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OVERVIEW OF COMBUSTION AND GASIFICATION OF RICE HUSK IN FLUIDIZED BED REACTORS

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Abstract—Rice is cultivated in more than 75 countries in the world. The rice husk is the outer cover of the rice and on average it accounts for 20% of the paddy produced, on weight basis. The worldwide annual husk output is about 80 million tonnes with an annual energy potential of 1.2×10^9 GJ corresponding to a heating value of 15 MJ/kg. India alone generates about 22 million tonnes of rice husk per year. If an efficient method is available, the husk can be converted to a useful form of energy to meet the thermal and mechanical energy requirements of the rice mills themselves. This paper provides an overview of previous works on combustion and gasification of rice husk in atmospheric bubbling fluidized bed reactors and summarizes the state of the art knowledge. As the high ash content, low bulk density, poor flow characteristics and low ash melting point makes the other types of reactors like grate furnaces and downdraft gasifiers either inefficient or unsuitable for rice husk conversion to energy, the fluidized bed reactor seems to be the promising choice. The overview shows that the reported results are from only small bench or lab scale units. Although a combustion efficiency of about 80% can normally be attained; the reported values in the literature, which are more than 95%, seem to be in higher order. Combustion intensity of about 530 kg/h/m^2 is reported. It is also technically feasible to gasify rice husk in a fluidized bed reactor to yield combustible producer gas, even with sufficient heating value for application in internal combustion engines. A combustible gas with heating value of 4–6 MJ/Nm^3 at a rate of 2.8–4.6 MW$_{th}$/m^2 seems to be possible. Only very little information is available on the pollutant emissions in combustion and tar emissions from gasification. The major conclusion is that the results reported in the literature are limited and vary widely, emphasizing the need for further research to establish suitable and optimum operating conditions for commercial implementations. © 1998 Published by Elsevier Science Ltd. All rights reserved

Keywords—Biomass, fluidized bed, rice husk, rice hull, paddy husk, combustion, gasification, review.

1. INTRODUCTION

Present energy use is largely dependent on fossil fuels which makes future sustainable development very difficult. There are drastic changes in the composition and behaviour of our atmosphere due to the rapid release of polluting combustion products from fossil fuels. A significant amount of the carbon dioxide emissions from the energy sector is related to the use of fossil fuels for electricity generation. As the demand for electricity is growing rapidly, emissions of carbon dioxide and other pollutants from this sector can be expected to increase unless other alternatives are made available. Further, the declining energy supplies and severe environmental constraints compel us to sharply focus our attention on the need for additional amounts of clean energy sources. Among the energy sources that can substitute fossil fuels, biomass fuels appear as the option with the highest general worldwide potential. In both the developed and the developing countries, the interest and activity for obtaining energy from biomass has expanded tremendously and dramatically in the last few years.

There are large quantities of residues, associated with agricultural production and processing industries and they can be used for energy production, provided that they satisfy the criteria of plentiful supply and local availability on a renewable and perpetual basis. In the Asia-Pacific region, these residues are in plenty since a wide range of crops are grown to produce food for 56% of the world's population[1] living in this part of the world. Unlike fossil fuels, which are limited in availability, these residues are not only abundantly available, but also renewable. The utilization of many agricultural residues is not economically viable because of the huge investments required for collection, transportation and storage. However, there are some biomass residues concentrated at specific location, where demand for energy also exists. They include rice husk at the rice mills, rice straw in the fields and bagasse at the sugar mills.

Rice, also called paddy, is cultivated in more than 75 countries in the world. The rice husk is the outer cover of the rice grain and is in the form of hull. It is also called rice hull or paddy husk/hull and sometime referred to as whole rice husk, in contrast to ground husk which is its finer form. It accounts for 14–35% of the weight of the paddy harvested, depending on the paddy variety and, on average, it represents 20% of the paddy produced,[2,3] on weight basis. The average lower heating value[2–4] of the rice husk is about 13–16 MJ/kg. It may be noted that the lower heating value is about one-third that of furnace oil, one-half that of good quality coal and comparable with that of sawdust, lignite and peat. The rice husk is also renewable in nature and less polluting due to its low sulphur and heavy metal contents.

The worldwide annual husk output[4] is about 80 million tonnes with an annual energy potential of 1.2×10^9 GJ, corresponding to a heating value of 15 MJ/kg. The total number of rice mills[3] in some of the countries is very large; there are about 92,000 rice mills in India, 60,000 mills in Indonesia, and 40,000 mills in Thailand. Some of them are larger mills capable of processing 10–20 tonnes per hour (TPH). India alone generates[5] about 22 million tonnes of rice husk per year as a by-product from rice milling.

It may not be economically viable to transport rice husks from the originating mill to a utilization site that is far away from the mill, due to its low energy density. In some areas, however, it may be feasible to collect husks from several mills found in the locality. Husk transported over a short distance can be competitive with imported diesel fuel which must be transported over a long distance within the country. Thus, if an efficient method is available, the husk can be converted to a useful form of energy to meet the thermal and mechanical energy requirements of the rice mills and the electrical power requirements in the locality. Fluidized bed technology seems to be the suitable technology for converting a wide range of agricultural residues into energy due to its inherent advantages of fuel flexibility, low operating temperature and isothermal operating condition.

This paper provides an overview of the previous works on combustion and gasification of rice husk in fluidized bed reactors, summarizes the state of the art knowledge and identifies potential areas for further research.

2. FLUIDIZATION AND FLUIDIZED BED REACTORS

A fluidized bed reactor takes advantage of the excellent mixing characteristics and high reaction rates of gas–solid mixtures. A simple fluidized-bed reactor consists of a chamber containing a bed of inert particles such as sand, supported by a distributor plate. Pressurised air is passed through the distributor plate and the velocity of the air is progressively increased so as to support the entire weight of the bed by the fluid drag on the bed particles due to the upward flowing air. The bed is then said to be incipiently fluidized, and it exhibits fluid-like properties above this particular velocity, called minimum fluidization velocity.[7–9] This moving mass of solid particles is called a fluidized bed. The turbulence of the bed increases with velocity, above the minimum fluidization velocity.

In energy conversion (for example, combustion or gasification) process, the fluidized bed is first heated externally close to the operating temperature. The bed material, usually sand, absorbs and stores the heat, while the turbulence and mixing of the bed keeps the temperature very uniform throughout the bed. When biomass fuel is introduced into the fluidized bed, the high heat and mass-transfer characteristics of the bed permits the rapid energy conversion at practically isothermal condition. The high surface area available in fluidized beds, and the constantly moving area per unit volume on which reactions can occur, result in good conversion efficiency, higher throughput, and lower operating temperature when compared to fixed beds. Uniform temperatures and high heating capacities of sand media permits a wide range of low-grade fuels of even non-uniform size and varying moisture content to be converted to desired products. Pre-processing of biomass feeds to acceptable particle size and/or moisture content, usually necessary for other conversion technologies, can then be minimized in fluidized-bed operations, as long as it could be conveniently fed into the bed.

The high thermal storage capacity inherent in the bed material acts like a thermal flywheel and may permit shutdown of the gasifier overnight and restart without external heating. Restarting of the unit without any preheating after 15 h of shutdown has been reported by Lepori *et al.*[10] Fluidized bed gasifiers can be scaled up with considerable confidence. Fuels can be combusted or gasified in a fluidized bed reactor, depending on air to fuel ratio. In combustion, excess air is supplied and fuel particles are retained in the reactor for sufficient residence time for complete oxidation to incombustible flue gases. In gasification, substoichiometric air just sufficient to gasify the feed into combustible gases is supplied.

Rice husk is a biomass fuel with relatively high ash content[3] of 16–23%. Its ash contains more than 95% silica, that gives rigid skeleton-like structure to the ash.[11–14] The traditional methods of rice husk combustion in inclined (stepped or perforated) grate furnaces are in general quite inefficient and convert only about half the energy available in the husk.[15] Husk is fed at the top of the grate in the above furnace, in which the air flows from the bottom. As the husk loading on the grate is far from uniform, while one section is starved of air, the other section is flooded with excess air. This non uniformity in the fuel-air ratio leads to a significant amount of unburnt carbon in the ash, resulting in a considerable loss of efficiency. A considerable amount of carbon is also trapped in the rigid ash skeleton and cannot be burnt or gasified, resulting in further loss of efficiency. As individual husk particles usually retain their original shape even after combustion due to their regid ash skeleton, the resulting ash occupies the same volume as the original husk.

The throat of the downdraft rice husk gasifiers were found to get clogged due to high volume of ash, in addition to slagging due to localized combustion in the throat zone. Although a range of rice husk gasifiers, mostly based on Chinese open-core design are being tested in some Asian countries, their technical characteristics for long operating hours are yet to be well established.[1]

Fluidized bed combustors and gasifiers seem to offer some distinct advantages due to their unique operating characteristics. The turbulence due to fluidization in the bed can break the rigid ash skeleton to make the trapped carbon available for conversion. Rice husk ash can easily be removed from the fluidized bed by entrainment in the gas stream, from which it can be separated by a particle separating system. The bed temperature can be kept below the ash slagging temperature by properly controlling its operating parameters and localized combustion can be avoided as long as isothermal bed condition is maintained by ensuring uniform fluidization. Hence, the fluidized bed reactors seem to be a promising choice for biomass fuels with high ash contents, particularly melting at relatively low temperatures.[16–18]

3. RESULTS AND DISCUSSIONS

The reported fluidization behaviours of rice husk are summarized in Table 1. Tables 2 and 3 show the detailed information on constructional and operating parameters of various fluidized bed reactors. The main observations and results of most of the studies carried out in the field of fluidized bed combustion and gasification of rice husk are summarized in Tables 4 and 5, respectively. It may be observed from Table 1 that the reported investigations were conducted in small lab or bench scale models. For the convenience of comparison, all reported values have been converted to SI units and air flow rates have been converted to corresponding equivalence ratios, which is defined as the ratio of actual to stoichiometric mass of air supplied per kg of fuel. In the absence of stoichiometric air or elemental composition in the report, a value of 4.7 kg of air per kg of dry rice husk[19] has been assumed.

3.1. *Fluidization behaviour of rice husk*

The quality of fluidization is one of the most important factors that influences the combustion and gasification efficiencies. The main observations and the results of fluidization characteristics of rice husk are summarized in Table 1. Fluidization quality can be controlled by changing superficial air velocity, within the permissible limit for a chosen particle size. In general, it is difficult to fluidize rice husk due to its cylindrical shape, non-granular and flaky nature.[20] Fluidization behaviour of rice husk improves when it is mixed with other solid particles forming a multisolid system.[11,14,20]

Table 1. Fluidization behaviour of rice husk

Reference	Main observations	Main results
Sen and Ghosh[20]	• Fluidization behaviour was studied using a perspex column with 76 mm diameter and 900 mm high and a multiorifice distributor plate • At the onset of fluidization, the husk bed expands and channels are formed in different regions. However, further increase in velocity results in an aggregative fluidized bed • Fluidization of ground/broken husk is smoother compared to the whole husk • When static bed height to diameter ratio is increased beyond 2.0, channelling is observed due to the mesh forming tendencies of particles. It is prominent with husk, compared to char and ash • Minimum fluidization velocity and bed pressure drop for whole rice husk are higher than that for ground husk. Similar trend is observed even with their ashes • Fluidization of mixtures of char, ash and husk shows channelling and poor movement of individual particles at low air velocities, but good mixing is observed at the bubbling velocity with little classification among the different particles • Bubbling velocities of char and the mixtures are the same as that of husk • Fluidization behaviour of whole husk char is little better than that of char but not as good as that of ash	• Minimum fluidization, bubbling and entrainment velocity for whole husk is 46, 100 and 110 cm/s respectively, whereas the corresponding values for ground husk are 26, 72 and 80 cm/s. Corresponding expanded bed height is about twice the static bed height • Good fluidization of whole husk or ground husk is possible in the form of aggregative fluidized bed at a velocity of about 2.5 times the minimum fluidization velocity • For ash, the minimum fluidization velocity is about 65% of that of husk and bubbling bed results at about 50% of the corresponding velocity for husk • Recommended operating velocity for the mixture of whole husk and its char and ash is 90–100 cm/s, whereas the same for ground husk mixture is 65–75 cm/s. Beyond these velocities, entrainment is dominant
Xu *et al.*[14] and Flanigan *et al.*[18]	• Fluidization of the rice husk seem to be difficult, unless it is mixed with sand and/or char and/or ash to form a multi-solid system • For normal fluidization process, sand to whole husk weight ratio of 20 is required and it results in excessive pressure drop • Fluidization behaviour of husk and its ash mixture is superior to that of husk and sand mixture • When husk char alone is difficult to be fluidized, it is easy to fluidize its mixture with sand • Ground husk is easier to fluidize and the mixture of ground husk and sand exhibits superior fluidization behaviour to that of whole husk and sand	• Ground husk exhibits a superior fluidization behaviour • Minimum fluidization and terminal velocities of husk ash is about 16 and 80 cm/s respectively • Minimum fluidization velocity of whole husk and sand mixture (weight ratio of 1:12) is approximately equal to the terminal velocity (80 cm/s) of sand • Minimum fluidization velocity of sand and char mixture (weight ratio 10:1) is equal to that of pure sand (234 μm). • Mixture of 3–7 kg of sand per kg of ground husk is required for better fluidization with 27–36 cm/s air velocity. At twice the minimum fluidization velocity, the bed expansion is about 2.5 times the static bed height.

Table 2. Fluidized bed reactor: constructional details

Reference	Reactor material	Reactor shape and size (mm)	Reactor height (m)	Insulation	Distributor details	Fuel feeding arrangement
			Fluidized bed combustor			
Peel and Santos[21]	Pipe lined with castable refractory	Cylindrical 200	*	Surrounded by water cooling coils	Perforated SS plate (1 mm diameter holes)	Screw or pneumatic feeding
Bhattacharya *et al.*[22,23]	Milled steel (water cooled)	Square 150 × 150	*	Refractory and glass wool	Milled Steel plate with 196 holes of 1 mm diameter, 10 mm square pitch	Screw feeding
Preto *et al.*[13]	Refractory lined	Rectangular 380 × 406	4.8	*	Nozzle type	Underbed feeding by screw feeder
Bhattacharya and Wu[1]	Milled Steel (water cooled)	Cylindrical 150	2	Rock wool	Perforated plate with 2.74% opening	Fed by screw feeder, 70 cm above distributor plate
			Fluidized bed gasifier			
van den Aarsen *et al.*[25]	*	Cylindrical 300	*	*	*	Screw feeding into the bed
Hiler[26]	*	300	*	*	Perforated plate	Screw and star feed wheel
Xu *et al.*[14]	*	Cylindrical 152	2.4	*	*	Fuel augured into the bed at 45 cm from bottom
Hartiniati *et al.*[27]	*	Cylindrical 400	3.66	*	*	Fed just above the distributor plate by screw feeder
Flanigan *et al.*[18]	*	Cylindrical 150	3.60	*	*	Fuel augured into bed at 1.8 m height from distributor plate
Bingyan *et al.*[11]	*	Cylindrical 150	3.7	*	*	Ground and whole rice husk were fed into bed at 0.5 m and 1.8 m respectively
Sanchez and Lora[6]	SS 316 with refractory lining	Cylindrical 200	2	Mineral wool	Perforated plate (2000 holes of 1.3 mm diameter)	Fed by screw conveyor, 50 mm above the distributor plate

*Data/details are not available

Table 3. Fluidized bed reactor: operating parameters

Reference	Bed material and mean particle size (μ m)	Static bed height (mm)	Static bed height to diameter ratio	Equivalence ratio	Fluidization velocity (m/s)	Bed operating temperature (°C)	Fuel flow rate (kg/h)
				Fluidized bed Combustor			
Peel and Santos[21]	Sand < 830	30–150	0.15–0.75	1.15	1.0–1.5	870°C	*
Bhattacharya *et al.*[22,23]	Sand 351–420	100	0.67	1.14	0.19–0.37	638–760	2–15
Preto *et al.*[13]	Sand 500	300–600	*	1.30–1.95	0.4–2.2	650–900	*
Bhattacharya and Wu[1]	Sand 300–500	*	*	1.1–4.4	*	700–750	7–9
				Fluidized bed gasifier			
van den Aarsen *et al.*[25]	Alumina*	600	2	0.27–0.34	*	750–950	50
Hiler[26]	*	*	*	0.15–0.38	*	523–907	*
Xu *et al.*[14]	Sand 234	*	*	0.18–0.21	60–75	700–815	9–22
Hartiniati *et al.*[27]	Alumina 486	60	1.5	0.30–0.48	*	721–871	75–105
Flanigan *et al.*[18]	Sand 826	*	*	0.21–0.29	*	500–757	14–18
Bingyan *et al.*[11]	Sand 225	*	*	0.26	60–100	500–800	15–20
Sanchez and Lora[6]	Alumina*	480–370	1.85–2.4	0.1–0.8	75	600–800	*

*Data/details are not available

Fluidization behaviour of char from husk is found to be a little better than that of husk, but not as good as that of ash.[20] Since the shape and size of char is similar to that of husk, a little improvement in fluidization quality of char over husk is attributed to decrease in inter particle friction resulting from decreased surface roughness. Although fluidization of mixtures of char, ash and husk exhibits channelling and poor movement of individual particles at low air velocities, good mixing and fluidization with little segregation can be achieved at bubbling velocity. In actual fluidized bed combustion or gasification, the bed contains rice husk and its char and ash, in addition to the inert bed material. It is possible to achieve good fluidization condition of sand, rice husk, and its char and ash mixture at 60–100 cm/s operating velocity.[11,14,20]

3.2. *Rice husk feeding in fluidized bed*

Biomass fuels usually pose difficulties in handling and feeding due to their poor flow characteristics. It is severe in the case of rice husk due to its low bulk density of about 100 kg/m^3 and abrasive and interlocking nature. Thus, rice husk is usually force-fed into the reactor, either mechanically by a screw feeder or pneumatically by air. Due to its low bulk density and high volumetric porosity, it is likely to carry a small quantity of air through feeding port.

3.2.1. *Feeding in combustion*. In general, there is no serious difficulty in feeding the rice husk into the bed using a screw feeder.[1,13] But, the feed rate by the screw feeder is reported to be non-uniform[13] at low feed rate levels and it is observed to vary cyclically due to some sort of "cyclic compression" process[13] which packs the rice husk until a minimum plug is developed before being fed. The pneumatic feeder also seems to be unreliable especially at low feed rates.[21] However, this does not lead to any detrimental effect on the combustion efficiency. It is advisable to provide a cooling jacket around the feeding screw to prevent the pyrolysis and carbonization of the husk before entering the bed by keeping its temperature low. Fuel feeding can further be smoothened by supplying secondary air through the feeding port and by vibration of the hopper.

3.2.2. *Feeding in gasification*. The feeding of whole rice husk from the top (counter flow) of a gasifier was studied by Bingyan *et al.*[11] and

Table 4. Fluidized bed combustion of rice husk

Reference	Main observations	Main results
Peel and Santos[21]	• Pyrolysis of fuel in the feeding port before reaching the bed disturbs the fuel flow • No bed agglomeration is observed, even in the continuous operation for a period of 8 h • High particle porosity appeared to allow more rapid ignition and better control of bed temperature	• The main limitation is ellutriation with fine particles and segregation with larger particles • Combustion in freeboard decreases with increasing bed temperature and fluidization velocity • Bed temperature and smoke control was difficult in shallow beds (<200 mm) with fuels of high volatile content
Bhattacharya *et al.*[22,23]	• Significant carry over of inert sand particles from the bed at high air flow rate is observed • Under normal operating conditions, virtually all the ash is entrained in the stream of the flue gas • Bed height influences the combustion intensity • Increase in bed height increases the sand entrainment rate	• Combustion intensity of 530 $kg/h/m^2$ can be achieved • Combustion intensity increases when the bed height is increased from 100 to 150 mm for same flow rate • Combustion efficiency ranges from 81 to 98%, depending upon air flow rates • Combustion efficiency increases with secondary air flow rate up to certain level, after which no appreciable change is observed • Combustion efficiency increases with secondary air flow rate up to certain level, after which no appreciable change is observed
Preto *et al.*[13]	• Higher temperature in the overbed region is observed for all fluidization velocities due to volatiles burning in the freeboard • Combustion efficiency shows no dependence on fluidization velocity and excess air and only minor dependence on temperature • CO emission increases with increase in fluidization velocity and temperature • Husk ash is very fine and easily ellutriated out of bed. Even low fluidizing velocity is sufficient to blow all ash out of bed	• Combustion efficiency of more than 97% with low emissions can be obtained over a wide range of fluidizing velocities • Carbon conversion efficiency of 96.9–98% can be attained CO emissions varies from 200 to 5000 ppm, whereas SO_2 and NO_x emission ranges are 50–150 ppm and 100–180 ppm (20–200 ng/J) respectively • CO emissions varies from 200 to 5000 ppm, whereas SO_2 and NO_x emission ranges are 50–150 ppm and 100–180 ppm (20–200 ng/J) respectively • Carbon content in the cyclone product varies from 1 to 4% • Cyclone ash contains about 98% silica (SiO_2)
Bhattacharya and Wu[1]	• Heat loss due to unburnt carbon increases with excess air level and also with combustion intensity for same excess air level • Heat loss due to CO in flue gas decreases with both the above factors • No particular operational problem is experienced in the lab or pilot combustor • Overbed feeding seems to be more convenient	• Combustion efficiency of more than 95% has been achieved • Typical heat loss due to unburnt carbon in ash is 1–3% and CO loss is 3–10% • Higher combustion efficiency could be achieved by proper splitting of total air into primary and secondary air and by providing enlarged freeboard • Pozzolana cement obtained by mixing rice husk ash and portland cement (30:70) is found to have higher strength

Table 5. Fluidized bed gasification of rice husk

Reference	Main observations	Main results
van den Aarsen *et al.*[25]	• Opportunities for temperature control are optimum in fluidized bed • Inert fluidized bed material prevents flow problems inside the reactor and also acts as a heat fly wheel • Temperature profile along the height of the reactor indicates an excellent homogeneous bed temperature under all circumstances • Equilibrium conversion of hydrogen, water, carbon-dioxide and carbon monoxide is fixed by the homogeneous water gas shift reaction. Gas phase conversion of 90% is observed • No ash sintering or ash removal problem has been observed during gasification of 1000 kg of rice husk over a period of 35 h and even after operating up to 940°C for 6 h	• LHV of the gas varies between 4.5 and 6 MJ/kg, which is sufficient enough to be used as fuel in internal combustion engines • While the volumetric gas yield increases with temperature, its heating value and concentrations of CO and HC decrease • Tar content in the gas decreases rapidly with temperature from 6000 mg/Nm^3 at 750°C to 800 mg/Nm^3 at 940°C and deeper bed could be used for further reduction of tar • Carbon conversion efficiency of about 90% and cold gas efficiency of 60 to 67% could be achieved
Hiler[26]	• Sorghum stalks, rice husk, corn cobs and cotton gin trash could be gasified to produce low energy gas in a fluidized bed • Gas composition is mainly influenced by equivalence ratio • Effect of the type of biomass fuel on the gas composition is minimal	• A 300 mm diameter gasifier can generate gas with thermal energy of 869 kW/m^2 of distributor area • Gas with a mean heating value of 6.6 MJ/m^3 and standard deviation of 0.8 MJ/m^3 has been produced at an equivalence ratio of 0.23 and bed temperature of 760°C • Cold gas efficiency of gasifier varies between 45 and 65%
Xu *et al.*[14]	• Equivalence ratio controls the bed temperature, which in turn strongly influences the gasification efficiency. Nearly isothermal conditions can be achieved at different temperatures • H_2/CO ratio, heating value and gas yield increase with the temperature • For a given air flow rate, nitrogen concentration in the product gas decreases with increasing temperature • Silica and potassium oxide in the ash melt at about 980°C and form a diffusional barrier for the gasification process • Above 900°C, water shift reaction dominates which causes only a shift in H_2 and CO compositions and hence no significant improvement in heating value can be expected • Gasification efficiency exceeds 60%, when the bed temperature is above 700°C	• Sand and ground hull mixture offers good fluidization behaviour. Sand to husk ratio of 3:7 is found to be desirable • Superficial velocity of 60–75 cm/s resulted in good fluidization and bed expansion • To obtain near maximum efficiency, temperature range of 700–980°C is recommended • The gasification rate varies between 2.8 and 4.6 MW_{th}/m^2 and the heating value between 5 and 8 MJ/Nm^3 • The carbon conversion efficiency is reported to be 75% • The bed temperature of 700–815°C, an equivalence ratio of 0.18:0.21, fuel flow rate of 13.6–18.2 kg/h and superficial air velocity of 60–75 cm/s are found to be the optimum conditions

Bingyan *et al.*[11]	• Gasification process is directly affected by fluidization quality. When the bed is operated from 60 to 100 cm/s, the bed temperature is uniform and the bed expansion is about twice the static bed height • Overbed feeding for whole husk and inbed feeding for ground husk seem to be advantageous • Influence of temperature on the gasification reaction is dramatic up to 730°C • Increase in temperature and fluidization quality increases the carbon conversion efficiency, gas productivity and gasification efficiency • Although gas quantity increases, its quality deteriorates above 730°C • Overbed feeding of whole husk offers improved performance over inbed feeding of ground husk	• Above 985°C, silica and potassium oxide fuse on the surface of the rice husk char and form a glass like barrier which prevents further reaction of the remaining material • Gas heating value increases from 2.64 to 5.5 MJ/kg, when temperature is increased from 500 to 730°C • Optimum gasification temperature for best quality gas is found to be 730°C at an equivalence ratio of 0.26. Bed temperature range of 680–750°C is recommended • Product gas with 5.25 MJ/m^3, 90% carbon conversion, and 60% cold gas efficiency with productivity rate of 4.44 MW$_{th}$/m^2 are the typical results achieved
Flanigan *et al.*[18]	• Ground husk is observed to have better gasification quality but it requires additional machinery and energy • Heating value of the gas decreases with temperature beyond 700°C • The char is not blown out of the bed until it is decreased from its initial size of 5 mm length to 0.4 mm • 25–30% of the energy in the rice husk is sufficient to supply the heat for gasification in the temperature range of 500–700°C • Reaction temperature of rice husk should be carefully controlled below 900°C, to avoid ash related problems • Gasifier efficiency can be improved to the extent of 10% by eliminating the heat loss by insulation and recovering the sensible heat of product gas	• Fluidization velocity of 67–98 cm/s provides good fluidization quality and bed expansion • When the temperature is increased from 500 to 700°C, the heating value of the gas increased from 2.6 to 5.2 MJ/m^3, while the cold gas efficiency and carbon conversion efficiency are increased from 21 to 58% and 55 to 90% respectively •2 has been achieved • Maximum heating value of the gas is achieved at 700°C • Surface heat loss from the gasifier is about 10 to 19%
Hartiniati *et al.*[27] and Panaka *et al.*[28]	• Increase in temperature requires higher equivalence ratio, that results in higher gas yield but decreases LHV of gas for the same fuel flow rate • For the same fuel flow rate, the equivalence ratio is to be raised from 0.30 to 0.48 to achieve gasification temperatures from 721 to 871°C • Gas quality is found to vary between 4.1 and 6.3 MJ/m^3, depending upon the bed temperature and/or equivalence ratio • Concentration of hydrocarbons decreases with increase in temperature as a result of thermal cracking • No operational problem was observed during 36 hours of continuous operation	• Decrease in LHV of gas and increase in air-fuel ratio with temperature for same fuel flow rate is due to higher requirement of air (that leads to dilution) to burn proportionately higher amount of fuel to increase temperature • Maximum energy of 12.3 MJ-gas/kg-fuel(daf) was produced at 93 kg/h of fuel flow rate and bed temperature of 785°C. LHV of gas under this condition is found to be 4.1 MJ/kg • Cold gas efficiency varies from 63 to 67%
Sanchez and Lora[6]	• Increase in equivalence ratio increases the gasifier efficiency initially and then decreases • The hot and cold gas efficiencies are reported to be 43% (max 53.9%) and 60% (max 65%) at the temperature of 759°C and equivalence ratio of 0.55	• It is found that 1.4 (max 2.1)m^3 of gas with LHV of 2.9 (max 4.0) MJ/Nm^3 is produced per kg of rice husk • The thermal capacity of the gasifier is 1.4 (max 2.1) MW per m^3 of bed volume at the husk flow rate of 1000 (max 3900) kg/m^{3}h

Flanigan *et al.*[18] Pyrolysis of husk takes place in the freeboard and top part of the hot sand bed and the resultant char settles into the bed. During this settling, the char is ground by the turbulent sand bed into small particles and simultaneously reduced by the gas. Most of the remaining char is burnt by the incoming air to release the heat energy to sustain the gasification process. The above researchers also fed ground rice husk from bottom (co-flow) of the gasifier. The volatiles released instantaneously in the bed by pyrolysis blow across the sand bed, because of which the resultant char is blown out of the bed with upward flowing air due to their smaller size. This problem becomes severe in view of the fact that rice husk contains more than 60% volatile matter. Combustion reactions happens mainly between the part of the gas and incoming air.

Since the combustion rate of char is much higher than the gasification rate, counter flow of ground husk offers low char and high ash production for the same operating conditions. For the same reaction temperature, counter flow offers 10% higher carbon conversion, 7–10% higher heat efficiency, 11–14% high ash content in char, 14–20% decreased char production and 30–40% higher gas productivity. The absence of actual percentages in the reference makes the above values less meaningful. Although ground husk seem to give improved performance, only a detailed investigation could establish the economic viability of the option, as it involves additional investment on required machinery for grinding as well as operating expenditure and extra-energy. No detailed report is available on overbed feeding of ground husk, but it can be expected that it could lead to severe ellutriation by the outgoing gas.

The whole rice husk can be conveniently fed right into the bed as well. As the whole husk char is larger in size and heavier in weight compared to the ground husk char, they could hardly be blown out of bed[18] by volatiles until they are reduced to finer particles or ash. If the gas produced from the gasifier is for thermal applications, either overbed or inbed feeding may be adapted. But, if the gas is to be used to develop shaft or electrical power, it is advisable to opt for inbed or underbed feeding, as it can promote tar cracking due to increased residence time in the bed.

3.3. *Fluidized bed combustion of rice husk*

The inherent advantages of fluidized beds, like high efficiency even with low grade fuels, compact combustion chamber with high heat and mass transfer rates, relatively low combustion temperatures and subsequently low emissions of NO_x, fuel flexibility and easy temperature control, make fluidized bed reactor an attractive option for the utilization of agricultural residues. The main observations and the results of the investigations of rice husk combustion in fluidized bed reactor are summarized in Table 4, whereas the reactor constructional and operation parameters are summarized in Tables 1 and 2, respectively. As rice husk contains high volatile content, considerable degree of freeboard burning of volatiles is observed,[1,13] particularly during overbed feeding. The extensive combustion of volatiles in the freeboard results in higher temperature in the freeboard zone than in the bed and a considerable amount of that heat is carried away by the outgoing gas. If the volatiles are burnt in the bed, the heat released will be mainly absorbed by the bed material. Hence the combustion in the freeboard should be avoided or decreased[21] by adopting inbed or underbed feeding instead of overbed feeding, by increasing bed temperature, fluidization velocity and bed depth.

3.3.1. *Combustion intensity*. A high combustion intensity to the tune of 530 kg/h/m^2 could be achieved[22,23] in a fluidized bed reactor. The maximum combustion intensity of rice husk in grate type furnace[24] is about 70 kg/h/m^2. Thus, combustion intensity in fluidized bed is about 7.5 times higher than the maximum possible combustion intensity in a grate type furnace per unit grate area. Combustion intensity increases with bed height due to increase in bed volume.

3.3.2. *Combustion efficiency*. The combustion efficiency is defined as the ratio of actual heat released in the combustor to the chemical energy in the fuel. It is normally in the order of 80% in the case of atmospheric bubbling fluidized bed combustors. Bhattacharya *et al.*[22] has reported a combustion efficiency of 81–98% and others[1,13] have reported more than 95%. Although the well controlled experiments in the small size reactors may offer higher efficiencies, no specific reason or data have been provided by the authors to substantiate the same. The reported typical heat loss[1] due to unburnt carbon in ash is 1–3% and due to unburnt CO in the flue gas is 3–10%. Combustion efficiency shows no dependence[13] on fluidizing velocity and excess air and only minor dependence on temperature. However, if the superficial velocity is very high, a part of the volatiles can be carried away in the flue gas that could result in reduction in combustion efficiency. Any such loss could be identified by the peak temperature at the top of freeboard. Heat loss due to CO in flue gas decreases[1] with excess air level for the same combustion intensity and it also decreases with combustion intensity for the same excess air level. While the effect of excess air is obvious, the effect due to combustion intensity may probably be ascribed to better gas mixing. No significant difference in combustion efficiency is observed, whether the husk is supplied underbed or overbed[1]. The combustion efficiency could be improved by properly splitting the total air into primary and secondary air and supplying them at appropriate level, and enlarging and insulating the freeboard to achieve higher residence time at sufficiently high temperature.

3.3.3. *Emissions*. CO emissions of 200–5000 ppm in the flue gas has been reported by Preto *et al.*[13] The higher CO emissions are observed at higher fluidization velocities, probably due to shorter residence time. SO_2 and NO_x emissions[13] are found to vary from 50 to 150 ppm and 100 to 180 ppm, respectively.

3.3.4. *Ash composition and its removal*. Combustion of rice husk in the fluidized bed is accompanied by a simultaneous attrition of ash particles. As a result, the ash produced by fluidized bed combustion is in the form of smaller particles compared with that obtained from a grate-type furnace.[22,23] The ash produced from husk is fine (less than 0.375 mm) and can be easily ellutriated out of bed, even by a low fluidization velocity[13] of about 54 cm/s. The ash collected from the cyclone contains[13] as high as 97.6% silica.

3.4. *Fluidized bed gasification of rice husk*

As the high ash content, low bulk density, poor flow characteristics and low ash melting point makes the other conventional types of gasifiers unsuitable for rice husk gasification, the fluidized bed gasifier[25] seems to be the obvious choice. Direct combustion of many biomass fuels, especially agricultural residues, in the fluidized bed is reported to cause deleterious coatings[26] on the bed particles, fouling of downstream components and hot metal corrosion due to the formation of some complex chemical compounds and eutectics that melts even at low temperatures. The basic problem is identified with the high ash content of the fuel source and its chemical composition. However, operating the fluidized bed in the gasification mode was also reported to reduce or eliminate[26] the bed-particle coating and fouling problems encountered in combustion.

3.4.1. *Effect of equivalence ratio*. Equivalence ratio is defined as the ratio of actual air supplied per kg of fuel to the stoichiometric quantity of air required per kg of fuel. In the process of gasification, part of fuel is burnt to release energy to sustain the endothermic gasification reactions. Equivalence ratio determines the fraction of the fuel that is burnt and the fraction of the fuel that is gasified in the reactor. It also affects fluidization quality and bed temperature. The lower limit of equivalence ratio is decided by the minimum quantity of air required to burn a part of the fuel to release enough heat to support the endothermic reactions, to attain required carbon conversion efficiency, to meet the sensible heat losses in gas, char and ash, and to maintain the required temperature of the reactor. As rice husk has a high ash content,[3] it requires relatively higher fraction of the fuel to be burnt. This ultimately demands a relatively higher equivalence ratio.

The upper limit of equivalence ratio is determined by the combined consideration of the reactor temperature, fluidization quality, gas heating value and tar content in the gas. As equivalence ratio increases, the reactor temperature continuously increases as higher proportion of the fuel is burnt. It is possible to obtain different operating temperatures by adjusting the equivalence ratio.[14] It is limited at the temperature where the ash melting is observed. As the bed expansion and the rate of ellutriation increases with equivalence ratio, the limit on ellutriation of bed and char particles mainly limits the equivalence ratio. While the gas quantity increases continuously with the equivalence ratio, its heating value deteriorates after a certain limit. It is mainly due to the fact that a proportionately high part of the fuel is burnt rather than gasified and partly due to dilution by nitrogen in air. Tar content in the gas drastically decreases[25] beyond 750°C. If the moisture content in the fuel is high, it demands for still higher equivalence ratio to evaporate the moisture and to raise the temperature of wet reactants.

For a given equivalence ratio the nitrogen concentration of the producer gas decreases[14] with temperature, as the rate of gasification increases with temperature. The additional amount of producer gas dilutes the inert N_2 stream and hence increases the heating value of the gas.[14] However, in practice, air flow rate is increased to increase the temperature, which in turn adds more nitrogen than the additional amount of product gas produced due to increased rate of gasification. Subsequently, the heating value of the product gas is decreased. The reported values of equivalence ratios for maximum gasification efficiency (Table 5) ranges from 0.2 to 0.55.

3.4.2. *Temperature limits*. The lower temperature in the gasification process is determined by the condition for complete carbon conversion. It mainly depends on the elemental composition of husk and the equivalence ratio. It is about[14] 700°C for the equivalence ratio of 0.2 and it decreases with the increase in equivalence ratio. If the gasification temperature is less than this lower limit, part of the carbon in the fuel remains unburnt and accumulates in the reactor, resulting in lower efficiencies. The higher temperature is limited by ash fusion conditions. It is in the order[11,14] of 1000°C and it primely depends upon the ash composition and the reaction atmosphere (like oxidation or reduction). Above this temperature, silica and potassium oxide in the ash fuses on the surface of the rice husk char particles forming a glass-like barrier[11,14] that prevents the further reaction of the remaining carbon.

3.4.3. *Producer gas yield and gasification rate*. Producer gas yield per kg of fuel increases with equivalence ratio and hence with temperature. As the temperature increases from 750 to 900°C, gas productivity[25] improves from 1.85 to 2.5 Nm^3 per kg of fuel. The gasification rate is found to vary[11,14] between 2.8 to 4.6 MW_{th}/m^2. It is worth to note that Hiler[26] has chosen a conservative value of 865 kW_{th}/m^2 to design a 30 cm gasifier to have a multi-fuel capacity to use agricultural residues like corn cob, sorghum, rice husk and cotton gin, as well as to ensure adequate gas production rate even at the worst conditions. It is also customary to express energy release per unit bed volume. A maximum of 2.1 MW thermal energy of gas can be produced per m^3 of bed volume.[6]

3.4.4. *Gas composition and heating value*. The concentrations of CO, H_2 and CH_4 mainly determines the heating value of the gas, since CO_2 and N_2 are inert and other combustibles are negligibly small. The concentrations of H_2 and CO increase and the concentrations of CO_2, N_2 and CH_4 decrease with temperature for a given equivalence ratio.[14,27] The heating value of the producer gas from rice husk is reported to vary from 5 to 8 MJ/Nm^3 by Xu *et al.*[14] and 4.5 to 6 MJ/Nm^3 by van den Aarsen *et al.*[25] and others. It may be noted that the higher gas heating value is reported by Xu *et al.* in spite of the low carbon conversion efficiency of 75%, compared to 90% that reported by van den Aarsen *et al.*[25] The heating value of the gas decreases[28] with increasing bed temperature, which demands for higher equivalence ratio and subsequent dilution.

3.4.5. *Gasifier efficiency*. The hot gas efficiency of the gasifier is defined as the ratio of chemical energy plus thermal heat in the gas to the chemical energy in the fuel and alternatively the cold gas efficiency is the ratio of chemical energy in the gas to that in the fuel. The cold gas efficiency of more than 60% could be achieved[11,14,16,25,26] in fluidized bed gasifiers. It is considerably higher than that achieved in down draft gasifiers,[29] which is in the order of 50%. The carbon conversion efficiency[11,25] in the order of 90% is reported in the fluidized bed gasifiers.

3.4.6. *Tar emissions*. The producer gas also contains condensable tar, which is considered highly undesirable especially for shaft power development. The tar is a mixture[30] of condensable heavy hydrocarbons with higher molecular weights. When producer gas is used for thermal applications, there may be no need for tar cleaning since tar burns well with smokeless flame[31] and also contributes to thermal energy. However, it is to be cleaned to its lowest level[32] of less than 10 mg/Nm^3 to be used for shaft power production in internal combustion engines, otherwise it may severely affect its maintenance and useful life. The tar content of the producer gas strongly depends on the reactor operating temperature and decreases[25] from 6000 mg/Nm^3 at 750°C to 800 mg/Nm^3 at 940°C. A deeper bed and/or catalytic cracking could be used for further reduction of tar.

4. CONCLUSIONS

As the high ash content, low bulk density, poor flow characteristics and low ash melting point makes the other conventional types of reactors unsuitable for rice husk utilization, fluidized bed reactors seem to be the suitable choice. The study of reported literature indicates that it is technically feasible to successfully burn the rice husk in a fluidized bed reactor, and combustion intensity of about 530 $kg/h/m^2$ can be achieved. Although a combustion efficiency of about 80% can normally be attained; the reported values in the literature, which are more than 95%, seem to be in higher order. It is also technically feasible to gasify rice husk in a fluidized bed reactor to yield combustible producer gases, even with sufficient heating value for application in internal combustion engines. A combustible gas with heating value of 4–6 MJ/Nm^3 at a rate of 2.8–4.6 MW_{th}/m^2 seems to be attainable. While the reported qualitative characteristics of rice husk gasification is consistent in almost all the reports, the quantitative behaviour seems to differ widely. In the absence of relevant data, it becomes difficult to identify the reasons for the varying quantitative behaviour.

The reported results are mainly from small lab or bench scale reactors and the data available are limited. There is hardly any evidence of commercial systems operating on agricultural residues for energy generation. Very little information is available on the pollutant emissions in combustion and tar emissions from gasification. It emphasizes the need for further research to establish suitable and optimum operating conditions for commercial implementations.

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