Making Charcoal from Rice Straw

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ABSTRACT

Rice straw constitutes an underutilized biomass resource in Asia. Wood charcoal, a common cooking fuel in Asia, draws on dwindling and valuable forest resources. This article reports laboratory research exploring the basic physical possibility of making charcoal pellets from rice straw.

Bench-scale pyrolysis tests with rice straw at 300°C (572°F) produced char, tar and a combustible gas. The mass of the combined char and tar was about half of that of the straw but contained 67 per cent of the energy. Energy in the gas was sufficient to operate the pyrolysis process. Pellets of densified char were made but were physically unstable. Addition of the tar as a binder improved stability.

INTRODUCTION

The mass of air-dry rice straw produced is approximately equal to the mass of the paddy or rough rice harvested. The magnitude of this rice straw residue resource can be visualized as being five times that of the paddy husk produced. With recent agricultural developments increasing both rice yields and the number of farmers practicing double-cropping of rice, certain areas in Asia have experienced increasing quantities of rice straw being burned in the field each year just to achieve disposal.

Rice straw in its natural form is not a convenient source of fuel. Furthermore, it is bulky to store and tends to decompose if left in moist condition in large stacks. The hypothesis investigated in this study was to see if rice straw could be converted to charcoal so that it could then serve as a fuel source, and be easy to transport, store and market using established commercial channels. It might be envisioned that a portable pyrolyzer could be moved from field to field to process stacks of rice straw into char, thus overcoming the logistic problems of centralized collection, transport and storage of the cumbersome straw material.

This investigation was aimed at characterizing only the elemental physical process of converting rice straw to char, and did not deal with field-scale systems. It was of interest to see if the basic process might permit a major reduction in the bulk of these materials while retaining much of the energy content in a solid form. Information from Knight *et al.* (1974) indicated that pyrolysis at temperatures below the 400°C that they had used, might produce the characteristics desired. Reference material cited by Jorstad and Cramer (1980) indicated that for wood pyrolysis, reactions in the 200 to 280°C range

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were mainly endothermic with mainly noncombustible gases being given off. Between 280 and 500°C, however, the reactions became exothermic and that carbon monoxide and methane were among the main gases formed. In this temperature range tars appeared and the wood was transformed into a very active form of charcoal. A system to process rice husk and chaff in such a manner in order to obtain the combustible gases for fuelling a grain dryer has been developed by Kaneko (1976).

The conventional charcoal process as described by Earl (1974), however, causes more than half of the energy content of the wood to be lost. Results obtained by Shafizadeh and Fu (1973) and Shafizadeh and Chin (1977) with pyrolysis of cellulose at 300 °C indicated that if temperatures could be held at this level, much of the energy content could be retained in the char and the tar, while reducing the resulting char-plus-tar mass to about half that of the cellulose input. Shafizadeh and Chin (1977) also found that if the cellulose were treated with diammonium phosphate, phosphoric acid or zinc chloride then the proportion of char obtained would be further increased and that of tar reduced.

The objectives of this exploratory study were to investigate laboratory-scale pyrolysis of rice straw in the temperature range of 250 to 400 °C and to determine some of the process characteristics. The suitability of these characteristics and of process output materials were then to be assessed in terms of a potential char market system.

EXPERIMENTAL PROCEDURE

The apparatus used for most tests is outlined in Fig. 1. A weighed sample of about 2.5 grams of oven-dry rice straw* was placed in the tube furnace. The entire system was purged of oxygen by blowing nitrogen through the system for approximately 10 minutes. Then the system was closed — and heat applied slowly to the tube furnace. Resistance heaters were also used on the ends of the tube protruding from the furnace to minimize condensation inside the tube. During heating, the system was

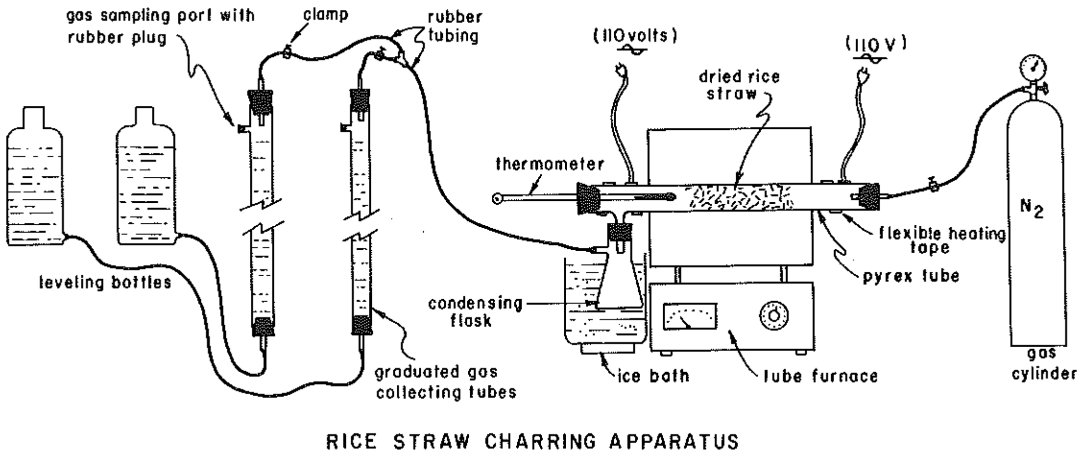

Fig. 1 Diagram of the experimental apparatus used in pyrolyzing rice straw.

*One straw sample was tested after being rewetted to 18 per cent moisture (w.b.).

kept at approximately atmospheric pressure by the leveling bottles, and note was taken of the gas volume displaced. Data on gas displacement and temperature inside the tube were recorded versus time. A simulated test run was made with no straw in the furnace tube to determine the amount of gas displacement due to thermal expansion. These data were then used to correct gas displacement values to represent net volumes of gas produced. Typical periods of heat application ranged from 20 to 40 minutes. Once the desired maximum temperature was reached the heat was turned off and the system allowed to cool. The char was then weighed. The tube and the condensate trap were flushed with acetone to remove all tar and the acetone was then evaporated from the solution at 62 °C to determine the amount of water and tar accumulated. This residual material was subsequently dried at 105 °C to partition the amount of water contained in it.

The gaseous material collected was subjected to analysis using a gas chromatograph. The straw and char materials were analyzed using bomb calorimeter tests, total carbon determinations and ash content tests. The tar was subjected to total carbon analysis, which according to Shafizadeh and Chin (1977) permits determination of the heat of combustion.

Larger amounts of char were produced by placing the straw in a flask, flushing the flask with nitrogen and then heating the flask in an oven to 275 °C while gas lines to the flask were allowed to bubble into a shallow water bath in order to prevent oxygen re-entry. This char was then used in trials with a research pelleting machine which compressed and extruded a cylindrical pellet (32.5 mm diameter) at pressures ranging from 17.2 to 44.8 MPa (2500 to 6500 lb/in^2).

Straw samples were pelleted with the same machine for comparison purposes. Some of these straw pellets were then subjected to pyrolysis in the flask to determine whether dense material could be processed as well as loose material.

RESULTS

Illustrated in Fig. 2 are typical data for temperature and net gas evolution plotted versus time during one test. These data are replotted in Fig. 3 to show the relationship between temperature and net gas evolution. These figures indicate that the large part of the gas was evolved between 175 and 275 °C and that further increases in temperature, up to 400 °C, had little effect on further gas production. It also appeared that once this temperature range was reached, then the gas was evolved rapidly. The five-minute period for the majority of gas evolution shown in Fig. 2 was believed due to the low rate of heating supplied by the tube furnace, and it is likely that gas evolution might have been obtained more rapidly if the material could have been heated more rapidly.

The tube furnace was equipped with a thermocouple and temperatures measured with this device were compared with those obtained with the mercury-in-glass thermometer inside the reaction tube. These comparisons indicated both instruments reading similarly up to about 120 °C after which the thermometer began to read higher than the thermocouple as long as there was a high rate of gas evolution. When gas evolution rate decreased the two temperature measuring devices again had similar readings. This tends to indicate that the process in which the gas was being given off was an exothermic one.

Analysis of the gases obtained showed a sizable background concentration of nitrogen as expected, but the main constituents added by the process were carbon monoxide (49.9 per cent, av.) and carbon dioxide (43.7 per cent, av.). Small amounts of methane (6.4 per cent, av.) were also occasionally found. Tests for higher hydrocarbons showed these materials not to be present in

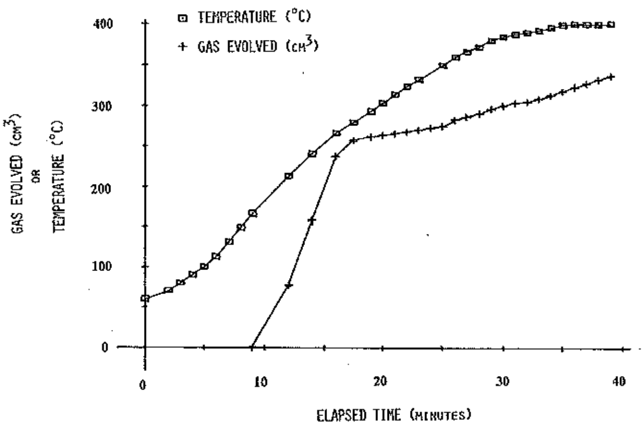

Fig. 2 Result data from a typical pyrolyzation experiment. The temperature is that measured inside the reaction tube, while the gas data is that for net gas evolution when using a dry straw sample of 2.5 grams.

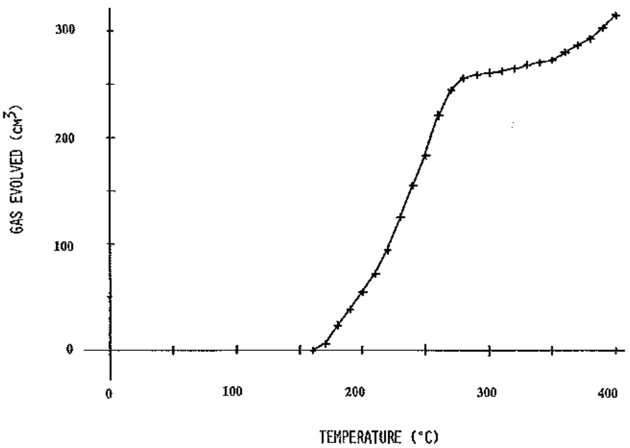

Fig. 3 Relationship between gas evolution and temperature for the experimental results illustrated in Fig. 2.

appreciable amounts.

Rice straw is characteristically high in silica. In addition, the muddy field environment tends to cause depositon of soil materials on the lower parts of the stem. Thus the test material used was found to have 16.2 per cent ash even though it appeared to be clean and free from obvious mud deposits. If the balance of the dry straw material were assumed to be composed of a $C_6H_{10}O_5$ material it would be expected that 37.2 per cent of the straw would be constituted by carbon. Tests indicated 40.1 per cent carbon.

Ash determinations were made at 550 °C and so the material measured as ash was not changed from the solid state in the pyrolysis tests. Consequently the char materials were found to be in the order of 35 per cent ash due to the loss of the gas and tar components during pyrolysis. The char was about

47 per cent carbon. Char produced at 400 °C had less carbon, more ash and a lower heating value (all by approximately 10 per cent) than the char produced at 250 to 300 °C.

Eight tests were run using the tube furnace. Six of these were free from operational irregularities and these six all produced similar results.* Table 1 contains data derived from composite average from these six tests. These data indicate that nearly 60 per cent of the energy in the straw was retained in the char alone. The tar contained an additional 8.5 per cent of the energy and the gas 6.2 per cent. The balance of the energy is believed to have been liberated in the exothermic reactions in which the carbon monoxide, carbon dioxide and tars were formed.

The data in Table 1 also indicate that the low-temperature pyrolysis process was capable of reducing the mass of the straw to char and tar components having 53 per cent of the original mass.

Table 1 Typical process ratios as obtained from pyrolyzation tests with rice straw at 300°C.

	Amount (g)	Carbon (g)	Enery Content (kJ)
Input			
Rice straw (dry)	100	40.1	1631
Output			
Char*	46.4	21.9	957
Tar	7.1	3.7	139
Carbon monoxide (5.65 l)	7.1	3.0	72 + (28)**
Carbon dioxide (4.94 l)	9.7	2.6	(103)**
Methane (0.72 l)	0.5	0.4	29
Material volatilized (62° to 105°C)	15.2	8.5	
Unaccounted-for non-solids	14.0	8.5	

*Besides containing 21.9 g carbon, the char also contained 16.2 g ash and 8.3 g non-carbon, non-ash solids.
**Quantities in parentheses represent heat energy given off in the exothermic reactions in which these materials were produced.

Rice straw has, as does most other natural cellulosic materials, certain aromatic substances which are liberated upon heating. In the process of evaporating the acetone at 62 °C, as well as in the drying of evaporation residuals at 105 °C, certain amounts of these aromatics were lost. In some cases these produced such an objectional atmosphere that these operations had to be done at times when the laboratory was otherwise not occupied. The aromatics would most likely have fuel energy value if combusted, but such values are not included in Table 1. Some tars and aromatics produced during the pyrolysis of coal and wood have carcinogenic properties. Investigation of such properties for the products of low temperature pyrolysis of agricultural residues would need to be done if the process was to be designed in full cognizance of human safety requirements.

*The test with the straw sample at 18 per cent moisture gave similar results to tests with dry samples and was thus included in the six mentioned above.

Twenty-five-gram samples of rice straw and of char were placed in the cylindrical pelleting machine which used a heated die. When the char materials were pressed to 44.8 MPa (6500 lb/in^2) the material became bound in the test cylinder. When 10 per cent water was added to the char and a pressure of 17.2 MPa (2500 lb/in^2) was used pellets were formed, but upon extrusion from the cylinder they tended to fissure and expand unevenly. All appearances of structural continuity of the char materials disappeared during the pelleting process, and the pelleted material had the appearance of a mass of charcoal dust that had been pressed together. The density of these individual char pellets prior to expansion was 0.86 g/cm^3 on a dry basis. The density of the corresponding straw pellets (made at 44.8 MPa) was 0.72 g/cm^3. These straw pellets were then subjected to pyrolysis and it was found that the process took place as well with these pellets as with loose, chopped material. The pellets expanded during pyrolysis and there appeared to be no basis for anticipating that gas flows would be impeded in such material. Photographs of a char pellet, a rice straw pellet and of a pyrolyzed straw pellet appear in Fig. 4.

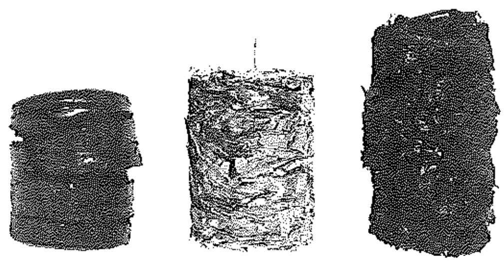

Fig.4 Photographs of a char pellet, a rice straw pellet and of a pyrolyzed straw pellet. Pellet diameter was 3.25 cm. The char and straw pellets each contained 25 grams of material.

DISCUSSION

The general characteristics of the pyrolysis process at 300 °C tended to satisfy the objectives of obtaining a 50 per cent reduction in residue mass while retaining 67 per cent of the residue energy. The extent of mass reduction might be expected to be even greater if residues with lower ash contents than the 16.2 per cent of the rice straw tests, were subjected to this same process. The ease and simplicity with which such a process might be operated in an on-farm or farm-business-center setting is important to the potential feasibility of the system.

If the residue material were to contain 20 per cent moisture, the heating process would require energy to evaporate this water as well as to raise the temperature of the residue to 300 °C. If the specific heat of the dry material is assumed to be 0.4 and the energy to evaporate water by direct heating as 2256 kJ/kg, then 920 MJ would be required to pyrolyze one tonne of such material entering the process at 20 °C (ignoring the heat given off in the exothermic reaction). The energy available from the carbon monoxide and methane (but excluding the energy in the aromatics, etc.) as produced upon pyrolyzation of this material, in addition to the heat given off in the exothermic reaction, would amount to 1851 MJ/tonne. Thus a process with a thermal efficiency of 50 per cent would be required if none of the heat contained in the char, tar or water vapour were to be recovered. The heat energy available from the process gases and the exothermic reactions could be increased by increasing the amount of air added in the process. Such a procedure, however, would also have the effect of reducing the energy in the char produced from a given amount of residue.

It might be envisioned that the tars would be condensed by passing the hot gases evolved over emerging char at temperatures slightly above 100 °C. The remaining gas materials could then be passed through a condenser cooled with ambient air to remove the water. These dried gases containing carbon monoxide and some low-boiling aromatics might then be fed directly into a burner — the combustion products from which would be mixed directly with the incoming residue. The emerging char, onto which the tar had been deposited, could then be pressed into briquettes or pellets, with the tar serving as a binding agent.

CONCLUSIONS

The process of pyrolyzing rice straw at 300 °C offers the possibility for using a char-tar mixture as a marketable fuel material which could serve as a common basis of exchange between residue holders and fuel users. Before such energy exchange systems could be implemented investigations need to be made into the carcinogenic aspects of the tar and other process by-products. Development of simple processing equipment designs remains to be undertaken, but there does appear to be technical feasibility for a process which would:

a) reduce residue mass by approximately 50 per cent;
b) retain 67 per cent of the energy content of the residue; and
c) produce a fuel material which is compact and not subject to deterioration in storage.

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