted in Figs. 7 and 8, show that the amplitude of the oscillation strongly depends upon the air/fuel ratio with the maximum occurring near stoichiometric operation. These results are consistent with previous Russian
$\alpha = \frac{(m_{\text{Air}}/m_{\text{Fuel}})_{\text{Exp}}}{(m_{\text{Air}}/m_{\text{Fuel}})_{\text{Stoich}}}$

Figure 7. Measured Acoustic Pressure Amplitudes for Experiments Conducted with Coal Burned under Different Air/Fuel Ratio and Nominal Coal Feed Rate of 50 gr/min.
Figure 8. Measured Acoustic Pressure Amplitudes for Experiments Conducted with Wood Burned under Different Air/Fuel Ratios and Different Steady Velocities.
results\textsuperscript{15} and it supports the previous claim that the pulsating combustors could be operated with little excess air, resulting in higher thermal efficiencies for the combustor.

Figure 8 also indicates that the amplitude of the oscillation depends upon the magnitude of the steady state velocity \( \bar{u} \), with the available data showing that an increase in \( \bar{u} \) leads to an increase in the amplitude of pulsation. These data indicate that the coupling (i.e., driving) between the combustion process and the oscillation strongly depends upon the magnitude of the steady velocity through the combustion zone. This result also indicates that this coupling process needs to be further investigated and that forced flow operation which provides an independent control of the magnitude of \( \bar{u} \) may be preferable in terms of providing means for controlling the operation of the pulsating combustor.

4. **Fuel Rich Operation.** Another significant aspect of the data presented in Figs 7 and 8 is the demonstration that pulsating combustion operation was achieved under fuel rich conditions (i.e., \( \alpha < 1 \)). Since for \( \alpha < 1 \) the exhaust flow is fuel rich and it could possibly be used as a fuel, then these results suggest that the developed pulsating combustor, or a modified version, could be possibly used in solid fuel gasification applications.

5. **Comparisons Between Pulsating and Nonpulsating Operation.** During the course of this study, it has been found that opening one or two small holes in the wall of the combustor tube a few inches above the combustion bed results in the cessation of the pulsations. This capability allowed for qualitative comparisons of the characteristics of the combustion zones and exhaust flows under pulsating and nonpulsating conditions. When the
combustor was pulsating, visual observations indicated that the luminous combustion zone was short exhibiting extremely intense "agitation" of the gases within the combustion zone. In addition, flamelets moving periodically downward (against the direction of the steady upward flow) through the holes of the wire mesh supporting the coal bed were observed. This downward motion was undoubtedly caused by the back-and-forth motion of the acoustic velocity near the combustion bed which is also responsible for intensified mixing within the combustion zone; the latter is probably responsible for the "compactness" of the observed combustion zone. In addition, the exhaust flow leaving the combustor appeared clear and smoke free.

When pulsations are absent, the combustion bed with the through air flow probably approximates the combustion in a stoker type combustor. In this case, observations of the fuel bed showed the presence of a relatively long luminous combustion zone that "started" someplace near the middle of the bed and extended some distance above the bed. Furthermore, the combustion zone lacked the "intensity" or "vibrations" observed during pulsating combustion and there were no flamelets protruding below the wire mesh coal support. Finally, the presence of black smoke was clearly visible in the exhaust flow.

Also, comparisons of exhaust flows concentrations showed that the presence of pulsations reduces CO and concentrations while increasing CO₂ concentration, implying that pulsations result in a more complete combustion process.
The observed differences in the characteristics of the combustion zones and exhaust flows between the two modes of combustion strongly support the argument that the presence of acoustic velocity oscillations near the combustion bed during pulsations is responsible for intensified mixing and, consequently, more rapid and complete burning of the solid fuel in the bed.

6. Multiple Fuel Operations. To date, pulsating operation was studied under this program utilizing different commercially available coals (one of which was supplied by Georgia Power) and a variety of woods containing different amounts of moisture. While the amplitude of the resulting pulsation depended upon the characteristics of the fuel, pulsating operation was obtained in all instances. As a matter of fact, the combustor had no problems burning wood with forty percent moisture content and freshly cut wood, which cannot be readily burned in most combustors.

These observations together with earlier\(^\text{19}\) successful operation of a Rijke tube combustor with a gaseous fuel suggest that Rijke type, pulsating combustors capable of multiple fuels operation, including low grade fuels (e.g., freshly cut wood), could be designed in the future.

7. Combustion Efficiencies. The carbon dioxide and carbon monoxide concentration measurements in the exhaust flow together with the measured air/fuel ratios, the determined coal composition (i.e., by ultimate analysis); and considerations of mass conservation were used to evaluate the combustions efficiencies of the system under different conditions in the forced flow mode of operation. For a coal feed rate of 50 gr/min and different air/fuel ratios, the combustion efficiency ranged from 89 to 98.5%
for values of $\alpha$ (i.e., the normalized air/fuel ratio) ranging from 1.03 to 1.22, respectively. The combustion efficiencies for corresponding non-pulsating operations were always found to be lower (e.g., in some instances 15% lower) than the values determined for pulsating operation.

8. Combustion Intensities. Using the computed combustion efficiencies and measured coal feed rates the combustion process heat release rates were calculated. Maximum heat release rates of 750,000 Btu/hr ft$^2$ were achieved with stoichiometric operations, a value that compares very favorably with energy release rates of recent state of the art combustors$^{20}$. 

9. Particulate Emission. A plot showing the relative amounts of particulates generated under different air/fuel ratios and nominal feed rate of 50 gr/min is presented in Fig. 9. A drastic reduction in particulates formation with an increase in $\alpha$ is observed with the particulates formation reaching an almost constant minimum level for $\alpha$ larger than 1.1. One should also note that for all of the tested $\alpha$'s, particulates formation was considerably higher under non-pulsating operation.

Report Summary

The results obtained under this research program demonstrated that unpulverized coal can be burned continuously and stably in a Rijke type combustor. Under pulsating operation, the presence of acoustic oscillations enhances the mixing between oxidizer and fuel which increases the efficiency and heat release rate of the combustor. Maximum amplitudes occur when the air/fuel ratio is nearly stoichiometric which suggests that
Figure 9. Dependence of the Particulate Generation upon the Air/Fuel Ratio for Nominal Feed Rates of 50 gr/min (m/c = ratio between collected mass of particulates and feed rate of the coal).
devices (e.g. boilers, water heaters, etc.) utilizing such a pulsating combustor should possess high thermal efficiencies. It was also verified that pulsating combustion operation of the developed combustor is possible for a variety of air/fuel ratios, including very fuel rich conditions (e.g. $\varphi = 0.36$). Under these fuel rich situations, the exhaust flow is combustible indicating that the developed Rijke combustor could possibly be also utilized as a coal gasifier. In closing, the results obtained under this program to date demonstrate that with further development, Rijke type pulsating combustors may provide energy users with an attractive means for deriving energy from coal.
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