PERFORMANCE CHARACTERISTICS OF AN EXPERIMENTAL
RIJKE TYPE PULSATING COMBUSTOR

ABSTRACT

An experimental study was conducted with a single-chamber pulsed combustor developed for the evaluation of fuels for gas turbine engines. The combustor, whose diameter was 1.7 m, was tested with air and fuel gas at lengths and the fuel used in the experiments was changed at intervals between 2 and 4 mm. Results of acoustic pressure amplitude, combustion efficiency, heat transfer to the wall, and CO concentration in the exhaust gases are presented. The combustor was tested at two different lengths, 240 and 320 cm. The test conditions varied between 157 and 162 dB. The maximum power released was approximately 1.7 MW/m² with 95% combustion efficiency using 10% excess air. The heat transfer to the wall increased with the presence of oscillations and was higher for the 320 cm combustor. For the same combustor length, the presence of CO in the exhaust gases was detected only for O₂ concentrations lower than 15%. On the other hand, in the 240 cm combustor, CO concentrations higher than 1% were measured even when the O₂ concentrations were of the order of 21%.

Key words: pulsating combustion.

ABSTRACT

An experimental work concerned with a modular Rijke type combustor developed for unpulverized fuels is presented. The combustor, whose diameter was 0.2 m, was tested with 240 and 320 cm lengths and the fuel used in the experiments was charcoal sized between 2 and 4 mm. Results of acoustic pressure amplitude, combustion efficiency, heat transfer rates, and particulate emission rates are presented for the two investigated lengths. The observed oscillation frequencies were on the order of 90 and 70 Hz, respectively, and the sound intensity varied between 157 and 162 dB. The maximum power released was approximately 1.7 Mw/m^2 with 95% combustion efficiency using 10% excess air. The heat transfer to the wall increased in the presence of oscillations and was higher for the 320 cm combustor. For the same combustor length, the presence of CO in the exhaust gases was detected only for O_2 concentrations lower than 1%. On the other hand, in the 240 cm combustor, CO concentrations higher than 1% were measured even when the O_2 concentrations were of the order of 2%.

Key words: pulsating combustion, Rijke tube.

INTRODUCTION

The pulsating combustion phenomenon was probably discovered by Higgins¹ when he observed the so called hydrogen "singing" flames in tubes. Later, in 1859, Rijke² discovered that the first acoustic mode of a tube opened at both ends could be excited when a previously metallic grid was positioned in the lower half of the tube. A similar experiment was independently carried out by Bosscha and Riess² who found that acoustic oscillations were also excited in an open ended tube when a hot flow a gas was cooled in the upper half.

The pulsating combustion process has been used in a variety of practical applications. Reports in the literature indicate that combustors utilizing the process present several advantages such as high combustion efficiencies and intensities^{3,4}, reduced pollutants formation^{5,6}, increased convective heat transfer rates^{7,8}, and cleaning of heater surfaces⁹. More recently, Zinn and co-workers¹⁰⁻¹⁴ confirmed some of these advantages with the burning of woods chips and low ash content coals in a Rijke type pulsating combustor in which the original heated metallic grid was replaced by a combustion bed.

This paper describes the characteristics of a developed Rijke type combustor in the burning of unpulverized charcoal. In order to search the combustion performance under new operating conditions, it possesses several differences in relation to that of Zinn and co-workers, among them an improved feed mechanism, a double size combustion bed and a water jacket to cool the combustion gases. Two combustor lengths were tested and the influence of frequency and amplitude of acoustic oscillations on combustion efficiency and heat transfer rates is analyzed.

EXPERIMENTAL FACILITY AND PROCEDURE

A cast iron, 20 cm internal diameter modular combustor whose schematic is shown in Figure 1 was developed and instrumented for the investigation. The device was tested in the lengths of 240 cm and 320 cm and the bottom grid of the combustion bed was in all cases positioned 12 cm below the quarter length section. A 65 cm internal diameter, 120 cm high decoupling chamber was attached to the bottom of the tube in order to keep the required open end boundary condition at the entrance section and to allow control of the air feed rate. The combustor possessed a feed modulus with an inclined 8 cm diameter feed tube on top of which different feed systems could be mounted. A metallic wire grid attached to a steel ring held the combustion bed. The grid was supported by a sliding rod mechanism that allows variation of the combustion bed position inside the combustor.

The feed system consisted of a perforated cylinder attached to a motor of variable speed. As shown in Figure 2, the scraper and the plane spring keep the fuel chunks from passing freely to the feed tube. The plane spring either removes the excess of fuel from the cylinder holes or opens to allow the passage of a larger chunk. Different perforated cylinders can be used depending on the characteristics of the fuel. The feed system operated smoothly and kept the fuel in the same size that it had in the hopper.

Air was provided through the decoupling chamber by an IBRAM model CR 8 radial compressor. The air flow rate was controlled by a valve and metered with a rotameter. Ambient temperature, pressure and relative humidity were obtained from a nearby meteorological station for the necessary corrections to the air composition.

The combustion gases were continuously analyzed by a CO/CO₂ Brumark model BR-AR-412 infrared analyzer and an O₂ Junkalor model

FIGURE 1 Schematic of pulsating combustor.

Perovskite thermo-magnetic analyzer. The gas sampling probe was located a few centimeters from the combustor exit plane. It consisted of a perforated tube containing several high mesh metallic screens. A sampling train dried the sample prior to analysis.

The amplitude and frequency of acoustic pressure were measured at a half length from the bottom of the tube using Kistler type 7261 piezoelectric pressure transducers, Kistler type 5038 charge amplifiers, and an Analog model F 8100 A frequency meter. The indicated measurement position corresponds to the acoustic pressure maximum amplitude of the fundamental mode of oscillation. The signals from the pressure transducers were displayed in a Tektronix model 7633 oscilloscope screen.

FIGURE 2 Detail of feed mechanism.

Four series of experiments were carried out and they are specified in Table I. The cooling water flow rate in the water jackets was in all cases 10 l/min. Ignition was achieved lighting wood chips soaked in alcohol.

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Temperatures were measured with beaded type chromel-alumel Omega thermocouples. All the data from the experiments were collected, stored and processed by a computerized data collection/analysis system. A schematic of the instrumentation is shown in Figure 3.

The fuel burned in the tests was unpulverized charcoal. Its elementary analysis, granulometry, heat value and moisture content are presented in Table I. Elutriated particles were collected in a box placed on the top of the combustor.

Four series of experiments were carried out and they are specified in Table II. The cooling water flow rate in the water jackets was in all cases 10 l/min. Ignition was achieved lighting wood chips soaked in alcohol.

- LEGEND
- 1-TEMPERATURE, THERMOCOUPLE
 - 2-ACOUSTIC PRESSURE, KISTLER 7261
 - 3-COMBUSTION GAS CONCENTRATION
 - 4-DIGITAL THERMOMETER
 - 5-TEMPERATURE, THERMOCOUPLE
 - 6-CHARCOAL
 - 7-COOLING WATER FLOW RATE
 - 8-O₂ ANALYZER, JUNKALOR PERMOLYT 2
 - 9-VOLTAGE RECTIFIER, INPT/LCP
 - 10-DIGITAL FREQUENCY METER, ANALOG 8100A
 - 11-DIGITAL MILLIVOLTMETER, S&E 1400
 - 12-OSCILLOSCOPE, TEKTRONIX 7633
 - 13-DATA COLLECTION SYSTEM, RIFRAN EUROMICRO
 - 14-MICROCOMPUTER, UNITRON AP3

FIGURE 3 Schematic of instrumentation.

LEGEND

- a - TEMPERATURE, THERMOCOUPLE TYPE K.
- b - ACOUSTIC PRESSURE, PIEZOELECTRIC TRANSDUCER KISTLER 7261.
- c - COMBUSTION GAS CONCENTRATION.
- 1 - DIGITAL THERMOMETER, RENE GRAF S 200.
- 2 - TEMPERATURE TRANSMISSOR, 0-100 °C, AUCONTROL TTT 701.
- 3 - TEMPERATURE TRANSMISSOR, 0-600 °C, AUCONTROL TTT 701.
- 4 - CHARGE AMPLIFIER, KISTLER 5006.
- 5 - CO/CO₂ ANALYZER, BRUMARK BR-AR-412.
- 6 - O₂ ANALYZER, JUNKALOR PERMOLYT 2.
- 7 - VOLTAGE RECTIFIER, INPE/LCP.
- 8 - DIGITAL FREQUENCY METER, ANALOG 8100A.
- 9 - DIGITAL MILLIVOLTMETER, S&E 1400.
- 10 - OSCILLOSCOPE, TEKTRONIX 7633.
- 11 - DATA COLLECTION SYSTEM, RIFRAN EUROMICRO.
- 12 - MICROCOMPUTER, UNITRON AP2.

FIGURE 3 Schematic of instrumentation.

TABLE I

Ultimate analysis and size distribution of charcoal

ULTIMATE ANALYSIS, DRY BASIS (% mass)		SIZE DISTRIBUTION	
		DIMENSION (mm)	% mass
CARBON :	87.5	2.00 — 4.00	95.3
HYDROGEN :	0.3	1.00 — 2.00	4.5
OXYGEN :	9.1	0.50 — 1.00	0.1
NITROGEN :	0.1	0.00 — 0.50	0.1
ASH :	3.0		
LOW HEAT VALUE : 31,740 J/g			
MOISTURE : 10.9 % (AVERAGE)			

RESULTS AND DISCUSSION

The first set of results is shown in Figure 5 which illustrates, for a typical test, the time variation of gas concentrations, frequency, pressure amplitude and temperature. As it can be seen from the figure, after the 15th minute of the experiment, the gas concentrations remained approximately constant and operation proceeded steadily. For the combustor mounted in the length of 320 cm, CO was only detected in the exhaust. The O_2 concentration were lower than 1%. On the other hand, for the combustor length was 240 cm, CO concentrations were observed even for O_2 .

TABLE II

Series of experiments performed

	COMBUSTOR LENGTH (cm)	NOMINAL AIR FLOW RATE (g/min.)	REAL AIR FLOW RATE (g/min.)	FUEL FEED RATES (g/min.)
SERIES # 1	320	900	880	65, 74, 79
SERIES # 2	320	1200	1160	91, 99, 108
SERIES # 3	240	900	930	72, 83, 92, 97
SERIES # 4	240	1200	1230	87, 113, 116, 117

As temperature decreased. As the experiment continued, the amplitude of acoustic pressure decreased, the flue gas temperature increased and the water temperature decreased.

The decrease with time of the acoustic pressure amplitude occurred in all the tests. This happened because as a test proceeds and the combustion equipment becomes hotter the combustion bed position for maximum acoustic amplification is shifted downwards from the initial quarter length position.

The performance of the combustor for the tested conditions is presented in Figures 5-8 and Table III. In all graphs, the normalized air/fuel ratio is the ratio $(\dot{m}_{AIR}/\dot{m}_{FUEL})/(\dot{m}_{AIR}/\dot{m}_{FUEL})_{STOIC}$.

RESULTS AND DISCUSSION

The first set of results is shown in Figure 4 which illustrates, for a typical test, the time variation of gas concentrations, frequency, pressure amplitude and temperatures. As it can be seen from the figure, after the 15th minute of the experiment, the gas concentrations remained approximately constant and operation proceeded steadily. For the combustor mounted in the length of 320 cm, CO was only detected in the exhaust gases if the O_2 concentration were lower than 1%. On the other hand, when the combustor length was 240 cm, CO concentrations higher than 1% were observed even for O_2 concentrations higher than 2%.

Pulsating operation started in all tests 3 to 5 minutes after ignition. The shift from non pulsating to pulsating operation was always followed by a strong agitation of the fuel particles which behaved like a spouting bed, indicating the occurrence of a better mixing process between oxidizer and fuel.

The effect of pulsations on heat transfer can be clearly seen by further observation of Figure 4. As pulsations started, the flue gas temperature decreased. As the experiment continued, the amplitude of acoustic pressure decreased, the flue gas temperature increased and the water temperature decreased.

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FIGURE 4 Time variation of gas concentrations, frequency, pressure amplitude, and temperatures in a typical test.

FIGURE 5 Dependence of the interval of acoustic pressure amplitude, p' , upon the normalized air/fuel ratio, α .

FIGURE 6 Dependence of combustion efficiency, η_c , on normalized air/fuel ratio, α .

FIGURE 7 Dependence of the percentage of heat value transferred to water, $Q_w/\dot{m}_c$, upon the normalized air/fuel ratio, α .

FIGURE 7 Dependence of the percentage of heat value transferred to water, $Q_w/\Delta h_c$, upon the normalized air/fuel ratio, α .

FIGURE 8 Dependence of the percentage of emitted particulates (in relation to quantity of fuel burned) upon the normalized air/fuel ratio, α).

where $\dot{m}_{AIR}$ is the air flow rate, $\dot{m}_f$ is the fuel flow rate and $(\dot{m}_{AIR}/\dot{m}_f)_{STOIC}$ is the stoichiometric air/fuel ratio.

Figure 5 shows the dependence of the pressure pulse amplitude upon the normalized air/fuel ratio. It can be observed that in most of the tests the pressure amplitude was higher at the larger air flow rates and did not depend on the combustor length.

TABLE III

Quantity and mean characteristics of elutriated particulates ((1): percentage of particulates in relation to total charcoal burned in the series; (2): ϕ = particle diameter, dimensions in mm; (3): Δh_c = heat of combustion; (4): UCL = unburned carbon loss)

SERIES	PARTICULATES (%) (1)	MEAN GRANULOMETRIC COMPOSITION (%)					MEAN Δh_c (J/g) (3)	UCL (%) (4)
		$\phi > 2.0$ (2)	$2.0 < \phi < 1.0$	$1.0 > \phi > 0.59$	$0.59 > \phi > 0.35$	$\phi < 0.35$		
1	1.7	0	10	41	15	34	-16,600	0.9
2	3.5	1	40	36	5	18	-27,800	3.1
3	2.5	1	34	36	8	21	-27,000	2.1
4	5.7	3	69	13	3	11	-29,000	5.2
Ash (%)		4	3	3	19	66		
Δh_c (J/g)		-31,740	-31,740	-31,740	-26,500	-11,100		

1.8 sec for the experiments of series # 2 and # 3, 60% larger for series # 1 and 50% shorter for series # 4. Highest combustion efficiencies were obtained for the largest residence times. The shortest residence times of series # 4 were apparently compensated by the higher observed amplitude of pulsations in the same series (except for the test carried out with $\alpha = 1.47$).

Data on heat transfer to the water jacket are presented in Figure 7, which shows, for different air/fuel ratios, the percentage of the fuel heat value that was collected by the water flow. Again, the gas residence time and the amplitude of pulsations

where $\dot{m}_{\text{AIR}}$ is the air flow rate, $\dot{m}_{\text{F}}$ is the fuel feed rate and $(\dot{m}_{\text{AIR}}/\dot{m}_{\text{F}})_{\text{STOIC}}$ is the stoichiometric air/fuel ratio.

Figure 5 shows the dependence of the acoustic pressure amplitude upon the normalized air/fuel ratio. It can be observed that in most of the tests the pressure amplitude was higher at the larger air flow rates and did not depend on the combustor length. This can be explained by the fact that, for a certain air/fuel ratio, at the larger air flow rates, the absolute heat release rates are larger and more energy becomes available for the acoustic oscillations.

Combustion efficiencies were calculated from the measured CO concentrations and carbon content of emitted particulates. The data are presented in Figure 6. As it can be observed from the figure, higher combustion efficiencies were obtained when the combustor was mounted in a length of 320 cm and operated at a nominal air flow rate of 900 g/min. The data from the experiments of the other three series fit approximately the same line. Probably two concurrent effects contributed for the arrangement of the data as they are shown in Figure 6: the gas residence time and the amplitude of pulsations. The gas residence time was approximately 1.8 sec for the experiments of series # 2 and # 3, 60% larger for series # 1 and 50% shorter for series # 4. Highest combustion efficiencies were obtained for the largest residence times. The shortest residence times of series # 4 were apparently compensated by the higher observed amplitude of pulsations in the same series (except for the test carried out with $\alpha = 1.47$).

Data on heat transfer to the water jacket are presented in Figure 7, which shows, for different air/fuel ratios, the percentage of the fuel heat value that was collected by the water flow. Again, the gas residence time and the amplitude of pulsations

affected the obtained data. For the same heat transfer area-see the plot corresponding to the combustion bed modulus - highest heat transfer efficiencies occurred for the largest residence times. When the residence times were approximately the same, as in series #2 and #3, higher heat transfer efficiencies occurred when the amplitude of pulsations were higher. The shortest residence times of series #4 were apparently compensated by the high amplitude of pulsations observed.

Data expressing the amounts of particulates emitted to the atmosphere are presented in Figure 8 and Table III. As seen in the data of Figure 8, larger quantities of particules were emitted during the experiments for which the air flow rates were larger and the combustor was shorter. Table III shows the average quantities of particulates and their heat content measured for each series. It can be observed from the table that particulates with sizes larger than 0.59mm had the same heat value of the charcoal and they contributed significantly for the build up of unburned carbon loss. This loss was only 0.9% when the particulates corresponded, in mass, to 1.7% of the fuel supplied, for the 320 cm combustor operating with a nominal air flow rate of 900 g/min. On the other hand, the unburned carbon loss increased to 5.2% for a particulate emission rate of 5.5% of the fuel, for the 240 cm combustor operating with a nominal air flow rate of 1200 g/min. No conclusive effect of pulsations on the particulate emission rates could be drawn from the experiments.

Finally, the heat output of the combustor was computed for all experiments. A maximum heat output of 1.7 Mw/m^2 was determined for the 320 cm combustor operating with a combustion efficiency of 95%. The heat output corresponding to the maximum combustion efficiency of 99% was 1.3 Mw/m^2 and it was also obtained with the 320 cm combustor. These values compare very favorably with existing fixed and fluidized bed combustors.

CONCLUSION

The main findings of this work can be summarized as follows:

a) A comparison between the experiments showed that an improved performance of the developed Rijke type combustor was obtained for a length of 320 cm with nominal air flow rate of 900 g/min. Under these conditions, the frequency of oscillations was approximately 70 Hz and the acoustic pressure amplitude varied between 20 and 10 mBar (160.0 and 157.5 dB). Under the same operating conditions, the percentage of elutriated particulates was of the order of 2% of the fuel, which implied in 1% loss of combustion efficiency.

b) The maximum power released per unit area was 1.7 Mw/m^2 , a value obtained with a combustion efficiency of 95% and a normalized air/fuel ratio of 1.10. In the condition of maximum combustion efficiency (99%) the power per unit area was 1.3 Mw/m^2 , which was obtained with a normalized air/fuel ratio of 1.13. The combustor length was still 320 cm.

c) In the 320 cm combustor the presence of CO in the exhaust was detected only for O_2 concentrations lower than 1%. On the other hand, in the 240 cm combustor, CO concentrations higher than 1% were measured even when the O_2 concentrations were of the order of 2%.

d) The experiments showed strong evidence that the heat transfer to the wall of the combustor is favored by the acoustic oscillations. For same pressure amplitudes, the effect is more significant for operation with the 320 cm combustor (and frequencies of approximately 70 Hz).

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REFERENCES The authors are grateful to FINEP (Financiadora de Estudos e Projetos, Brazil) for support of this work under contract number 44/85/0260/00.

- 1 Lord Rayleigh: *The Theory of Sound*, 1945, vol. 2, p. 224.
- 2 Seemits, H.: Experiences with pulsating tube firing in an experimental installation. *Pulsating Combustion, the Collected Works of F.R. Heynat*, H.W. Thring, ed., Pergamon, 1961, p. 262.
- 3 Hanby, V.I. and Brown, D.J.: A 50 lb/hr pulsating combustor for pulverized coal. *J. Inst. Fuel*, 1958, 41, p. 423.
- 4 Belles, F.E.: R & D and other needs for exploitation of pulse combustion in space-heating applications. *Proc. of the Symposium on Pulse-Combustion Technology for Heating Applications*, Argonne National Laboratory, 1979, p. 167.
- 5 Putnam, A.A.: A review of pulse-combustor technology. *Proc. of the Symposium on Pulse-Combustion Technology for Heating Applications*, Argonne National Laboratory, 1979, p. 1.
- 6 Fedorov, B.N.: Experimental study of the effect of acoustic oscillations on heat transfer in a gas flow. *Inzherno - Fizicheskii Zhurnal*, 1972, 31(1), p. 61.
- 7 Hanby, V.I.: Convective heat transfer in a gas-fired pulsating combustor. Published by ASME, 1968, paper n° 68-WA/FU-1.
- 8 Baskin, Y.L.: Pulsating combustion chambers as furnaces for steam boilers. *Thermo Engineering*, 1965, 12(9), p. 23.
- 9 Zinn, B.T., Carvalho, J.A., Jr., Miller, N. and Daniel, B.R.: Development of a pulsating combustor for burning of wood. *Proc. of the Symposium on Pulse-Combustion Applications*, 1982, OAI-82/0009.2, p. 11.1.
- 10 Zinn, B.T., Miller, N., Carvalho, J.A., Jr., and Daniel, B.R.: Pulsating combustion of coal in a Rijke type combustor. *Proc. of the Nineteenth Symposium (International) on Combustion*, The Combustion Institute, 1982, p. 1197.

REFERENCES

- 1 Tyndall, J.: On sounding and sensitive flames. *Physical Sciences*, 1970, 2, p. 30.
- 2 Lord Rayleigh: *The Theory of Sound*, 1945, vol. 2, p. 224.
- 3 Sommers, H.: Experiences with pulsating tube firing in an experimental installation. *Pulsating Combustion, the Collected Works of F.H. Reynst*, M.W. Thring, ed., Pergamon, 1961, p. 262.
- 4 Hanby, V.I. and Brown, D.J. A 50 lb/hr pulsating combustor for pulverized coal. *J. Inst. Fuel*, 1968, 41, p. 423.
- 5 Belles, F.E.: R & D and other needs for exploitation of pulse combustion in space-heating applications. *Proc. of the Symposium on Pulse-Combustion Technology for Heating Applications*, Argonne National Laboratory, 1979, p. 167.
- 6 Putnam, A.A.: A review of pulse-combustor technology. *Proc. of the Symposium on Pulse-Combustion Technology for Heating Applications*, Argonne National Laboratory, 1979, p. 1.
- 7 Federov, B.N.: Experimental study of the effect of acoustic oscillations on heat transfer in a gas flow. *Inzherno - Fizicheskii Zhurnal*, 1977, 31(1), p. 61.
- 8 Hanby, V.I.: Convective heat transfer in a gas-fired pulsating combustor. Published by ASME, 1968, paper n° 68-WA/FU-1.
- 9 Babkin, Y.L.: Pulsating combustion chambers as furnaces for steam boilers. *Thermo Engineering*, 1965, 12(9), p. 23.
- 10 Zinn, B.T., Carvalho, J.A., Jr., Miller, N. and Daniel, B.R.: Development of a pulsating combustor for burning of wood. *Proc. of the Symposium on Pulse-Combustion Applications*, 1982, GRI-82/0009.2, p. 11.1.
- 11 Zinn, B.T., Miller, N., Carvalho, J.A., Jr., and Daniel, B.R.: Pulsating combustion of coal in a Rijke type combustor. *Proc. of the Nineteenth Symposium (Internacional) on Combustion*, The Combustion Institute, 1982, p. 1197.

- 12 Carvalho, J.A., Jr., Wang, M.R.; Miller, N., Daniel, B.R., and Zinn, B.T.: Controlling mechanisms and performance of coal burning Rijke type pulsating combustors. *Proc. of the Twentieth Symposium (International) on Combustion*, The Combustion Institute, 1984, p. 2011.
- 13 Wang, M.R.: Mechanisms and performance of coal burnong Rijke type pulsating combustors. *Ph.D. Thesis*, 1985, Georgia Institute of Technology.
- 14 Carvalho, J.A., Jr., Miller, N., Daniel, B.R. and Zinn, B.T.: Combustion characteristics of unpulverized coal under pulsating and non-pulsating conditions. *Fuel*, 1987, 66(1) p. 4.