Technology for gasifying pulverised bio-fuels including agricultural residues

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This paper presents both the fundamental and technological aspects of gasification of pulverisable agro-residues, more particularly rice husk. The fundamental aspects are related to the times required for flaming and char conversion processes. The technological aspects described here are related to the gasification process using a cyclone reactor. The aspects of reactor design, cooling and cleaning systems are addressed. Limiting the tar fraction in the gas needs good mixing between the gas and the red hot char arranged in a circulating fluid bed for the ash handling system. Cleaning the gas (of particulates and some tar) is achieved by a centrifugal separation process aided by the injection of a water jet. The experience gained from the developmental programme on the gasifier operation leading to power generation via the dual-fuel mode on an existing diesel engine is also described. The gasifier operates on an air-to-fuel ratio of 0.95 to 1.0 and the consumption rate of husk when the gas is fed to an internal combustion engine in dual-fuel mode with 80% diesel replacement is 1.5-1.55 kg/kWh of electrical energy, confirmed from several long duration tests. This is lower than the value of to 2 to 2.2 kg/kWh reported for Chinese gasifiers. The conversion-fixed carbon in the rice husk char achieved in the reactor is about 50%, the cold gas efficiency being about 70%. The fuel is pulverised to a mean size of 0.75 mm with about 35% by weight less than 0.4 mm. The reduction in the size of the agricultural residues is to enable the same gasifier to be used for all the pulverisable fuels; accordingly, the same gasifier is able to successfully gasify sawdust and sugarcane trash. Some issues related to handling sugarcane trash are also discussed. The treatment of the ash/residue is in the dry mode and therefore, the requirement of water is comparable to that in wood gasifiers and is much less than in Chinese fixed bed gasifiers. Another important aspect of the study is the measurement of the NO_x in the engine exhaust which has shown that the NO_x level for the dual-fuel mode is one-eighth of that in diesel-alone mode over the entire power range up to full load.

1. Introduction

Gasification is the process of converting solid fuels to gaseous fuel through combined oxidation and reduction with oxidant (air) in sub-stoichiometric conditions. The pyrolysis gases first burn with air and the products of combustion are further reduced by the left-over char residue to carbon monoxide and hydrogen. The gas thus produced is composed of carbon monoxide, hydrogen, methane, and some higher hydrocarbons, besides inerts, namely, carbon dioxide and nitrogen. The gas also contains traces of condensable compounds termed tar and some fine dust, which must be restricted to less than about 100 ppm each if the gas is to be used in internal combustion engines.

The advantage of gasification over direct combustion is that at low power levels (from 3 kW$_e$ to a couple of MW), electric power can be generated economically by using the cooled and cleaned combustible gas as a fuel in internal combustion engines – reciprocating or gas turbine engines. The conventional method of electricity generation from solid fuels by raising steam and using it in a steam turbine is cost-effective only at power levels of many MW$_e$.

The overall efficiency of the energy conversion process via reciprocating engines is about 15 to 20% at a level of 20 kW$_e$ power, 25 to 30% at 100 to 150 kW$_e$, 30 to 35% at 200 kW$_e$ and above. Gas turbines give efficiencies about 5 to 10% lower than reciprocating engines. However, the maintenance cost of gas turbine engines is generally lower than that of reciprocating engines. One has a further facility of using the exhaust gas in either case (reciprocating or gas turbine engines) in co-generation mode either for electricity through steam turbines or, more practically, for raising process steam.

At high power levels (5 MW or more), the hot gas can be used economically as fuel in boilers for raising high pressure steam for power generation using steam turbines. For thermal applications, for example in foundries and drying equipment, gasification and subsequent combustion will provide for much cleaner combustion with good control over the instantaneous power.

Dense solids fuels such as wood, corn cobs, and cotton stalks can be gasified using a fixed bed gasifier and such systems have been developed and deployed in the field during the last several years [Mukunda et al., 1993, Mukunda et al., 1994]. However, fixed bed systems are not suitable for gasification of agro-residues and other solid wastes which can be classified as pulverised fuels.

Table 1. Bulk densities of common pulverisable fuels

Fuel (sun-dried)	Bulk density (kg/m^3)
Sawdust (<3 mm)	300-350
Rice husk	100-130
Rice husk pulverised (<2 mm)	380-400
Sugarcane trash (cut to <15 mm)	50-60
Sugarcane trash (pulverised, <4 mm)	70-90
Groundnut shells	120-140
Groundnut shells (pulverised, <2 mm)	330-360

Table 2. Thermophysical properties of some pulverised fuels

Fuel	Calorific value (MJ/kg) at 10% moisture	Ash (%)	Ash melting point (°K)
Sawdust	16±.5	0.5-1.0	> 1400
Rice husk	13±.5	18-20	> 1400
Sugarcane trash	15±.5	5-6	750-1000
Groundnut shells	15±.5	4-6	> 1200

Fluidised bed and cyclone gasifiers have been under development for these fuels [Mukunda et al., 1994, Waldheim et al., 1993]. The present paper describes the progress made in this laboratory in developing a cyclone gasifier for pulverised fuels.

2. Pulverised fuels and their properties relevant for gasifier operation

Fuels whose physical form is like leaves or flakes, or those consisting of very light thin-walled material characterised by very low bulk densities, can be treated by pulverising. An alternative treatment of randomly sized wastes of physically varying forms is by briquetting, which calls for size reduction to an acceptable level before briquetting is carried out. Since the more widely understood treatment of wastes is briquetting and it involves size reduction anyway, it is suggested that *this material can be handled by the present method without having to go through briquetting.*

The materials that can be classified as pulverised fuels are sawdust, which is a waste from the wood industry, coconut coir pith, which is a waste from the coir industry, bagasse, wastes from herbal industries, and weeds like epotorium and parthenium which are otherwise considered useless. Other fuels that can be pulverised are rice husk, peanut shells, rice straw, wheat straw, thin cotton stalks, and sugarcane trash.

2.1. Fuel properties

The properties of the wastes that affect the gasification system are the density, the ash content and the ash fusion point. Table 1 shows the bulk density of several fuels.

As can be noticed, the bulk density of the fuels is low and also varies widely. This feature leads to problems in handling agro-residues. The cost of transportation of these fuels is high because of the low bulk density. Techniques like bagging can indeed raise the density. If, however, the functional requirement also demands a pulverised condition, it may be better that the pulverising is done at the source and the fuel is then transported so that the benefits of density increase are obtained. An exception is sugarcane trash, available largely in the form of thin long leaves, whose bulk density does not increase greatly after cutting and also after pulverising. Cutting to small size (<10 mm) may be adequate for sugarcane trash if the thermochemical conversion process does not demand pulverising. As is seen in Table 1, there is a variation by a factor of five in density among the different fuels. Hence, if a system is to be designed for multi-fuel option, the fuel feed system must take this factor into account. For example, if the system has been designed for rice husk, and it is decided later to deploy the same system for sugarcane trash, the fuel feed system must account for increase in volumetric feed rate by a factor of four. Thus it is important that these differences are recognised and taken care of right at the design stage.

Points related to thermal aspects are addressed next. Table 2 shows the calorific value, ash content and the ash melting point of a few agro-residues.

Most biomass on an ash-free basis has the same composition, and hence has nearly the same calorific value on ash-free basis. The calorific value of the whole biomass is in the range 13-16 MJ/kg. As can be seen, rice husk represents one extreme in terms of ash content. The choice of 10% moisture is because sun-dried biomass on storage attains approximately this level of moisture content. The ash melting point is influenced by the inorganic elements in the biomass coming from the growth process, needing the nutrients, all of which are drawn from the soil. If the ash fusion point is lower than 600°C or more than 1000°C, then the process of extraction of the residue from the reactor is straightforward. If however, the ash fusion point is between 600 and 1000°C, then the residue extraction process needs to be aided. The ash content decides how the oxidation and reduction processes are enhanced or retarded since the ash does not contribute to energy generation but takes away heat. In this sense, rice husk offers the greatest challenge since its ash content is very high (~20%).

The ash analysis of a few biomass fuels is presented in Table 3.

The major components are silica, alumina, iron oxide, magnesium oxide, and calcium oxide, apart from potassium and phosphorus oxides. Other elements are present in small quantities.

3. Elements of the gasification system

The various elements of the cyclone gasification system (shown in Figure 1) are the reactor, the feed system, the start-up system, the cooling system, the cleaning system, and a control system. An engine – compression or spark
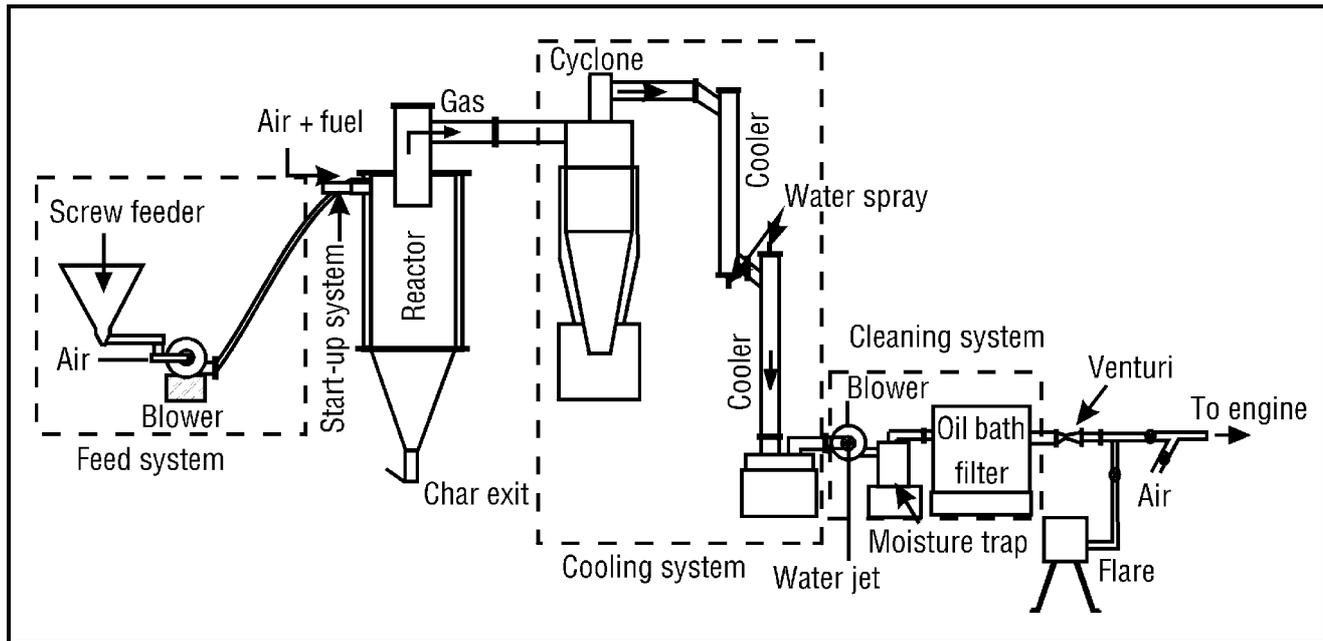
Figure 1. The powdery biomass gasifier and its subsystems

ignition kind – is required if the gas is to be used for generating mechanical or electrical power. We shall examine each of these now.

3.1. The reactor

Figure 2 shows the details of the reactor. It has tangential ports for introducing the pulverised fuel along with air, the air-to-fuel ratio being held sub-stoichiometric. For small gasifiers (of power levels ≤100 kW$_e$) one tangential feed port is satisfactory. At higher power levels it may be necessary to provide more ports. The reactor has an outer mild steel shell 3 to 6mm thick inside which is a 75 to 100 mm thick ceramic lining. This lining is built up of either rammed ceramic mass or lightweight refractory bricks. Typical qualification temperatures of these bricks are about 1000°C.

Normally the bottom of the reactor is open to the ambient atmosphere through a small exit duct as in a cyclone. In some instances, removal of the partly converted char or ash from the reactor bottom requires the assistance of a separate screw system.

The choice of the material for the central exit duct at the top is a critical element in the design. The choice is between ceramic-coated creep-resistant high temperature metal or high temperature light ceramic shell. The exit gas velocities are restricted to about 3 to 5m/s.

For a 100 kW$_e$ system the diameter of the reactor is about 0.5m, the height being 1.8m including the conical region. For a 4MW$_{th}$ (1MW$_e$) system, the diameter is about 2m and the height, including the conical region, is about 3.5m.

3.2. The feed system

Amongst the several methods tried, the one involving the combination of a screw feed and blower to convey it to the tangential entry of the cyclone has been found most suitable for power levels of 100 kW$_e$ and beyond. The problems of the screw feed are that the material loaded into the hopper will not feed itself into the section con-

Table 3. Composition of the ash of a few fuels

Ash constituent	Fuel		
	Sawdust	Sugarcane trash	Rice husk
SiO_2	49.0	65.3	86.1
CaO	22.3	8.2	3.5
Al_2O_3	7.6	7.3	0.58
Fe_2O_3	6.8	5.5	0.37
MgO	4.5	4.6	0.55
K_2O	3.3	5.4	1.7
P_2O_5	3.6	1.1	0.33
Na_2O	1.3	0.6	0.12
TiO_2	0.3	0.7	0.04
B_2O_3	0.4	0.4	0.72
N_2	0.8	0.8	0.1
ZnO	0.07	0.06	–
Chlorides	<0.001	<0.001	0.1

taining the screw because of the low bulk density and the wall friction allowing the material to remain stagnant even at large cross-sections of the order of 400 mm. For this reason, a separate mechanical agitator is mounted in the hopper to disturb the material near the wall of the hopper and impart a motion in the lower region so that the pulverised material is helped to move down. The system needs recalibration when fuels are changed since the bulk density of the fuel can vary widely – from 70 to 350 kg/m^3 – depending on the fuel. Another parameter which affects the design is the height difference between the feed system blower location and the tangential entry into the

Figure 2. The reactor

radiant type or externally convective cooling (with water) or a combination of both depending on the field conditions. This brings the temperature down to 200 to 250°C. The next step is to spray-cool the gas flowing in the duct. The cooling water flow rate required is about 60 l/min at a head of 30m. The cooling section is split into two parts, one with a spray upwards and the next with the spray downwards. The injector is of impinging type, so designed that the spray holes are large enough to let through dirty water (being recirculated), yet provide satisfactory atomisation. The water used for cooling heats up slowly and, therefore, there must be an external spray cooler system which brings back the temperature to near ambient conditions. About 100 m^3 of water would be adequate to run the system for 15 to 20 hours continuously without an active water cooling system. An external spray tower is called for if the availability of water is restricted.

3.5. The cleaning system

The direct cooling system is itself a major part of the cleaning system. About 80% of the coarser particulate matter and some tar compounds are taken away by the water due to close contact with the gas. This is the reason for arranging both counter-current and co-current spray. However, producing engine-consistent quality gas calls for further treatment of the gas stream. An advanced version of this section is a blower-based cleaning system. In the suction region of the blower, a jet of cooling water is directed to the hub of the rotor. The jet gets finely atomised and the water droplets agglomerate with the particulate matter. Due to the high rotational speed, the dirty mist hits the wall and flows out into another cyclone which separates gas from the dirty water and delivers it to a final sand-bed filter. The sand-bed filter consists of a 90 mm thick bed of sand particles of size 1-2 mm. An area of $2m^2$ is sufficient for a 100 kW_e system with the pressure drop across the sand-bed filter less than 20 mm water gauge. The cleaning system reduces the dust and tar content to less than 50 ppm each.

Typical operational time before the lapse of which the sand-bed filter is to be cleaned is about 250 hours. However, operation in off-design conditions and at fuel-richer mixture ratios compared to the design value can necessitate the maintenance of this system at intervals of less than 100 hours.

3.6. The control system

The control system is designed to take care of the total (fuel + air) feed rate as well as the air-to-fuel ratio. It is different from the control system needs of a wood gasifier [Mukunda et al., 1994] where it is sufficient to control the gas flow rate. This is because the fuel feed is self-controlled in the case of the wood gasifier. The dual control in the case of the pulverised fuel gasifier is managed by controlling the overall gas flow rate out of the reactor by a control valve on the pipe line and the pulverised fuel feed rate by controlling the speed of the screw conveyor. It must be ensured that the gasifier system operates close to the nominal mixture ratio. If the mixture becomes too rich, the temperature in the reactor will fall, leading to excessive tar level in the gas, and if the mixture becomes

cyclone. The blower capacity in terms of pressure head should account for the above height difference and the air should have enough velocity (above the settling velocity of the particles in air) so that the pulverised material can be carried into the reactor.

3.3. The start-up system

The start-up system involves heating up the reactor walls to about 600°C and beyond this temperature, self-sustained operation of the gasifier is possible. After many trials a system was developed in which the biomass being gasified is burnt with the assistance of a fossil fuel burner during the initial heating-up period. This is described in more detail in Section 4.

3.4. The cooling system

For a 100 kW_e system, the gas at the exit of the reactor has a thermal power of about 325 kW and a temperature of 750 to 800°C. This gas must be cooled to within about 5°C of the ambient temperature so that there will be no condensation of moisture along the ducting taking the gas to the engine. The cooling load is about 45 kW. This cooling is achieved through a combination of indirect and direct type cooling. The indirect cooling is essentially

Figure 3. Gasifier configuration for thermal application – version used for tea drying

too lean the gas calorific value will decrease. Load management during engine operation can be conveniently handled by bypassing the gas not immediately required by the engine into a flare or a thermal system designed to use the waste heat from the engine exhaust.

3.7. The engine-alternator system

The power package is unaltered except in the air intake region. This is modified to accept the gas-air mixture. The intake manifold of the engine is connected to a box, which houses the air filters, and to which is connected the pipe carrying the gas-air mixture. The fuel gas and air are mixed upstream of the box and separate valves are provided on the air and gas lines to control the fuel-air ratio. A bypass for the gas to a separate burner is also provided to check the quality of the gas before the gas is ingested into the engine and to act as a ballast in case of sudden load reduction in the engine. The air filters act as the final security cleaning device before the gas enters the engine cylinder.

3.8. Variants of the system for thermal applications

The cooling and cleaning systems discussed in the earlier sections are essential only for using the gas in internal combustion engines. For generation of heat – high grade at 1000-1300°C for metal melting applications, medium grade at >600°C for generating steam for power generation applications, or low grade at >300°C for generating process steam – it is not necessary to cool, and in some cases to clean, the gas. In some applications, such as drying tea or other food materials, it is essential that the combustion products be clean if they come in direct contact with the material being dried. The direct-contact drying is desirable because of the highly enhanced efficiency of the process over the indirect contact process. To meet the different applications, two variants of the gasification system are suggested. Figure 3 shows the variant that is

meant for drier applications. The feed system with a blower to handle the pulverised fuel and the reactor are similar to the elements described earlier. The hot gas at the exit of the cyclone passes through another cyclone to eliminate as much fine dust as possible. This reduces the dust loading from about 4-6 g/m^3 to 1-2 g/m^3. The direct cooling system is eliminated; but a water-injected blower is used to remove fine dust escaping the cleaning cyclone. After burning the gas in the burner, the temperature is brought down to the gas temperature required at the drier by diluting with excess air in the mixing chamber. Additional heat recovery is possible by taking the dilution air through an annular passage around the gas duct.

The water-injected blower can be eliminated in the case of thermal applications that do not call for very clean gas, such as for raising steam or for metal melting.

4. The reactor design

The reactor must be designed so as to complete the oxidation reactions of biomass with air and reduction reactions of the char with the products of combustion, namely, carbon dioxide and water vapour. Experiments to determine flaming and char combustion times have been conducted on rice husk and wood and the results are given in Table 4.

Single particle combustion with rice husk has flaming times of about 3-4s and char burning time of 40-65s. For a group of particles put together randomly, the flaming and char conversion times are 6-8s and 150s respectively. Conversion in a hot atmosphere of the products of combustion is very slow and did not seem complete at all. These results suggested the need to pulverise the husk. Pulverised particles at sizes of about 1mm showed flaming time of 2-3s and char conversion times of about 30-40s depending on the arrangement and access to oxygen.

Table 4. Flaming and char glowing times of rice husk

Material	T, K	Flaming time, s	Glowing time, s
Whole husk	973	3.5-4	40-65
Half husk, width 2mm	973	2-3	32-45
Quarter husk, width 1mm	973	2-3	30-40
A group of 75 whole husks randomly arranged	973	6-8	152
A group of pieces of wood char similar in size to husk	973	–	55
Whole husk char with hot product gases of combustion	1300	–	> 600

The experiments in a hot environment of products of combustion showed again inordinately long times for the conversion of the char. These led to the conclusion that it may not be possible to get complete conversion of the biomass, more specifically of rice husk, in a single reactor. Partly converted char would have to be accepted. Experiments in a small cyclone gasifier suggested that if too large a residence time was allowed agglomeration of the hot char particles would result in unwanted collection of the hot char inside the reactor, leading to stoppage of the reactor functioning. Pulverising was found essential because full- or half-husk feed showed that the heat release was restricted to a small region, hence the wall temperature was not uniform in the circumferential direction, and the gas quality was uneven. Use of pulverised husk (0.5 mm or less) showed good gasification features with consistent and acceptable quality gas; however, performance with regard to tar generation was somewhat erratic. On some occasions there was little tar in the cooling/cleaning train even after an hour of run; on others, there was an unacceptable amount of tar in less than an hour's run. Attempts to eliminate tar by using a hot wood char bed with the possibility of raising the local temperature by allowing the leakage of a small amount of air into the system showed positive performance, though no detailed measurements were made. At this stage it was decided to scale up to the 100 kW$_e$ level since the cost of the feed system alone ruled out acceptance of the low-power level system on economic considerations.

The design of the cyclone reactor was based on the high-efficiency cyclone separator [Perry and Chilton, 1973]. The gas flow rate required to run a 100 kVA diesel engine in dual-fuel mode at a diesel replacement of 75% is about 55 g/s. Taking a gas residence time of about 2s, the dimensions of the cyclone were 0.5m diameter, 1.1m long cylindrical section, and 0.65m long bottom conical section ending in a 50 mm diameter pipe at the bottom for the extraction of the residue (see Figure 1). The cylindrical portion of the reactor wall was made of 6mm thick mild steel and had an inner diameter of 0.62m. The inside of this shell was lined with insulating firebricks (750 kg/m^3 density) to a thickness of 30 mm; inside this was provided another layer of high temperature abrasion-resistant ceramic of thickness 30 mm. The inner layer was made up of rammed mass of "Whyteheat K" manufactured by the Associated Cement Companies (ACC) and had a density of 2200 kg/m^3. This configuration is one of the several variants that could be successfully used for the reactor lining. The top plate was also handled similarly with only the rammed mass.

For starting the reactor, the walls have to be heated to more than 600°C. With a small gasifier and during early trials with a 100 kW gasifier, a biomass stove delivering a thermal power of 35 kW was used to heat the reactor [Mukunda et al., 1993, Mukunda et al., 1988]. This was satisfactory for heating the unlined reactor used during early experiments. During this phase the reactor was made of AISI 304 stainless steel with outer alumino-silicate insulation. With ceramic-lined reactors, the power of such stoves was insufficient and a diesel/kerosene-fired burner of 60-100 kW was designed and used for starting. The burner uses an air-blast atomiser with a swirl combustion chamber. With this burner the reactor walls can be heated to about 600°C in about 45 min. However, the transition from ignition to steady operation of the gasifier was not smooth and it was felt desirable to reduce the diesel/kerosene used for start-up. Hence, further modification was made to the reactor by placing the burner close to the fuel-air entry port, as shown in the plan view of the reactor in Figure 2. With this arrangement the flame from the burner impinges on the biomass-air mixture, igniting the biomass. The biomass feed can start within 5 min of igniting the burner. The power required from the kerosene burner is only about one-tenth of the gasifier power and the gasifier can be brought to steady operating conditions within 15-20 min of starting the kerosene burner.

5. Test experience and performance

The test experience of running the gasifier with several elements altered during the development for testing new ideas has been extensive. Not only has the experience gained helped to determine the good performance of the system, but experience has also been gained to determine aspects causing poor performance of the system.

About five hundred hours of testing has been completed in the last four years in which several hundred hours were short duration tests involving measurements on part or whole of the system to understand the behaviour of the components. The long duration tests, where significant measurements have been made, total about 60 hours with most useful data being obtained in about 40 hours of test duration exclusive of the heating period. While most of the results obtained were on pulverised rice husk, some data on sawdust and some very limited experience on pulverised sugarcane trash have also been acquired.

5.1. Experience on rice husk

5.1.1. Effect of particle size

One of the important questions to ask is whether size reduction of rice husk is necessary at all. Some data on the burn-time of full and powdered rice husk were given in Section 4. Initial experiments showed that rice husk, available either in full form or half-piece form (obtained depending on the system adopted for the separation of the

grain from the husk), was inadequate for the purpose of gasification as it was found that the gas quality was not consistent and at times even pyrolysis reactions were incomplete. Pulverising was found unavoidable and further experiments with controlled particle size distribution were conducted to determine the maximum acceptable particle size for satisfactory gasification. The fineness of the powder obtained is controlled by selecting the mesh attached to the pulveriser through which the powder comes out of the pulveriser.

A series of experiments were conducted using the husk pulverised through different mesh sizes, 1.8, 2.0, 2.2 and 2.5 mm, and the resulting particle size distribution determined by sieve analysis. Figure 4 shows the particle size distribution of the different powders. Experiments on gasification were performed with each of the samples in otherwise similar conditions for durations of one to one and a half hours. The wall temperature history at various locations in the reactor from each of the experiments is presented in Figure 5. There is hardly any change in reactor wall temperatures between the two cases using powders obtained with 1.8 mm and 2mm size mesh. But when the powder produced with 2.2 mm mesh is used, the reactor wall temperatures become lower by 100 to 150°C at all locations. However, there is no significant variation in the exit gas temperature from the reactor among the various cases. Char residue coming out in the first two cases (1.8 and 2mm mesh) was red hot, while that in the third case (2.2 mm mesh) was black and smoky. Hence for the third case there does not seem to be enough residence time for the pyrolysis and char conversion reactions to complete. From this it appears that the husk must be pulverised through at least 2mm mesh. Pulverising to finer sizes does not seem to give any significant advantage though additional energy is required for pulverising. The amount of husk pulverised per kWh of energy is 16 kg for 2mm mesh and 14 kg for 1.8 mm mesh.

5.1.2. Engine operation and gasification mixture ratio
Experiments with operating the diesel engine in dual-fuel mode were performed after first operating the gasifier in burner mode to check on the quality of the gas. On the basis of the quality of the flame in the burner, it was known that at air-to-fuel ratios in excess of 1.3, the gas quality was poor. Around 1.17 ± 0.02 the gas quality was reasonable, with the measurements of the calorific value showing 4.7 ± 0.2 MJ/m^3. If the gas was led into the engine at this stage, the best diesel replacement obtained at, say, 70 kW$_e$ load would be around 40%. The operating air-to-fuel ratio was to be brought to 0.97 ± 0.02 in order that the diesel replacement would increase to levels above 70%. At this point the measured diesel replacement was $83 \pm 2\%$ at a load of 50 kW$_e$ and $77 \pm 2\%$ at 60 kW$_e$. The change in air-to-fuel ratio for better operation on the engine even though the calorific value would perhaps not be too different is argued to be due to the nature of the gas composition. Slightly fuel-rich operation of the gasifier would lead to gas with a larger hydrogen content, thus improving the combustion efficiency. This explanation is tentative and needs to be reinforced by more care-
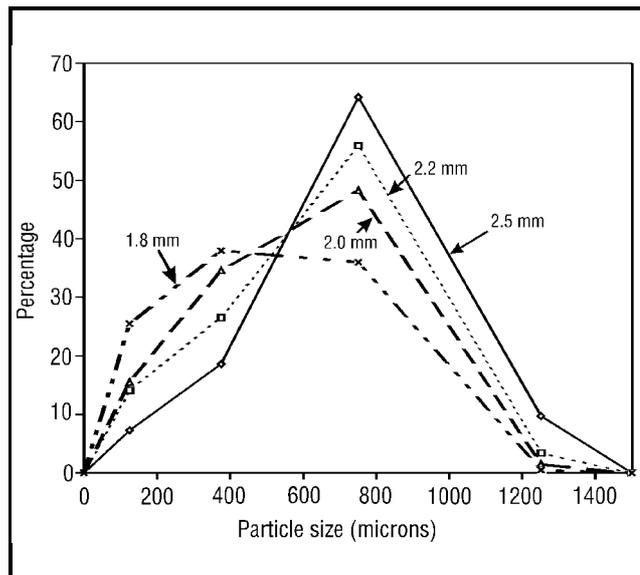
Figure 4. Particle size distribution of rice husk obtained by using different mesh sizes in the pulveriser.

ful measurements of the gas composition.

The worrisome point about the slightly richer condition for gasifier operation is the higher amount of tar in the gas. Though the clean-up system would be able to take care of the load, the increased maintenance of the clean-up system itself would be an additional bother. The reason for the higher tar load (typically 1000 mg/m^3) is possibly due to the weak contact between the tar-laden gas and the hot char. Taking the gas through the red hot char bed in a circulating fluid bed reactor is expected to increase the contact and time of contact as well, and hopefully bring the tar to a level comparable to that for wood gasifiers [Mukunda et al., 1993, Mukunda et al., 1994].

5.2. Operation with other fuels -- sawdust and sugarcane trash
Operation with sawdust was found straightforward, with, again, good gas composition (leading to diesel replacement in excess of 80% at loads of 60-65 kW$_e$) at air-to-fuel ratio of 1.5 ± 0.02. Problems of tar were much less in this case than in the case of rice husk.

Limited operation with sugarcane trash pulverised to 5mm mesh size showed that the operation is straightforward, with no serious problems of tar generation. There were two major problems with sugarcane trash. One of them was that the ash softening of sugarcane trash occurred in the range 700-900°C and the char agglomerated and obstructed free movement of ash from the reactor. Another problem was related to feeding. Because of low density and fibrous structure there was a tendency for the powder to bridge inside the feed hopper. Providing a mechanical agitator in the feed hopper more or less resolved this problem. Further, the rate of pulverisation that could be achieved was one-fourth that of rice husk in the same pulveriser (60 kg/hr of sugarcane trash instead of 200 kg/hr of rice husk in a pulveriser powered by an 11 kW motor). Further experiments are planned to check if merely trimming the leaves to small size would be sufficient for satisfactory operation of the gasifier.
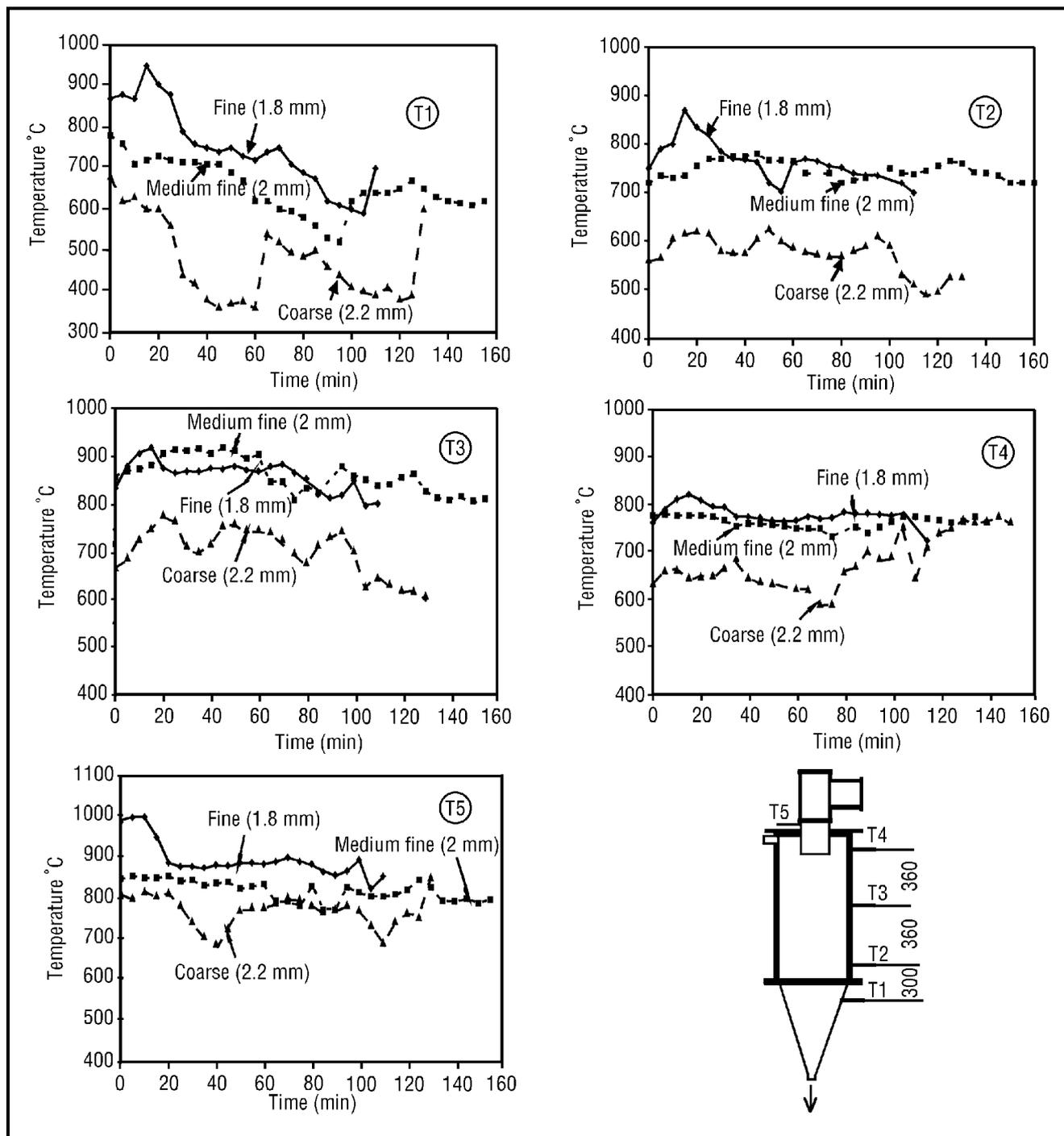
Figure 5. Variation of wall temperatures at different locations in the reactor with time when powders obtained with different meshes in the pulveriser are used.

5.3. Particulates and tar (P+T) in the gas

Measurements of these were taken for rice husk with iso-kinetic sampling procedures perfected on the wood gasi-fier for the Indo-Swiss test [Mukunda et al., 1994] at the cold end after the sand-bed filter. These measurements showed the level of particulates and tar (P+T) to be less than 120 mg/m^3. The amount of P+T was equally distrib-uted as subsequent analysis showed. Most of the P+T was otherwise trapped in the blower and the cyclone after the blower. It could be removed after dismantling the system elements. The amount of P+T so collected varied between 2000 and 4000 mg/m^3. The fine dust behaved not too dif-ferently from tar and chemical treatment was necessary to separate the two. Such a separation led to about 30 to 35% tar in the lumps of P+T recovered from the system. These levels of tar are not easy to handle and therefore a separate thermochemical system involving a circulating bed system is currently under study. Limited observations have shown that neither sugarcane trash nor sawdust pro-duced such amounts of tar. These are to be subjects of more careful study.

5.4. Engine operation and exhaust gas composition

Measurements of engine exhaust for O_2, CO_2, and NO_x were made. Figure 6 shows the oxygen fraction and tem-
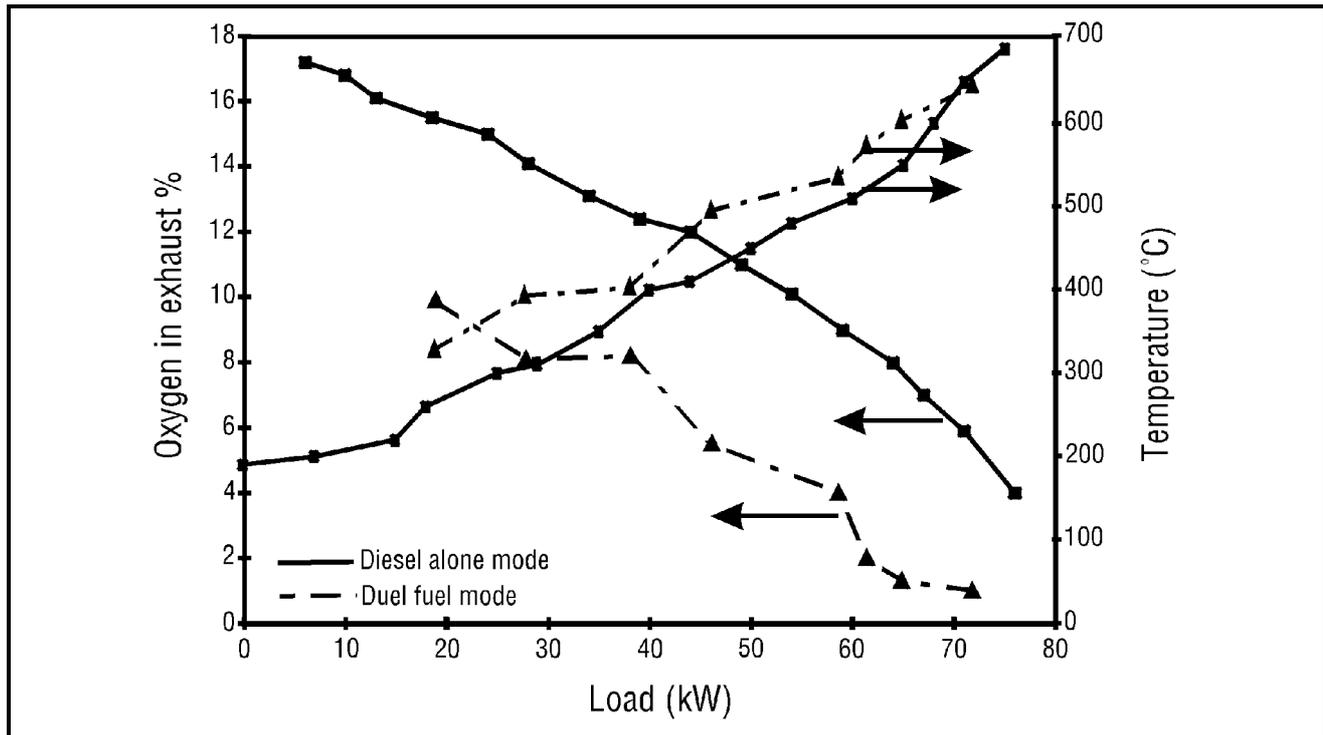
Figure 6. Oxygen level and temperature at the engine exhaust in diesel and dual-fuel mode of operation.

perature in the exhaust with load in kW_e for both diesel-alone and dual-fuel mode. It can be seen that the oxygen fraction drops to about 4% at 75 kW_e for diesel-alone mode and to 1% at 72 kW_e for dual-fuel mode. Increase in load beyond this value would lead to excessive smoking in the exhaust and stalling in the case of dual-fuel mode. Therefore 80 kW_e is the maximum deliverable load at Bangalore (1km altitude) in diesel-alone mode and 72 kW_e is the peak delivered load in the dual-fuel mode for an engine rated at 96 kW_e. Thus there is 10% derating of the engine in the dual-fuel mode. This is a factor related to the availability of excess air at nominal load. Thus, engines designed for dual-fuel operation may need to allow for excess air to eliminate the derating. The consumption of husk per kWh of electricity generated is about 1.5 kg and the cold gas efficiency of the gasifier is 70%. The cold gas efficiency is better than the value of 61% reported for Chinese gasifiers [Anon, 1985].

A very important and interesting discovery was made at this point. It was found that maximum diesel replacement always implied low concentration of O_2 in the exhaust gas – about 1.5 to 2%. Any attempt at trying to increase the diesel replacement by reducing the air flow rate and increasing (simultaneously) the gas flow rate caused the engine to stall, implying that the energy input through the (gas + diesel + air) would not be adequate to take up the load. It is now planned that every diesel engine working in dual-fuel mode should have an exhaust oxygen monitor as a part of the control system arrangement. This plan includes those engines working on wood gasifiers.

The measured values of NO_x are shown for both diesel-alone mode and dual-fuel mode in Figure 7. It can be clearly seen that the NO_x level is much lower – by a

factor of five or so. This is due to the lower temperatures of combustion occurring in the engine in dual-fuel mode. Thus, gasifier-based power generation devices are environmentally more benign.

6. Cyclone system vs. fluidised bed system

The question that needs some consideration is the choice between the cyclone and fluidised bed systems because the circulating fluidised bed system has been more extensively used in Western technologies and the cyclone system has not been tested as much. In the case of the simple fluidised bed system, the range of flow rates over which the system can be operated is limited by the range, which is narrow, of velocities for fluidisation. Thus if the system works at all it would be at a fixed power. Designs involving changes in the cross-section over which the flow occurs are complex and have been adopted in a limited sense for combustion applications which are more benign than gasification. Hence, the use of simple fluidised bed systems may be taken to be a poor alternative. Circulating fluidised bed systems offer an alternative to account for varying power levels. The residence time of the gas in these systems is low and there are therefore serious problems of tar in the gas. These systems are designed for larger proportions of tar in the gas as a rule (reported tar levels go up to 10 to 15 g/m^3). Consequently, they have a separate tar cracking system; the most extensive studies conducted use dolomite [Waldheim, 1993] as the tar cracking medium. One of the major issues is the fluid and particle paths through a reactor in a fluid bed system; the beginning and end paths are not clear. It is entirely possible that a new particle may enter the exhaust stream and therefore contribute to tar more significantly. A cyclone assures a well-demarcated path with a beginning and an
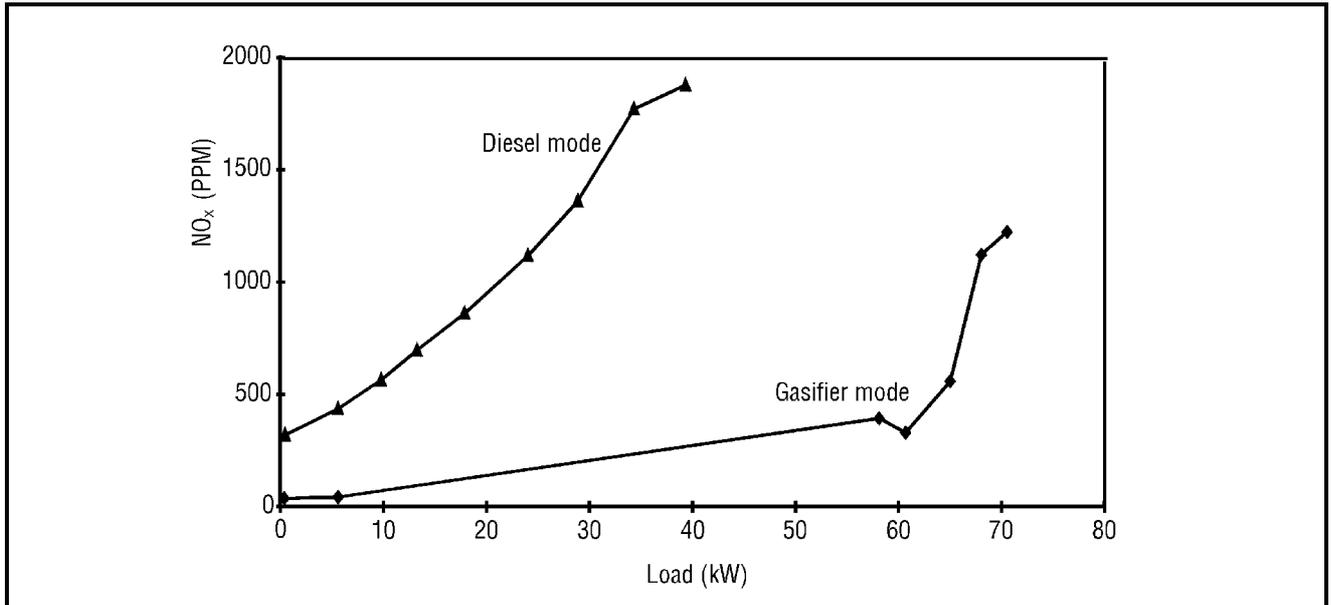
Figure 7. NO$_x$ levels in the engine exhaust in diesel and dual-fuel mode.

end and therefore mixing of the reacting solid fuel at different levels of conversion is unlikely, and consequently one can expect the tar level to be controlled. The problem with a cyclone reactor is that the contact between the gas and the char is not as great as one would expect in a fixed bed gasifier. This leads to higher level of tar in a cyclone reactor than in a fixed bed gasifier. Strategies to handle this have been outlined earlier.

7. Overview and final remarks

This paper has discussed the basic and technological aspects of pulverised fuel gasifiers for agricultural residues. The basic design is conceived to accommodate various fuels with different densities and ash content. Most questions of technology are addressed in this paper. For thermal applications and electricity generation applications where water for cooling and cleaning is abundant, the problem of gas-cleaning is indeed handled relatively easily, by discharging into the drain/field at standard pollution limits without causing additional loading on the system. However, if there is a limited amount of water that has to be recycled, then it will be necessary to improve the water quality by reducing the particulates and tar in the gas, particularly for a rice husk-based system.

Two new features on which progress has been made are in the data on exhaust gas. The first refers to the fact that at optimum diesel replacement, the oxygen content in the exhaust goes to very low values – 1.5 to 2%. This fact can be used as a control element. This feature is perhaps valid even for gas engines. The oxygen content in

the exhaust can be used to optimise the performance of gas engines.

The second feature is the amount of NO$_x$ in the exhaust. It is shown that dual-fuel operation in comparison to diesel-alone operation reduces the NO$_x$ content to less than one-fifth. This is due to the lower peak flame temperatures with producer gas combustion when compared to diesel-alone operation. This is a very important feature for today's environmentally conscious world. ∎

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