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INVESTIGATION ON THE BURNING OF UNPULVERIZED COAL IN A SELF EXCITED ACOUSTIC FIELD

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Abstract

This paper presents results obtained with the burning of unpulverized coal in a Rijke type pulsating combustor. The developed combustor basically consists of an open ended tube where a fuel burning bed is located in the middle of its lower half. The release of heat in this location excites the fundamental acoustic mode of the tube and the resulting oscillations lead to a very intense and efficient combustion process. The main performance data presented include: combustion efficiences, heat release and transfer rates.

INTRODUCTION

The presence of acoustic oscillations during combustion (the phenomenon called pulsating combustion) was first observed by Higgins |1| in 1801 with the "singing flames" that occurred when hydrogen was burned in a pipe opened at both ends. The origins of oscillations in any combustion chamber were described by Rayleigh and his fundamental criterion |2,3| . The criterion, which is derivable from the conservation equations |4|, states that if heat is added to an acoustically oscillatory mass of a gas, the amplitude of oscillations will increase if the heat addition takes place when the pressure is higher than the average; the same affect will occur if heat is extracted when the pressure is lower than the average |3|.

Probably the best known application of pulsating combustion was the use by the Germans of the Schmidt (or quarter wave) tube |5,6| to propel the V-1 bombs in World War II. The interest on the subject has persisted over the years because of reports evidencing several associated economical advantages, among them increased convective heat transfer rates |7|, reduced slagging |8,9| , high combustion efficiences |9,10|, high combustion intensites |8,9,10|, and low pollutants formation |11|.

The great majority of the developed pulsating combustors consumed either gaseous or liquid fuels. The attempts to burn solids consisted of quarter wave type combustors operated with pulverized coal |8,9,10|. These presented some difficulties related to the maintenance of the acoustic oscillations for a long period of time. The difficulties occurred mainly because of: (a) the high characteristic combustion time of the coal particles and (b) the presence of valves near the combustion zone. It should be pointed out that in a quarter wave combustor, fuel and air enter the reaction zone during the phase of negative acoustic pressure and the heat release needs to occur during the phase of positive acoustic pressure, i.e., the characteristic combustion time of the fuel must be of the order of half of the period os oscillations |12|. In the case of solid fuels, this characteristic combustion time is longer than in the case of liquid and gaseous fuels and, in order to shorten it, the above referenced pulverized coal combustors required preheating of air and coal.

This paper shows results of an investigation initiated with the objective of determining the performance characteristics of a coal pulsating combustor that did not experience the difficulties encountered by quarter wave type combustors. A Rijke type |2,13,14| combustor was selected for the investigation and the reasons leading to the choice of such configuration will be presented just after the following brief description of the original Rijke tube.

The Rijke tube was discovered in 1859 when it was observed that strong acoustic oscillations were excited when a heated metallic gauze was placed in the lower half of a vertical tube opened at both ends |2,13,14|. A schematic of the Rijke tube with its associated acoustic wave structure is provided in Fig.1. Related experiments were conducted by Bosscha and Riess |2,13,14| who independently discovered that acoustic oscillations were also excited when an upward flow at a hot gas was cooled by a cold grid placed in the upper half of an open ended tube. It was also observed that oscillations were not excited if either heating in the upper half or cooling in the lower half of the tube was applied. These results indicate that higher amplitude oscillations could be achieved with a tube opened at both ends in which the upward flow is heated in the lower half and cooled in the upper half. A theoretical analysis, based on the Rayleigh criterion, showing the necessary conditions for driving of acoustic oscillations in a vertical tube opened at both ends is presented in Ref. 15.

In the Rijke tube combustor described in this paper, the original heated metallic gauze was replaced by a coal burning bed located at the L/4 position of the vertical tube. This combustor (Fig. 2) is characterized by absence of valves and by simplicity of design. Zinn and his co-workers |16| verified that such a combustor operates stably with no coal pulverization required. Also, there was no requirements of reduction of the characteristic combustion time to nearly half of the period of the oscillations since, in a Rijke type pulsating combustor, the coal particles could remain in the combustion bed for an unrestricted interval of time.

This paper presents a typical test and average performance data of the developed Rijke type pulsating combustor.

THE EXPERIMENTAL APPARATUS

The developed pulsating combustor (Fig. 2) consisted of cylindrical iron segments with internal diameter of 5.5" and wall thickness of 0.25". The total length was 108". A 3.02 ft^3 decoupling chamber was attached to the combustor and it served to guide the combustion air into the reaction zone without altering the required open end boundary condition at the bottom section of the tube. Air was supplied by a 120 psig compressor. The air mass flow rate was controlled by a regulating valve and a rotameter.

Unpulverized coal was supplied for combustion by means of a calibrated auger type feed system. The coal size averaged between 1/4" - 1/2" before feeding. The burning bed was supported by a 16 hole per square inch grid held by a 1/4 inch wide, 1/2 inch thick, ring attached to the inner wall of the combustor. Three 2 inch diameter quartz viewing windows were used to observe the reaction zone during the experiments.

The acoustic solutions for the fundamental mode of a tube opened at both ends indicate that the amplitude of acoustic pressure is a maximum at the half section of the tube. Therefore, the dB level of pulsations was measured at this location by means of a Kistler type 60(X)B1 pressure transducer coupled to a Kistler type 504E amplifier. The frequency of oscillations was measured from the acoustic pressure signal by means of a Monsanto model 104A frequency meter. Temperatures were measured with chromel - alumel thermocouples at 1 ft below the combustor's exit section (three thermocouples), 1 ft above the combustion bed, and at the air inlet section.

Two Beckman model 864 (infrared), a Beckman model 865 (infrared), and a Beckaman model 951A (chemiluminescent) analyzers were, respectively, used to determine the CO, CO_2, SO_2 and NO_x concentrations in the exhaust flow. The knowledge of the CO and CO_2 volume concentration and of the operating air/fuel ratio plus considerations of mass conservation yielded the average combustion efficiencies of the system. A combined gas-particulates sampling train (illustrated in Fig. 3) was designed and constructed to both (a) condition the sample prior to gas concentration analyses and (b) collect particulates isokinetically in the exhaust flow.

All the data from the tests were stored and reduced with the utilization of an HP model 2100 S minicomputer-disc system.

The coal burned in the experiments was bituminous with the following average ultimate analysis: 1,65% Moisture, 77.16% Carbon, 4,95% Hydrogen, 1,35% Nitrogen, 0.04% Chlorine, 2.09% Sulphur, 5.37% Ash, and 7.39% Oxygen.

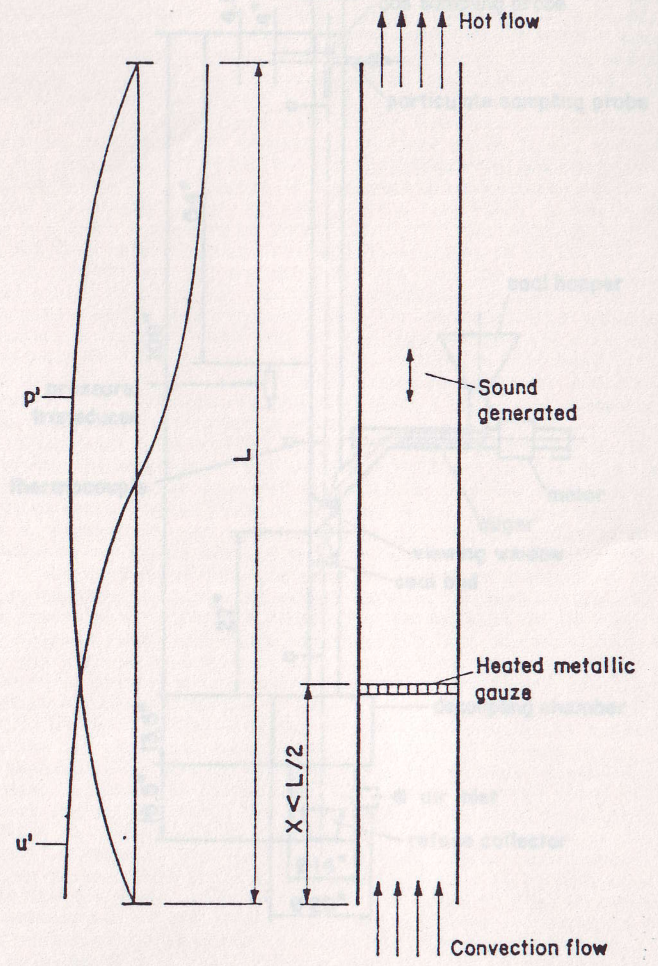

Fig. I. The Rijke Tube and Associated Acoustic Wave Structure.

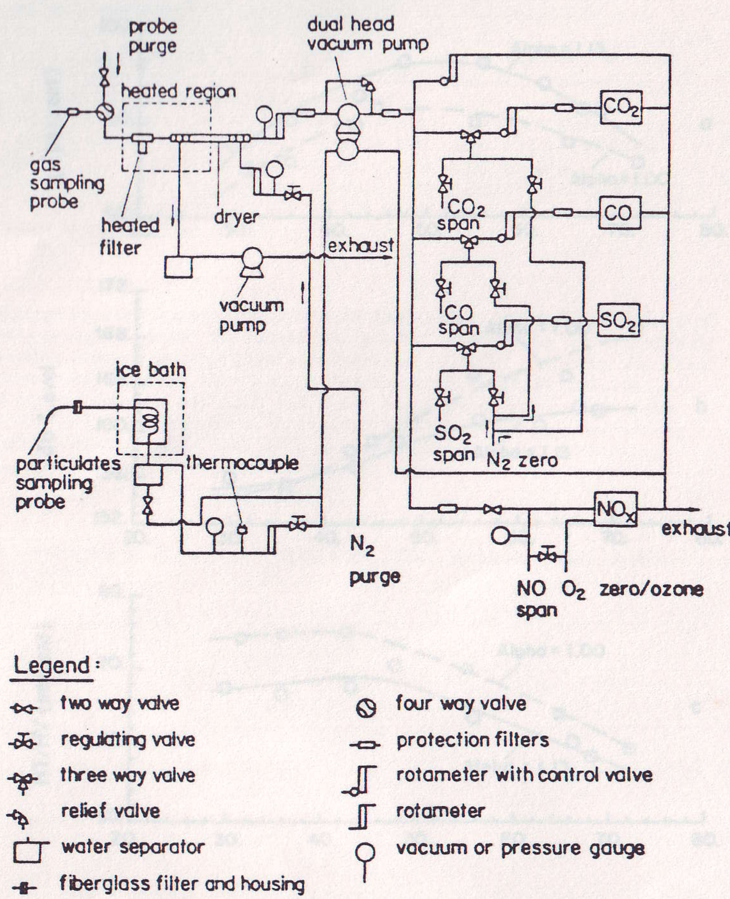

Fig. 3. Schematic of the combined gas – particulates sampling train.

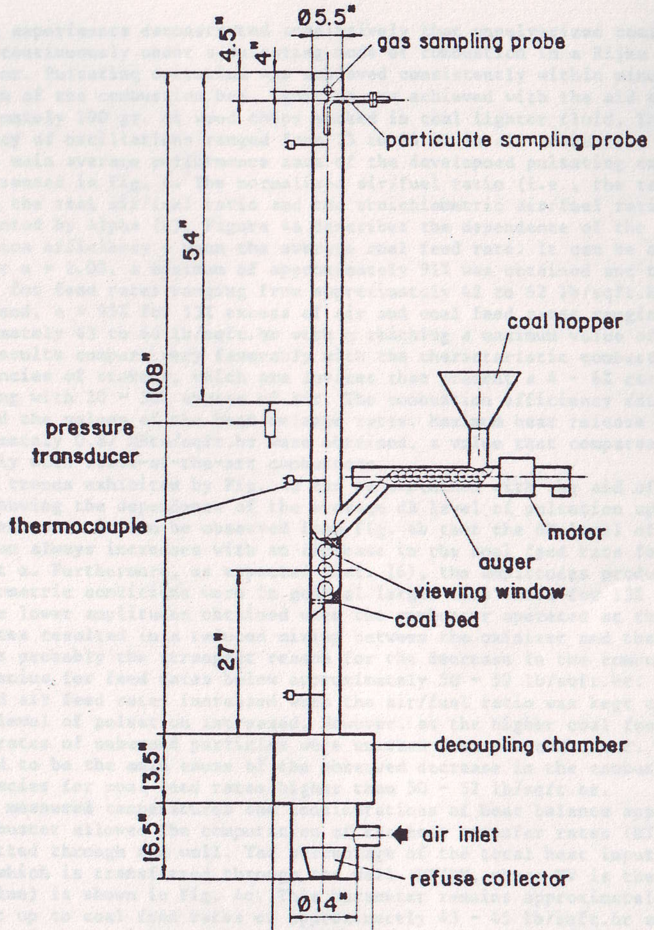

Fig. 2. Schematic of the developed Rijke tube pulsating combustor.

RESULTS AND DISCUSSION

The experiments demonstrated conclusively that unpulverized coal can be burned continuously under a pulsating mode of combustion in a Rijke type combustor. Pulsating operation was achieved consistently within minutes after ignition of the combustion bed. Ignition was achieved with the aid of approximately 100 gr. of wood chips soaked in coal lighter fluid. The frequency of oscillations ranged from 75 to 84 Hz in all tests.

The main average performance data of the developed pulsating combustor are presented in Fig. 4. The normalized air/fuel ratio (i.e., the ratio between the real air/fuel ratio and the stoichiometric air/fuel ratio) is represented by Alpha (α). Figure 4a describes the dependence of the average combustion efficiency η upon the average coal feed rate. It can be observed that for $\alpha = 1.00$, a maximum of approximately 91% was obtained and that $\eta > 90\%$ for feed rates ranging from approximately 42 to 62 lb/sqft.hr. On the other hand, $\eta > 95\%$ for 13% excess of air and coal feed rates ranging from approximately 43 to 60 lb/sqft.hr with η reaching a maximum value of 97%. These results compare very favorably with the characteristic combustion efficiencies of stokers, which are devices that present a 4 - 6% carbon loss operating with 20 - 30% excess of air. The combustion efficiency data provided the values of the heat release rates. Maximum heat release rates of approximately 0.87 MBtu/sqft.hr were obtained, a value that compares very favorably with state-of-the-art combustors.

The trends exhibited by Fig. 4a can be explained with the aid of the graph showing the dependence of the average dB level of pulsation upon the coal feed rate. It can be observed from Fig. 4b that the dB level of pulsation always increases with an increase in the coal feed rate for constant α. Furthermore, as expected (Ref. 16), the amplitudes produced under stoichiometric conditions were in general larger than those for 13% excess of air. The lower amplitudes obtained when the combustor operated at the lower feed rates resulted in a reduced mixing between the oxidizer and the fuel, which is probably the strongest reason for the decrease in the combustion efficiencies for feed rates below approximately 50 - 52 lb/sqft.hr. As the fuel and air feed rates increased when the air/fuel ratio was kept constant, the dB level of pulsation increased. However, at the higher coal feed rates, higher rates of unburned particles were emitted from the combustor. This is believed to be the main cause of the observed decrease in the combustion efficiencies for coal feed rates higher than 50 - 52 lb/sqft.hr.

The measured temperatures and considerations of heat balance applied to the combustor allowed the computation of the heat transfer rates (HT) transmitted through the wall. The percentage of the total heat input to the system which is transferred through the wall (HT/HV, where HV is the coal heat value) is shown in Fig. 4c. This parameter remains approximately constant up to coal feed rates of approximately 43 - 45 lb/sqft.hr and then decreases for the higher coal feed rates. The graph of Fig. 4c represents a primary measurement of the system's thermal efficiency. It must be pointed out that no effort was expended to reduce the flue gas temperature. In other words, the value of HT/HV will improve significantly if the wall is cooled (by water, for example).

The average amounts of NO_x produced by the combustor were always lower than 600 ppm. There was no evidence of NO_x concentration reduction by the effects of pulsations. The reasons for this are believed to be the existence of organically bound nitrogen in coal which originates the so called fuel NO_x. Only the levels of thermal NO_x (NO_x originated from the oxidation of the nitrogen in the air) are expected to be reduced in the presence of acoustic

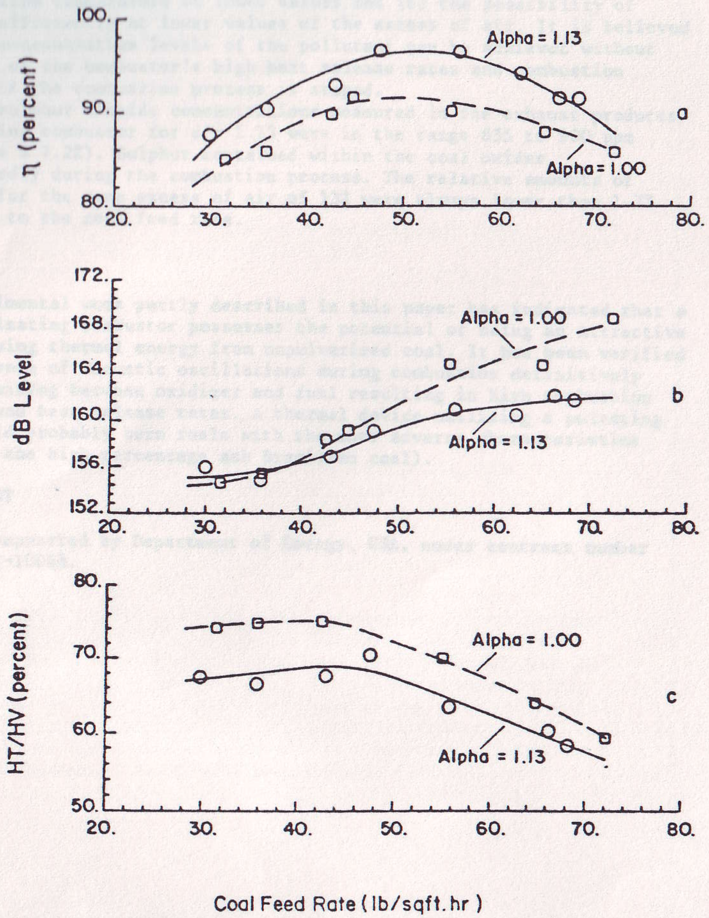

Fig.4. Dependence of the Combustion Efficiency, dB Level of Pulsation and Percentage of Heat Transmitted to Wall upon the Coal Feed Rate.

oscillations because of (a) the occurence of high heat transfer rates that keep the reaction temperature at lower values and (b) the possibility of burning fuel efficiently at lower values of the excess of air. It is believed that reduced concentration levels of the pollutant can be achieved without deterioration of the combustor's high heat release rates and combustion efficiencies if the combustion process is staged.

Finally, sulphur dioxide concentrations measured in the exhaust products of the pulsating combustor for $\alpha = 1.13$ were in the range 835 to 900 ppm (i.e., 900 ppm $\pm$ 7.2%). Sulphur contained within the coal oxides straightforwardly during the combustion process. The relative amounts of particulates for the same excess of air of 13% were always lower than 1.7% when compared to the coal feed rate.

CONCLUSION

The experimental work partly described in this paper has indicated that a Rijke type pulsating combustor possesses the potential of being an attractive means of deriving thermal energy from unpulverized coal. It has been verified that the presence of acoustic oscillations during combustion definitively enhances the mixing between oxidizer and fuel resulting in high combustion efficiencies and heat release rates. A thermal device utilizing a pulsating combustor could probably burn fuels with the most adverse characteristics (for example, the high percentage ash Brazilian coal).

ACKNOWLEDGEMENT

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