VTT

REPORT OF THE PULSATING COMBUSTION DEVELOPMENT BY INPE/VTT IN 1993

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ABSTRACT

The report describes the tests carried out with the acoustic pulsating combustor. The tests were made at the Brazilian National Space Research Institute (INPE) under a cooperation project with Technical Research Centre of Finland (VTT).

Various experiments were carried out. The goal of the experiments was to study how the heat exchanger that was installed in the upper decoupling chamber will affect on oscillations and functioning of the device and what is the effect of the decoupling chamber size on oscillations. Besides, ash/fuel circulation by means of two cyclones was studied and the main performance characteristics of the pulsed combustor were determined. Effect of the combustor tube diameter and length on amplitude and frequency was studied also. Various tests were made varying the grate position in the combustor tube.

The ultimate goal of the pulsating combustion research made by INPE and VTT is to develop a Rijke type pulsating combustor appropriate for industrial-scale energy operating units.

CONTENTS

1 TEST SET UP AND PROCEDURE

The pulsating combustor configuration is shown in Figure 1. The main principles of functioning of the device have been explained in detail in References /1-5/. In comparison with the earlier configuration, a heat exchanger was installed into the upper decoupling chamber. The heat exchanger was designed to reduce the gas temperature from around 800 °C (load 100 %) to 150 - 200 °C. It consisted of six annular coils that formed three separate circuits connected to same inlet and outlet water lines. The water mass flow rate through each circuit was measured before the tests to be the same in each of them. According to the measurements the mass flow rates were equal, as supposed, since the length of each circuit was the same. During the tests only the total inlet mass flow rate was measured. Two cyclones were used to circulate and to remove the fly ash. Figure 2 shows schematically the particle flows inside the cyclones. The indices ash and cm refer to pure ash and to combustible matter, respectively. The first cyclone circulates the particles back onto the grate in order to decrease their combustible matter content before entering the second cyclone. The second cyclone removes fly ash from the flue gas.

The fuel feed rate was measured by weighing the fuel. The air flow rates were measured with an orifice plate. The total air flow rate was later calculated also on the basis of the flue gas composition and the fuel mass flow rate. The air temperature was measured at the bottom of the combustor tube. The flue gas temperature was measured with thermocouples at the outlets of combustor tube and heat exchanger.

The pressure oscillations were measured at two positions with piezoelectric pressure transducers (P1, f1 ~ amplitude and frequency at one fourth of the tube length, P2 and f2 at one half of the tube length) and amplified thereafter. The signals were studied with an oscilloscope for the determination of amplitude and frequency.

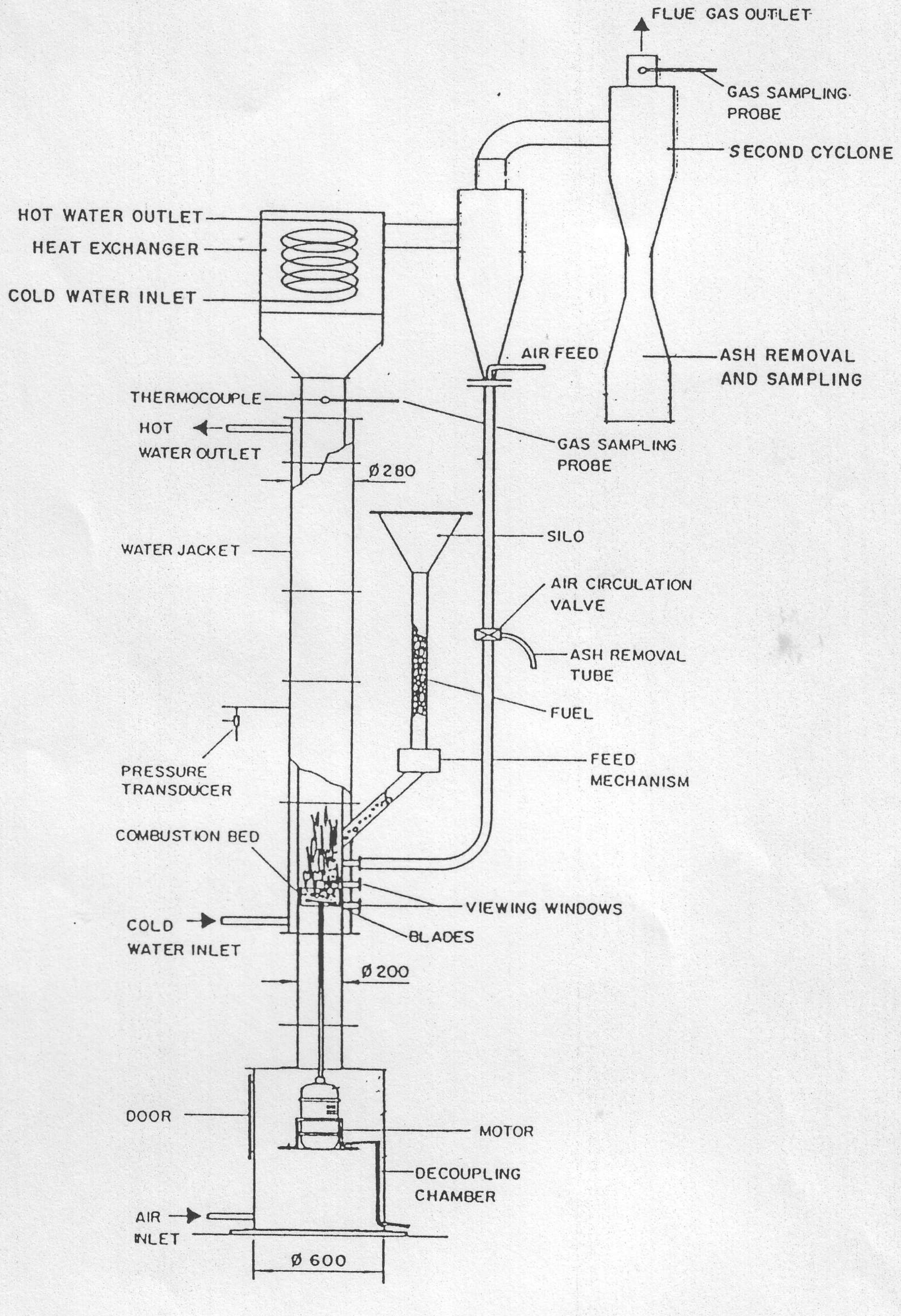

Figure 1. Experimental device.

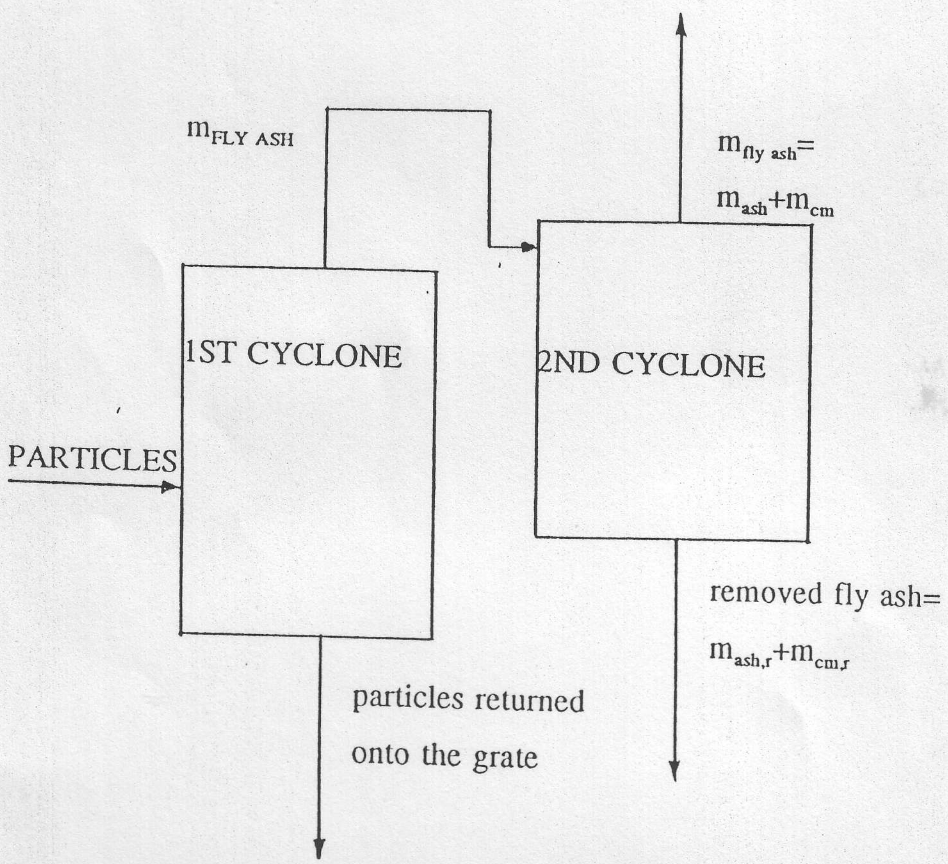

Figure 2. Particle flow diagram of the cyclones.

The oxygen and carbon monoxide contents of the flue gas were measured with paramagnetic analyzer at the outlet of the second cyclone.

The combustion bed is equipped with blender that rotates 18 r.p.m.

The fuel that was used in the tests, was Finnish pelletized peat. The composition of the fuel is presented in Table 1. In a couple of tests sod peat and wood chips were used instead of pellets.

Table 1. Composition of the fuel.

Element	Mass per cent
C	55.00
O	29.10
H	5.81
N	2.62
S	0.24
Ash	3.83

The other fuel characteristics were as follows:

-	moisture content	11.6 %
-	lower heat value on dry basis	21.05 MJ/kg
-	amount of volatiles	67.0 %
-	diameter of pellets	12 mm
-	length of pellets	15...25 mm

In the beginning of a test, the fuel bed was lighted using wood cubes and gas to ignite them. After the ignition the fuel feeder was turned on.

During the test the fly ash was collected into a container that was underneath the second cyclone. The fly ash was analyzed later to determine the amount of combustible matter in it.

2 RESULTS

2.1 THE EFFECT OF HEAT EXCHANGER ON THE OSCILLATIONS AND ON THE PERFORMANCE OF THE PULSED COMBUSTOR

As explained before, the heat exchanger was installed into the upper decoupling chamber. Its position inside the decoupling chamber is shown in Figure 1. The heat exchanger decreases the cross-sectional area for gas flow by one fourth (from 0.28 to 0.21 m^2).

Five tests were carried out to determine the operational parameters of the combustor. Table 2 shows the main parameters. Test 1 was made only to verify the proper functioning of the combustor and measuring devices.

Table 2. Results of the tests 1 - 5.

Test	P_1, mbar	f_1,H_z	P_2, mbar	f_2,H_z	T_{in}, °C	T_{out}, °C	CO, %	O_2, %
1	Test 1 was made to confirm the proper functioning of the device							
2	27 - 39	76 - 78	29 - 40	76 - 77	610 - 665	170 - 205	0.0 - 4.0	1.6 - 6.6
3	24 - 38	76 - 81	29 - 40	76 - 81	590 - 745	185 - 265	0.0 - 3.6	3.1 - 9.2
4	26 - 43	-	20 - 42	75 - 78	610 - 690	200 - 240	0.0 - 4.5	3.1 - 9.1
5	34 - 44	72 - 82	29 - 40	72 - 82	695 - 795	200 - 295	0.0 - 1.5	3.2 - 5.7

P1, P2	are the pressure amplitudes in the before-mentioned positions
f1, f2	are the frequencies in the same positions
Tin	is gas temperature at the combustor tube outlet (~gas temperature at the heat exchanger inlet)
Tout	is gas temperature at the heat exchanger outlet

CO, O_2 are the CO and O_2 contents in flue gas

The tests showed that it is possible to run the pulsed combustor in pulsating mode with installed heat exchanger. The heat exchanger does not have an effect on amplitude or frequency of the oscillations. The amplitude was between 24 - 43 mbar, that is even slightly higher than in previous tests /1 - 4/. The frequency stayed unaltered.

CO content varied in great extent during all the tests even though most of the time it was close to zero. Every now and then, however, it raised suddenly even up to 3 - 4 %. This was due to partial blocking of the ash/fuel circulation tube, as could be find out later when some modifications were made with the circulation system. Depending on the same fact, high amount of excess air was needed. On the other hand, combustion was not tried to be perfectly optimized, since these first five tests were made in first place to find out, if the heat exchanger has an effect on the oscillations.

The heat exchanger could drop the gas temperature from 600 - 800 °C down to 170 - 295°C. It was observed that the heat exchanger outlet temperature had a slight tendency to raise during all the tests. This is due to fouling of the heat exchanger tubes, since the heat exchanger was not cleaned during or between the tests. When the upper decoupling chamber was opened after the fifth test, it was found out that the heat exchanger tubes were covered with a layer of ash (in order of 1 - 2 mm) and incompletely burnt fuel. The heat exchanger was cleaned then with the compressed air.

The heat flows from the gas to the water in the combustion tube and in the heat exchanger were calculated on the basis of the measured water mass flow rates and temperatures. Table 3 shows the results.

The efficiencies are relatively low, since there is no isolation around the combustor tube or the upper decoupling chamber. The heat loss is obviously high

Table 3. Heat transfer in the combustor tube and in the heat exchanger.

Test	2	3	4	5
Tube, kW	measurement out of order	61	67	75
Exchanger, kW	- " -	18	21	24
Fuel input, kW	108	108	123	123
Efficiency, %	-	73	72	80

especially in the decoupling chamber that is not surrounded by a water jacket like the combustor tube. These losses might be easily reduced almost insignificant by using isolation. However, it was not considered important yet in this stage of the development of pulsating combustor, when the experimental device is still simple in technical details. The flue gas temperature is also relatively high and should be lowered by means of frequent cleaning or extension of the heat exchanger surface. Additional losses were caused in tests also by incomplete gas combustion resulting in high CO concentrations.

2.2 THE TESTS WITH CYCLONES

Five different cyclones were used in tests 6 - 13. The tests were made to confirm that the cyclones do not have an effect on oscillations and functioning of the device. The original two cyclones of the device were replaced by smaller cyclones to improve the particle separation efficiency. The smaller cyclones cause a clearly higher pressure drop. It was supposed that the higher pressure drop may have an effect on oscillations. Table 4 shows the main dimensions of the cyclones and the estimated (calculated) pressure drop through the cyclones. Cyclones 3a and 3b are exactly similar.

Table 4. The main dimensions and the pressure drop of the cyclones.

Cyclone	1	2	3a	3b	4
l, m	1.0	0.8	0.6	0.6	0.48
d, m	0.25	0.2	0.15	0.15	0.12
ΔP, kPa	0.3	0.8	2.5	2.5	6.1

Table 5 shows the sets of two cyclones that were used in each test.

Table 5. The sets of cyclones in each test.

Test	6	7	8	9	10	11	12	13
Cyclones	1, 2	1, 2	1, 2	1, 3a	1, 3a	3a, 3b	3a, 3b	3a, 3b, 4

The same measurements were made during the tests as in tests 2-5. Besides of the measurements, the ash from the second cyclone was taken to be analyzed after each test. The ash was weighed and the amount of the combustible matter in it was determined.

The main results without the ash analysis are presented in Table 6. After the test 10 some modification was made to change the position of the secondary air flow. The modification was made to avoid the blocking in the ash/fuel circulation tube. As it can be seen from Table 6, during the tests 6 - 10 the CO content raised up to very high values every now and then as it did during the tests 2 - 5. This could occur also when excess of air was considerably high (O_2 ~ 7 - 8 %). After the position of the secondary air flow was transferred downward the circulation tube, the blocking of the tube decreased significantly. As a consequence, the CO formation also decreased remarkably. The CO content of the flue gas was then most of the time zero. However, even then there were some sudden peaks of CO formation and CO raised to around 1 per cent, as indicated in table (tests 11 - 13).

Table 6. Results of the tests 6 - 13.

Test	P_1, mbar	f_1, H_z	P_2, mbar	f_2, H_z	T_{in}, °C	T_{out}, °C	CO, %	O_2, %
6	20 - 37	75 - 81	21 - 37	74 - 81	585 - 685	180 - 255	0.0 - 0.3	4.0 - 8.2
7	19 - 41	76 - 82	20 - 41	76 - 82	580 - 760	190 - 285	0.0 - 4.7	2.4 - 7.9
8	24 - 39	76 - 83	26 - 36	76 - 83	600 - 770	220 - 300	0.0 - 2.0	2.2 - 8.9
9	19 - 38	78 - 81	19 - 36	77 - 81	575 - 720	220 - 270	0.0 - 2.7	1.3 - 7.7
10	25 - 34	76 - 82	24 - 32	76 - 82	580 - 785	220 - 300	0.0 - 4.2	3.8 - 8.0
11	31 - 42	77 - 81	31 - 40	77 - 80	695 - 790	270 - 315	0.0 - 0.9	1.7 - 3.5
12	29 - 40	76 - 82	29 - 39	76 - 82	655 - 820	280 - 335	0.0 - 1.4	0.9 - 4.6
13	27 - 36	76 - 80	25 - 37	77 - 80	700 - 770	270 - 350	0.0 - 0.7	0.5 - 3.3

The modification helped also to reduce the amount of air excess. The O_2 content of the flue gas was between 0.5 - 4.6 per cents, most of the time 2 - 3 per cents. This may be considered as a relatively low percentage, since the technical structure of the air staging is not necessarily optimal. For example, only 20 % of the total air feed may be delivered in secondary air. This may limit the overall mixing between the gas and air. Other positions and shapes of the secondary air inlet should also be tested. The distribution of secondary air through several air ports around the tube might also make the local stoichiometry in the mixing region more uniform.

Even though the blocking in the circulation tube decreased, the functioning of ash circulation/secondary air feed was still not as good as desired. Therefore, this part of the device will be replaced with a rotary gas lock in future experiments. This will help to maintain more stable continuous combustion conditions for the determination of required minimum excess of air in pulsating combustion. The minimizing of the air excess is important in reducing of NOx formation and heat loss of flue gas.

The use of smaller cyclones with consequent higher pressure drop did not change the amplitude and the frequency of pulsations. As can be seen from Table 6, the frequency and the amplitude stayed unaltered. In test 13 when three cyclones were used, the pressure drop was, however, as high that the flue gas began to leak out in some extent from between the combustor tube elements. Therefore the cyclone 4 was not used in following tests. It was observed also after the test that the container of this cyclone was practically empty (only 9 gr of ash) and it, therefore, did not improve the separation efficiency significantly.

Table 7. Ash removal from flue gas.

Test	6	7	8	9	10	11	12	13
	*							
$\dot{m}_{ash,in}$, g/s	0.343	0.216	0.236	0.236	0.227	0.209	0.239	0.276
$\dot{m}_{ash,r}$, g/s	0.061	0.173	0.142	0.132	0.195	0.137	0.152	0.166
η, %	18	80	60	56	86	66	64	60
$\dot{m}_{fuel}$, g/s	5.6	6.3	6.9	6.9	6.7	6.1	7.0	8.1
* ash content of the fuel 7.2 % in test 6, 3.8 % in other tests								

Table 7 shows the results related to ash removal. The efficiency of ash removal is typically in order of 60 %. The efficiency vary in some extent also between the tests when the same set of cyclones was used (Table 5). This is probably due to the relatively short duration of the tests, generally about two hours, and the variation in fuel and air mass flows.

In test 6 the efficiency was very low due to high ash content of the fuel. In three last tests the mass flow rate of the fuel was increased from 6.1 to 8.1 g/s. However, it did not decrease the separation efficiency as much as was supposed. The differences are insignificant when taking into account the uncertainties in the determination of the separation efficiency.

The separation efficiency on average can not be considered very high. On the other hand, these technically simple cyclones were used in first place to recirculate the unburnt fuel (first cyclone) and to help in determining of mass flow rates in the combustor. The separation efficiency could probably be improved significantly by substituting the cyclones with commercially used cyclones. This is considered to be done in future work.

Table 8 shows the losses caused by the combustible matter in fly ash. It was supposed that the fly ash outflow of the second cyclone has the same percentage of combustible matter in it as the ash removed from the bottom of the second cyclone. This approximation at least should not underestimate the total loss. The combustible matter was supposed to be carbon. This approximation also can not underestimate the loss. Therefore, the losses presented in Table 8 are maximum losses.

Table 8. The loss caused by unburnt fuel, %.

Test	6	7	8	9	10	11	12	13
In fly ash	3.9	1.6	2.7	3.1	1.0	2.7	3.2	2.0
In removed ash	0.9	6.4	4.1	3.9	6.1	5.3	5.7	6.9
Total	4.8	8.0	6.8	7.0	7.1	8.0	8.9	8.9

The losses are too high to be acceptable in practical combustion equipments. However, if the removed ash would be recirculated also, the total loss would probably be considerably lower, since most of the unburnt fuel is in removed ash. In addition, the mean particle size of removed ash is small, that helps its recombustion under prevailing residence time/temperature conditions in the combustor tube. In case of practical combustors the recirculation from the second cyclone will be probably necessary or the separation efficiency of the first cyclone should be very high. If the recirculation is used, a third device for the separation will be required, a scrubber or a bag filter for instance or even a third cyclone, depending on the prevailing environmental restrictions.

Table 9 shows the overall burning rate per grate area (P"= fuel input/grate area,).

Table 9. Overall burning rate per grate area, MW/m^2.

Test	6	7	8	9	10	11	12	13
P"	3.3	3.7	4.0	4.0	3.9	3.7	4.1	4.7

The values are high. This is the main advantage that the oscillations give. With peat pellets it seems to be easily possible to achieve values in order of 4 MW/m2. In case of higher values (test 13), more control of the fuel bed is required. The upper limit for the overall burning rate comes from the velocity of the primary air. When the burning rate is increased, the air flow rate has to be increased also. As a consequence, its velocity through the grate and the fuel bed will increase and the flow will carry more and more particles from the bed. Finally the conditions in the bed are not any more stable enough to produce a required heat source for oscillations at one fourth of the tube length. Therefore, the particle size and the density of the fuel have an effect on maximum overall burning rate.

2.3 THE TESTS WITH SOD PEAT AND WOOD CHIPS

The sod peat was grinded to have a mean particle size around two centimetres. The following properties were determined for this fuel:

- moisture content 18.9 %
- lower heat value on dry basis 20.7 MJ/kg
- ash content 2.4 %.

The density of the peat was not determined, but it is clearly lower than the density of the pellets, since it has not been compressed in the same way as the pellets.

The test was carried out following the same procedure as in other tests with the same measurements. There was more instability in overall functioning of the combustor than with the pellets, since the fuel feeder did not work satisfactorily with this fuel. This is due to lower fuel density and slightly bigger particle size. The structure and the dimensions of the feeder are not appropriate for this fuel resulting in frequent blockage.

During the test the measured values varied in following ranges:

- P1	21 - 40 mbar
- f1	72 - 78 Hz
- P2	21 - 39 mbar
- f2	72 - 78 Hz
- Tin	570 - 740 °C
- Tout	260 - 305 °C
- CO	0.0 - 0.6 %
- O_2	2.8 - 9.7 %

Ash was removed with the second cyclone as before. The results are shown in Table 10.

Table 10. Ash removal parameters, sod peat.

$\dot{m}_{ash, in}$, g/s	0.107
$\dot{m}_{ash, r}$, g/s	0.021
η, %	20
$\dot{m}_{fuel}$, g/s	5.5

The efficiency of ash removal was low. This is obviously due to low density of the fuel and high percentage of fine particles in fuel caused by fuel processing, transportation and feeding. The combustible matter content of the removed fly ash was 63 per cents depending probably also on the high amount of fine particles. The losses caused by combustible matter outflow in flue gas and in removed ash were:

- in fly ash 5.2 %
- in removed ash 1.3 %
- total 6.5 %.

The total loss is of same order as with pellets. Although the combustible matter content in ash was higher, the total loss caused by unburnt fuel in it was of same order, since the ash content of the fuel is lower. Most of the unburnt fuel is in fly ash and therefore can not be reburnt even if additional second recirculation would be used as explained before. This is why the loss caused by unburnt fuel may be more difficult to minimize in case of sod peat. On the other hand, as sod peat is normally used in energy generating units, its particle size is clearly higher and it does not contain as much fine particles as the test fuel. Therefore the fly ash outflow is probably lower. For these tests sod peat was processed to decrease the particle size and to make the feeding possible that way. The overall burning rate per grate area was 2.9 MW/m^2. Hence it was lower than with the pellets. This is in first place due to the already mentioned problems of fuel feeding. It was not possible to feed more fuel than the feeding rate that corresponds 2.9 MW/m^2. Therefore it is impossible to know on the basis of this test if the overall burning rate might be even higher. The feeder structure should be modified to make higher feeding rates and the use of bigger particle size possible.

After the test with sod peat, one trial with wood chips was made. However, the wood chips blocked the feeder almost immediately in the beginning of the test and it was impossible to continue the test. Later the wood fuel was used in the tests with a bigger combustor tube as described in the following chapter.

2.4 THE EFFECT OF COMBUSTOR TUBE DIAMETER AND LENGTH ON THE FREQUENCY AND THE AMPLITUDE OF PULSATIONS

Various tests were made to obtain information of the effect of the combustor tube diameter and length. The test arrangement was very simple. Two open-ended tubes were equipped with grates that were made of iron net. The grates were loaded with the fuel in the beginning of each test. There was no possibility to feed more fuel onto the grate during the tests. Therefore the tests were very short, normally 5 - 10 minutes. During the tests only the frequency and the amplitude of the pulsations were measured.

The bigger tube has the diameter and the length as shown in Table 11. Table shows also the distance of the grate from the bottom of the tube, l_1, and the fuel that was used in each test (wood chips or peat pellets).

Table 11. The dimensions of the bigger combustor tube, the grate position and the fuel in tests 16 - 24.

Test	16 - 18	19 - 20	21 - 23	24
d,m	0.60	0.60	0.60	0.60
l, m	2.55	2.55	3.40	3.40
l/d	4.3	4.3	5.7	5.7
l_1, m	0.58	0.58	0.73	0.69
l_1/l	1/4.4	1/4.4	1/4.7	1/4.9
fuel	wood	peat	wood	wood

Five tests (16 - 20) were made first without changing the length of the tube. The length of the tube was increased then from 2.55 m to 3.4 m (tests 21 - 24). The experimental combustor that was used in tests 1 - 15 has clearly higher l/d (3.2m/0.2m = 16). These tests proved that l/d of the tube may be much lower to make the tube oscillate.

The results of the tests 16 - 24 are presented in Table 12. The amplitude presented is its maximum value during the test. When the fuel was changed to be peat (tests 19 - 20) instead of wood (tests 16 - 18), the amplitude decreased clearly. This was due to worse ignition of the fuel bed in case of peat pellets. The fuel burned only in the border region of the bed. This might be avoided by using mechanical grate like with the smallest combustor tube. Such a grate, however, was not available for these tests. On the basis of these tests should not make the conclusion that peat as a fuel produce a lower amplitude of the oscillations.

When the tube length was increased to 3.40 m (tests 21 - 23), the frequency decreased, as supposed. The frequency may be calculated:

$$f = \frac{\sqrt{\gamma R T}}{3L} \tag{1}$$

where γ is the ratio of specific heats,
R is gas constant,
T is average gas temperature in the tube and
L is tube length.

The frequency in tests 21 - 23, in comparison with the tests 16 - 18, should be according to equation 1

$$f' = \frac{l}{l'} f \tag{2}$$

f is mean value of the frequency in tests 16 - 18, l is tube length in tests 16 - 18,

l' is tube length in tests 21 - 23.

This gives f' = 54, that matches well with the measured values (Table 12).

Table 12. Measured frequencies and amplitudes in tests 16-24.

Test	f_1, Hz	P, mbar	
16	70 - 72	20	wood
17	70 - 75	25	tube length 2.55 m
18	70 - 75	30	
19	65 - 66	3.5	peat
20	70 - 73	10	tube 2.55 m
21	51 - 58	6.0	wood
22	50 - 59	15	tube 3.40 m
23	50 - 59	16	
24	50 - 59	15	wood, tube 3.40 m, grate position lowered (Table 11)

The tube length seems to have an effect on amplitude also. The amplitude lowered from 20 - 30 mbar to 6 - 16 mbar. Since there is obviously a dependence between amplitude and overall combustion rate interacting in both directions, the lower amplitude indicates a lower combustion rate. The lower frequency 50 - 59 Hz (and the longer tube) seems to produce lower amplitude and probably a lower combustion rate than the frequency 70 - 75 Hz. This should be confirmed with additional tests. In such tests, it should be possible to measure the overall combustion rate besides of the amplitude and the frequency and to vary the combustion tube length (and hence the frequency also) in a wide range to get a more generalized dependence between the frequency, the overall combustion rate and the amplitude. Such tests would help to find the optimal tube length for industrial-scale combustors. Besides of the optimal oscillations and the combustion rate, the optimal tube length has to be chosen taking into account such additional limitations as the required particle residence time in the furnace for example. This type of experiments are considered to be done in future.

An additional feature that has to be taken into account is a position of the grate. It is possible that the difference in amplitudes is at least partially due to the non-optimized grate positions. According to basic rule for the position of the heat source in Rijke tube, the heat should be released at L/4 from the bottom of a tube. In case of solid fuel combustion the heat release occurs in fuel bed and in a region above the bed. Therefore the heat release has a distribution along the tube. This distribution depends on the fuel properties like moisture, amount of the volatiles etc. Therefore the grate position should be changed when the fuel or its properties are changed. However, as will be explained later, additional tests proved that the oscillations are not very sensitively altered if the grate position is changed in certain limits. Some indication of this was found also in test 24, when the grate position was lowered in comparison with the tests 21 - 23 and the amplitude and frequency stayed unaltered.

The smaller tube has the diameter and the length as shown in Table 13. The results of the tests are presented in Table 14. Three first tests were made with same parameters. The grate position was then lowered from 0.4 m to 0.36 m. This had no significant effect on amplitude or frequency. The fuel was changed then to be peat. The amplitude decreased in some extent. The variation of the frequency during the tests was higher than with the wood as a fuel. However, the

Table 13. The dimensions of the smaller combustor tube, the grate position and the fuel in each test.

Test	25 - 27	28	29	30	31	32
d, m	0.33	same tube for all tests				
l, m	2.08					
l/d	6.3					
l_1, m	0.40	0.36	0.40	0.36	0.40	0.36
l_1/l	1/5.2	1/5.8	1/5.2	1/5.8	1/5.2	1/5.8
fuel	wood	wood	pellets	pellets	sod peat	sod peat

Table 14. Measured frequencies and amplitudes in tests 25-32.

Test	f_1, Hz	P_1, mbar	
25	95 - 97	15	wood
26	90 - 93	10	
27	91 - 95	13	
28	90 - 92	13	
29	84 - 97	9	peat pellets
30	86 - 97	9	
31	86 - 99	7	sod peat
32	85 - 98	6	

differences between the results of the tests 25 - 28 and 29 - 32 are not high enough to draw generalized conclusions between these three fuels, although the peat seems to produce a lower amplitude as it did in the tests with the bigger combustor tube also. This may depend on different packing of the fuel bed, on worse ignition and on less uniform combustion of the fuel. These features may not necessarily affect if a mechanical grate is used as it will be used very probably in industrial-scale furnaces.

For the tests 30 and 32 the grate position was lowered as indicated in Table 13. The amplitude and the frequency stayed unaltered.

2.5 THE EFFECT OF GRATE POSITION ON THE AMPLITUDE AND THE FREQUENCY

Eighteen tests were made with the smaller combustor tube to determine the amplitude and the frequency as a function of the grate position. The grate position from the bottom of the tube was changed stepwise with 4 cm step from 68 cm to 0 cm. Wood chips were used as fuel in all tests. The results are presented in Figure 3. There are weak oscillations even if the grate is positioned at the tube bottom. The amplitude increases then until the grate is 20 - 24 cm from the bottom and stays around on the level of 10 mbar until 52 cm that is one fourth of the tube length. After that the amplitude decreases and the oscillations disappear completely at 68 cm. Hence the position of the grate in vertical direction may be chosen in relatively wide ranges without affecting on the oscillations. This is a very useful result considering of the practical furnaces. In such a furnace the grate position may not be changed (at least not very easily) after the installation of the grate. If the oscillations would depend very sensitively on the grate position, it

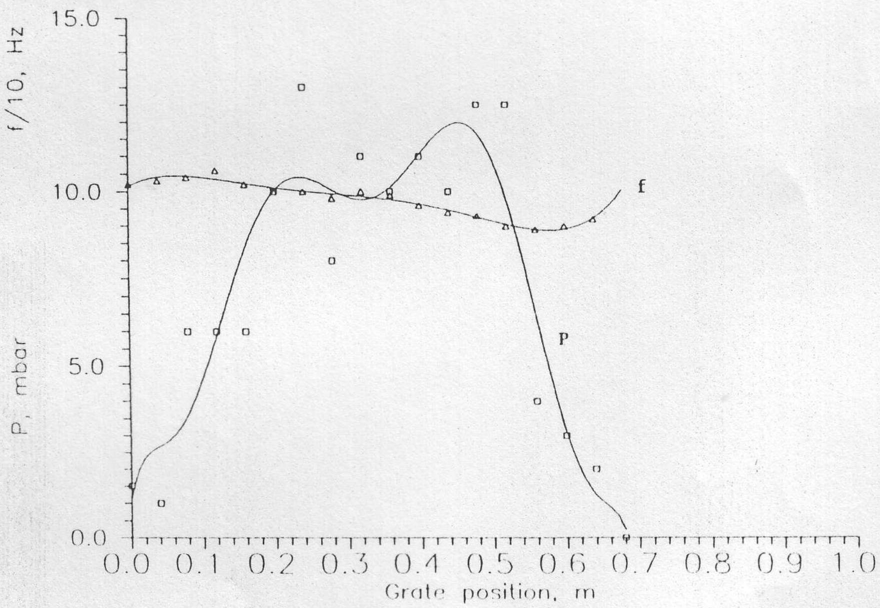

Figure 3. Amplitude and frequency as a function of the grate position.

would be time-consuming and expensive to try to find the optimal grate position. Especially it might make the use of different fuels difficult or even impossible, since the heat release from different fuels does not proceed similarly in vertical direction.

The grate position has an effect on the frequency also. The frequency has a tendency to increase slightly when the grate position is lowered. This is probably due to the higher mean value of the gas temperature in the tube. A lower grate position means a longer flue gas region above the grate and a shorter region of the cold air underneath the grate causing a higher mean value of the temperature. As the equation 1 shows the frequency increases proportionally to the square root of the temperature.

2.6 THE TESTS AFTER THE MODIFICATIONS OF ASH/FUEL CIRCULATION SYSTEM

Modifications of the ash/fuel circulation system were made to avoid the blocking in the circulation tube. Therefore a feeder with gas lock was installed underneath the feeder and the ash removal tube was removed. Figure 4 presents the combustor after the modifications.

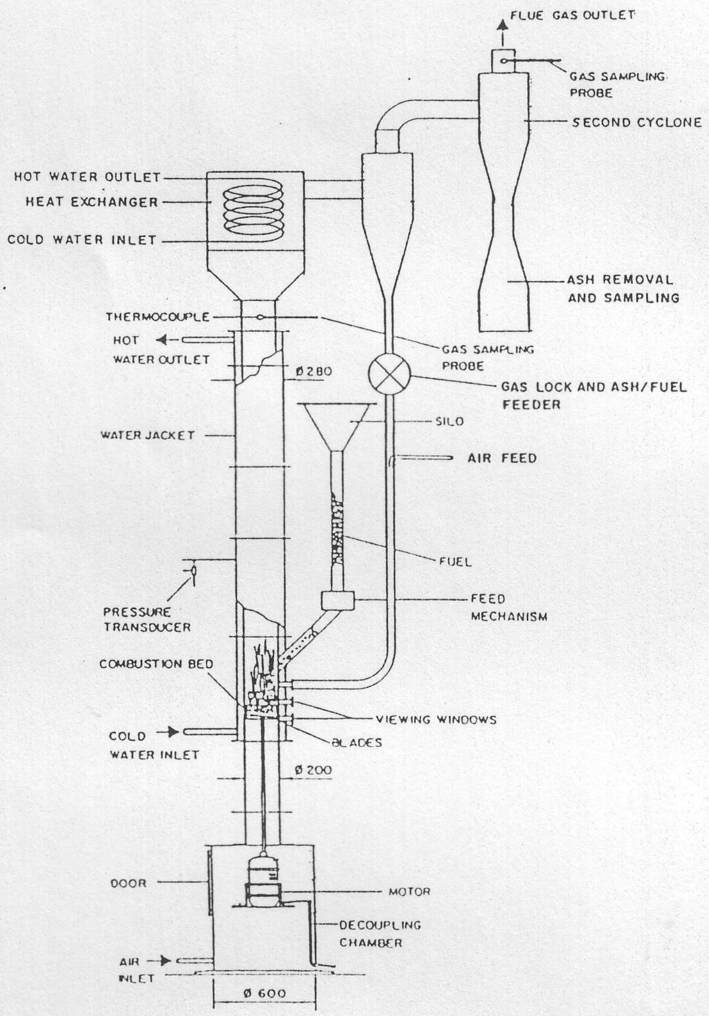

Figure 4. The combustor after the modifications.

Two tests were made after the modifications. The main results are presented in Table 15.

Table 15. Results of the tests 51-52.

Test	P_1, mbar	f_1, H_z	P_2, mbar	f_2, H_z	T_{in}, °C	T_{out}, °C	CO, %	O_2, %
51	27 - 36	79 - 82	25 - 33	79 - 82	745 - 810	305 - 340	0.0 - 1.2	2.0 - 4.5
52	33 - 41	76 - 81	31 - 41	77 - 81	700 - 790	275 - 330	0.0 - 1.3	2.7 - 5.2

In comparison with the results of the tests 11-13 that were made after the first modifications of the ash/fuel circulation system, the main measured parameters stayed practically unaltered. There were still some high CO formation peaks as indicated in table. Figure 5 shows CO and O_2 contents as a function of time in test 51. It can be concluded on the basis of the figure that CO peaks are not caused because of the blockage in the ash/fuel circulation tube, but they are depending on the low level of excess of air. If the tube would be blocked like it did in tests 6-13, the O_2 content would increase simultaneously with CO peaks. Figure shows that this is not the case. CO is formed when O_2 level is low. This is normal behaviour in combustion. Figure shows also that CO is not formed when O_2 content is higher than around 3.5 %. This means reasonably low level of required excess of air and it means also that now the CO formation can be prevented easily by means of air feed control.

Table 16 shows the loss caused by unburnt fuel. The total loss is somewhat lower than in tests 11-13, although still too high to be acceptable. The loss of the unburnt fuel in removed ash has stayed practically unaltered, but the loss in fly ash is now clearly lower than before. The loss in fly ash can be considered acceptable and is of same order as in different practical combustion devices. This is a promising result, since the removed ash can be easily recirculated and the loss probably decreased significantly as was explained before in chapter 2.2.

The separation efficiency increased clearly also. The gas lock probably improves the ash/fuel circulation preventing the blockage in the circulation tube. As a consequence, the gas/particle flow to the second cyclone is more stable, since

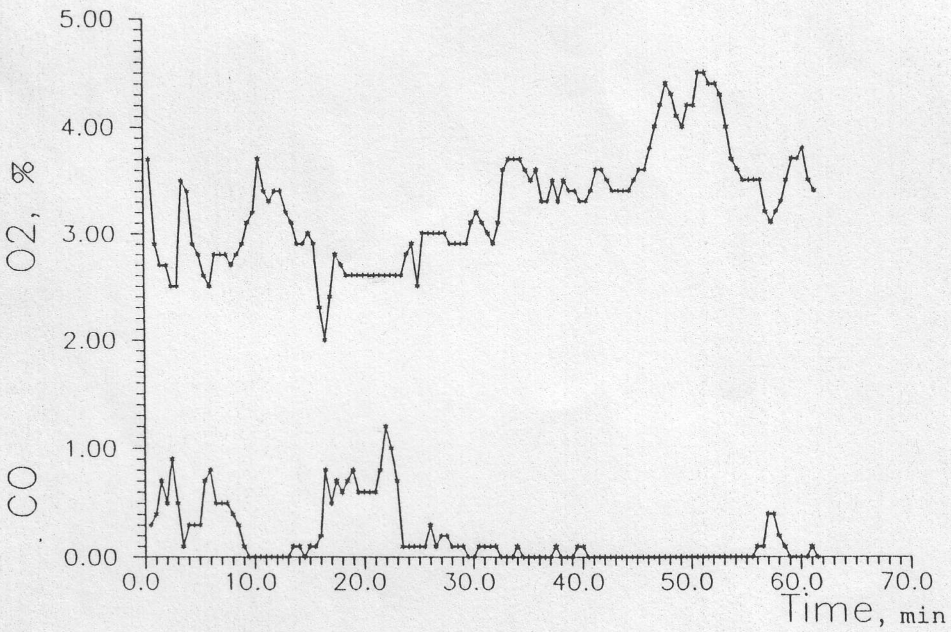

Figure 5. CO and O_2 of flue gas as a function of time.

during the blockage the first cyclone obviously does not function properly and the particle flow to the second cyclone may be very high as long as the tube is blocked. These peaks in tests 11-13 obviously decreased the separation efficiency and increased the combustible matter content in fly ash.

Table 16. The loss caused by unburnt fuel and the efficiency of ash removal, tests 51-52.

Test	51	52
In fly ash	1.0	0.3
In removed ash	5.6	5.1
Total	6.6	5.4
η, %	85	95

The overall burning rates per grate area were now 4.1 and 4.0 MW/m^2 that is of same level as in tests 11-13.

The modifications improved the device remarkably. The ash/fuel circulation can be improved still by recirculating the fly ash from the second cyclone. It could be done even using the same gas lock feeder with the first cyclone. This would be probably the most simple way to recirculate the fly ash.

2.7 PERFORMANCE ON PARTIAL LOAD AND THE EFFECT OF DECOUPLING CHAMBER SIZE ON PULSATIONS

Since the decoupling chambers are only indirectly participating in the combustion, it would be useful to minimize their volumes. This is important especially in case of the industrial-scale boilers, since the size and the price should be minimized to improve the technical and economical competitivity of the equipment.

Table 17. Results of the tests 53-54.

Test	P_1, mbar	f_1, Hz	P_2, mbar	f_2, Hz	T_{in}, °C	T_{out}, °C	CO, %	O_2, %
53	24 - 38	75 - 82	26 - 36	76 - 82	690 - 790	295 - 320	0.0 - 1.4	2.7 - 5.1
54	16 - 26	73 - 77	16 - 25	73 - 77	510 - 655	200 - 230	0.0 - 1.4	2.0 - 6.5

Table 18. The loss caused by unburnt fuel and the efficiency of ash removal, test 53-54.

Test	53	54
In fly ash	0.5	2.8
In removed ash	5.2	3.2
Total	5.7	6.0
η, %	91	53

The size of the upper decoupling chamber of the experimental device can not be decreased significantly, since the heat exchanger inside the chamber occupies most of the volume. The lower decoupling chamber was filled with sand almost up to the bottom of the rotating motor of the grate to decrease the chamber volume. The volume ("waste space") decreased this way around 70 %, when the volume occupied by the rotating motor is not included. One test was made then to obtain main combustion characteristics for comparison with the previous tests. The results are presented in Table 17, test 53.

Compared with the results of the tests 51-52, the values are practically the same as in those tests. The decreasing of the lower decoupling chamber volume had no effect on combustion. The results of the ash removal, Table 18, test 53, and the overall burning rate per grate area (4.2 MW/m^2) stayed also unaltered.

More extensive tests should be done in different ranges of the combustor size, for instance d = 0.2 - 1.0 m and l = 1.0 - 5.0 m, to obtain generalized rules for minimum decoupling chamber volumes. Such data would be useful for the design of the industrial-scale boilers. Tests might be done with simple tubes without mechanical grates or cyclones, like described in chapters 2.4 and 2.5.

One test was made with partial load to confirm that the load may be controlled without problems. The load was around 60 % of the previous test. The results are presented in Tables 17-18, test 54. The amplitude of the oscillations decreased clearly, as supposed. The frequency decreased slightly also, since the mean value of the gas temperature in the tube is lower because of the lower load. The gas temperature before and after the heat exchanger decreased as natural, when the load is decreased. CO and O_2 contents stayed around the same. However, now it was possible to prevent CO formation using somewhat lower air excess, corresponding 3 % of O_2 in flue gas. On the other hand, the control of the fuel bed (air/fuel ratio) seemed to be more difficult causing CO peaks more easily than before. This is probably due to the lower bed height that makes the variation of the air/fuel ratio more sensitive.

The total loss caused by unburnt fuel did not change, but its distribution changed such way that the loss in fly ash grew. The separation efficiency became low. The cyclones do not work optimally, since the gas velocity in the cyclones is lower on partial load.

3 SUMMARY

The tests proved that the heat exchanger that was installed into the upper decoupling chamber did not affect on pulsating mode of the combustor. Amplitude and frequency of the oscillations were of same order as without the heat exchanger.

The heat exchanger was designed to reduce the gas temperature from around 800 °C to 150-200 °C, as it did in first tests. However, fouling of the exchanger tubes raised the gas outlet temperature in following tests. Since the heat exchanger is placed in gas flow before the cyclones, it has a tendency to foul easily. Therefore, in case of industrial-scale furnaces, a lot of attention should be paid to this fact. The heat exchanger should be equipped with soot blowing or with another possibility for easy cleaning. An extension of the heat exchanger surface could be used also either before or after the cyclones. This could be used optionally when the gas outlet temperature of the main exchanger is higher than required. One option is to place the main exchanger after the cyclones. This option however has at least three disadvantages. Since the gas will enter the cyclones in higher temperature (~800 °C instead of ~200 °C), the cyclones have to be designed larger, if optimal gas inlet velocity 20-25 m/s (and maximum separation efficiency) is required. Besides, more expensive cyclone material and more isolation has to be used because of the higher temperature. Structure of the boiler becomes less compact also because of the additional volume needed for the heat exchanger.

The cyclones of the combustor were replaced by smaller cyclones since the gas inlet temperature was now lower than before because of the exchanger. The use of smaller cyclones with consequent higher pressure drop had no effect on pulsating mode of the combustor and amplitude and frequency of the oscillations stayed unaltered. On the other hand the smaller cyclones did not improve the particle separation efficiency in required extent either.

After the already mentioned modifications, ash/fuel circulation system was replaced with a rotary gas lock in order to prevent the blocking of the circulation tube and to guarantee more stable conditions for combustion on and above the grate and for gas/particle flow in the cyclones. These modifications helped to prevent the blocking of the circulation tube and the consequent CO formation. The particle separation efficiency improved significantly also. The loss of unburnt fuel in fly ash was now reasonable, corresponding that in industrial-scale furnaces. Combustible matter content of the ash that was removed from the second cyclone was still unacceptable. This might be lowered by recirculating the ash from the second cyclone also. The use of commercial cyclones might help too.

The frequency is inversely proportional to the combustion tube length. This was confirmed with the tests also. The tube length seems to have an effect on amplitude too.

The combustion tubes with larger diameters than in previous tests /1-4/ could oscillate too. It was proved also that the tube length/diameter ratio can be much smaller than that in previous tests. These can be regarded as very useful results considering the future practical applications of the pulsating combustion.

The oscillations do not depend very sensitively on the position of the grate (or the heat source). The amplitude is of same order if the grate position is varied from 1/10 to 1/4 of the tube length.

The decoupling chamber volume was decreased 70 % without having an effect on functioning of the device. More data should be obtained for design of the industrial-scale furnaces.

According to one test that was made using partial load, the combustor can be operated on partial load, 60 % in this case. Smaller loads should be tested also.

The oscillation phenomenon is possible probably with various fuels. Sod peat and wood chips were tested besides of peat pellets. Wood chips could not be tested in the combustor because of feeding problems. The tests with other combustor tubes showed that at least same level of the oscillations is achieved with wood chips as a fuel. With sod peat the main combustion characteristics are comparable with the pellets excluding lower overall burning grate per grate area. This is depending on the density and particle size of the fuel.

Considering the application of the pulsating combustion method in industrial-scale furnaces, the tests produced various useful results. The results related to the tube diameter and the length/diameter ratio are of importance from practical point of view as well as the possibility to use a heat exchanger in upper decoupling chamber and cyclones with high pressure drop.

Future research is still required. The loss of unburnt fuel should be decreased significantly. The recirculation of the ash removed from the second cyclone and commercial cyclones should be tested. The air staging and other positions and shapes of the secondary air inlet should be tested also. Additional research should be done to obtain the dependence between frequency, amplitude and burning rate of the fuel. Minimization of the decoupling chamber volumes is of practical importance also.

REFERENCES

/1/ Ferreira, M.A., Bressan, C., Victório, J.R.S., Carvalho, J.A, Heiskanen, V-P., Burning of Finnish Peat Pellets in a Brazilian Experimental Combustor, Proceedings of the 3rd Brazilian Thermal Science Meeting, Volume II, p. 761 - 766, Itapema, 1990.

/2/ Ferreira, M.A., Bressan, C., Carvalho, J.A., Heiskanen, V-P., Report of the Pulsating Combustion Tests at INPE, December 1991, Research Report, Brazilian National Space Research Institute/Technical Research Centre of Finland, 9 p., 1992.

/3/ Ferreira, M.A., Bressan, C., Carvalho, J.A., Heiskanen, V-P., Report of the Performance Tests of a Pulsating Combustor with Fly Ash Circulation. Research Report, Brazilian National Space Research Institute/Technical Research Centre of Finland, 11 p., 1992.

/4/ Ferreira, M.A., Bressan, C., Carvalho, J.A., Heiskanen, V-P., Report of the Performance Tests of a Pulsating Combustor with Two Cyclones. Research Report, Brazilian National Space Research Institute/Technical Research Centre of Finland, 11 p., 1993.

/5/ Ferreira, M.A., Bressan, C., Carvalho, J.A., Heiskanen, V-P., Performance Tests of a Pulsating Combustor with Fly Ash Circulation. Workshop in Pulsating Combustion and Its Applications, August 2-5, 1993, Lund University, Sweden, 2p.