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Tube-in-basket burner for rice husk. I: Properties of husk as a fuel and basic design considerations

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Abstract. Rice husk, the main by-product of milling paddy, is one of the more easily available and abundant renewable energy resources. None of the husk combustion systems available at present is suitable for those who have relatively modest energy requirements and whose options in the matter of alternate energy sources are limited and costly. Decentralised post-harvest processing and small scale rural industries are examples. The Tube-in-Basket (TiB) husk burner described here is a compact, simple and easy-to-fabricate device, which produces a clean and concentrated flame with high combustion efficiency. As a low cost heat module, using an agro-residue as fuel, TiB holds promise of contributing towards meeting the energy demand of the rural segment of society in the underdeveloped countries. Part I of this communication deals with rice husk, its combustion characteristics, and some pertinent aspects of the existing husk combustion systems. It then describes the design criteria for TiB taking into account the properties of husk as a fuel. Performance data of a prototype batch TiB is included to demonstrate the validity of the basic design.

Keywords. Rice husk; husk characteristics; husk combustion; TiB burner; design criteria; batch burner.

1. Introduction

More than 400 million tonnes of rice paddy is grown world-wide per annum, including about 80×10^6 t in India alone. This crop is distributed over a large number of countries, a majority of which are underdeveloped and lie on the great rice belt that extends from the Equator to 40°N and runs longitudinally from 70° to 140°E (Ghosh *et al* 1960). Nature has enclosed the rice grain in a tough silica-wood composite material called rice hull or husk. The husk protects the grain from attack by birds. In order to get at the rice grain, it is necessary to break open or split the husk into halves, either by hand pounding or in huller or sheller type paddy milling machines. Rice husk, which constitutes 16 to 25% by weight of the harvested crop, is by far the main by-product of paddy.

In many places husk is viewed as an agro-waste, of nuisance value, whose disposal can be both costly as well as hazardous and pollution generating. It is, however, one of the more abundant renewable energy resources available to man, evenly distributed and locally available wherever rice paddy is grown. Indeed, considerable quantities of husk

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are burnt as a primary fuel, mostly for raising steam for parboiling of rice (*eg* in India), also for running rice mills (Thailand), generation of electricity (Surinam), and in other industries needing process heat for drying, curing and roasting of agricultural produce, and for community cooking, etc (Beagle 1978). The husk combustion systems and gasifier units available presently are not suitable for meeting the energy needs of post-harvest processing and other small scale rural based industries. The reason lies in their large size, high cost, complexity and low combustion efficiency. Hence, many rice growing areas—amidst a plentiful husk supply—are heavily dependent on either firewood, which is becoming increasingly scarce on account of indiscriminate felling of trees, or on costly fossil fuels, which may have to be transported over long distances from their sources of supply. This fuel hunger of the exploding population in the underdeveloped countries—the energy crisis of the world's poor—has remained largely unnoticed and uncared for (Eckholm 1976).

There is then a need to find optimal means for utilising the energy in husk, specially tailored for those whose requirements of energy are relatively modest and whose options in the matter of alternate energy sources are limited and costly in terms of both money and damage to the environment. The purpose of this and the following paper is to describe a husk combustion device which appears to meet this need. TiB: tube-in-basket husk burner, gives a clean, concentrated shooting flame with a high combustion efficiency. It is simple and compact in design, inexpensive and easy to fabricate, and as such it holds promise of meeting numerous energy needs in the areas where husk is surplus. This part of our communication includes fuel and combustion related properties of husk, and the basic design criteria for TiB.

2. Rice husk

The yield of husk and its physical characteristics and chemical composition vary depending on the paddy strain, the nature of the soil, the climate and the agricultural practices employed. The following summary of relevant data is compiled from a number of sources (Houston 1972; Beagle 1978; Govindarao 1980; Kaupp & Goss 1981–83). Husk particle has an oval concavo-convex shape; the length is 2–4 times the width. Thus a typical sheller husk particle is 4–5 mm long, 1–2 mm wide and about 0·5 mm thick. Because of its shape, the bulk density is only 85 to 110 $kg\,m^{-3}$. Therefore bulk storage and transportation of husk over long distances for large scale centralised burning is uneconomical. The moisture content of husk depends on the ambient humidity and varies from 6–20%; at 50% relative humidity the equilibrium moisture content is about 9% on a wet basis. The chemical analysis of dry husk in % weight is: carbon—39–42; oxygen—30–34; hydrogen—5; nitrogen—0·6; sulfur—0·1; ash—16–23.

The main constituent of ash is silica, about 95%. It is present in husk in the form of a hydrated opaline phase, finely interwoven with the organic matter. On account of its high internal porosity and surface area, rice husk ash is by far the cheapest bulk source of reactive silica and a valuable material having numerous applications (Govindarao 1980).

The approximate analysis of dry husk in % weight is: volatile matter—60–69 (62); fixed carbon—15–22 (18); ash—16–23 (20); calorific value—12·54–15·88 $MJ\,kg^{-1}$ (14·63 $MJ\,kg^{-1}$) or 3000–3800 $kcal\,kg^{-1}$ (3500 $kcal\,kg^{-1}$).

For rough calculations the average or more frequently reported values given in parentheses are deemed adequate. It is noteworthy that of all the common crop residues husk has the highest ash content and the lowest volatile matter content. The calorific value of husk is about one-half of good quality coal, one-third of furnace oil and is comparable with that of saw dust, lignite and peat. Global production of $\approx 80 \times 10^6$ t husk per annum is the equivalent of 170 million barrels of crude oil in energy content (Beagle 1978), and the 18×10^6 t husk generated in India yearly is equivalent to $4{\cdot}27 \times 10^6$ l of diesel oil if it were gasified to producer gas with 70% conversion efficiency (Kaupp & Goss 1981–83).

3. Combustion of husk

Rice husk is a difficult fuel to burn. It does not ignite easily, is flame retarding, and at low temperatures, either self-extinguishing or smoky. On the other hand, paradoxically, large heaps of burning husk are almost impossible to extinguish and will continue to smoulder and smoke even under the torrential rains of the tropics. Although not well understood in detail, this characteristic combustion behaviour of husk is undoubtedly related to its morphology—intertwining of silica and the woody matter, the voluminous bulk of the husk bed with a large void component and low thermal conductivity, a pronounced tendency to agglomerate and cake thermally, and an exceptionally high ash residue whose bulk is not significantly less than that of precursor husk (Beagle 1978; Kaupp & Goss 1981–83).

On heating, husk particles begin to blacken and char at around 250 to 300°C. In a static bed, combustion occurs in a number of distinct stages (Hamad 1981–83). Pyrolysis invariably precedes the burning of char, even in the presence of an adequate supply of flowing air. Photomicrographs show that the bumpy, outer surface of husk after pyrolysis acquires sharp, at times hook-like peaks. This surface feature coupled with the condensation of wood-tar results in the agglomeration and caking of char, and restricts its combustion and flowability (Kaupp & Goss 1981–83). Thus the conventional gas producers are found to be unsuitable for husk feed and require major modifications in their design for achieving a steady gas output. In a static bed, the rate of combustion is very slow due to insufficient flow of air in the interior of the heap. The heat released is spread over a large volume, and the combustion efficiency is erratic and poor.

Not surprisingly, then, it has been widely recognised that husk is relatively easier to burn in a suspended state than in a static bed, and several fluidized-bed, air-suspension and cyclone types of furnaces have been designed in recent years (Beagle 1978). Even in the inclined step-grate type furnace, which is the work horse husk burner all over the world and the standard equipment for husk fired boilers in India, a fairly large proportion of husk feed is combusted in suspension as it slides and falls down in the combustion chamber. Apart from the fact that this furnace is beyond the reach of many people who have only a modest energy need and limited funds, space and supply of husk, it also has a number of technical drawbacks:

(i) On the basis of unit heat released, the equipment is relatively cumbersome, large in size and costly, comprising as it does of a husk feed box or platform, step-grate, combustion chamber, flue channel and chimney.

(ii) Because a portion of husk burns in suspension, a great deal of ash is always airborne. The system is therefore inherently pollution generating, unless expensive additional equipment is installed for cleaning the flue gases.
(iii) Combustion efficiency tends to be low and variable; amount of unburnt carbon in the residue can be as high as 50%. This is because (a) the rate of combustion drops steeply once the husk particle slides or falls down to the bottom of the combustion chamber and becomes part of the char heap which lacks adequate supply of air in its interior, and (b) sudden and intense liberation of heat as the husk particle travels through the fire zone closes up the fine pores, thereby sealing the unburnt carbon in the silica matrix. Some improvement can be achieved by mechanically feeding husk, for more uniform and controlled combustion, and by air blowers for enhancement of the draft. Naturally, these additions entail a significant increase in the cost and complexity of the system.
(iv) The ash produced is of very non-uniform quality; a mixture of almost unburnt husk, char containing upto 50% combustible matter, and hard burnt, occasionally even fused, inert ash formed in the localised hot spots. This erratic ash quality poses major difficulties for the utilisation of this otherwise valuable source of reactive silica.

These comments on the step-grate furnace are also valid, to a lesser or greater degree, for other furnace designs, as well as the husk gasifier units which are now coming into routine use (RAPA 1982).

4. The TiB burner

The TiB burner was designed keeping in view the combustion characteristics of husk and the drawbacks of the currently available combustion systems discussed above. In particular the volatile matter is liberated at relatively low husk temperatures and it is burnt separately in a burner tube. This arrangement prevents overheating of the char and sealing or constriction of the pores within the char particles.

Concurrently, large volumes of air—part of it preheated as it passes through the hot ash—is forced through the husk bed so as to burn off as much residual combustible matter in char as possible. Figure 1 shows the basic design features of TiB. It consists of a cylindrical basket made of wire-mesh or perforated metal sheet. In the middle stands a burner tube, also made from a perforated sheet. A damper is provided at the base of this tube for control of the secondary air of combustion. The annular space between the tube and the basket is filled with husk. When lit from below in a prescribed manner, combustion of volatile matter occurs in the burner tube and flames emerge from its mouth.

TiB performs three functions, that of a gas generator or gasifier, a gas holder and a gas combuster in a single compact unit.

(i) On heating the bottom layer of husk, volatile matter evolves first at about 250 to 300°C and simultaneously husk begins to char. The residual wood-tar and carbon burn and a fire zone or bed is created which gradually moves upward in the husk bed.
(ii) As the layer of husk immediately above the fire zone is heated up its volatile matter is released. The numerous pore spaces in the loosely packed bed of husk are quickly filled up with the liberated gases.
(iii) The hot burner tube acts concurrently as a chimney. It creates a pressure drop across the husk bed, causing air to rush in from the bottom and side of the basket. As a

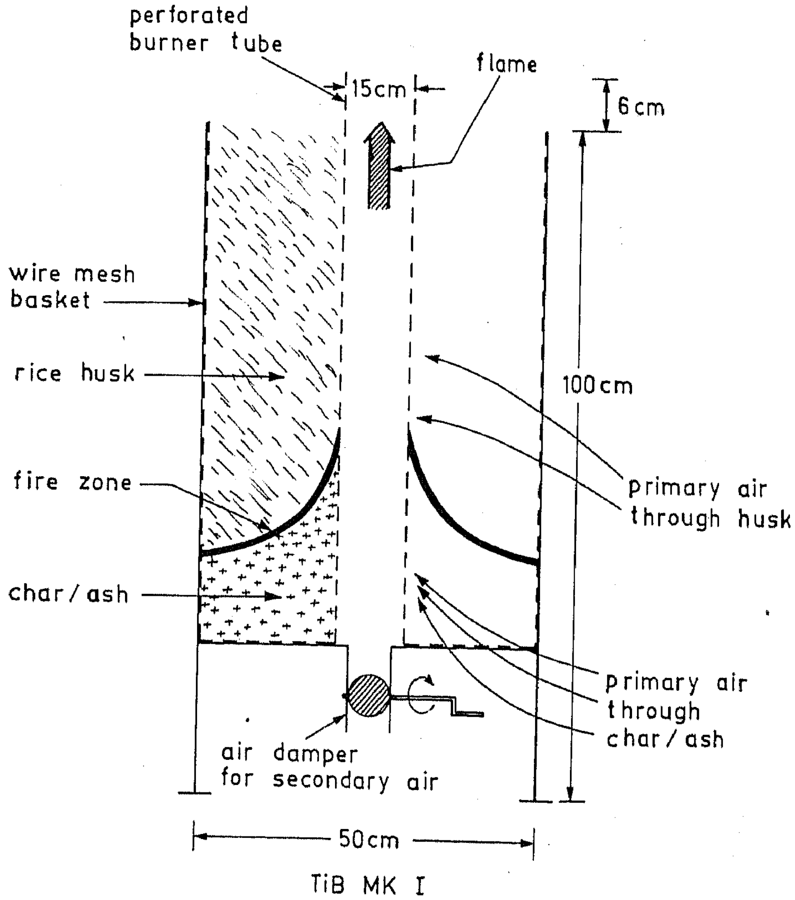

Figure 1. Basic design of TiB MK I, batch rice husk burner.

consequence, a mixture of preheated air and volatile matter enters the tube where it gets ignited, resulting in a shooting flame from the mouth of the tube.

5. Design criteria

It will be evident from the description of TiB that its stable and satisfactory performance is contingent on a rather delicate balance of mass flow and heat exchange between the husk bed and the burner tube, as well as on the ratio of combustible gas and air in the tube. The problem is compounded by the fact that the mechanical structure of the husk/ash bed undergoes large changes as more husk is converted into ash and the bed slides and settles down, resulting in random and somewhat wide fluctuations in its permeability and resistance to heat transfer. These changes, in turn, can lead to localised over-heating or undercooling of the bed and, what is even more important, throw the gas/air ratio in the burner tube outside the range of stable combustion. In view of these characteristics of TiB, considerable effort was initially spent in establishing the optimal design parameters. This exercise entailed proposing a working hypothesis for the performance of TiB, carrying out trials on different TiB configurations, and analysing the results in order to identify the important design parameters and operational factors.

5.1 *Hypothesis*

Based on preliminary trials and physical insight, the following hypothesis was proposed, and subsequently verified by experiments to determine the necessary conditions for the satisfactory performance of TiB:

(i) A glowing bed of husk at the bottom acts as the producer of volatiles.

(ii) Adequate supply of primary air is needed for burning off the fixed carbon in charred husk and thus maintaining the bed in a glowing state.

(iii) Adequate supply and some control of the secondary air from the bottom of the burner tube or from the side is needed for complete combustion of volatile matter in the tube.

(iv) Sufficient height of the burner tube in relation to the annular width of the husk bed is needed in order to overcome the resistance to gas flow across the bed. In other words, burner tube diameter, its height and annular width are the most important dimensions.

(v) Enough agitation of husk bed is needed to prevent short circuit paths for air flow through the bed.

(vi) An ash disposal mechanism which should disturb the fire zone as little as possible, is needed for continuous operation of TiB.

5.2 *Experiments*

A large number of experiments for evolving the basic design of TiB, optimising its dimensions and establishing design criteria for scale-up were carried out. The design data were as follows (see figure 2):

(*i*) *Burner tube:* Burner tubes used were of perforated sheet (3 mm dia. holes spaced 4 mm apart from their centres) 25 cm high and of 5, 7·5 and 10 cm diameter. The tubes were hung 5 cm above the base of the basket. In some experiments the top 20 or 12·5 cm

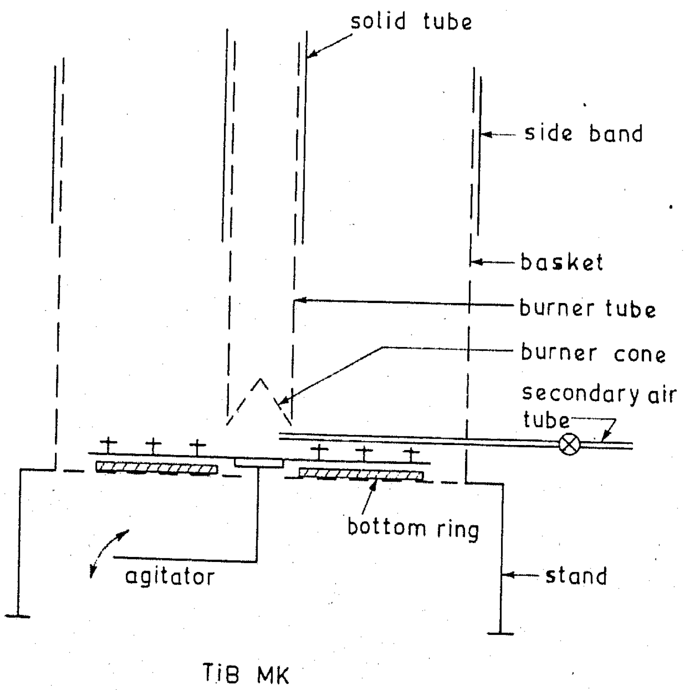

Figure 2. A composite drawing of TiB showing various modifications and additions tried for evolving the design.

of the perforated tube was blocked by snugly fitting a solid tube. This was done to prevent cold air from entering the upper portion of the tube and cooling the flame.
(*ii*) *Basket:* Wire mesh (3 mm square opening) baskets of 15, 19 and 23 cm diameter and 25 cm height were used. By taking an appropriate combination of basket and tube diameters, a wide range of husk bed widths, with constant chimney height, could be obtained, which in turn varied the rate of air flow through the bed. In some experiments, side bands were placed on the top portion of the basket to force entry of the air to the lower portion of the basket over the fire zone. In other experiments the air flow from the perforated bottom of the basket was throttled by placing on the bottom thin rings of 7·5 cm inner diameter and 22·5 or 12·5 cm outer diameters. This was done to force the primary air to flow through the husk/char bed. *ie* to block the short circuit path into the burner tube from its periphery.
(*iii*) *Secondary air inlet:* For ingress of additional secondary air for complete combustion of gases in the burner tube, provision was made for either a damper fitted below the burner tube (figure 1) or a side air tube through the husk bed, with a stopper at the outer end for control of the flow rate (figure 2).
(*iv*) *Burner cone:* In many trials, an inverted cone made of perforated sheet was fitted snugly at the bottom of the burner tube in order to improve the flow pattern and combustion characteristics of the gas/air mixture.
(*v*) *Agitator:* To break up rice husk ash-lumps and to facilitate the flow of husk from above, agitators of various sizes with different numbers of prongs were fitted at the bottom. For example, a typical agitator design consisted of a number of crosses, with 2·5 cm high prongs made of 3 mm diameter rods.

5.3 *Results and analysis*

Almost all combinations of burner tubes and baskets with or without the side band, bottom rings and solid tubes in place, were investigated. Additional runs were made with burner cones and with different procedures for agitation and tapping the fuel bed. In the absence of a convenient quantitative objective function, the criterion of merit employed was entirely qualitative and based on empirical observations and experience of (i) reliable starting of the burner (ii) ease of operation (iii) a stable flame not requiring much skill for sustenance and (iv) well burnt ash. Scores of runs carried out in this manner led to a number of interesting and useful conclusions:

(i) Without solid tube, side band and bottom ring, that is, with free access of air, several burner tube/basket combinations failed to provide sustained combustion. The results can be presented conveniently in a matrix format:

Burner tube dia (cm)	Basket dia (cm) 15	19	23
5	✓ (5)	× (7)	× (9)
7·5	✓ (3·75)	✓ (5·75)	× (7·75)
10	✓ (2·5)	✓ (4·5)	✓ (6·5)

✓ Satisfactory combustion; × no sustained combustion; number in parenthesis is the annular width = (basket dia − tube dia)/2.

Since the height of the chimney in these runs was fixed at approximately 25 cm, the results suggested that for an adequate draw of air through the husk bed, its radial width should not exceed 1/4th the height of the burner tube. Moreover, since the suction in a chimney is directly proportional to its height, other things being equal, it is not unreasonable to assume that the above rule is applicable to a chimney of any given height. On the other hand, irrespective of the width/height ratio, a minimum annular width of about 5–6 cm was found to be desirable, otherwise bridging of particles and short circuiting of air through the gaps became a problem.

(ii) Incorporation of side bands and bottom rings did not lead to any noticeable change in the burner performance.

(iii) Blocking of perforations in the upper portion of the burner tube by a solid tube had no effect on the combustion, as long as the height of the husk bed was not permitted to drop appreciably. However, it did lead to reduction in smoking of husk in the upper free surface adjacent to the burner tube mouth.

(iv) The radially inflowing primary air was mostly consumed in sustaining the fire bed. Therefore a provision for secondary air was found to be necessary for complete combustion of gases in the burner tube. The best point for the entry of secondary air was at the base of the burner tube rather than through the side tube.

(v) The burner cone was beneficial in a number of ways. It deflected the secondary air to the side for better mixing with the incoming gases through the burner tube perforations. By imparting a swirling motion it also broke up the laminar flow pattern of the gases. And finally, its red hot surface facilitated rapid ignition of the raw gas mixture.

(vi) Some kind of gentle agitation at the bottom of the ash bed was necessary to break up the ash lumps and particle bridges, induce the husk to flow downwards smoothly and to maintain spatial uniformity in the fuel bed.

6. TiB MK I: batch burner

In order to verify the authenticity of the design criteria based on geometric similarity established in the last section, a scaled-up TiB was constructed. This TiB MK I (batch mode) had a basket of 50 cm diameter and 100 cm height, the burner tube was of 15 cm diameter and 106 cm height. In this design, the radial width to chimney height ratio was roughly 1/6, well within the upper bound of 1/4 arrived at earlier. For secondary air, a damper was provided at the base of the burner tube (figure 1).

In a single batch run, TiB MK I burnt about 10 kg husk for 60 min of sustained flame. The run could be extended to 90 minutes by topping the bed once or twice with husk whenever it settled down. Temperature of the flame measured 15 cm above the tube mouth in the open was 825 ± 75°C. Data were taken when the burner was operated in an enclosed space free of windy conditions. In the presence of moderate or high winds, the flame tended to become erratic and unstable, and the combustion of husk in the basket proceeded in an uneven manner with a bright fast glowing bed on the side facing the incoming wind and a dark sluggishly smouldering bed on the opposite side. At the end of the run, the flame gradually died out or receded into the burner tube. Now the tube emitted colourless and smokeless hot air for 4 to 6 hours whose temperature at the mouth of the burner tube dropped from 500 to 600°C initially to 100 to 150°C at the end. This heat came from oxidation of the residual wood-tar and carbon in char and from the heat content of hot rice husk ash bed. The ash at this stage was of light grey colour, had less than 2 to 3% carbon and was amorphous and very reactive with a surface area of 60–70 $m^2 g^{-1}$ by Brannauer-Emmett-Teller (BET) method (Kapur 1984–85). Because of the inflow of air from the sides and bottom, the surface of TiB remained remarkably cool at all times, except for an occasional transitory localised hot spot. Temperature profile of the bed at different times, as measured by thermocouples at 24 locations, is shown in figure 3. It will be seen that except in the immediate vicinity of the burner tube, temperatures were generally below 700°C. The maximum temperature was about 500°C only in the vicinity of the basket wire mesh in the lower portion. Due to continuous inflow of air, most of the heat liberated in this region was carried inwards to the burner tube. A small fraction of heat was unavoidably lost by radiation through the wire mesh openings. Prevention of this loss required a thermal shield all around the basket. But in view of cost consideration, this feature was not incorporated in the final designs of TiB burners. However, a primary objective of the TiB design, namely, to drive out the volatile matter at relatively low temperatures and to prevent sealing of pores, was fulfilled. This coupled with a high air flow rate assured high combustion

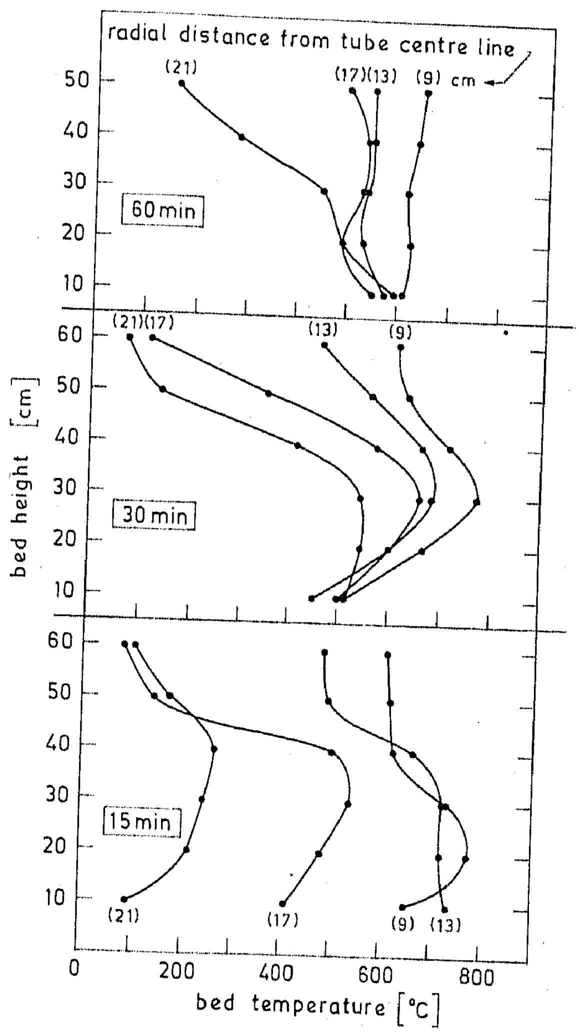

Figure 3. Temperature profiles of char/husk bed at 15, 30 and 60 minutes of firing TiB MK I.

efficiency, as quantified in part II where three working models of TiB are discussed in detail.

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