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# Final report on the project “Powdery Biomass Gasifier”

## Extended Abstract

This report provides a description of the scientific and technological effort that has gone into the development of pulverisable bioresidues largely of agricultural origin over the period 1990 to 1998 at the Combustion, Gasification and Propulsion Laboratory (CGPL), Department of Aerospace Engineering, Indian Institute of Science. This period of research and development has been marked by support from MNES in two major segments – Phases I and II between 1990 to 1995 and another segment between 1995 to 1998. Even though a report has already been issued about the work completed between 1990 to 1995 and this report should constitute the report of the work between 1995 to 1998, for the sake of better understanding and completeness, this report includes the work completed under this project during the entire period; however, the work completed during 1995-1998 is also specifically identified.

The work started with the realization that agro-residue based gasifiers for power generation should be capable of accepting a range of agro-residues as these are seasonal and for the operation to be economical, it is important that the same gasifier should accept a multiple of fuels. One way of eliminating the differences in the physical structure of the fuels – like ground nut shell, sugarcane tops and leaves having entirely different shapes, is to pulverize them to nearly same sized particles. Other differences in terms of ash content and therefore, the air-to-fuel ratio for operation in gasification mode would be expected to be a part of the design allowing for its variation. Based on the experiments made on open top downdraft gasifiers up to 1986 with pelleted pulverized agro-fuels, it had been concluded that *this route was beset with problems*. The reasons were as follows: Pelletization involved the use of a binder like mollases. At nominal power, the presence of inorganic compounds led to the reduction of the melting point of the ash and this led to ash fusion into large inorganic masses preventing the flow of material subsequently. Briquetted fuels were not generally available due to lack of good machines, and those briquetted fuels that were available were of such poor quality that they would flake into thin pieces. This led to excessive pressure drop through the reactor of the gasifier and therefore a restriction on the flow rate and therefore its power. Due to these considerations, it was thought that it would be better to work with pulverized bio-residue directly instead of pelletizing or briquetting.

Based on fundamental considerations with only marginal indications of support from literature, cyclone configuration was chosen to perform the gasification process. The principal features in support of this thinking were that this would be a very neat way of bringing together the pulverized fuel and oxidizer, namely ambient air into intimate contact to allow reactions to take place. Further, some fine char particles in fine suspension could also participate in reduction reactions and permit higher conversion. The large velocities involved in the tangential direction would ensure better heat and mass transfer processes. The system also helps in the extraction of ash/fine char residue in a natural way as was observed from preliminary experiments. One of the deficiencies is that the flow inside the system is complex particularly in the hot condition making it difficult to understand the two-phase reactive processes inside. Before taking up systematic development, several conceptual studies were performed with variants of cyclone and a few others to determine if any one of these systems

offered comparatively greater simplicity in terms of operation. Following this, cyclone systems with ambient pressure operation and positive pneumatic feed were chosen for development. Systematic developmental studies from 25 kWth through 100 kWth to 1 MWth were conducted to establish the successful operational regime as well as to determine the problems with off-nominal conditions of operation. The system elements like feed, ash discharge and start up systems were to be experimented with as these depended in part on the available systems from market. The extraordinarily low density of 60 kg/m$^3$ for pulverized sugarcane trash posed severe material movement problems in the hopper and were overcome with considerable effort. If the system had to accept pulverized rice husk as well (with a density of 350 kg/m$^3$), the design had to account for a density range of a factor of 6 and this was resolved through the use of appropriate gearing system. The final system with a wide hopper, a device to move the material down, a screw conveyer and an appropriate dump into the suction of a blower transporting the air-fuel mixture to be blown into the reactor through a tangential slot *partially open* to the atmosphere was chosen. The start-up system tried out was a pulverized fuel stove (based on sawdust) as follows: the stove was set to one tangential slot, lit and allowed to function. The entry slot was sealed after the inner wall of the cyclone reactor had attained a minimum temperature of 800 K. Transition into normal operation was performed by injecting pulverized fuel from leaner condition quickly to fuel rich conditions valid for gasification. Subsequently, it was decided to change the start-up system to liquid fuel burner of appropriate power level (100 kWth – about 10 kg/hr of petroleum fuel). This was accepted as a more realistic alternative.

Several developments took place on the cooling and cleaning system. The higher load of particulate and tar (P & T) compared to open top downdraft reburn gasifiers for woody bioresidues under development at the laboratory was thought to be combated by using water injection into the blower which provides the suction needed to operate the whole system. This was shown to work very well through the measurement of particulates and tar at the exit of the sand bed filter. During this period a lot of parallel development on solid bioresidue gasifier was taking place and both these developments took benefits from each other. It was around September, 1994 at the time Bioresources' 94 conferences took place at Bangalore, that the developments on 100 kVA electric gasifier were demonstrated on the electrical mode with explicit measurements of load, diesel replacement, particulates and tar at the exit of the gasification system. Subsequently, the developments concentrated on large thermal systems using sawdust, pulverized rice husk and sugarcane trash, mango stone dust and the like. A 525 kWth combustor concept based on an inclined cyclone was tried out. The reason for this is as follows. The original design was a vertical cyclone with facility for char/ash removal at the bottom. This system is 2 m tall. The feed system which is based on blower was needed to be designed to carry the particulate matter in a pneumatic dense phase transport mode since the air to fuel ratio is on the rich side. It was thought if the choice of an inclined cyclone was made and the height of the entry was made at a lower height, it would help reducing the problems of feeding. Experimental studies and operational experiences over a fifty hour period showed that inclined cyclone would not be very appropriate and it would be far more convenient to operate a vertical cyclone, more particularly, due to unfavorable distribution of pressure inside the reactor causing problems of char extraction from the reactor.

The design was then altered back to vertical cyclone and the system was put together with appropriate feed system modifications. This essentially consisted of a blower with a higher pressure rise (500 mm instead of 300 mm water gauge). The system was run at 1.5 MWth using sawdust and later at 1.2 MWth with pulverized rice husk for as long as several hours and stable operation was established. The configuration used an ejector to enable drawing gases through the system. This is in addition to the air-fuel mixture pumped through the reactor. To ensure that gases which are combusted in a burner later have a much reduced content of potassium and sodium salts, the gas is cooled in another cyclone so that particulate matter is captured in this cyclone.

Throughout the development cycle, two aspects of concern were being debated. First, whether the particulate and tar level generated at the hot end would permit an acceptable cooling and cleaning system. It is entirely true to say that systems developed in this country on rice husk by others did not particularly concern themselves with these questions and went ahead with marketing these under MNES subsidy programs. Perhaps there was not even a test on P & T measurement in most systems for good documentation of the performance of these gasifiers even though the standard MNES specifications contain upper limits for P & T. Even though MNES specifications are on cold P & T, there are indirect indications of hot P & T through specifications on the minimum period required to be assured for maintenance of the cooling and cleaning train. Unfortunately, these aspects have not been technically adequately addressed till now.

The second point concerned the training required to run the system with advantage. This point was considered important because the bioresidue-to-energy environment for gasification systems was such that there were complaints about poor performance due to inadequate training even with woody biomass gasification systems which were much simpler to operate. It is quite another matter that even declared performance targets in some of the marketed gasification systems were such that diesel replacements were about 70 % even though systems with diesel replacements higher than 80 % were available.

These thoughts almost found an answer when tests were being conducted on grass and powdered waste from furniture industry (restholz) from Switzerland were to be tested for performance including P & T. The commitments led to the use of standard open top wood gasifier for tests on these bioresidues. The restholz was available in the form of large briquettes (100 mm dia.) but of poor integrity. It was decided to try these out directly. At 30 % of the nominal load, the system performed very well and the run made for a short duration with higher flow rates (about 50 % of the load) was very satisfactory. This gave impetus to pursuit of this approach further. Swiss grass was tried out directly in the gasifier after the material was chaff cut and pulverized. Even these experiments showed encouraging results. In fact, the problems normally expected with ash fusion in these residues with high ash content including the problematic salts of potassium with low ash fusion temperature were not faced. Perhaps, part of the answer was in the low fluxes used in the tests – about a third of the nominal flux. Nevertheless, this interesting feature was a sufficient incentive to pursue the idea of using the open top downdraft system for such light agro-residues. At this time the thesis of Dr. Kaupp entitled “gasification of rice hulls” actually published in 1972 came to the attention of the investigators. A careful study of this excellent piece of research contained many remarks several of these based on research of an earlier period of time supporting the persistent observations made during the experiments at CGPL. Briefly stated in the present context, for circumstances in which small particles sizes and heating rates are prevalent in the cyclone reactor, rapid pyrolysis is a natural consequence (particle sizes of 250 microns to a millimeter diameter and particle temperature rise rates of 400 to 1000 C / s). Rapid pyrolysis implies greater generation of tar (in fact liquid bio-fuel generation strategies are essentially based on this thought) or liquid components. For gasification processes, one must aim at enhancing gas output and reducing substantially the liquid components. Thus by using a cyclone gasifier, we may be, by design, causing greater generation of tar which is to be cracked subsequently. One can make a conceptual statement on the reactor behavior: we are creating a larger fraction of liquid components which are cracked in a suspended state in which high temperature and oxidative conditions in part and reducing reactions in part also are encouraged to reduce the high molecular compounds. Thus while the performance of the reactor as a tar reducing device may be good, the fact that small particle sizes are used leads to the creation of a larger amount of tar, a feature which is against the aims of a gasifier design.

The arguments made above show that cyclone reactor may not be the best device to generate tar free cold gas. It may not also be the best thermal system since pulverizing the fuel leads to a fair fraction of fine particles in the feed stock which will find their way out of the reactor as char/ash particles and therefore need a good cyclone to remove them. Perhaps it would be better to use solids of larger size so that the fraction of small particles will be low in the feed stock itself and thus help reduce the carry over of fine particulate matter. It is entirely possible that even here a cyclone may be needed to reduce particle carryover which may occur during operations like grate rotation or grate shaking performed once in a while to reduce the pressure drop through the reactor. It is these set of thoughts combined with the fact that briquetting agro-residues is an industry in itself, currently gaining prominence in the country (due to lack of firewood resources) that led to the motivation to use the standard solid bio-residue gasifier for light agro-residues as well. A further feature thought to make this strategy all the more viable is the fact that transportation of light agro-residues using petroleum fuels is expensive and enhancing the density near the source of these fuels helps in reducing the transportation costs (density increase can be as much as ten to twenty times the actual density). In fact, this feature in positively affecting the economy of fuel availability costs at the power station may be a strong driver to use briquetting approach in the financial packaging of power stations.

This report describes the experiments made at various stages, conclusions drawn therefrom and the logic for subsequent developments. It includes a few developments made subsequent to the closure of the project. A photographic coverage of the project is provided as an appendix to help appreciate the developments.

Difficult to understand the two-phase reactive processes inside. Before taking up systematic development, several conceptual studies were performed with variants of cyclone and a few others to determine if any one of these systems offered comparatively greater simplicity in terms of operation. Following this, cyclone systems with ambient pressure operation and positive pneumatic feed were chosen for development. Systematic developmental studies from 25 kWth through 100 kWth to 1 MWth were conducted to establish the successful operational regime as well as to determine the problems with off-nominal conditions of operation. The system elements like feed, ash discharge and start up systems were to be experimented with as these depended in part on the available systems from market. The extraordinarily low density of 60 kg/m$^3$ for pulverised sugarcane trash posed severe material movement problems in the hopper and were overcome with considerable effort. If the system had to accept pulverised rice husk as well (with a density of 350 kg/m$^3$), the design had to account for a density range of a factor of 6 and this was resolved through the use of appropriate gearing system. The final system with a wide hopper, a device to move the material down, a screw conveyer and an appropriate dump into the suction of a blower transporting the air-fuel mixture to be blown into the reactor through a tangential slot *partially open* to the atmosphere was chosen. The start-up system tried out was a pulverised fuel stove (based on sawdust) as follows: the stove was set to one tangential slot, lit and allowed to function. The entry slot was sealed after the inner wall of the cyclone reactor had attained a minimum temperature of 800 K. Transition into normal operation was performed by injecting pulverised fuel from leaner condition quickly to fuel rich conditions valid for gasification. Subsequently, it was decided to change the start-up system to liquid fuel burner of appropriate power level (100 kWth – about 10 kg/hr of petroleum fuel). This was accepted as a more realistic alternative.

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# Chapter 1

## Introduction

A careful consideration of the alternate energy sources in the form of bioresidues showed that the dependence of woody biomass alone should be reduced and alternate routes involving loose agro-residues should also be considered. The reason is both technical and political. Even though waste woody biomass was and is available in specific areas like coffee and tea plantations, distant localities covered with forest, where woody waste will slowly oxidise due to aerobic bacteria, and these material can be used profitably by thermochemical conversion, it is true that public perception is largely that woody biomass is unavailable. Hence, it was considered important that loose agroresidues like sawdust, rice husk, rice straw, bagasse, sugarcane trash, etc. should be considered as bioresources for power generation. It is with this objective that a project was sanctioned towards the scientific development of technologies towards power generation from these fuels. An assessment of the scientific work done outside India shows that very significant work was done and is being done on woody bioresidues but very little on agro-bioresidues. There are reasons for this. The amount of bioresidues from forest plantations is so large in USA and large parts of Europe that their first attention when considering power generation via bio-residues will be based on forest residues and agro-bioresidues will appear next. The next important point is that any conceptualisation of projects will be at a large level and immediate attention will be paid to combustion route. Such an effort in USA led to severe deposition problems inside the boiler that this approach was given less attention. This implies that it is far more important for India to develop the techniques of gasification keeping in mind the background the problems faced in other countries.

### 1.1 What does this report contain?

This report contains details of some basic studies and also developmental efforts involved in gasifying low density and high ash content agricultural residues discussed above. Details of basic study (1) conducted in understanding the combustion behaviour of agro residues like rice husk has been explained. This is followed by a detailed report of various stages evolved in realising the concept of cyclone gasifier. The later part deals with the experimental work carried out in gasifying various kinds of agro-residues with the end use involving generation of power. Based on the present study, the approach involving briquetting the fuels for use in gasification is discussed and results from tests are presented.

### 1.2 What are Pulverised fuels?

Fuels whose physical form is like leaves or flakes, or those that consist of very light thin walled material characterised by very low bulk densities can be treated by pulverising these fuels. Generally, an alternate treatment of randomly sized wastes with varying physical forms is by briquetting (2) which calls for size reduction to an acceptable level before briquetting is performed. Since the more widely understood treatment of wastes is by briquetting and it involves size reduction any way, it is suggested that this material can be handled by the present method without having to go through briquetting.

The materials that qualify for pulverised fuels are sawdust, a waste from wood industry; coconut coir pith, a waste from coconut coir industry; bagasse, a waste from sugar industry; wastes from herbal industries; and weeds like epotorium, parthenium which are otherwise considered useless. Others which can be pulverised are rice husk, peanut shells, rice straw, wheat straw, thin cotton stalk and sugar cane trash.

### 1.3 What about the availability of Agro residues?

India is a country with agriculture being the backbone of its economy. The total land covered under agriculture amounts to 170 million hectares. The agro residue from the agricultural practices forms a major share of the available biomass in the country. The amount of agroresidue from agricultural operations is presented in Figures 1.1a, b, c as a function of time.

Figure 1.1d shows the availability of rice husk and sugar cane trash in our country. It is seen that the total amounts to about 400 million tonnes per annum. Of these residues, some will qualify for woody bioresidue: Maize cobs, cotton stalk, coconut shell, and jute stalk. This amounts to about 5 %. Rest of the material is loose agro-residue capable of being pulverised easily. Many of these residues are used for fodder. Some are used for construction activities. It is estimated that about 25 to 30 % is used for combustion purposes. These agro residues are either being under utilised or inefficiently, leading to environment problems. Figure 1.2a, b, c, d show the current utilisation pattern of agro-residue in India. In the environmentally conscious recent times, ban on the traditional combustion of bioresidues is being implemented through legislative measures.

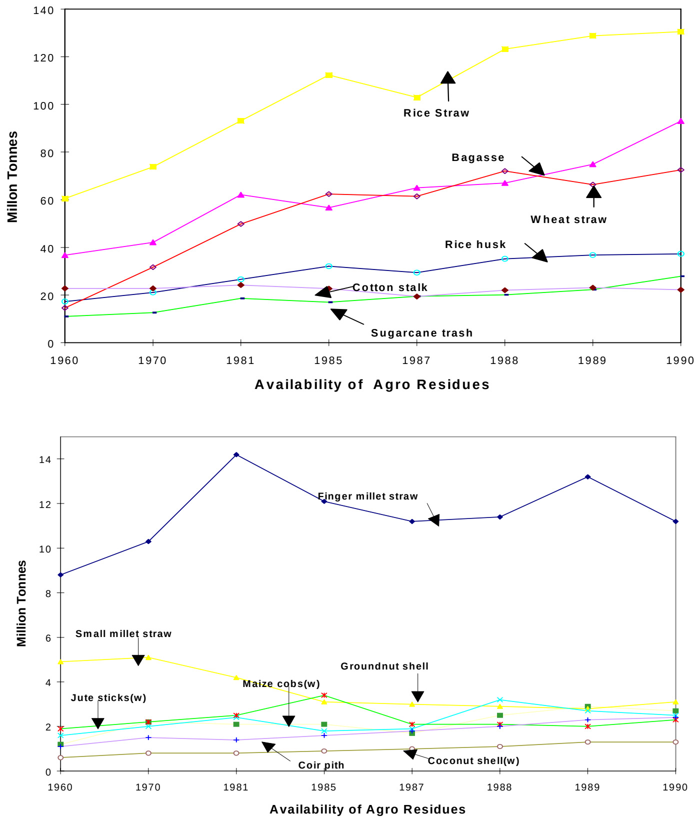

**Figure 1.1a,b,c  Availability of bioresidues from agricultural operations as a function of time**

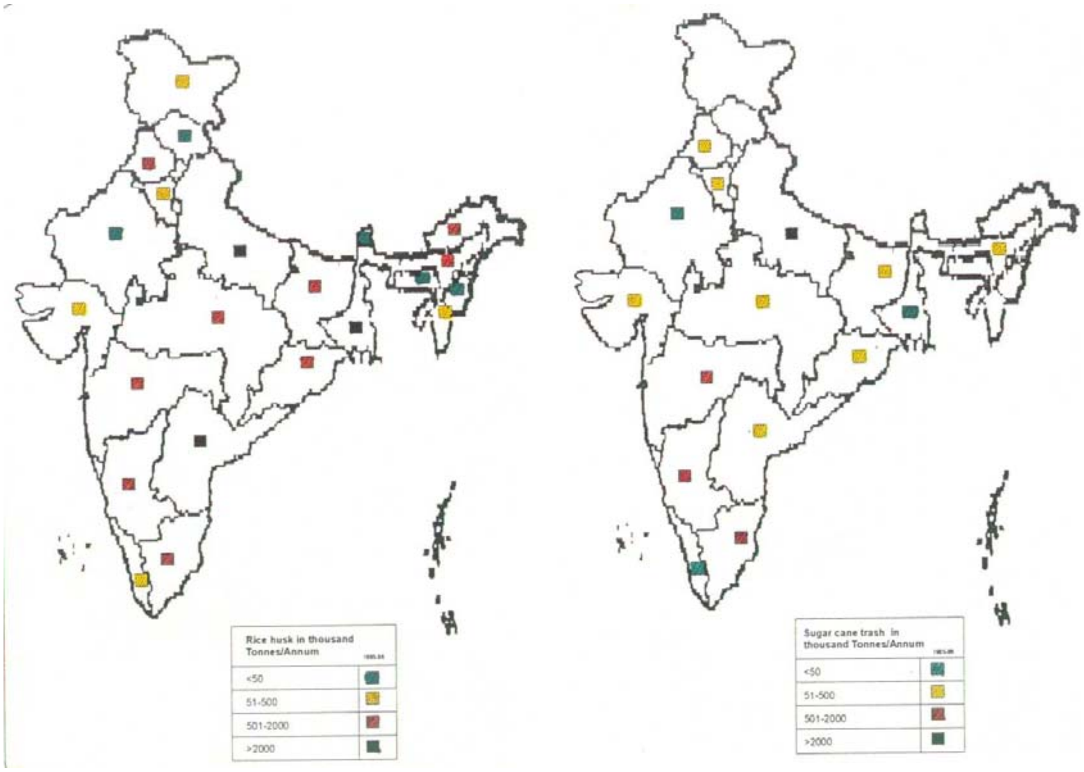

**Figure 1.1d Availabilitry of rice husk and sugar cane trash in India**

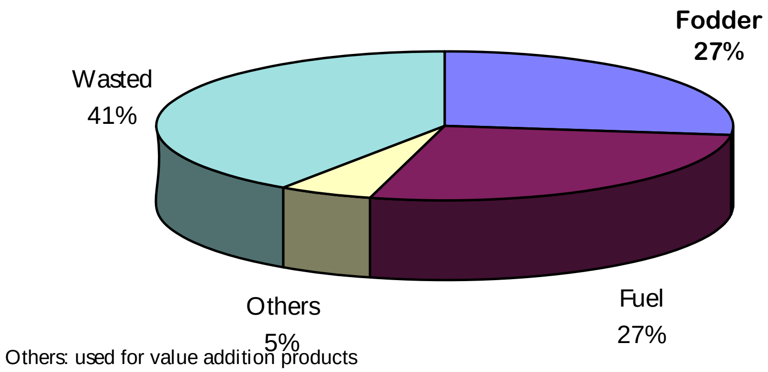

Figure 1.2a Current utilisation pattern of agro residue in India

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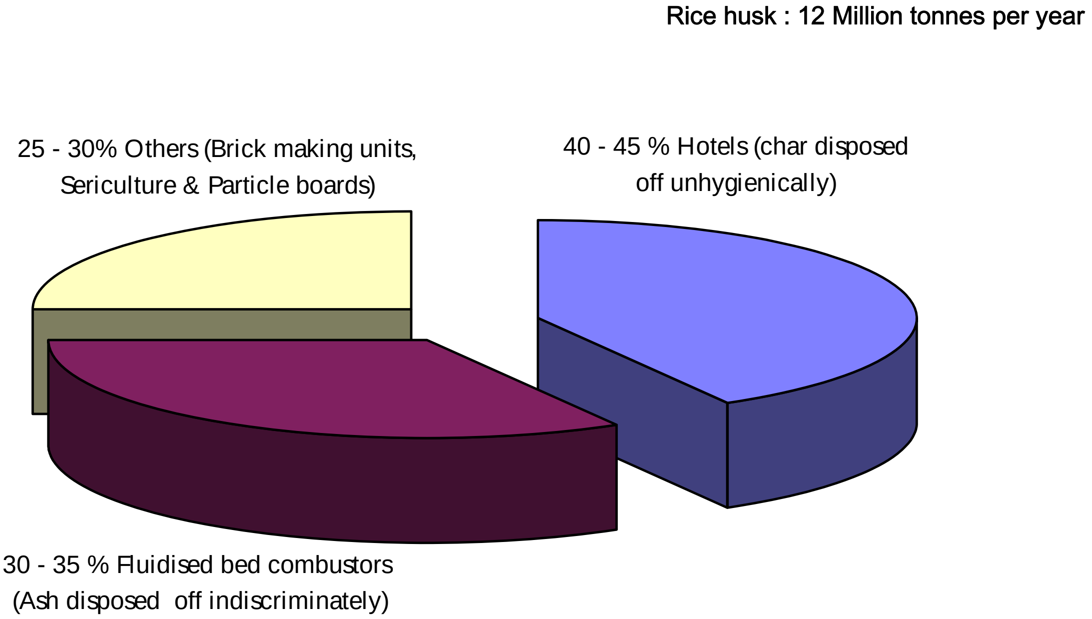

Figure 1.2b Current utilisation pattern of rice husk in India

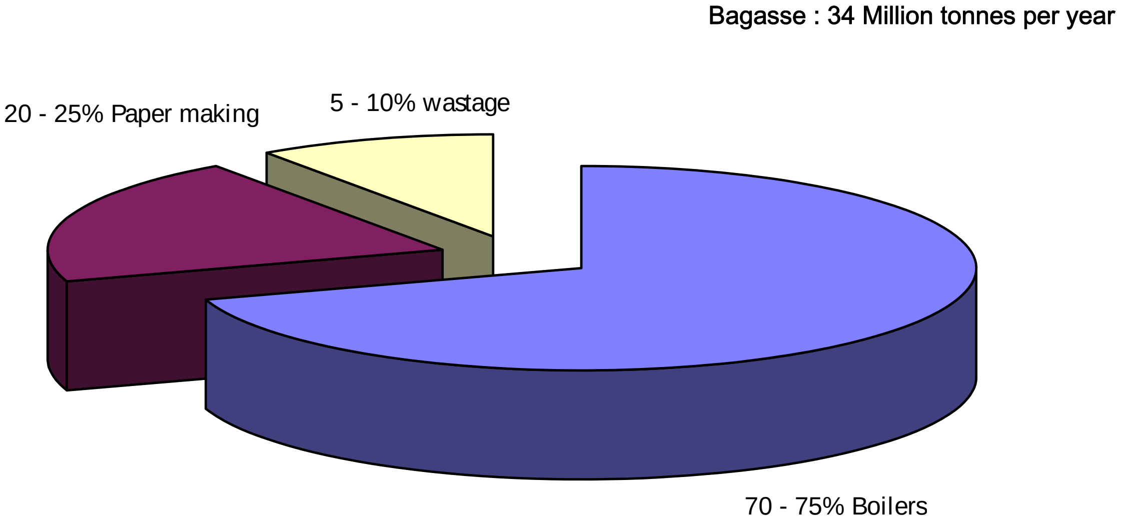

Figure 1.2c Current utilisation pattern of bagasse  in India

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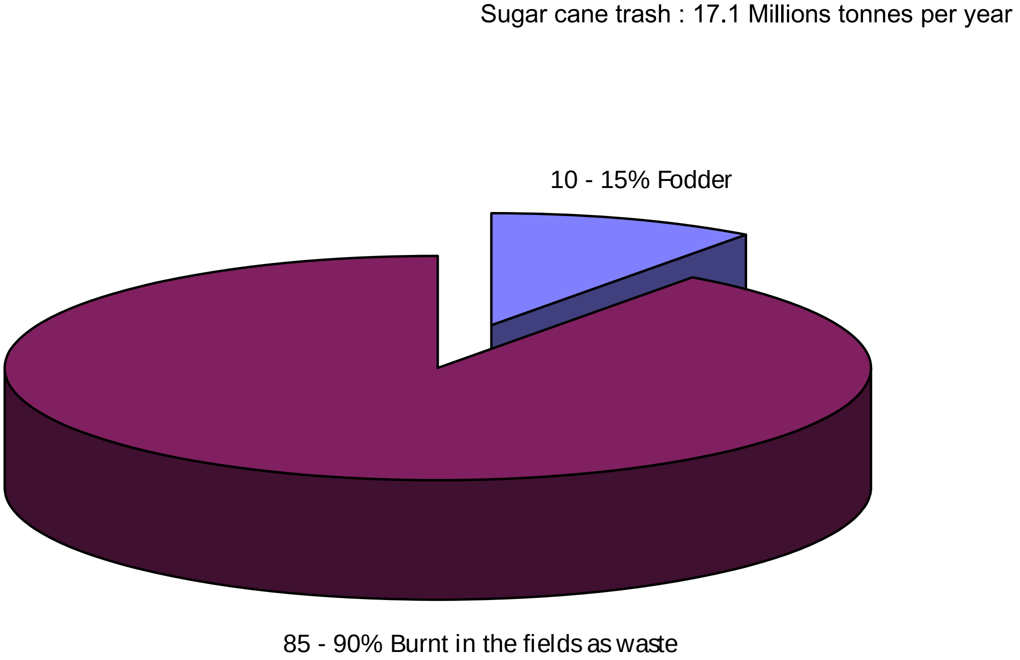


Fig. 1.2d Current utilisation pattern of sugar cane trash in India

Thus there is need to develop methods for utilising the bioresidues for better end use efficiency. The best efficiency possible appears when the solid fuel is converted into a gas so that high quality external combustion for thermal applications or internal combustion in reciprocating engines for power generation is possible. In order to do this one should understand and evaluate the important properties of these agro-residues.

### 1.4 Properties of agro residues

The first important property addressed is the bulk density. Table 1.1 shows the data on several fuels. As can be noticed, the bulk density of the fuels is small and also varies widely.

**Table 1.1 Bulk densities of common pulverisable fuels**

| **Fuel (Sun dry)** | **Bulk Density (kg/m$^3$)** |
|---|---|
| Sawdust (< 3 mm) | 300 - 350 |
| Rice husk | 100 - 130 |
| Rice husk pulverised (< 2mm) | 380 - 400 |
| Sugar Cane trash (chaff cut) | 50 - 60 |
| Sugar Cane trash (pulverised, < 4 mm) | 70 - 90 |
| Ground nut shells | 120 - 140 |
| Ground nut shells (pulverised < 2mm) | 330 - 360 |

This feature leads to problems in handling agro-residues - the cost of transportation of these fuels being high since the bulk density is small. Techniques like bagging can indeed raise the density. If however, the functional requirement also demands pulverised condition, it may be better that pulverising is performed at the source and then transported so that the benefits of density upgradation are obtained. An exception in point is sugar cane trash available largely in the form of thin long leaves whose bulk density does not improve greatly between chaff-cut condition and pulverised state. Simply chaff-cutting may be adequate for sugarcane trash if the thermo- chemical conversion process does not demand pulverising.

The second point concerns the widely differing densities of the fuels. If system design has to account for multi-fuel option, because of the seasonal availability of residues, then the fuel feed system must take into account a factor of five in the density variation. This is evident if we consider the options of using rice husk and sugar cane trash.

The points related to energy content in different biomass are addressed next. Table 1.2 shows the calorific value, ash content and the ash melting point of few agro-residues.

**Table 1.2. Thermophysical properties of some pulverised fuels**

| Fuel | Calorific Value (MJ/kg) at 10% moisture | Ash (%) | Ash melting point (K) |
|---|---|---|---|
| Sawdust | 16 | 0.5-1.0 | > 1400 |
| Rice husk | 13 | 18 - 20 | > 1400 |
| Sugar cane trash | 15 ± .5 | 5 - 6 | 650 - 700 |
| Groundnut shells | 15 ± .5 | 4 - 6 | > 1200 |

Since biomass on an ash free basis has nearly the same composition, the calorific value can be expected to influenced by the ash content. As can be seen, rice husk represents one extreme in terms of ash content. The calorific value is typically between 13 to 16 MJ/kg. The choice of 10 % moisture is related to storage at ambient sun dry condition. 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. The ash melting point seems high enough not to pose any problems.

In the case of rice husk, the ash having large fraction of amorphous silica can be treated to extract the highly valuable (commercially) material by pulverising the husk and further handling it in the gasification mode in a manner that the amorphous quality is preserved. The properties of the wastes which affect the gasification system are the density, the moisture fraction, the ash content and the ash fusion point. If the ash fusion point is smaller than 600 °C or more than 1000 °C, then the process of extraction of the residue from the reactor will be straight forward. If however, the ash fusion point is in the window 600 to 1000 °C, then the residue extraction process needs to be aided. The ash content will decide how the oxidation and reduction processes are enhanced or retarded since the ash will not contribute to energy generation but take away the heat. In this sense rice husk offers the greatest challenge since its ash content is very large - 20 %. Density affects the process of feeding - if the system has been designed for rice husk, say and it is decided later to deploy the same system for sugar cane trash, the fuel feed rate in the screw feeder will come down by a factor of four. Thus it is important that these differences are recognised and taken care of at the design stage itself. We will now look at the basic aspects of utilising these bioresidues.

### 1.5 What is Gasification?

Gasification is the process of converting solid fuels to gaseous fuel. It is not simply pyrolysis; pyrolysis is only one of the steps in the conversion process. The other steps are combustion with air and reduction of the product of combustion, (water vapour and carbon dioxide) into combustible gases, (carbon monoxide, hydrogen, methane, some higher hydrocarbons) and inerts, (carbon dioxide and nitrogen). The process leads to a gas with some fine dust and condensable compounds termed tar, both of which must be restricted to less than about 100 ppm each if the gas is to be used in internal combustion engines.

### 1.6 What use is gasification?

The great advantage of gasification over direct combustion is that at small power levels (from 3 kWe to couple of MW's) one can generate electric power by using the cooled and cleaned combustible gas as a fuel in internal combustion engines like reciprocating engines (diesel or gasoline engines) and gas turbine engines.

The energy conversion process via reciprocating engines leads to efficiencies of 15 to 20 % at 20 kWe power level, 25 to 30 % at 100 to 150 kWe level, 30 to 35 % at 200 kWe and above particularly in turbocharged mode.

The energy conversion via gas turbines leads to efficiencies about 5 to 10 % lower than reciprocating engines. The maintenance cost of the gas turbine engines is generally lower than in reciprocating engines because the reciprocating motion is more taxing structurally than rotary motion.

One has a further facility of being able to use the exhaust gas in either case (reciprocating or gas turbine engines) in cogeneration mode either for electricity through steam turbines or more practically, for raising process steam.

At large power levels one can use the hot raw gas as a gaseous fuel in raising high pressure steam in boilers for power generation via steam turbines. Typically these are considered economical at 10 MWe or better.

For thermal applications like in foundries, drying equipment, gasification and subsequent combustion will imply much cleaner combustion with a good control on the instantaneous power.

### 1.7 Why not use woody bioresidue gasifier?

Of the several gasifier systems evolved over a period of time, the open top down draft wood gasifier system developed at IISc has been proven to be the most convenient and efficient. The schematic of a 100 kWe open top down draught wood gasifier system is shown in Figure 1.3.

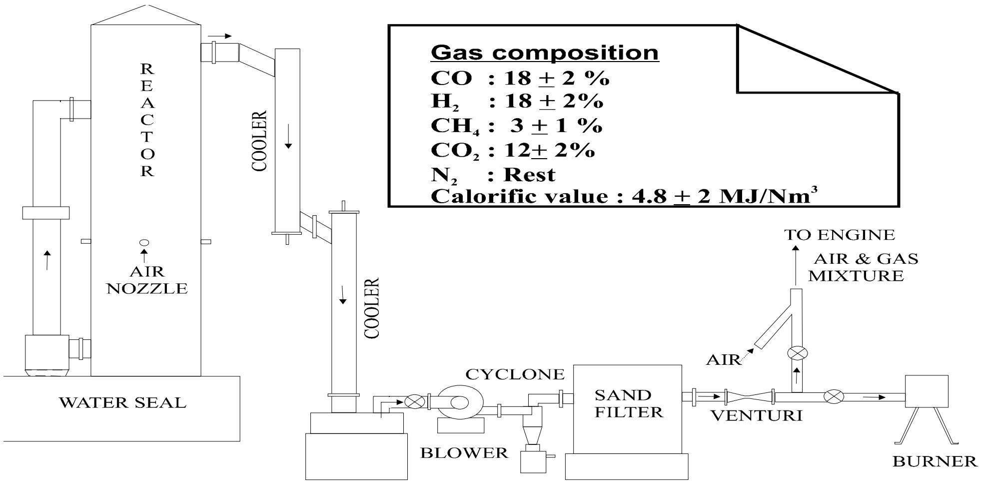


Figure 1.3 Schematic of wood gasifier for power generation application

In gasification, the solid-to-gas conversion is carried at sub-stoichiometric conditions with air-to-fuel ratio being 1.5:1 to 1.8:1. This system is meant for woody biomass having bulk density in excess of 250 kg/$m^3$ and moisture of less than 15 %. The wood pieces are loaded from top and they move down the reactor by gravity. The wood pieces after undergoing drying and devolatisation in the upper zones, leave behind the char. The volatiles undergo oxidation in the combustion zone, with air being partially supplied by the surrounding nozzles, and the remaining drawn from the open top. The product gases of oxidation further gets reduced by a bed of charcoal and yield a combustible gas having a calorific value of 4.5-5.0 MJ/kg, with an average composition of CO : 20 + 1%; $CH_4$ : 3 + 1%, $H_2$ : 20 + 1%, $CO_2$ : 12 + 1% and rest, $N_2$. The product gas thus generated during the gasification process is combustible. A gasifier system basically comprises of a reactor, where the gas is generated, and is followed by a cooling and cleaning train which cools and cleans the gas. The clean combustible gas is available for power generation in diesel engine - alternator set or heat in burners.

Several reasons for wood gasifier system not being suitable for agro residues in the loose form that were considered in the early periods of the project are:

1. Since the material movement is by gravity, and the bulk density of agro residue is low, there will be problems with respect to material movement in the reactor, because wall friction can prevent downward movement.
2. The pulverised form of the bioresidues leads to packing and hence air flow is impeded. A different way of expressing this is that for the same flow rate pressure drop is very high. It may also cause channelling of the flow along some paths.
3. In case of rice husk, other than char conversion being poor the gas gets laden with tar. Moreover, the char needs to be extracted from the reactor on a continuous basis.

Because of the above reasons, the use of down draft wood gasifier was considered unviable for pulverised fuels. It must be pointed out however, some designs (Chinese) utilise the open top system. These systems can be thought of as pyrolisers, since the char is extracted away with no conversion of carbon in the char. There are also problems of extraction of tar in the cleanup system and more frequent maintenance of the engine. As will be discussed later, by utilising the briquetting technology, it is possible to use woody biomass gasifiers for loose agro-residues also. In this case however, there will be need to change several elements so that a single system can handle a range of fuels.

As will be noticed in the later part of this report, a come back to the use of wood gasifiers on its own terms by essentially briquetting the fuels to high density has been explored and tested on a few fuels.

### 1.8 Why study the basic combustion process?

The phenomena of conversion of solid to gas occurs in stages with volatalisation and reaction in the gas phase occurring in series. Understanding the rates of these processes helps in the design of the reactor. This is why it is important to study the different unit processes.

The combustion of any bioresidue can be understood by conducting experiments on simple geometrical spheres. This will be helpful in understanding the reactions of bioresidue/char in the reactor of a gasifier. During the complete combustion (or stoichiometric combustion) of biomass, the initial phase is flaming followed by glowing combustion. The brief description of the two phases is as under :

### 1.8.1 Flaming

It is a time period in which the biomass loses all its volatiles. The volatiles burn in a gas phase and a steady flame engulfs the sample. The experimental depiction of flaming process undergone by a sphere of woody biomass is shown in Figure 1.4a. At the end of flaming, the density of the specimen will be reduced to one-third the initial value. The change in volume is not appreciable with char having around 75% of the initial volume. Char and ash will be left as residue at the end of this reaction.

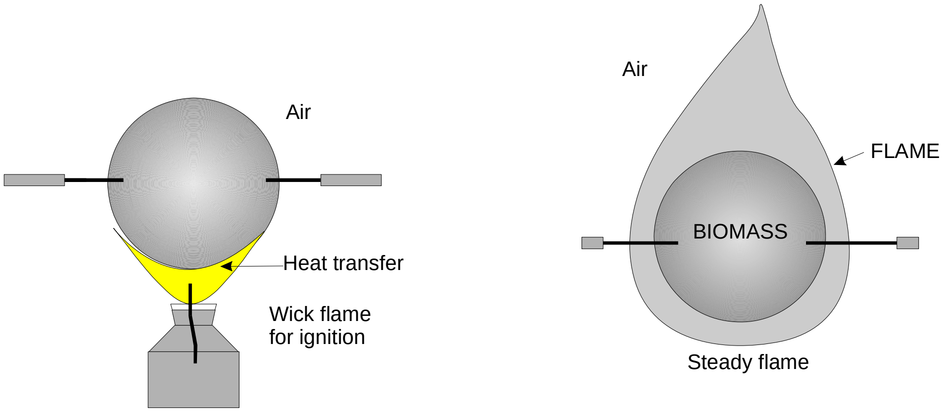


**Figure 1.4a Flaming process of a biomass sphere**

### 1.8.2 Glowing/Char reduction

It is characterised by slow reduction in the size of the char with density being roughly the same. The converted char forms a layer of ash on its surface with the reaction proceeding in the interior. A fully converted char leaves ash behind. The glowing process undergone by a char sample is shown in Figure 1. 4b.

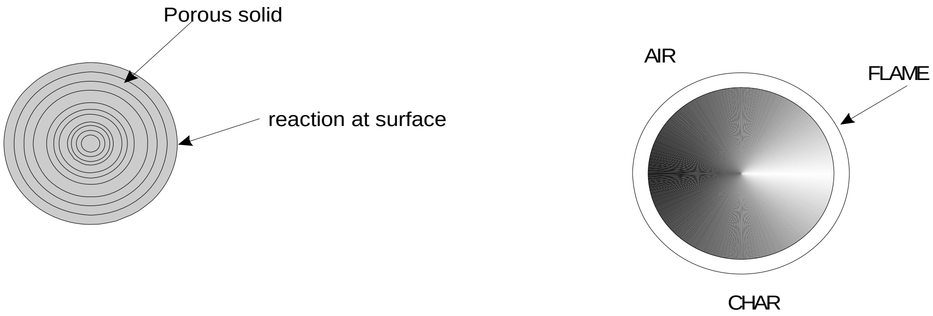


**Figure 1.4b Glowing process of a biomass char**

### 1.8.3 Basic study on Rice husk

Basic combustion studies were conducted on agro-residue like rice husk so as to know the char conversion rate and to understand its influence in the design of gasifier. Amongst the powdery biomass, the second classifying feature is the percentage of ash in the biomass. Rice husk, sugarcane trash and groundnut shells are high in ash content. The high ash content not only reduces the amount of heat released per unit mass of the char but also ash fusion/clinkering at high temperatures makes the process of combustion/gasification difficult. Table 1.2 also reflects the percentage of ash in different agro residues.

Based on a study of earlier work (Kaupp, 1981) and some preliminary studies in the laboratory, it was concluded that rice husk would be the biomass most difficult to gasify (for its high ash content and with silica being more in the ash) and hence, it was considered first. For gasification it is necessary to know the time for pyrolysis and the time for char conversion with oxygen, carbon dioxide and water vapour. The time for volatilisation and char oxidation were measured for spheres of wood by Mukunda et~al, (1984) and, by Sridhar et~al, (1993) for both teak and soft wood. Table 1.3 shows the data for teak wood.

**Table 1.3 - Flaming and char oxidation times for teak wood spheres**

| Dia (mm) | Flaming time, $t_f$, s | Char glowing time, $t_g$, s |
|---|---|---|
| 10 | 60 ± 5 | 220 ± 5 |
| 15 | 120 ± 5 | 500 ± 5 |
| 20 | 200 ± 5 | 780 ± 5 |
| 25 | 270 ± 5 | 1000 ± 5 |

These fit into a $d^2$ law - $t_f /\rho d^2$ ~ a constant and $t_g /\rho d^2$ ~ a constant, implying that the processes are diffusion limited. The study on wood is used as a reference for an understanding the behaviour of agro-residues.

Along similar lines experiments were conducted on single full rice husk and on carefully fragmented pieces of husks which were later extended to a group of husk pieces randomly placed in a porous stainless steel basket. The experiments were conducted by introducing a porous stainless steel basket with a single husk into a furnace kept at 1073 K or higher. The results of the study are summarised in Table 1.4.

**Table 1.4 - Flaming and glowing time for rice husk in air at $T_O$**

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

The time required for glowing is far larger than that for flaming and it seems to increase dramatically when the material is bunched together. Perhaps the oxygen cannot access the surface easily because of some property of rice husk caused by interparticle effects which reduce its surface area. Quarter and half husk have the same kind of flaming and glowing times implying that what matters is the thickness of the husk.  The fact that full husk has a large glowing and flaming  time implies that  access of oxygen to the inner surface of the husk is probably low.

Thus it is clear that the access of oxygen (in air) to the char is very important. A comparison of the time taken by wood char pieces  of about the same weight, indicates that rice husk char is about one—third as reactive as wood char which causes further complications to the their use in wood gasifiers. For instance, measurements in the IISc wood gasifier using 15 mm size chips show that volatalisation is complete in about 10 minutes but the residence time of the char before it becomes ash is as large as 90 minutes.

The problem with rice husk char is that approximately 50 % of its  weight is inert (silica) and as such heat release rates per unit mass of the char are much lower than in wood char. This implies spreading the material to obtain large surface area per unit volume in the reactor is far more detrimental while using rice husk than with wood chips. Thus one notices, several unfavourable properties of  rice husk  (not identified specifically earlier) compared to wood for its gasification. Therefore, it is not surprising that reactors for gasification of rice husk which are as good as those for the wood chips are unavailable today.

A further piece of evidence from full scale gasifier experiments on sawdust and pulverised rice husk has shown that in the case of sawdust, the char is nearly oxidised at the exit from the reactor whereas rice husk char takes a very long time for oxidation. No precise timings can be identified because, the rate of flow of rice husk char is so large that in any meaningful experiment, one needs to store the red hot char in a basket. Typically, such a basket holding the char takes a few days for oxidation in most of the zone except the top layer which gets cooled off and therefore remains unconverted. In a similar situation with wood char the contents would be ash even before the material reaches the basket. This experience succinctly explains how different rice husk char is compared to sawdust.

### 1.9 Summary

This chapter identifies the problem and the fundamental approach taken to help design a reactor system for gasifying agro-residues. The fundamental studies that were carried out are also described.

# Chapter 2

## Earlier work - international and national

Ref. 2.1: 25 MWe Floyd Myers Marsh rice husk (+rice straw) based power plant in California, USA reported in Power, p. S.15, 1983

A power plant conceived around rice husk which the Sacramento valley mills generated at a staggering 0.3 million tonnes/year by milling about 1.8 million tonnes of paddy every year was scheduled to be built by 1989 when this report has been filed. The technology is based on suspension firing of pulverized rice husk, perhaps partly rice straw which appear to be pneumatically introduced into the furnace with associated natural gas burners as pilot burners operating all the time. Pulverizing the rice husk is done essentially to raise the density of husk from about 120 to 150 kg/m$^3$ to 250 to 300 kg/m$^3$ to help store larger amounts in the silos designed. Natural gas burners for start-up also are provided. The plant has 50 tonne/hr grinding capacity to deliver 25 tonnes/hr of pulverized husk. The overall plant efficiency appears to be between 27 to 30 %, seems to be on the high side. Unfortunately, the details of power generation process, primarily the choice of peak pressure and temperature of the steam cycle are not provided to make an independent assessment of these values. It is not also clear how much of rice hull conversion takes place inside the furnace. Several aspects of the technology seem well thought out: keeping velocities in the furnace low to reduce tube erosion; Gas temperature indicated is about 860 $^o$C and this appears reasonable; Technological details of fuel and ash handling system as well as straw grinding. There is no information later about the plant operational details afterwards. Even a current enquiry regarding this plant has not resulted in any response.

Ref. 2.2: "Alkali deposits found in biomass boilers" NREL/TP-433-8142, SAND96-8225, Vol. II, Feb 1996 (available to the public from NTIS, US department of commerce, 5285, port Royal Road, Springfield, VA 22161).

They conducted a study on eleven biomass fuels representing a broad class of commercially available fuels: (a) straws and grasses (herbaceous biomass), (b) pits, shells, hulls and other ligno-cellulosic biomass, (c) woods and waste fuels of commercial interest.

Herbaceous fuels contain silicon and potassium as principal ash forming constituents. They are also high in chlorine and exhibit severe ash deposition problems due to the reaction of alkali with silica to form alkali silicates that melt or soften at temperatures as low as 700 $^o$C and reaction of alkali with sulfur to form alkali sulfates on heat transfer surfaces. All biologically active alkali, potassium in particular is traced to be the principal cause of most deposits. There is also the non-biological form of the alkali in soils and it exhibits much less reactivity. What is potassium to biomass is sodium to coal. Calcium is not considered a serious depositing agent even though ash formation from calcium follows the paths generally denoted for potassium and boiler operations can go on satisfactorily with grasses and straws with high calcium content. While chlorine has been identified as a potential reactive chemical element, in its absence alkali hydroxides are stated to form the most stable gas phase species in moist oxidizing environment. In so far as the conceptual framework for ash deposition, four mechanisms are postulated: inertial impaction, thermophoretic deposition, condensation, and chemical reaction.

***One of the most important findings is that ash fusion temperature data does not predict the ash deposition behavior adequately. This implies that standard information on ash***

***behavior with temperature determined from laboratory studies may not provide adequate indication to ash behavior on grates except in qualitative terms.***

This report has provided an interesting view of the developments in USA in this area. These are best summarized in their own words.

***Quote*** "Following the enactment of the Public Utilities Regulatory Policy Act (PURPA) in 1978, the installed US capacity in biomass fueled power generation increased ten-fold to roughly 7 GWe. In California alone, 66 independent power generating facilities operated on biomass fuels (excluding solid waste) in 1993, with 47 generating or co-generating electricity and 19 generating steam only (CEC, 1994). All are direct combustion type units. The 47 power stations utilize standard Rankine cycles, and represent a combined generating capacity just under 900 MWe, or about 2% of the electric generating capacity utilized by the state. The total energy generation from these facilities is close to 6 TWh $y^{-1}$ from 6.6 million dry tons of fuel, with an average electricity generating efficiency of 17% and composite availability of 74%. Net efficiencies on advanced fluidized bed boilers range as high as 23% with availabilities in excess of 90% (Grass and Jenkins, 1994). Private investment in the California industry totals about \$3 billion, and power sales amount to roughly \$0.5 billion per year. Most of the recent development in biomass power was stimulated by economic incentives provided by favorable contractual arrangements for power sold to utilities (such as "Standard Offer 4" contracts in California), although there exist substantial, environmental incentives in the reduction of local air pollution from open burning of crop and forest residues, and mitigation of global climate impacts by rapid carbon recycling when biomass replaces fossil fuel.

The major type of biomass fuel used is wood, including mill wastes, forest thinning, and urban wood fuels (demolition wastes, yard prunings, and similar materials). Other fuels include agricultural wood as orchard prunings and tree removals, nut shells and hulls, pits, and other processing wastes. Most of the facilities constructed in California operate under permits requiring the reduction or offset of atmospheric emissions from other sources (Grass and Jenkins, 1994). ***Perhaps one of the biggest disappointments in the development of the biomass power industry in the state was the inadequacy of the technologies employed to utilize straw as fuel, even though several facilities obtained air permits on the basis of offsetting field burning emissions from field crop residues.*** Straw firing leads to rapid and excessive fouling of boiler heat transfer surfaces, as well as slagging and agglomeration in furnaces. The exclusion of straw was not intentional by design. Many manufacturers fully expected to be able to handle straw in their facilities. Although there was evidence from coal-fired facilities and small-scale biomass research tests that straw might create substantial problems with slagging and fouling in conventionally designed boilers, the problem was not widely recognized until most of the existing capacity was already in place. Facilities permitted to burn straw are now buying and reselling the straw for non-burning disposal, without benefit of the energy value of the material as fuel. The problem of fouling and slagging is not restricted to straw materials, however. All facilities suffer economic loss from fireside deposits, with those firing more of the agricultural and urban fuels and less of the clean wood fuels incurring greater maintenance costs and availability losses. To remain economically feasible, power plants must increasingly burn lower quality fuels prone to slagging and fouling.

The motivation to develop new fuels for some power stations is driven by regulation and legal agreements more than by economics or availability. For example, under Title I of the U.S. federal Clean Air Act Amendments of 1990, states designate areas within their boundaries as attainment, non-attainment, or unclassifiable for each of six pollutants.

Designations are based on either federal or state air quality standards. Operating permits for all biomass-fired power stations are based in part on their impacts on air quality. For power stations in or near non-attainment areas, permits often require a net *reduction* in the amount of pollutant (NOx, particulate matter, etc.) generated in that area. This is accomplished by use of offset fuels, straw representing a common example. In these permits, power stations agree to dispose of straw that would otherwise be burned in the field. Combustion of straw in this manner can reduce the amount of pollutant generated from field burning to such an extent that it more than compensates for the residual pollution from the power plant.

Problems vary from fuels handling and storage to seasonal variations in both the amount and the quality of the supply. Arguably the most daunting issue, and the subject of this investigation, is the inorganic material in the fuel and its impact on the combustor. For example, essentially all biomass-fired power stations in California that were designed and permitted based on using straw as an offset fuel opt to dispose of straw by other means. These decisions are driven by the consistent experience of unmanageable bed agglomeration, slagging deposits, an convection pass fouling when burning straw…..In many cases, addition of as little as 10 % straw to the boiler fuel supply for a electric power-generating facility causes an unscheduled shutdown within a few hours. Field experience with some other offset or alternative fuels (orchard *prunings,* nut shells or hulls, fruit pits, etc.) demonstrates borderline operation, with blend ratios limited to only 10-15 % when fired with wood.

Elements from the fuel deposit in several different forms in boilers. High silica slags frequently form in the high temperature furnace regions as alkali and alkaline earth metals react with silica or sulfur to form molten composites and glasses. Slag masses can form and accumulate on grates or running slags may form on walls – especially refractory walls with high surface temperatures – but also on water-walls. Wall slags are commonly seen in the vicinity of the fuel feed ports. Slags can form as rock-like, ribbon-like, hair-like, or other structural forms. Agglomerates also occur, composed of sand and ash particles bound by fused, glassy materials arising from reactions between the fuel elements or other compounds in the furnace. Agglomeration is a common problem in fluidized bed combustors, where reactions in the bed can lead to the formation of large aggregated composites of bed media and ash, with eventual defluidization of the bed and plant shut-down. Fireside fouling deposits occur on all heat transfer surfaces, but especially on cross- flow tubes situated in the convection passes of boilers. Fouling of furnace water-walls in fluidized beds typically has not been of concern because of the active abrasion by bed media particles. Fouling of water-walls in the convection passes occurs routinely, however, although not generally with the same severity as cross-flow tube surfaces. Particle separation devices, such as cyclones, located at the furnace exit in circulating fluidized beds are also subject to severe fouling.

Potassium is a macro-nutrient for plants. Along with potassium, straw invariably contains a substantia1 amount of chlorine, usually at levels greater than 0.2% and up to 3% dry weight (Jenkins, 1989). Straw also contains substantial amounts of silica, usually in macro-nutrient concentrations, although its role in plant nutrition is not entirely clear. The role of minerals in plant nutrition has been described by (Marschner, 1986). Rice straw, for example, contains about 10% of dry weight as silica. By itself, silica does not present much of a problem for biomass boilers. Rice hull, which may contain 20% by weight silica, does not easily slag and foul in boilers when fired alone because the ash is relatively pure in silica (> 95% $SiO_2$ in ash, typically) and the melting point is high (> 1650 $^oC$), although there exist other problems related to crystalline transformations and the atmospheric emission of cristobalite, a known respiratory hazard, if combustion conditions are not properly controlled. Silica in combination with alkali earth metals, however, especially with the readily volatilized forms of potassium present in biomass, can lead to the formation of low melting point compounds which readily slag and foul at normal biomass boiler furnace temperatures (800- 900$^{o}$C). Chlorine can be an important facilitator in fouling, leading to the condensation of alkali chlorides on heat transfer surfaces in the boiler, and promoting the development of alkali sulfates. Chlorine may be an important element in the vaporization of alkali species leading to the formation of more severe deposits. Sugar cane bagasse, which has long- been used successfully as boiler fuel, and which is derived from another high potassium, high silica herbaceous crop, does not exhibit the same fouling tendencies as straw and sugar cane trash (tops and leaves) because both potassium and chlorine are substantially leached from the fuel in the process of extracting sugar.

Unlike straw, wood contains very little silicon, and the mature stem wood that makes up the majority of wood fuel, including urban wood fuel, also contains substantially lower amounts of potassium, usually only about 0.1% dry weight. Potassium is a highly mobile element in plants, and moves to younger, actively developing tissues, leaving the mature stem wood depleted in potassium. Facilities burning the leaf and branch fractions of wood, or coppice materials from short rotation woody cultures (SRWC), will also encounter higher levels of potassium (as well as nitrogen and sulfur) in the fuel. This is already apparent in the agricultural wood fuels (e.g. annual prunings) currently burned in boilers. Although wood fuels are inherently low in silica, adventitious material such as clays and other soil components brought in with the fuel include silica and can lead to fouling, although usually at reduced rates compared to straw. Urban wood fuels can include substantial amounts of adventitious materials from manufactured products. The chemistry of inorganic transformations in boilers is quite complex, involving multiple physicochemical pathways among alkali, alkaline earth, and other inorganic and organic species in the fuel. The principal components of interest include silicon, potassium, chlorine, sulfur, iron, phosphorous, magnesium, calcium, titanium, carbon, hydrogen, and oxygen. Sodium and aluminum, which are not normally found in inherently high concentrations, may be introduced as soil or through prior processing operations, as with sodium in olive pits, and may also influence the fouling behavior. For most biomass fuels, the elements silicon, potassium, calcium, chlorine, sulfur, and to some extent, phosphorous, appear to be the principal elements involved in the fouling of boiler surfaces.

Deposit formation also depends on the boiler design and operation. Differences in slagging and fouling behavior have been observed for the various types of grate, fluidized bed, and suspension boiler designs. Superheater fouling depends to a large extent on the furnace exit gas temperature, a feature recognized by industry in the control of fouling deposits. Many existing biomass boilers were designed with furnace exit gas temperatures of 900 $^{o}$C or higher. Coupled with cross-flow superheaters typically employed, severe fouling is frequently observed in such units. Reducing the temperature to control deposits can lead to derating the boiler with undesirable economic consequences.” ***Unquote***

As can be noticed, the concern shown by the investigators on ash fouling related problems is very significant.

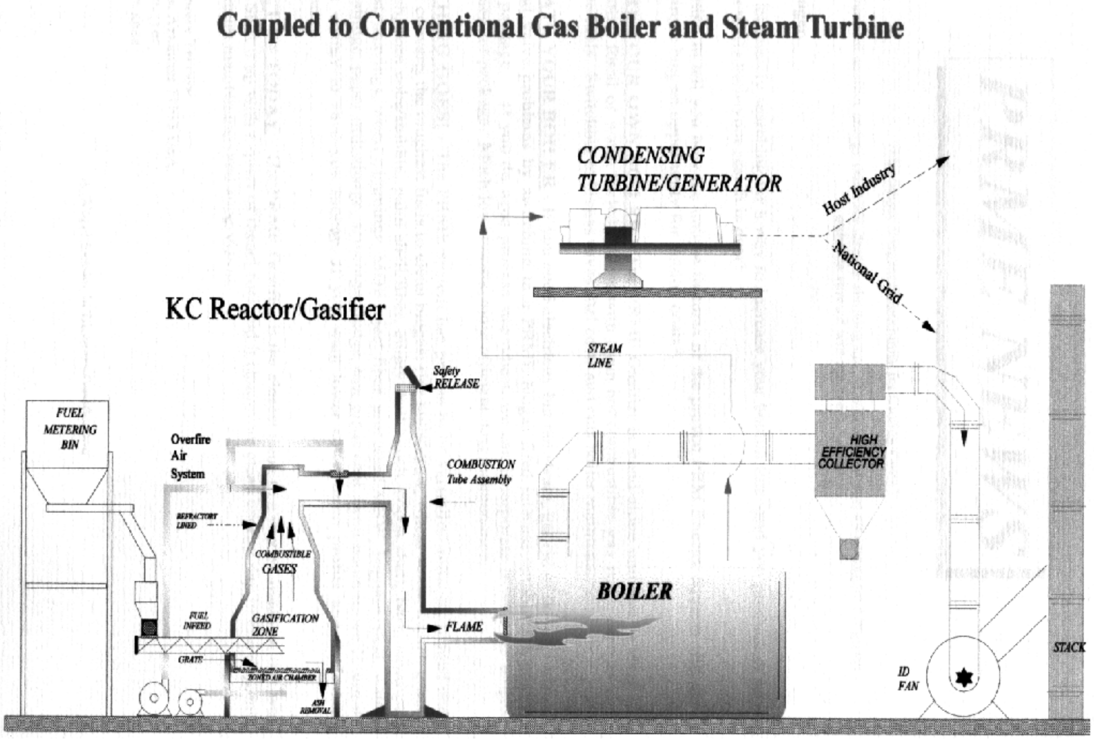


Figure 2.1  PRME Gasification System

## Ref.  2.3: Gasification system developed and marketed by PRM systems, 1982+

This development is an interesting one on *large power thermal systems*. Figures 2.1 and 2.2 illustrate the schematic of the overall system and the reactor section. The reactor constitutes a vertical cylindrical shell narrowed at the top is lined inside with refractory material capable of withstanding 1560 $^{o}$C in a reducing atmosphere. The cross section reduction at top is claimed as a device to enhance mixing of the product gas with combustion air. The grate at the bottom is large and sized for a 1.1 to 1.2 MW/m$^2$. Rest of the process is described in their words.

***Quote*** " ..Fuel is metered  to the gasifier by a water cooled screw conveyor that discharges into the drying and heating zone of the gasifier. The bin is equipped with an in-feed leveling conveyor that delivers fuel to the gasifier. The speed of the out-feed conveyor is automatically adjusted by the automatic control system to maintain a preset temperature in the first stage gasification zone.  Discharge from the out-feed conveyor is directed through an impact weigh metering device that provides precise indication and control of the fuel feed rate. Fuel is introduced to the gasifier by *a water cooled screw conveyor* that discharges into the drying and heating zone of the gasifier.

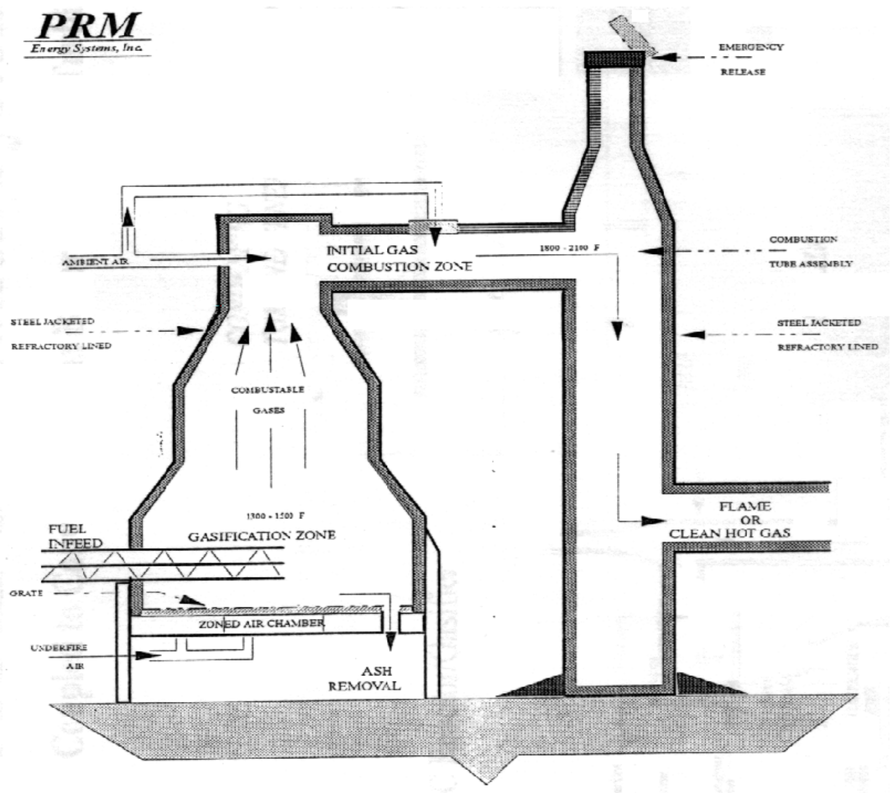


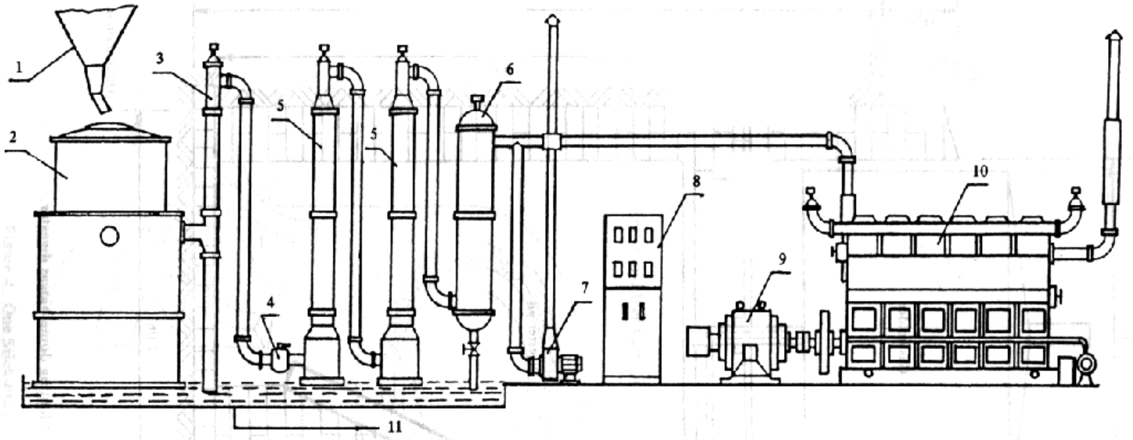
**Figure 2.2 Details of the Gasification Reactor**

The gasification process is controlled by the proportional application of gasification and combustion air in a manner that supports efficient gasification. Residence time in the gasifier is varied by a residence control system that is adjusted to achieve a target quality of the ash residue.

In the gasification zone of the gasifier approximately 10 to 12 % of the stoichiometric air requirement is admitted into the gasification air distribution zone. The application of gasification air is multi-zoned and controlled to maintain proper temperature required to volatilize the biomass and *allow partial combustion of the fixed carbon.* Temperatures in this zone are controlled between 600 and 1300 $^{o}$C depending on the particular biomass and the required ash quality. A low gasification air flow rate (< 10 cm/s) through the gasification zone coupled with a low feedstock entry point and continuous ash discharge minimizes the amount of particulate matter entrained in the gasifier exhaust.

Combustion of the gases starts in the combustion tube assembly where the temperature of the gases is increased to promote thermal cracking of tars and hydrocarbons that were liberated during gasification. Partial combustion of gases in the combustion tube assembly, automatic continuous ash discharge and precise control of the zoning of the gasification air produces a clean, low BTU content gas that can be burned in the combustion tube and chamber for drying applications or in the radiant section of the boiler. The gasification rate is controlled by the demand from the dryer or the boiler. The boiler exhaust is clean and may be used for direct drying applications including food grains." ***Unquote***

There is also a claim that the gas from the gasifier can be cooled and cleaned for use in reciprocating engines. The terminology of biogas used by in their document is incorrect and should be replaced by producer gas. While it is true that they have built some large size plants at 4 to10 tonnes per hour of rice husk system, there are no indications that electricity via reciprocating engine systems have been built. In fact, there are no indications to the establishing of the gas composition, particulate and tar data from the gasifier meant for electricity generation system to enable one to accept the claims of this possibility.



1. Paddy husk tank
2. Paddy husk gas producer
3. Ash flushing tube
4. Stop cock
5. Filter and cooling tower
6. Gas storage tank
7. Blower
8. Distribution panel
9. A.C. Generator
10. Paddy husk gas engine
11. Sewage

Major technical specifications:

| | |
|---|---|
| Type: | vertical water-cooled vertical inline, four-stroke and electric spark ignition |
| The number of cylinders: | 6 |
| Bore: | 250mm |
| Stroke: | 300mm |
| Compression ratio: | 8.5 |
| R.P.M. | 600 |
| Rated power: | 160kW |
| Husk consumption: | 2-22 kg/kWh |
| Started with compressed air Ignition order: | 1-4-2-6-3-5 |
| Rated voltage: | 400/230v |
| Excitation form: | PCCE |
| The weight of generator and alternator: | 10T |
| The weight of gas producer: | 9T |

**Figure 2.3 Overall Schematic of the Chinese Gasification System**

## 2.4 Chinese rice husk based gasification system

(RAPA Bulletin on Rural Energy, p. 25, 1/85 and p. 18, 2/1987)

It is an open top system with rice husk fed directly into the open top. Figures 2.3, 2.4, and 2.5 shown below contain details of the entire system, the reactor alone and the cooler/scrubber for a typical 140 to 160 kWe gas engine based system. The details of the gasifier are as under:

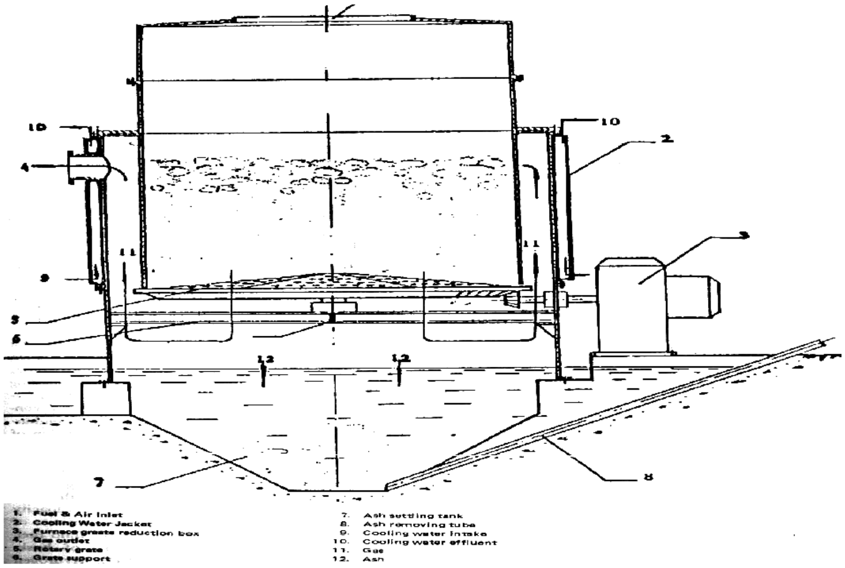


**Figure 2.4 The Reactor section of the Chinese Gasification System**

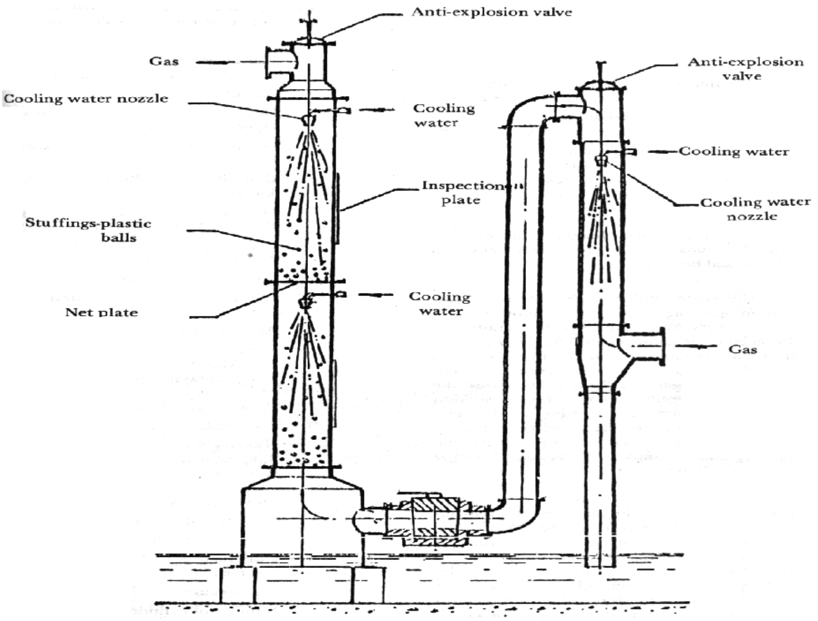


**Figure 2.5 The Cooler/Scrubber of the Chinese Gasification System**

Reactor details: Gasification chamber volume: 6.8 m$^3$, Height of the effective gasification zone: 1 to 1.5 m, peak temperature in the gasification zone: 1000 $^o$C, gas temperature at outlet: 300 to 400 $^o$C, gasification efficiency: 61 %, consumption of husk: 280 to 350 kg/h, gas generation rate: 785 m$^3$/h.

The cooling and cleaning system details are as follows. Ash flushing tube: peak gas velocity: 6.9 m/s, water spray pressure: 1.5 atms., water flow rate: 2.4 m$^3$/h.

Cooling tower: peak gas velocity: 3.1 m/s, water spray pressure: 1.5 atms, water flow rate: 4.8 m$^3$/h, reservoir volume: 0.65 m$^3$.

Gas engine details: Rated power: 140 kW. No. cylinders: 6, bore: 250 mm; stroke: 300 mm, swept volume: 14.7 liters. compression ratio: 8.5, speed: 600 rpm, average effective cylinder pressure: 4.07 atms., exhaust temperature: 450 $^o$C; gas consumption rate: 5.6 m$^3$/h, engine oil consumption rate: 3.4 g/kWh, ignition sequence: 1-4-2-6-3-5, temperature of cooling water: 50 to 55 $^o$C (inlet) and 70 $^o$C (outlet); Ignition advance: 28 to 32 $^o$ before TDC; minor overhaul at the end of 150 to 160 hours of operation. Lubricating oil and filters are cleaned once in 600 hours.

The important element in the reactor is the grate which is rotated by a motor with a gear reduction to enhance the torque. The gas is taken around the jacket, presumably to keep the inner wall hot. The char with very little conversion will drop down into the water seal and get washed out. The gas goes through cooling towers with each tower stuffed with plastic balls (about 30 - 40 mm dia.). The gas is expected to have 30 mg/m$^3$ of dust. Cooling water required for this about 7.2 m$^3$/hr (large).

The Chinese development which must have taken place some time between 1975 and 1982 is important since it appears to have influenced the developments in Thailand, Philippines, and very recently even India in specific sectors.

The claim of cleaning with plastic balls 30 to 40 mm dia. Also seems difficult to accept since any possible fine dust could find its way through large spaces between the spherical packing of the plastic material). One plant was established in Burma and the problem claimed is that the amount of cooling water is large – 20 m$^3$/h. This does not seem consistent with the design details presented above (only 7. 2 m$^3$/h is called for).Some work on running diesel engines on dual-fuel mode has been performed using the chines technology for rice husk at low power levels – 7.5 kWe Lombardini L-20 diesel generator running at 1800 rpm. Shown in the accompanying Figure 2.6 are the results (from a paper “gasification of rice hulls [development and preliminary results] by Francisco B. STA. ANA) in which the results of diesel replacement vs. load are shown.

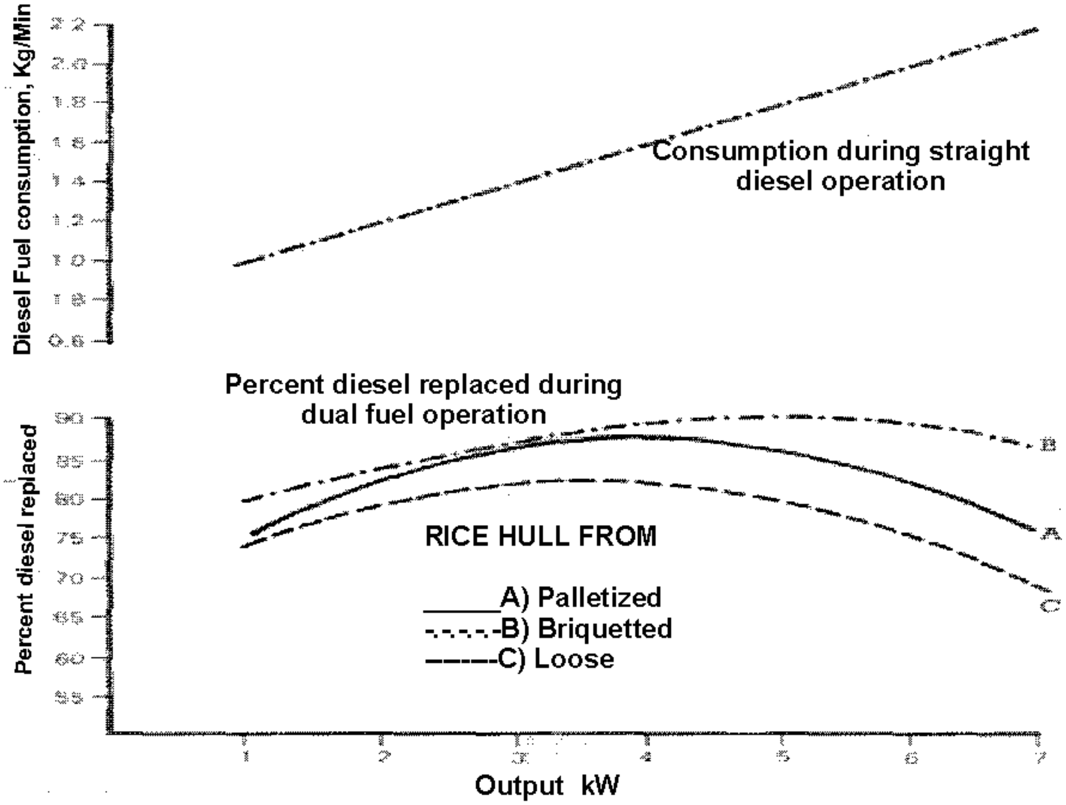


**Figure 2.6 Diesel replacement by producer gas from Rice Hulls in dual Fuel operation of a 7.5 Lombardini L-20 Diesel Engine at 1800 RPM**

The results indicate that briquetting rice hulls leads to much higher diesel replacement – as much as 90 % even up to 80 % of the nominal load whereas with loose rice husk, the diesel replacement is limited to 80 % at half the nominal load and 70 % at near full load. Another set of results show that for operation at San Carlos city (Negros occidental), the diesel replacement is limited to 70 %. Unfortunately, greater rationalization of the results is not possible due to lack of any details in the above paper.

## 2.5. Indian rice husk based gasification system.

Technologies for rice husk have been experimented upon at IIT Bombay and developed into commercial systems at Ankur Technologies, Baroda and AEW, Tanaku. These have been built around Chinese designs and concepts, application being related to dual-fuel operation on diesel engines. Performance is limited to about 65 – 70 % gasification efficiency and a diesel replacement of 70 %.

## 2.6 Indian sugarcane trash gasification system.

Dr. Anil Rajvanshi and colleagues at Nimbkar Agricultural Research Institute have devoted several years of their attention to the development of sugarcane trash based gasification plants for power as well as heat generation under a ministry sponsored project. They have put together a comprehensive report on their findings. Two models of gasifiers were developed. The first one was used to understand the choice of various parameters of gasification. They concluded that the maximum reactor temperature should be limited to 900 $^{O}$C to avoid clinker formation. The second model, an open top throat-less system, 300 mm ID reactor size for generating 70 $nm^3$/h of gas (sugarcane trash consumption rate of about 35 to 40 kg/h, with a char residue of 20 to 25 %) with continuous feeding and char removing operations. The gas from the second gasifier was fed into a dual-fuel diesel engine of 15 kVA capacity. Their findings on various aspects are summarized below.

### a. Feed storage, preparation and characterization

Long sugarcane leaves stored in open piles was found to be a convenient method for storage. The mesh like arrangement prevented rain water from wetting the interior of the pile, thereby ensuring the availability of dry feed stock even during rainy season. They chaff-cut the material in a chaff cutter. The labor and energy requirements are indicated as 14 hours and 16 kWh per dry tonne respectively. The leaves had a bulk density of 26 to 40 kg/$m^3$ and an ash content varying between 6 to 10 % with a low ash deformation temperature of 900 $^oC$.

### b. Gasification data in flare mode

Both models were tested for 550 an 670 hours at gas flow rates of 24 to 70 $nm^3$/h. Bed heights were set at 0.6 to 0.8 m in the operation. The corresponding fuel consumption is 13 to 42 kg/h corresponding to specific gasification rates of 180 to 600 kg/$m^2$h. Gas temperature at the gasifier outlet was 350 to 400 $^oC$ The gas calorific value turned out to be 3.6 to 4.6 MJ/$nm^3$ and was independent of specific gasification rate. There were fluctuations even in a single test from 3.6 to 4.6 MJ/$nm^3$. Char generation varied between 15 to 30 % of the fuel gasified and the char had a calorific value of 19 to 24 MJ/kg indicating that the volatile fraction was still significant in the char. The tar content of the raw gas was 7 to 15 g/$nm^3$ compared to 0.1 to 0.3 g/$nm^3$.  This placed an undue load on the tar cleanup system. The system was tested with other bio-residues like sweet sorghum stalks, bagasse, sunflower and wheat residues, cotton stalks and grasses. There were problems with residues at high moisture content. They seem to have concluded that greater amount of testing was needed before the system could be declared satisfactory.

### c. Gasifier-generator set data in dual-fuel mode

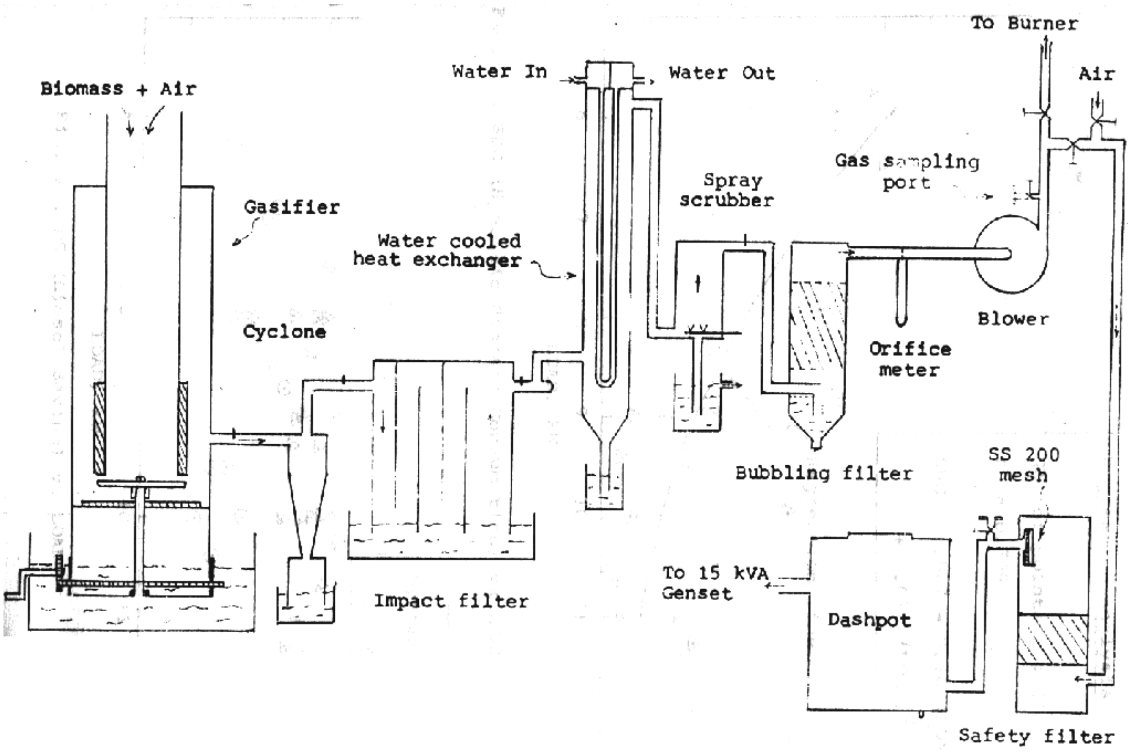


Figure 2.7 The overall schematic and the cleaning system for 15 kVa sugarcane trash Gasification system of Rajvanshi & co-workers

Using a fairly elaborate cooling and clean-up system involving an impact filter, spray scrubber, and a bubbling filter, a schematic of which is presented along with the complete system in Figure 2.7**,** the gas was conditioned for use in a diesel engine. Operations experience of over 200 hours were acquired. The specific fuel consumption (*sfc*) in dual fuel mode was found fairly independent of the load, but strongly dependent on the pressure drop of the gasifier. When the pressure drop on the gasifier line was less than 400 mm water gauge, the *sfc* was in the range of 15 to 90 g/kWh ver the range of loads – 4.5 to 11.3 kWe. This corresponds to diesel replacement of 70 to 92 %. For pressure drop larger than 400 mm water gauge, the *sfc* increased to 70 to 150 g/kWh with diesel replacement amounting to 50 to 70 %. The constancy of *sfc* over the load range is attributed to the use of a blower on the gas line between the gasifier and the engine.

Problems with the operation were identified as inadequate load following ability in the absence of control system. Change in load of 10 % was accounted for without any change in *sfc* but greater increase in load was accompanied by drastic increases in diesel consumption. Decrease in load was accompanied by knocking and over-speeding of the prime mover. Measured cold gas efficiency remained at 40 to 60 % as in flare mode. The overall conversion efficiency varied from 13.5 % at 3.5 kWe load and 25 to 30 % at 10 to 11 kWe load. The corresponding values in diesel mode were 19 % at 4 kWe and 29 % at 10 kWe load. They conclude that dual fuel operation would be better suited for constant load applications rather than varying loads. Their further concern was that the contaminants at the end of gas conditioning system was 100 to 450 mg/m$^3$ and even downstream of safety filter, the contamination level was about 100 mg/m$^3$ in excess of what is required for engine applications.

### d. Gasifier – Engine maintenance questions

Problems of gasifier reactor were related to the choice of materials of construction. Inner wall made of AISI 316 deformed after 311 hours and became non-operational after 653 hours. The outer jacket made of mild steel was exposed to wind and suffered corrosion and was to be completely replaced after 850 hours inspite of being coated with two coats of red-oxide primer. Impact filter and SS mesh had to be cleaned every 20 hours. Char bed in the bubbling-cum-packed bed filter had to be replaced after every 50 hours. Cyclone inlet and outlet had to be cleaned after every 100 hours. The air-water cooler had to be cleaned every 175-200 hours. Most of these tasks took between 10 to 45 minutes.

### e. Direct heat applications

The same gasifier used on the flare mode tests were converted to thermal applications. The flow rate range was set as 16 to 93 nm$^3$/h giving a turn down ratio of 6.4. Flame temperatures in the specifically designed burner were noted as 1240 $^{o}$C. Measured cold gas efficiencies of the gasifier were 38 to 53 % and the furnace efficiency were 39 to 51 %. Thus the net efficiency from sugarcane trash to heat is 14 to 26 %. These efficiencies are not entirely significant to suggest the use of this technique for heat; however, it must be recognized that there are no established methods of using sugarcane trash for heat applications. Experiments with jaggery producing unit seems to have resulted in efficiencies of about 20 %, about 5 % more than conventionally fired natural draft furnaces.

### f. Char briquetting machine

The investigators have contemplated the use of the char with a reasonable amount of calorific value into pellets by mixing the material with bovine dung. This seems to have yielded pellets which when used in furnaces have led to water boiling efficiencies of 11 to 15 %.

### g. Status of technology

While proof of concept has been taken to advanced levels, the investigators feel that the technology needs further development. Mechanized feeding and char removal systems need considerable development. Gas conditioning system also needs to be improved, specially for shaft power applications. Their greatest concern is the material of construction, particularly of the reactor.

### Comments and Observations on the work of Dr. Rajvanshi and colleagues.

It is admirable that the investigators have made a systematic and thorough study within the limits that they were encompassed in the environment they worked. This is because, several of the limitations that they have stated, particularly on the materials of construction could have been overcome had they experienced a more industrialized environment. Surely, ceramic materials were known even at the time of their experiments and this could have been adopted by them. A more subtle set of conclusions can indeed be drawn from their work indicating to a different direction of future development effort. This concerns the use of chaff cut sugarcane trash. As was experienced by them, the instantaneous pressure drop across the hot fuel bed could fluctuate. This would lead to fluctuations in the gas composition which could be partly offset by using a large storage vessel for the gas. But changes of fuel richness through the bed would inevitably lead to high level of tar generation, a feature experienced by the investigators. It is therefore important to ensure that the instantaneous air-to-fuel ratio does not deviate much from a nominal and set value. Two possible routes exist. *If one wishes to use the fixed bed concept for whatever reason, one has to use briquettes made of sugarcane trash.* In view of the documented, though limited Philippine experience, briquetting leads to higher and more consistent diesel replacement, apart from reactor bed pressure drop being nearly constant. The other route is to use a cyclone reactor with pulverized sugarcane trash to ensure near constancy of air-to-fuel ratio and better heat transfer and other properties. It is clear that the first route noted above holds a better chance of reducing contaminants like tar and particulates more than the approach taken by the investigators. As to whether cyclone system will hold this promise is not explored in the literature. It is in fact the subject for the present research and development study.

### 2.6 Thesis by Dr. Kaupp on rice hull utilisation

The thesis brought out in a book form by Dr. Kaupp is an outstanding document which departs from traditional literature in gasification area which is more a description of actual systems deployed rather than a critical approach to design based on fundamental principles. It is a voluminous document that addresses nearly all aspects of gasifier design, reactor, cooling, cleaning and other aspects and on each of these aspects, fundamental principles are used to analyze the approaches that are likely to succeed. It describes the differences between wood gasifier and rice husk gasification systems, puts rice husk under intense scientific investigation, its structure, pyrolysis and gasification aspects. It also brings together enormous amount of information from various sources to present a very comprehensive picture of the entire technology. *The interesting point is that it was examined very late into the development effort of the present authors and hence had only the benefit of comparing experiences on many aspects.* There are still some observations in this book which need to be critically evaluated before being accepted. This book has 10 chapters. There is a mix of woody biomass and rice husk in the discussion in many chapters. This is indeed a correct approach to enhance understanding.

Chapter 1 is the introductory chapter. While discussing parameters required for satisfactory operation of the gasifier, six parameters are identified – physical shape of fuel particles and fuel bed structure, moisture content, volatile matter, ash content, ash composition, and energy content. *It is surprising that one of the major parameters of operation, namely, the fuel density is ignored.* Further, after stating that biomass has nearly the same composition on an ash free basis (on the next page in the document), identifying moisture content and ash content should have been good enough for identifying the energy content. Why such an explicit statement of energy content is required is not obvious.

Chapter 3 discusses the history of producer gas engine systems. It is very instructive to read the history of gasification described here. Apparently, one make of charcoal gasification plant was designed for export to India in 1901. One other insightful remark from this work is the problem of manufacturers in those days being simply interested in producing the plants, selling and walking away without consideration for subsequent support, a feature which appears to continue even today. Describing the fascinating developments of the second world war period in Sweden he states "…In December 1939, about 250,000 vehicles were registered in Sweden. In the beginning of 1942, the total number of vehicles still in service was 80,000, about 90 % of which were converted to producer gas drive with in an year and a half. In addition almost all of 20,000 tractors were also operated on producer gas. Forty percent of the fuel used was wood and rest charcoal. Dried peat was used to some extent.

This fast and almost complete conversion was accompanied by a drastic decline of imported petroleum from 11 million barrels to almost 800,000 in 1942".

One another point that is made is that gasifiers are highly fuel specific and therefore there is need to be careful about the nature of fuels used for gasifiers. This does not seem to be consistent with the understanding reflected in later chapters of the thesis. It is not clear at all why the gasifier should be so sensitive to the properties of the bio-fuel to this degree of alarm. Surely, use of bio-fuel does not imply sanction to mix it with sand, grit and other extraneous inorganic material and expect performance. But from all that has been known it is not clear at all that running gasifiers with a variety of biomass would lead to any problem whatever.

Chapter 6 deals with the properties of rice husk. While describing the causes of slagging in rice husk gasifier, the entire process is described in some detail. "… The fuel bed developed characteristic caves that were glazed with a layer of molten snow-while ash…. The cause of this slag formation is clearly localized complete combustion of the rice hulls to highly localized airflow. The formation of a cave or channel allows air to reach the carbon surface at an equivalence ratio of unity. Because of the poor conductivity of the fuel bed and radiation within the caves, localized temperatures remain high resulting in melting of the rice hull ash. The installed thermocouples showed only normal gasification temperature of 900 to 1200$^{o}$C. Thus, one might be tempted to wrongly conclude that slagging took place at low temperatures since the thermocouples were not placed where the slagging was actually occurring". The schematic of the slagging process is illustrated with a figure.

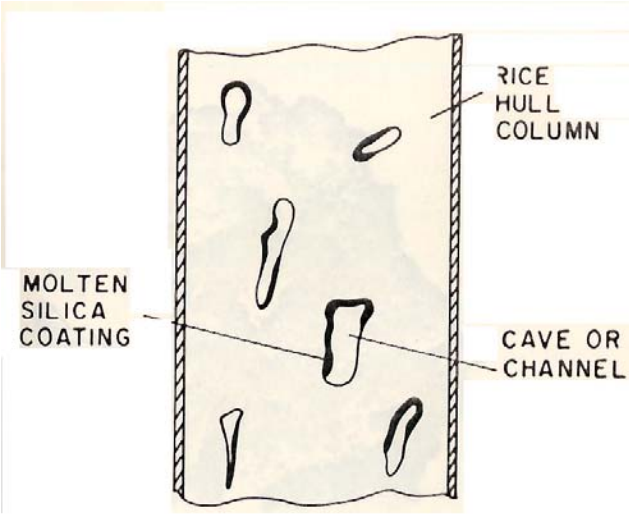


**Figure 2.8 Schematic of slag formation in a rice hull fuel bed (caves not to scale)**

As can be noted from Figure 2.8, the fuel bed develops caves with some parts of rice husk being glazed with the layer of snow-white molten ash. The cause has been identified as due to the complete localised combustion of rice hulls due to high localised flow. In these cases, the thermocouples showed only 900 to 1200 $^{o}$C. This should not be interpreted in terms of low temperature slagging, but that the correct peak temperature has not been picked up by the thermocouple. Somewhat similar features were noted with rice hull pellets. Although no channel formation was observed, hot spots were observed and in isolated cases melting and bonding at contact points.

Further discussion is presented on caking of rice hulls and pellets. Because of the shrinkage of the rice hulls during volatilisation, shrinkage around walls and at specific intermediate zones takes place allowing air to pass through these channels. This causes caking of pellets, due again to melt down of the ash at the edges.

Thus even though rice hull ash has a high softening temperature (> 1400 $^oC$), slagging and caking phenomena cannot be avoided at reasonably high superficial gas velocities. Unburned rice hull bed is considerably more stable than char bed. Rice hull channel formation velocity is about 0.2 m/s. Char hull channel formation velocity is stated to be about 0.1 m/s. Thus it is important to keep the peak velocities less than 0.1 m/s if channelling is to be avoided. At this superficial gas velocity of 0.1 m/s, the pressure drop across 1 m deep rice hull bed is 20 mm water gauge and can be taken to scale linearly over bed depths of as large as 5 m. The pressure drop across a char bed is about 6 times that across rice hull bed. Thus for conditions noted above the pressure drop is expected to be 120 mm water gauge.

Chapters 7 and 8 deal with the physical features of rice hulls under thermal decomposition and the associated pyrolisis products. Through the examination of photomicrographs, he concluded that the carbon is tightly woven into the silica skeleton in the rice hull. The size reduction due to pyrolisis is about 50 %. However, the length reduction is marginal. Char residue is brittle and disintegrates readily on the application of minimal mechanical force. In a rather loosely connected discussion on the optimisation of the generation of tar-like products, he brings out that tar or liquid production is enhanced for rapid pyrolisis conditions of a heating rate of a 1000 – 100,000 $^oC$/s. For gasification purposes, one should aim to generate little tar. This is favoured by relatively low heating rates , < 1 $^oC$/s (p. 164 of the thesis). Even this will not be adequate to meet the low tar levels demanded by engine operations. One should seek tar reduction in the reactor, perhaps by the char itself. Using realistic data – thickness of a hull of 0.25 mm, length of the hull of 1.5 mm, typical velocities of about 0.2 m/s, Reynolds number is estimated at 2 and Biot number at 0.06. These are further used to estimate the heat up time of the hull from 20 to 1000 $^oC$ as 0.5 s. For higher Nusselt numbers typical of fluid bed systems, the heat up time is reduced to lower than 0.1 s. Under these conditions, the generation of tar is significant and that is why fluid bed gasifiers and certainly circulating fluid bed systems become gas generators with unacceptably high levels of tar – far more than can be acceptable to reciprocating engines. Pyrolisis gas from rice husk in the temperature range of 250 to 450 $^oC$ is composed of about 55 to 60 % $CO_2$, 35 to 38 % CO, 2 to 4 % $CH_4$ and $H_2$, $C_2H_4$, and $C_2H_6$ totally composed of less than 1 % (the composition is on a dry basis). The average yield from pyrolisis is 45 % char, 18 % gas, 27 % water and 10 % dry tar. The energy fraction lost due to charring is 45 to 55 % on a dry basis. Rice hull char is composed of 45 % ash, 45 % carbon and the rest volatiles.

Chapter 9 addresses the important question on the cracking of tar in rice hull char bed. In the preliminary discussion he brings out that downdraft gasifiers with throat normally used in wood gasifiers cannot be used for rice hull gasifiers since its presence prevents smooth downward movement of the fuel essentially because it is light and the bridging tendencies are anyway significant due to factors discussed earlier. In an apparatus (taken from Kaupp’s thesis), shown below (Figure 2.9), the in-plane tar and the exit plane tar amounts are measured and the ratio exit plane tar to in-plane tar is taken as a measure of tar cracking ability.

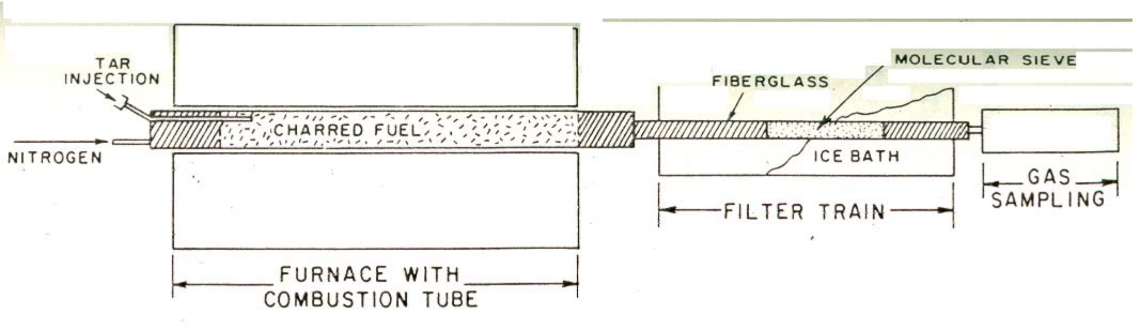


**Figure 2.9 Experimental set up for tar cracking tests**

Experiments were conducted both with rice hull char as well as pelleted rice hull char bed at various temperatures – 680, 800 and 900 °C. In the former case, the char surface area is 3000 to 4000 $m^2/m^3$ and the bed porosity is 75 to 85 %. In the case of pelleted char, the surface area is 300 to 400 $m^2/m^3$ and bed porosity 40 to 50 %. As a reference, the tar is run through the empty reactor and thermal cracking ability is also determined. The results from his work are presented in Figure 2.10.

It is clear that char does cracking of the tar catalytically since the tar conversion is much higher than in empty tube. Of course, as temperature increases, both curves come closer.

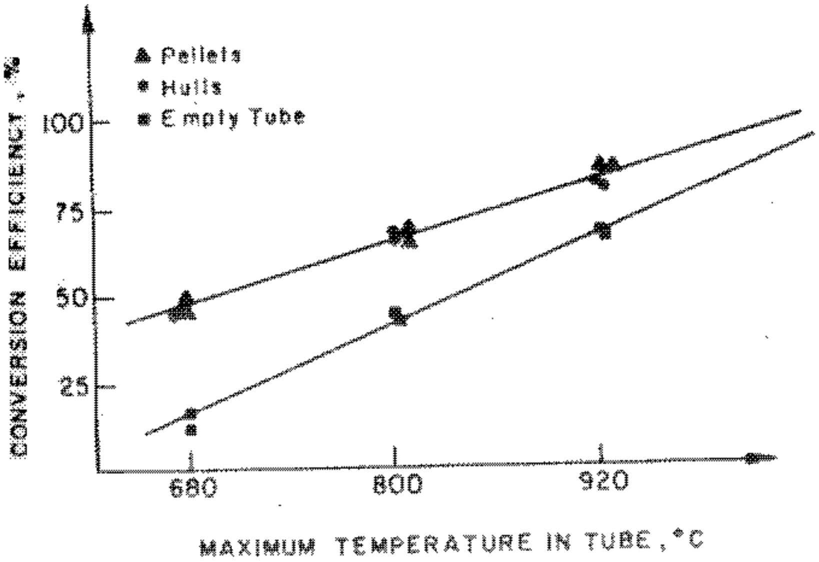


**Figure 2.10 Tar conversion efficiency, experimental results**

Chapter 10 contains a great deal of information on the design characteristics of rice husk gasifiers.

On the whole, the study of this work is very useful for anybody interested in rice hull gasification.

## 2.7 A series of papers by Tiangco, Jenkins, Goss and others:

V. M. Tiangco, B. N. Jenkins, and J. R. Goss, Optimum specific gasification rate for static bed rice hull gasifiers, Biomass and Bioenergy, v. 11, pp. 51-62, 1996; V. M. Tiangco, B. M. Jenkins, J. R. Goss, W. J. Chancellor, and I. R. Camacho, Variation of engine performance with reactor size for a rice hull fuelled gasification system, Paper No. 90-6076, American Society for Agricultural Engineers, 1990.

The gasification system considered for experimentation by them is shown in Figure 2.11. The reactor design is similar to the IISc open top system designed, built and tested in 1986+. The reactor is a twin shell system without a simple light up system. It has the other elements of cooling and cleaning system. The achieved gasification rates scale onto a superficial gas velocity vs specific gasification rate (SGR) plot with peak superficial velocities of 0.12 to 0.16 m/s. This range of values is consistent with the observations by Kaupp noted earlier (of 0.1 m/s to prevent local ash melting). They have measured the propagation rate of the flame front, both apparent and actual. The actual rate is the sum of the apparent rate and the settling rate. Figure 2.12 a and b show the results of these rates as a function of the specific gasification rate (SGR). For a superficial velocity of 0.1 m/s, the SGR is about 200 $kg/m^2h$. The measured cold gas efficiency from this system is presented in Figure 2.13. The peak conversion efficiency is about 55 % and occurs at SGR of 200 $kg/m^2h$, a value recommended for operation with superficial velocity of 0.1 m/s

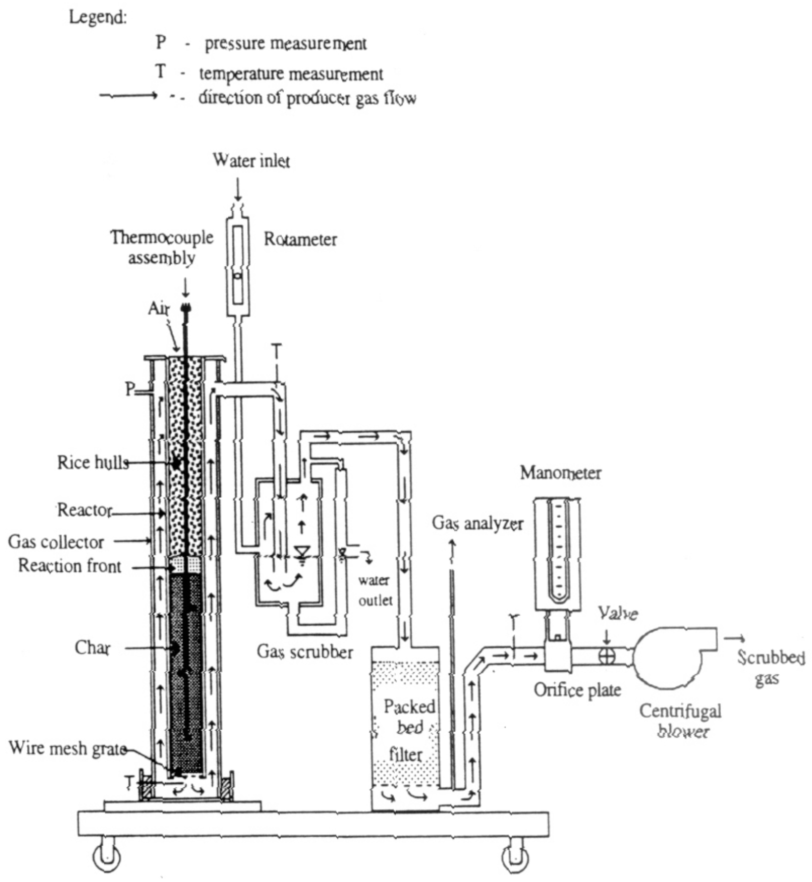


Figure 2.11 Schematic experimental configuration of the gasifier system

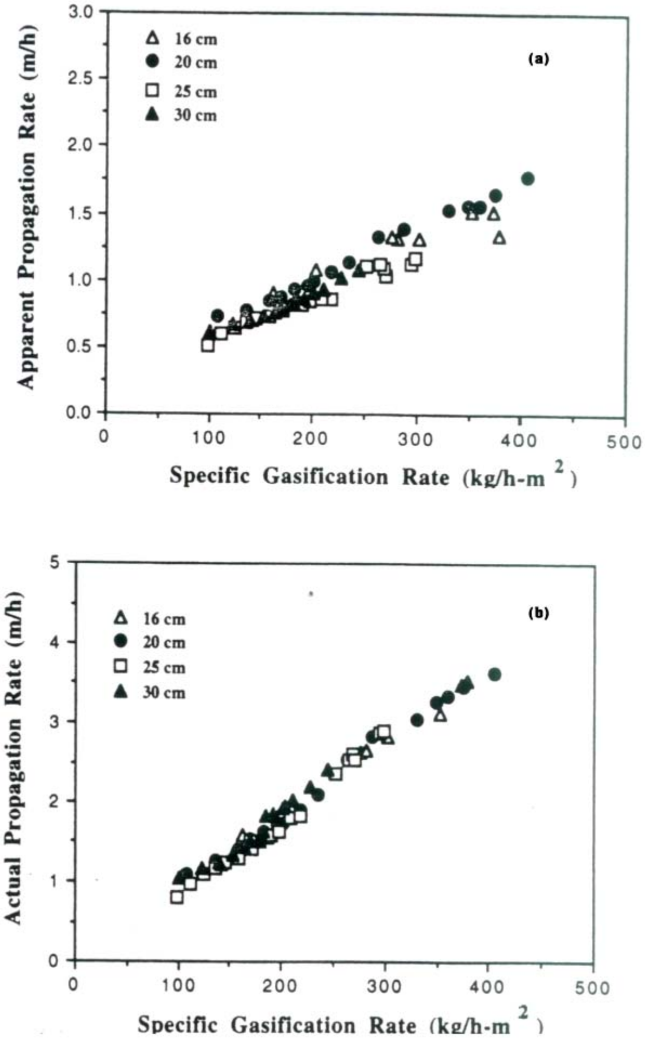


**Figure 2.12 Velocity (a) and actual velocity (b) of reaction front as a function of specific Gasification rate for 16, 20, 25 and 30 cm reactors**

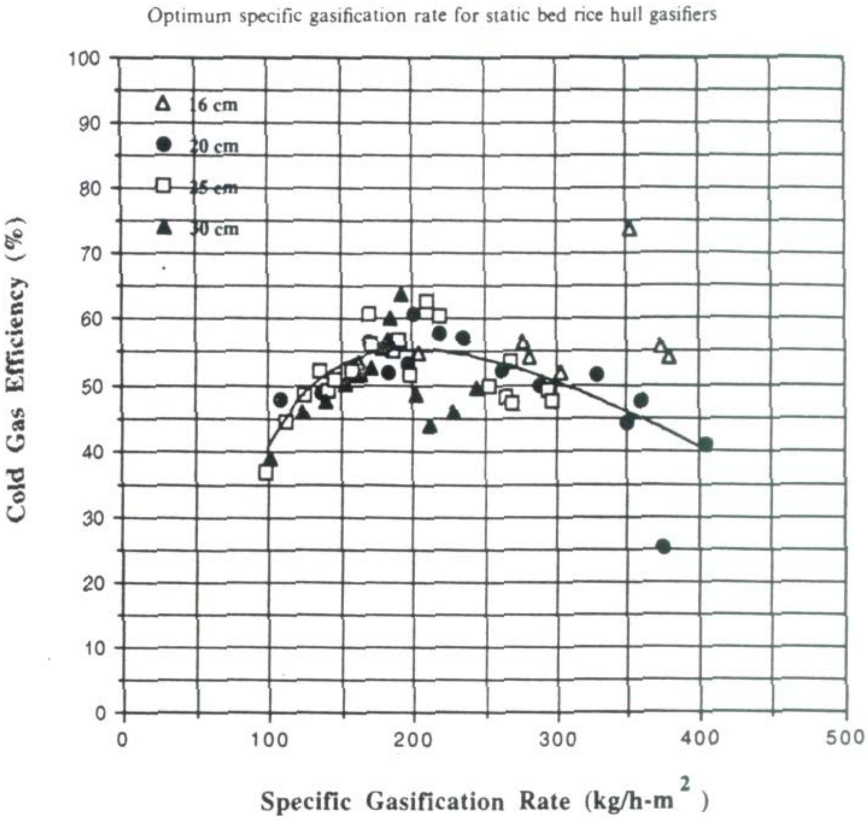


**Figure 2.13 Actual and computed gas efficiency**

The results of connecting the gas to an engine are described in the second paper identified above. The engine used was a Briggs and Stratton model 243431 single cylinder SI engine rated at 7.5 kW brake power at 3600 rpm on gasoline. The system configuration used is shown in Figure 2.14. (Fig. 1of the paper by Tiangco et al) The overall equivalence ratio of operation has been measured as being near unity. The output of the engine in producer gas mode is between 3 and 3.3 kW, about 45 % of the gasoline value and the overall thermal efficiency from rice husk to power is 10 to 12 %.

**Figure 2.14 System configfuration**

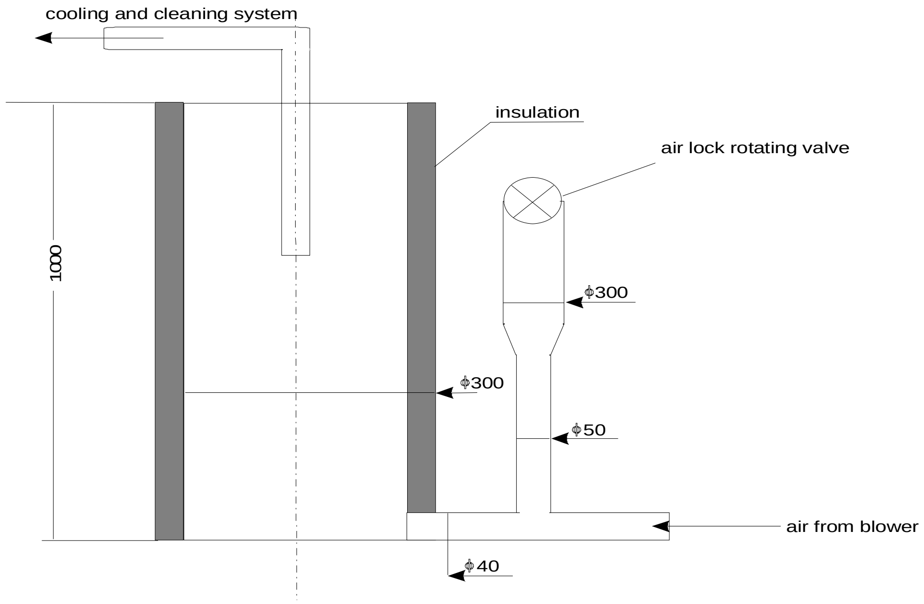
# Chapter 3

# The Current Work : The Cyclone gasifier

## 3.1 Initial reactor designs

As the basic data were being gathered, some reactor designs were tested, to obtain indicators for a possible good design. The need for high residence time for full conversion of char was thought to be achieved using a design called an inverse cyclone as shown in Figure 3.1

**Figure 3.1 The inverse cyclone system**



After the initial start up involving heating of the walls (using wood char and wood pieces), rice husk was fed into the reactor. Though there were problems of the rice husk feeding, these were largely overcome with modifications in the feed system. Combustible gas was obtained, but not of a good quality (as judged visually). After a while, there was build up of material on the inside of the reactor. The red hot char particles were found bridged in a symmetric cylindrical manner and had reduced the inside cross section of the reactor considerably. Beyond some point, feeding became a problem due to the increased resistance inside the system. Tests with powdered rice husk showed no better results. The fine char particles in the output gas were removed by a wet cleaning system. As the quality of the gas as well as the extent of char conversion were not satisfactory, this system was abandoned. But it can be said that the degree of investigation was inadequate to conclude that this design would not work. In order to prevent the material build up at the bottom, it was thought that one could use a water seal, a simple arrangement to take away the residue. It was contemplated to have a bottom feed for the powdered husk and a modification to the top region to draw away the gas from the central region and fed to a cyclone. This meant essentially a classical wood gasifier of open top design but with fuel feeding from the bottom. Figure 3.2 shows the elements of the system, which was a modified version IISc wood gasifier.

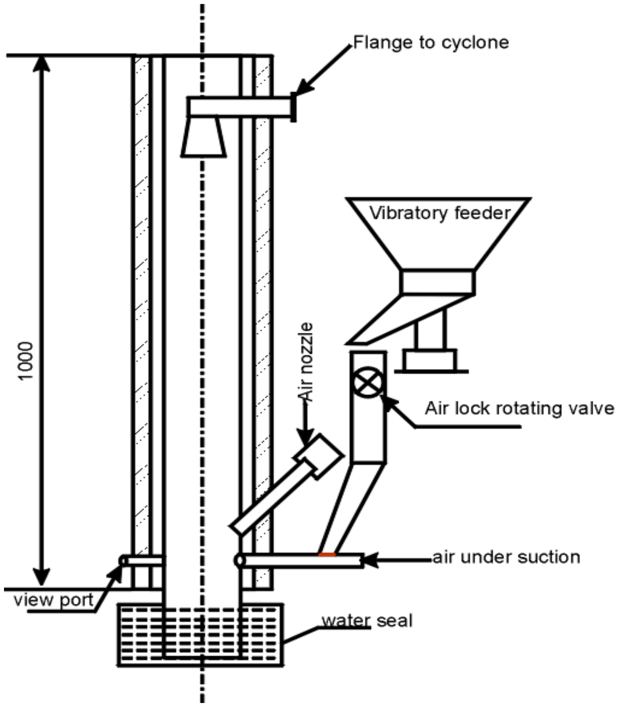


**Figure 3.2 The second design, a modified IISc woody biomass gasifier design**

After the initial start- up on charcoal and after ensuring that the wall temperature had reached 1000--1100 K, the powdered rice husk was fed. In the initial stages the gas quality was found fluctuating and after 30 minutes got stabilized to a reasonable quality gas (inferred only from visual observations of the burning gas) for about an hour. The cyclone removed the char and there seemed to be no conversion to ash. The residence time in the oxidising, high temperature environment appeared inadequate. The gas was found to contain tar. The temperature at which the wall stabilized and did not exceed 1050 K at any time and the upper regions were even colder. The lower temperature in the relatively large sized reactor (for the flow rates set at 1.5--2 g/s of fuel and 1.2--1.5 g/s of air) was thought to be responsible for the large amount of tar in the gas. Thus, this design produced average quality gas with high tar content and the gas generation rate was not consistent. Also conversion of the carbon in the char could not be accomplished. Therefore the above design was abandoned.

Then it was thought that perhaps the pyrolysis part of the rice husk could be handled efficiently in the cyclone, but a larger residence time was necessary for the char. Hence the cyclone with a short flaming zone was connected to a larger volume where the char could collect and possibly get converted. The system details are shown in Figure 3.3 This configuration took a long time to heat up and after feeding the rice husk powder, the wall temperature began to build up. However, shortly afterwards, it was found that the gas was not combustible.

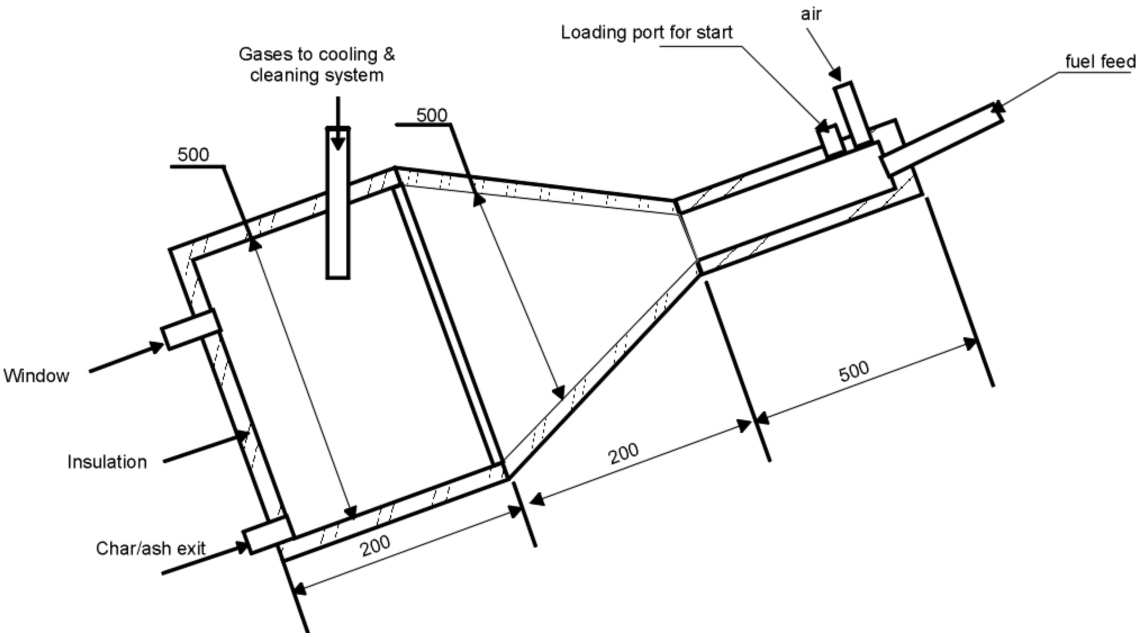


Figure 3.3  The third configuration

Nothing could be done to encourage the system to produce combustible gas though the A/F ratio was maintained near to unity. It was recognised that air was not available to the char in the downstream section and this was responsible for the non-conversion of char. Further it was observed that as time progressed the region near air entry got cooled and the combustion region was moving towards the gas exit. Clearly, the gasifier was approaching asymptotic extinction state. That is to say, the hot gases being taken away from the relatively high speed air entry zone could be counter productive in terms of stabilising the exothermic heat release zone. This system was therefore abandoned.

It was then thought that both flaming and char conversion zones could be separately fed with controlled air supply from a porous sloping metal surface which could remain hot because of heat release in the immediate vicinity. This led to another configuration. Again, initial start up took a long time. Combustion of rice husk was satisfactory and no conversion of the rice husk char was possible. Further, the gas coming out of the system was not combustible. The wall temperatures were in excess of 830 K in most places, and the temperature exceeding 1000 K in some places. Yet there was no combustible gas.  Further, efforts were abandoned since char conversion could not be effected in the system.

An examination of all these efforts showed that obtaining white ash from rice husk is possibly a stupendous task as the ability to provide enough air/oxygen to the char particles for sufficient time seemed extraordinarily difficult. At this stage, it was thought that the cyclone experiments performed two years earlier were readopted, abandoning the efforts to obtain white ash.

The final adopted version based on normal cyclone operation is shown in Figure 3.4 a 25 kW thermal system.  Several intricate details of start-up, running the system at near constant power, the range of A/F for obtaining good gas with minimum tar, extracting the char in a passive manner were understood. It is  possible to obtain good quality gas for as long as is necessary. The essential idea during start-up is to heat the walls to in excess of 1000~K so that the transition operation with the powder is smooth. Once the reactor walls were hot, the fuel feed was started and gradually raised to the normal value, which was typically between 1.8--2 g/s (6.5--7 kg/hr).

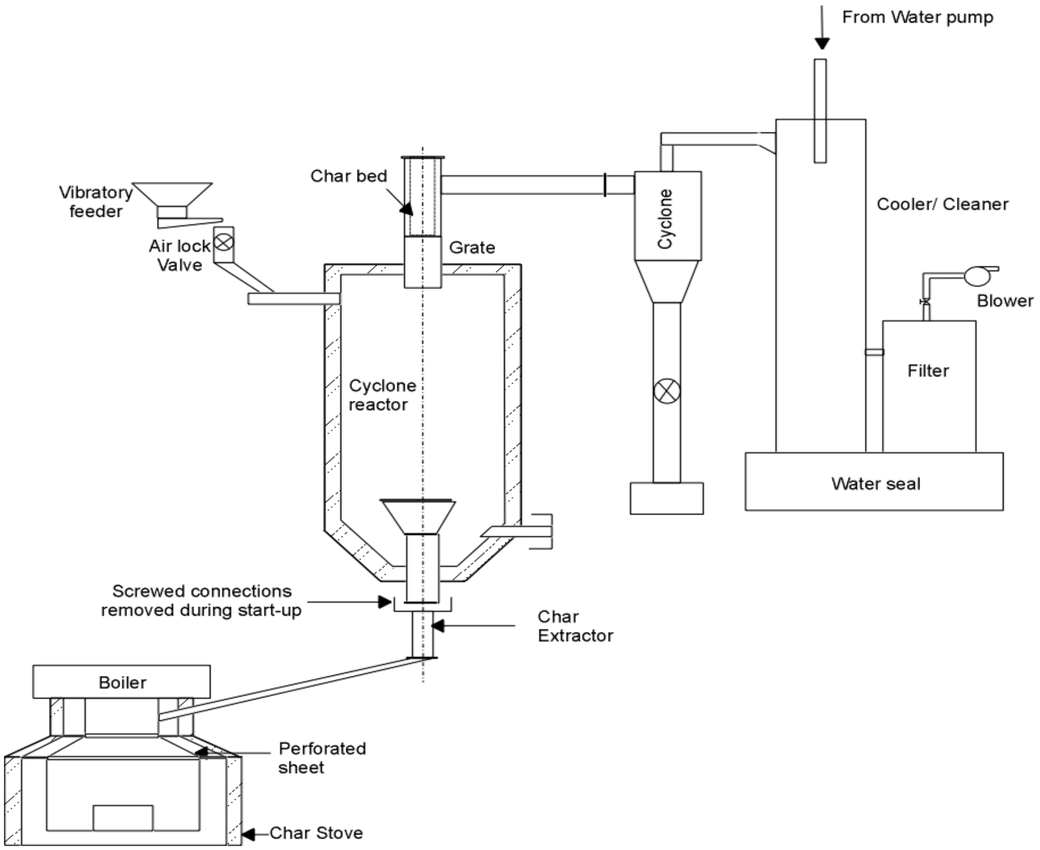


**Figure 3.4 The complete cyclone gasifier system**

The corresponding total gas flow rate measured by a venturimeter is about 3.8--4.5 g/s. Thus the air flow is estimated to be about 2--2.5 g/s. The A/F turns out to be about 0.9--1.1 or so. The gas quality was judged to be excellent. Measurements of calorific value of the gas resulted in the range of 5 - 6 MJ/kg. During the run, beyond A/F of 1.2, the gas quality dropped abruptly. The A/F was not reduced below 0.9 because of the possibility of generation of excess tar. The cyclone design inherently had inbuilt facility to discharge the unburnt solid residues using the simple cyclone principle. All this time, there would be minor pressure pulses inside the reactor which pushed about a few percent of the powder out of the air entry region at a frequency of 0.5--2 Hz. In fact these pulses were taken to be synonymous with good operating condition. In the cooling system, it was noticed that tar was estimated to be 250--350 ppm. This is not considered small and has to be eliminated.

Instead of using hot dolomite bed for tar cracking as reported earlier by several researchers, a bed of charcoal was used as an alternate. Tests were carried out on the system with the hot gas coming in contact with the char bed. For a reactor temperature of about 1200 K the char bed temperature was about 1000 K. At an A/F of about 1.2 for the case of rice husk, the charcoal consumption was about 6 - 10% of the total rice husk consumed. Runs up to 4 hours had indicated consistent gas quality with low tar content in the range of 100 ppm.

In order to investigate the performance of the gasifier with other powdery biomass, sawdust was used for gasification. At a gas flow rate of about 4.5 g/s a steady quality gas was obtained with an A/F of about 1.8. This increase in A/F compared to that for rice husk is due to the volatile fraction in the saw dust being more compared to rice husk. Reactor and char bed temperatures of 1200 K and 1000 K respectively, were recorded. Analysis of the ash content in the char indicated that the carbon in the char had got partially converted which didn't seem surprising as wood char is highly reactive.

Based on the above experience, a gasifier to energise a 100 kW engine, using powdery biomass as the fuel was designed in during 1991 Tests indicate that the scaling effect from the 5 kW version to the 100 kW level has benefited in establishing a better thermal environment, which is helpful in reducing the tar level in the gas.

### 3.2 The prototype — First generation

Prior to arriving at the present configuration of cyclone gasifier system several configuration were tried and tested. After establishing the reactor design, the system was tested using different forms of coolers and scrubbers. The elements of this first generation configuration is as follows.

#### 3.2.1 The Reactor

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. Conversion times of rice husk with hot air at 700 $^0$C suggest that flaming times are 1 to 1.5 s for individual husk elements and 5 to 7s for the conversion of char into ash. For a group of particles put together rather randomly, the times of flaming are about 3 to 5 s for flaming and 100 to 150 s for conversion to ash. Some pieces get shielded by other particles and conversion is not complete. Conversion in a hot atmosphere of the products of combustion was very slow and did not seem complete at all. These results suggested the need to pulverise the husk. Pulverised particles at sizes of 1.0 mm or so showed flaming times less than a second and char conversion times of about 3 to 5 s depending on the arrangement and access to oxygen. The experiments in a hot environment of products of combustion showed again inordinate times for the conversion of the char. These led to the conclusion that it may not be possible to expect the conversion of the biomass, more specifically rice husk to ash completely in a single reactor since the times of flaming and conversion of char to ash are widely different. Partly converted char would have to be accepted. Experiments in a small cyclone gasifier suggested that residence time if allowed was large, agglomeration of the hot char particles would result leading to unwanted collection of the hot char inside the reactor so much so the functioning of the reactor would stop after a while. For the 250 mm dia small cyclone gasifier, pulverising was found essential because full or half husk feed showed that the heat release was restricted to a small region and 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 occasions there was little tar even after an hour of run; on others, there was unacceptable amount of tar in less than an hours' 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 100 kWe level since the cost of feed system itself prohibited the acceptance of the low power level system on an economic basis.

Keeping in mind the above features, a stainless steel reactor was designed. Figure 3.5 shows the details of a 100 kWe system. The details of the reactor is shown in the inset of Figure 3.5. The reactor was constructed completely using SS 304. The top portion was essentially cylindrical, measuring about 500 mm dia with the bottom tapering into a cone. The bottom end of the cone formed the exit for the char/ash. The reactor was provided with two tangential ports, one for pre- heating and the other for fuel feeding. There was provision made for measurement of wall and gas temperatures as shown in the figure. The outer surface was insulated with alumino-silicate blanket and further cladded with aluminium to reduce heat loss.

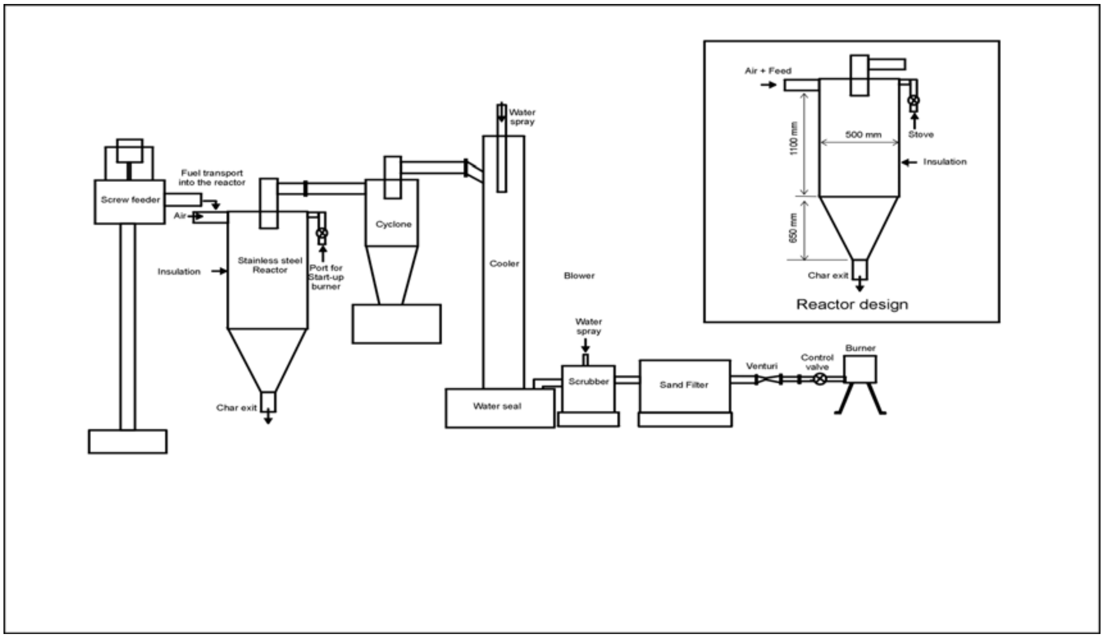


**Figure 3.5 Configuration of first generation Powdery Biomass Gasifier System**

### 3.2.2 The Start-up system

With regard to the start-up system, design involving pulverised fuel stove (with sawdust) was used successfully. The power level of the stove was typically 25- 30 kW with a burn time in excess of 30 min. The pulverised fuel stove was attached to the reactor during 20 to 25 min of heating time and detached when the reactor walls had gained sufficient heat and wall temperatures were typically 550 to 600 $^0$C. The four core (30 mm dia) stove as shown in Figure 3.6 typically measured 200 mm in diameter and 1200 mm height.

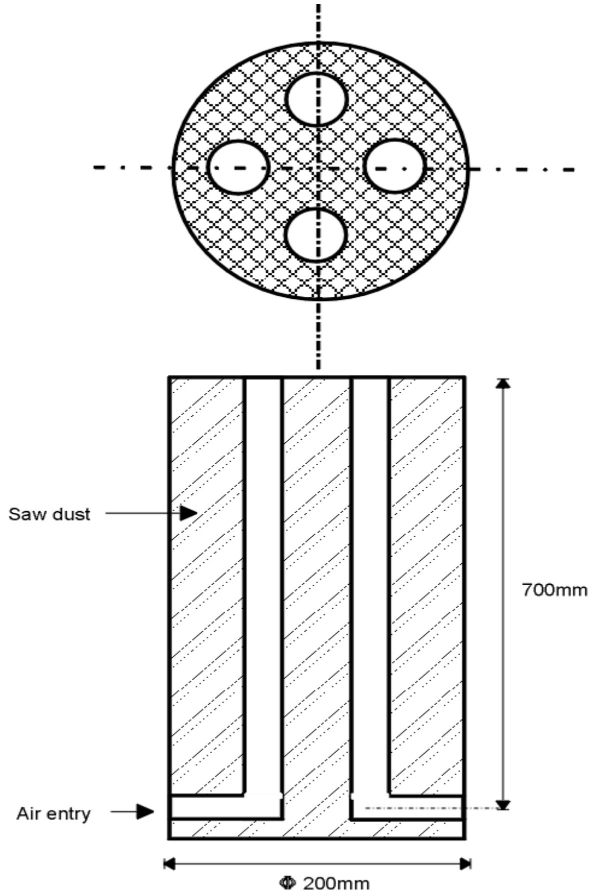


**Figure 3.6 Four core pulverised biomass stove**

### 3.2.3 The Feed system

The feed system based on screw conveyor was used for feeding the fuel into the reactor. The screw feeder was essentially mounted on a raised platform with the exit of the feeder being in line with tangential inlet of the reactor. The material delivered at the tangential entry was taken into the reactor due to the inflow of air caused by the suction of the blower. There was provision for varying the feed rate with in the feeder. The screw feeder was mounted on a weighing balance based on load cell arrangement. This directly displayed the feed rate in kg/hr averaged over few minutes.

### 3.2.4 The cooling system

Initially a cooling system based on water spray was deployed for cooling the gas, but the cooling effect was insufficient and the exit gas temperature was relatively high, causing condensation in the filter down stream. Therefore a cooling system based on principle of filtration pump for better mixing of gas with water was conceived as shown in Figure 3.7. A filtration pump is a device which works on the principle of an ejector. It has a line for the liquid and another for the gas. It carries a small reservoir at the base. When the liquid jet flowing in the line hits the reservoir and expands, it creates suction due to which the gas is sucked from the gas line. The two fluids mix thoroughly in the chamber and there after the gas is exited from the top and the coolant from the bottom. A sub-system was built in similar

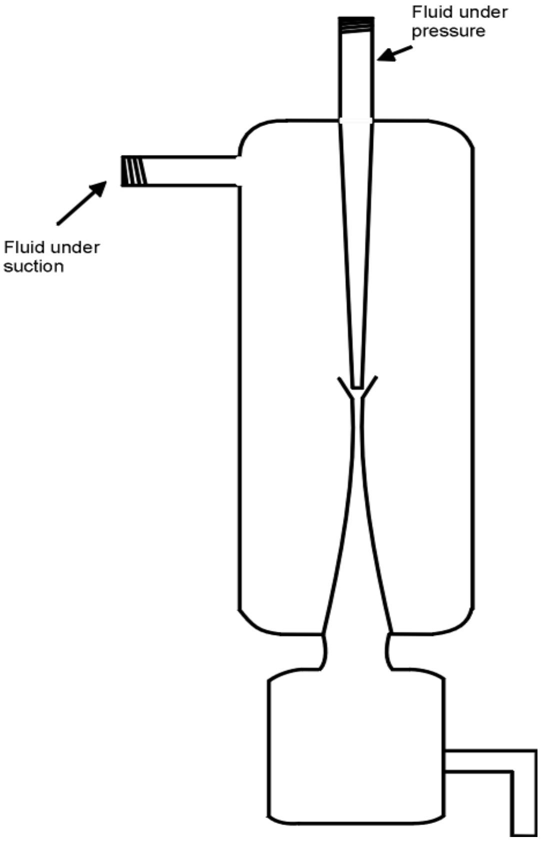


**Figure 3.7 Filteration pump**

lines but of slightly larger dimensions and deployed in the circuit. Measurement towards static pressure and temperature were made at strategic locations so as to evaluate its performance. But as the test results were not impressive, an additional cyclone with a inner water spray arrangement was experimented. The system performed fairly well, even so this was changed to an impinging water spray arrangement.

### 3.2.5 The Scrubber

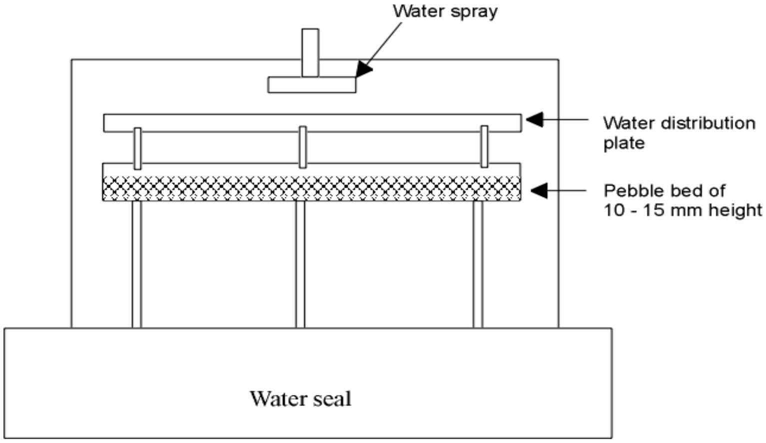


**Figure 3.8 Scrubber**

The scrubber was formed by a thin layer of pebble bed of 5mm size spread over a perforated mesh as shown in Figure 3.8 A water spray arrangement was provided above the pebble bed. A thin layer of water of constant height (about 5 mm) was retained on sand bed with the excess water over flowing. The gas was sucked by bubbling through the sand bed and water layer, in the process there was mass transfer in the form of dust and tar to the flowing water. It was difficult to draw definite conclusions about its performance. This was dispensed in the subsequent tests.

### 3.2.6 Sand Filter

A two tier sand bed filter as shown in Figure 3.9 having a filtering area of 1.5 $m^2$, with a bed thickness of 90 mm, comprised of 250 - 650 ❍m sand particles was used as a security filter. Earlier to arriving at two tier system, a cylindrical filter formed by a bed of 60 mm thick was used for some time.

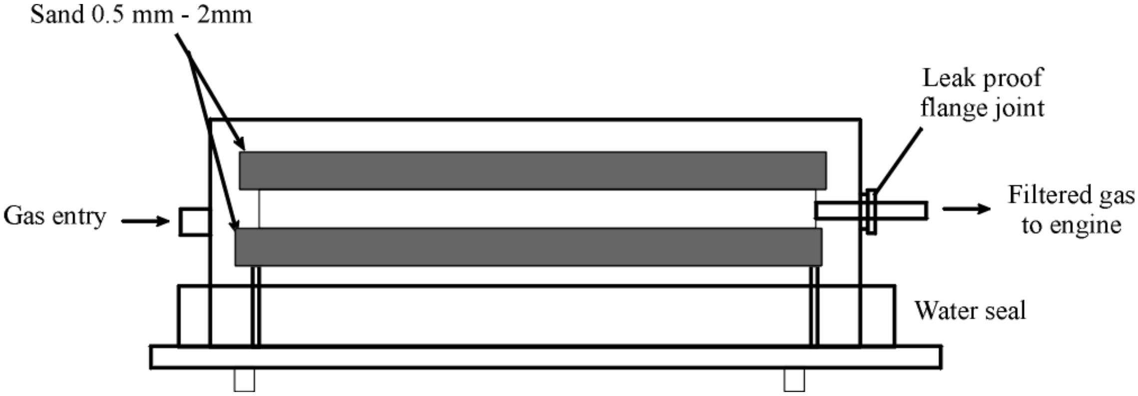


**Figure 3.9 Sand bed filter**

Using the first generation configuration a series of tests were conducted using both rice husk and saw dust amounting to over 60 hrs duration. During the course of these tests, several problems were encountered and overcome to some extent. There were a number of changes made particularly in the cooling and cleaning train in order to arrive at a more reliable system. In the course of these runs unusually high tar was generated in the process of gasification. Pressure drop problems in the filter downstream were experienced. When the reasons for high tar generation was carefully examined, there was a basic flaw detected in the cyclonic reactor design. Entry velocities in excess of 10 m/s is a prerequisite for adequate cyclonic action. But in the present reactor it was discovered that the entry velocity was of the order of 5 to 6 m/s which was far below the requirement and a possible reason for high tar generation. To get the required velocities modifications were required in the tangential entry region. But as the reactor exit was distorted beyond possible repair, a new ceramic reactor was thought to be more appropriate incorporating the necessary modifications.

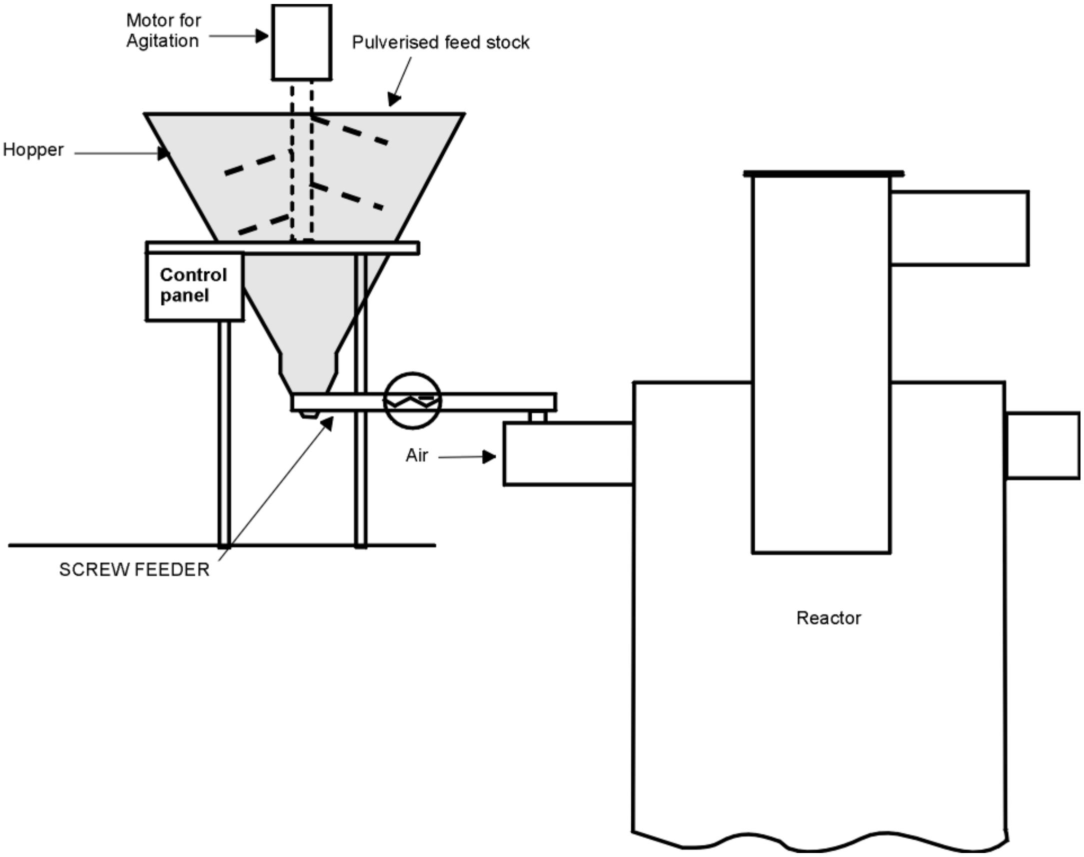
## 3.3 Development of sub-systems

In our effort of developing a cyclone gasifier, several sub-systems had to be developed in parallel in order to meet the specific requirement of the gasifier system. Among these the feed stock conveying system and the start-up system assumed major prominence.

### 3.3.1 Feed stock conveying system

Several configuration of feeders were tested for consistent feeding of fuel into the reactor. These include the screw feeder, pneumatic feeder and the vibratory feeder. Screw feeder was tried by placing it on a elevated platform, slightly above the tangential entry of the reactor. The material falling due to gravity at the tangential entry port was getting carried by the in flowing air into the reactor. This configuration was tried in the first generation prototype system for quite some time as shown in Figure 3.10

**Figure 3.10 Screw feeder fuel feed system**



But there were frequent problems of material pileup at the reactor entry and screw feeder jamming. It would have been possible to eliminate the feeder jamming problem using vibratory feeder but the material pile up would still persist. Therefore it was thought it would be more appropriate if the material is conveyed in pressure mode. As a result of this line of thinking a pneumatic feeder was conceived and built at the laboratory. The pneumatic feeder working on the principle of ejector conveys feed at an air to fuel ratio less than 2% of the stoichiometry. This needed a special design with compressed air at 0.5 MPa, which means it required an air compressor of the order of 6 CFM capacity. The feeder consists of two stage ejector as shown in Figure 3.11. The air as it enters the primary ejector section, expands over a small volume thus causing suction in the vicinity. Around this vicinity is the hopper built to contain the feed material. In the process the material is picked by the flowing air and exits the feeder with some momentum. This helps the movement of the pulverised fuel into the bottom section. Keeping walls of the conical bin smooth material movement was achieved with no problem. In order to convey the feed over a particular distance (about 2.0 m horizontally or at 2.5 m along an inclination) the momentum of the particles needs to be enhanced and this is done using secondary ejector. Typical diameter of primary and secondary jet is 1 and 1.5 mm. The feed rate was measured by placing the feeder on a electronic balance, which indicated the feed rate averaged over certain period of time. This

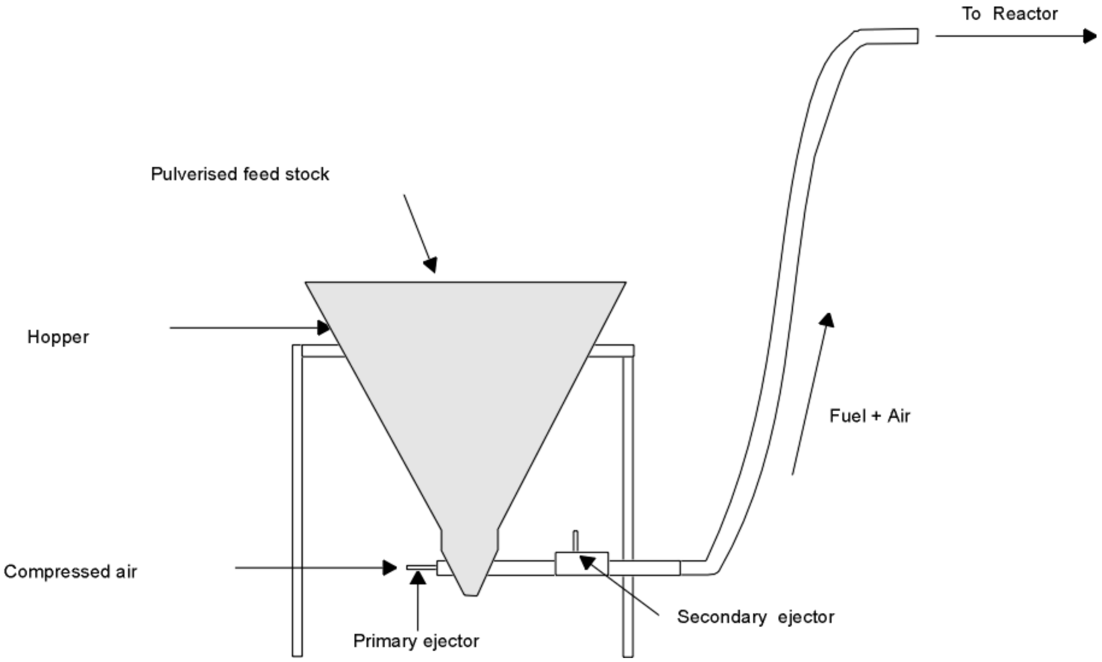


Figure 3.11 Pneumatic fuel feed system

was cross checked by quantifying the total material used. The fuel feed rate that could be achieved with this system was just about 75 to 80 kg/hr but can be enhanced using a higher capacity compressor. A typical calibration chart of pneumatic feeder using rice husk is shown in Figure 3.12

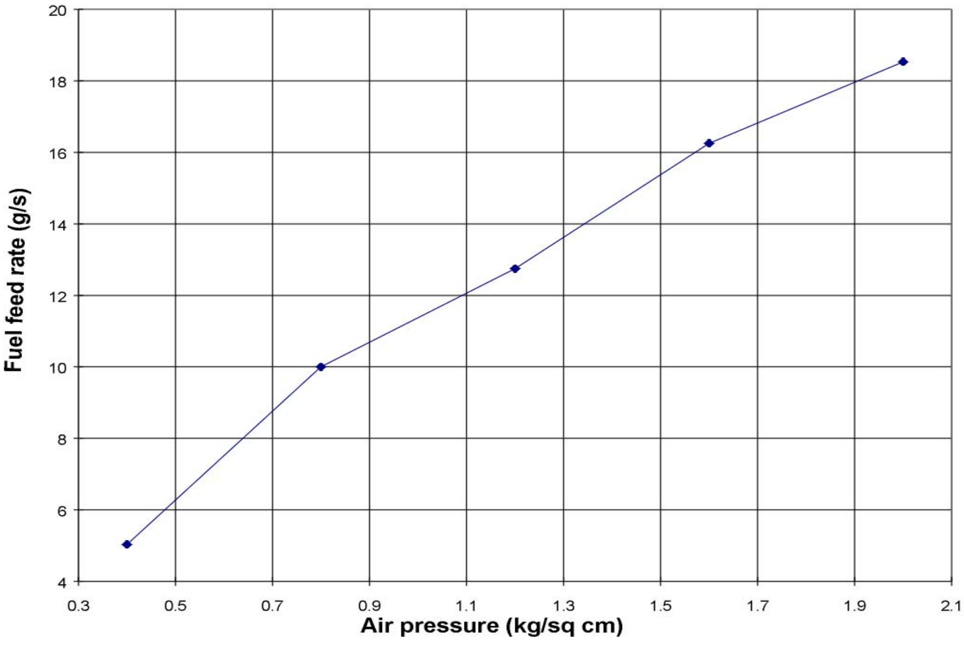


**Figure 3.12 Calibration chart of pneumatic feeder using pulverised rice husk (about 2mm size)**

The pneumatic system performed well in conveying pulverised fuels like saw dust and rice husk. The consistency in feeding rate was pretty high and accuracies was within + 5%. But the system was quite sensitive to the mean particle size of the feed material. Change in the size meant the system had to be recalibrated. However, with sugar cane trash, there were two problems. Firstly, the material was not moving down; perhaps the self weight was inadequate for the material to move down by itself. Secondly, because of the low density, the maximum feed rate whatever was nearly one sixth of pulverised rice husk. Both these were such that this system of feed was to be abandoned for sugar cane trash.

As the pneumatic system was sensitive to the nature of feed, a feed system which could perform irrespective of the nature of feed was thought to be more appropriate from the point of operating the gasifier on a variety of feed materials. This line of thinking got us back to the screw and vibratory systems. Using one of these systems in conjugation with blower will be able to meet the feeding requirement. It is possible to mount the blower and feeder systems at floor level and convey the feed to the required height. The feeder basically does the metering work and the blower conveys the feed to the required height (about 2.5 - 3.0 m). It was found doing experiments that for a 100 kWe system a blower with a discharge of less than 200 $m^3$/hr at 200 mm wg would suffice the requirement of 60 to 75 kg/hr. Experiments with vibratory feeder revealed that there was a tendency for particle separation with the coarser material moving on to the top thus causing changes in the feed pattern, especially with rice husk. This change in the feed pattern has effect on heat release rate and in turn results in fluctuation of reactor wall temperatures. As a mixture of fines and coarse is the desired pattern of feeding, vibratory feeder failed to meet the requirement in case of rice husk. Therefore once again the screw feeder had to be considered to perform the task. The screw feeder which was bought for this purpose had a agitator arrangement provided in the hopper to prevent void formations and thus changes in feed metering rate. The new arrangement of the screw feeder and blower is shown in Figure 3.13

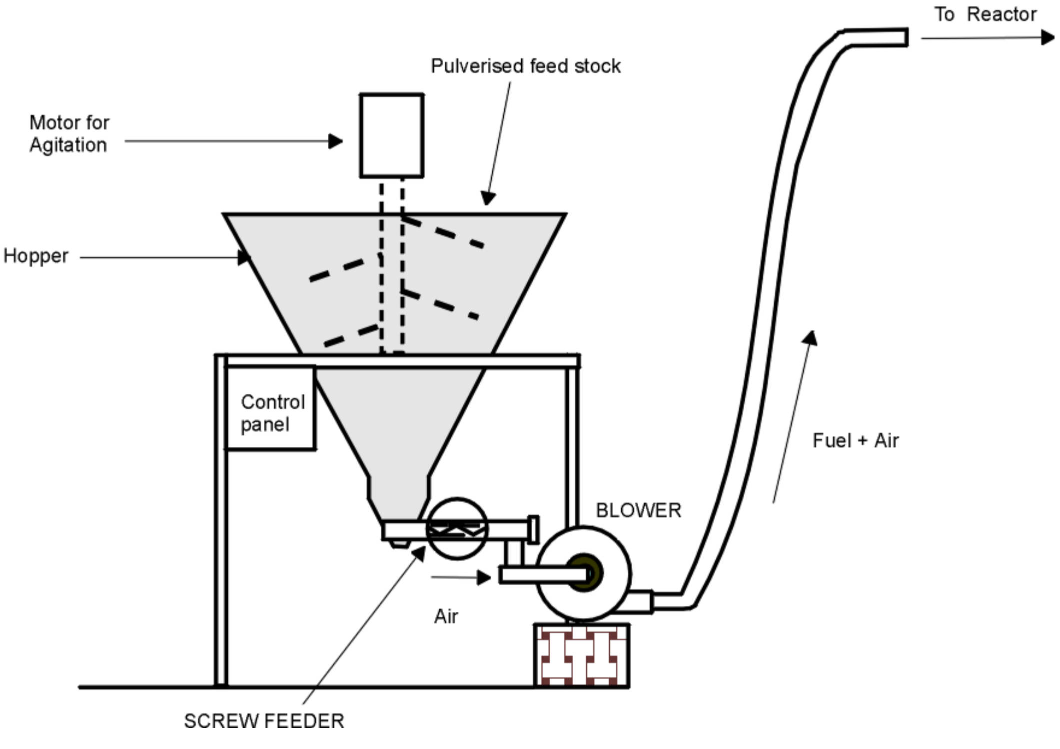


**Figure 3.13 Screw feeder and blower based fuel feed system**

The screw feeder is powered by a 0.5 hp DC Motor and driven through a speed reduction arrangement. The speed of the screw could be varied by varying the input voltage of the DC Motor and thus the amount of feed metered. The feeder was pre-calibrated for a particular sized feed stock at different input voltages and in turn these voltages were used for setting at a particular feed rate for the operation of the gasifier. The calibration chart for pulverised rice husk is shown in Figure 3.14. The feed material that falls by gravity at the entry of the blower, gets carried due to the suction of the blower and the resultant air + fee mixture is delivered into the reactor under pressure. The blower required for this operation has to be of open vane type with discharge at the top so as to prevent jamming of material inside it. The conveying line provided at the exit of the blower is typically 35 mm diameter, with velocity being in the range of 0.5 m/s.

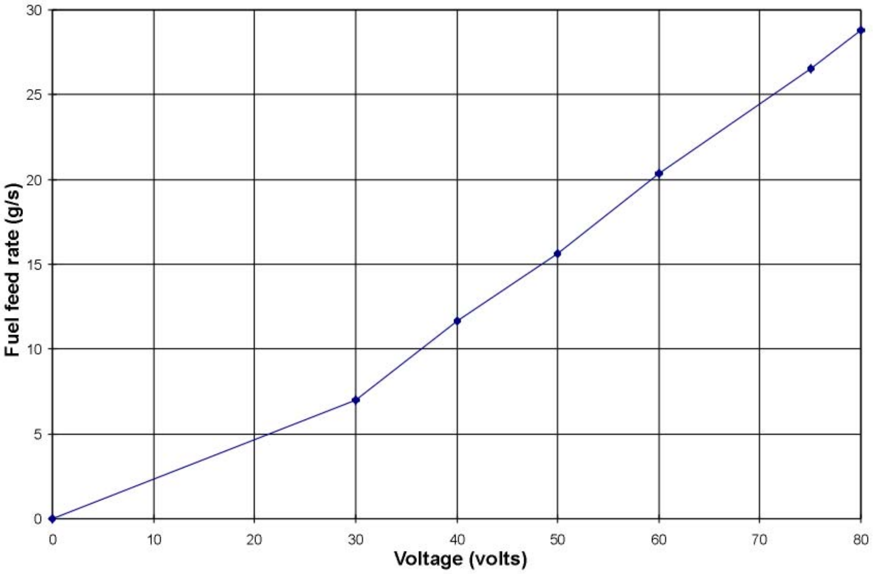


**Figure 3.14 Calibration chart of screw feeder using pulverised rice husk (about 1.8mm size)**

### 3.3.2 Start-up system

In the first generation system, pulverised fuel stove was used for initial pre-heating the stainless steel reactor to about 600 $^{0}$C. The power level of the multi-core stove was typically around 25 -30 kWth, measuring 200 mm in outer diameter and about 1.2 m height. Sawdust was mostly used as the fuel, with the burn time being around 35 to 40 min. Four cores, each of 35 mm diameter was used as shown in Figure 3.6, with the top surface covered with a layer of ash so as to prevent oxidation. The four cores provided the effective surface for burning, with air being drawn through the air ports. There were also additional air ports provided at the top so as to allow better mixing of volatiles with air and release heat. Energy of the order of 150 MJ was released in the heating period. The stove could be conveniently attached to the reactor during heating time and detached at the time of commencement of the feed. However, the four core stove was insufficient to meet the heating requirements of the ceramic reactor, due to larger thermal mass to be heated. Energy of the order of 120 MJ was required for heating the reactor walls. Therefore, alternate method of heating was explored and this led to the development of a kerosene burner of 60 kWth capacity. The initial burner tried was based on the principle of working of a pressure stove. The construction details of the burner is shown in Figure 3.15

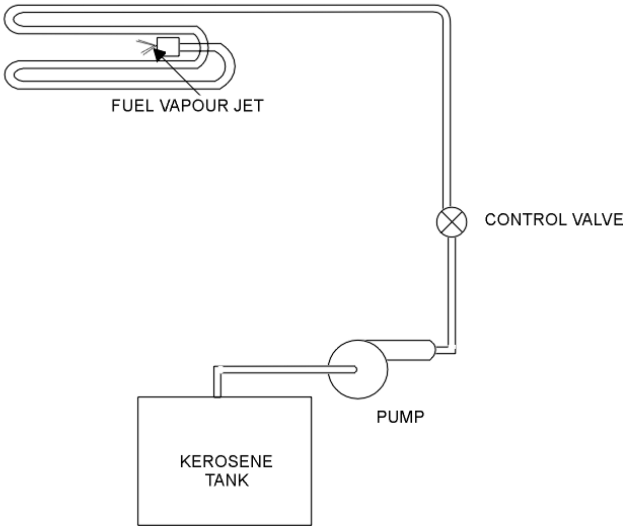


**Figure 3.15 The earlier kerosene start-up system**

A centrifugal pump for used for pressuring the fuel, which pumped the fuel to a coiled tubing, heated externally during start-up. The other end of the tubing terminated to a 2 mm diameter orifice, located axially with respect to the outer tubing, acting as a flame holder. The heating time with this system was typically around 30 to 40 minutes and worked fairly well except for few occasional blockages at the orifice. This led to the development of a kerosene atomised burner. The intricate details of the atomiser is shown in Figure 3.16

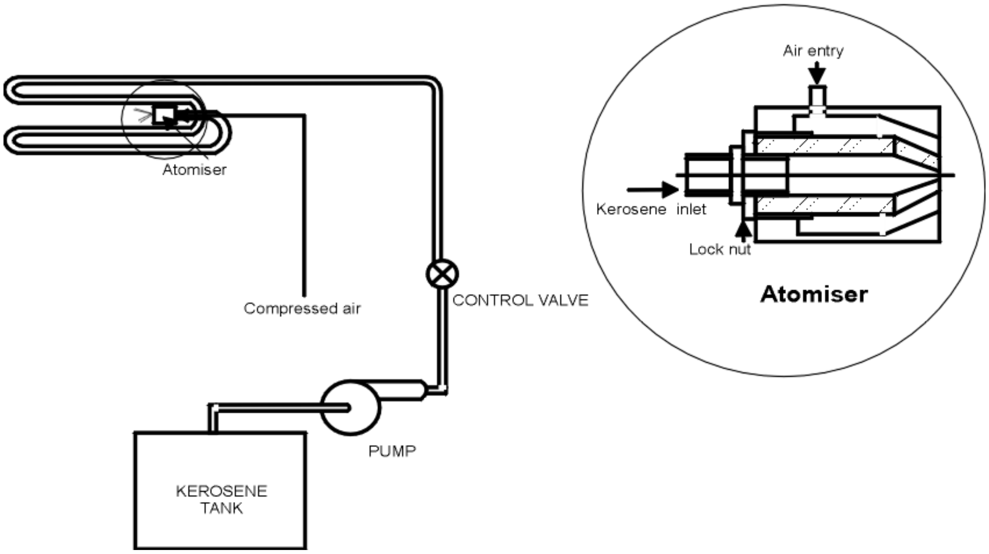


**Figure 3.16 The kerosene atomiser start-up system**

The atomiser was placed centrally in a outer tubing measuring about 70 mm in diameter, an additional flame holder was provided axially such that the atomised spray from the airblast atomiser directly impinged on to the flame holder. This was done with an intention of having a stable flame. The burner was started initially by supplying heat externally in a form of a wick flame. The required air was drawn due to the suction effect caused by the blower downstream of the reactor. The system became self sustainable once the atomised fuel got ignited with correct matching of A/Fs. The atomiser demanded an additional requirement of compressed air at 2 bar pressure for adequate atomisation of the fuel. Nevertheless, the performance of the system became much more reliable. In the latest design, a swirl effect has been introduced by providing a tangential inlet, measuring 100 mm x 20 mm for air entry thus making the burner flame more stable. The present configuration is shown in Figure 3.17. Presently the burner is started by supplying heat in the form of a wick flame, it is possible to automate it by providing a LPG burner with an in-built ignition system.

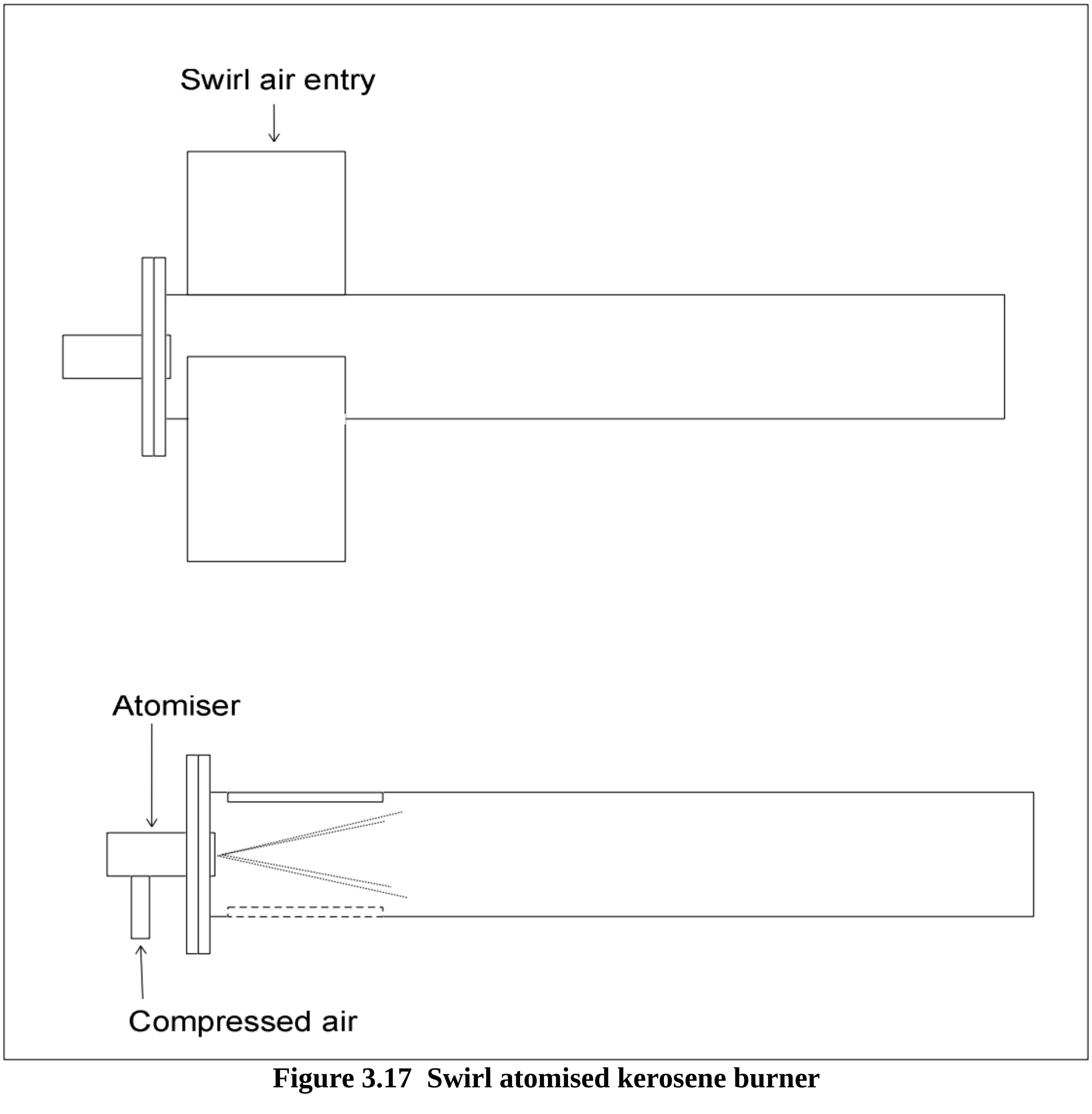


**Figure 3.17 Swirl atomised kerosene burner**

### 3.4 The Second generation Prototype

This system includes a new ceramic reactor and a cooling system, similar to the one used in IISc wood gasifier system. But there is a change in the clean-up system which includes a blower with a water spray arrangement. The schematic of the overall system is shown in figure 3.18. The system element details are as follows.

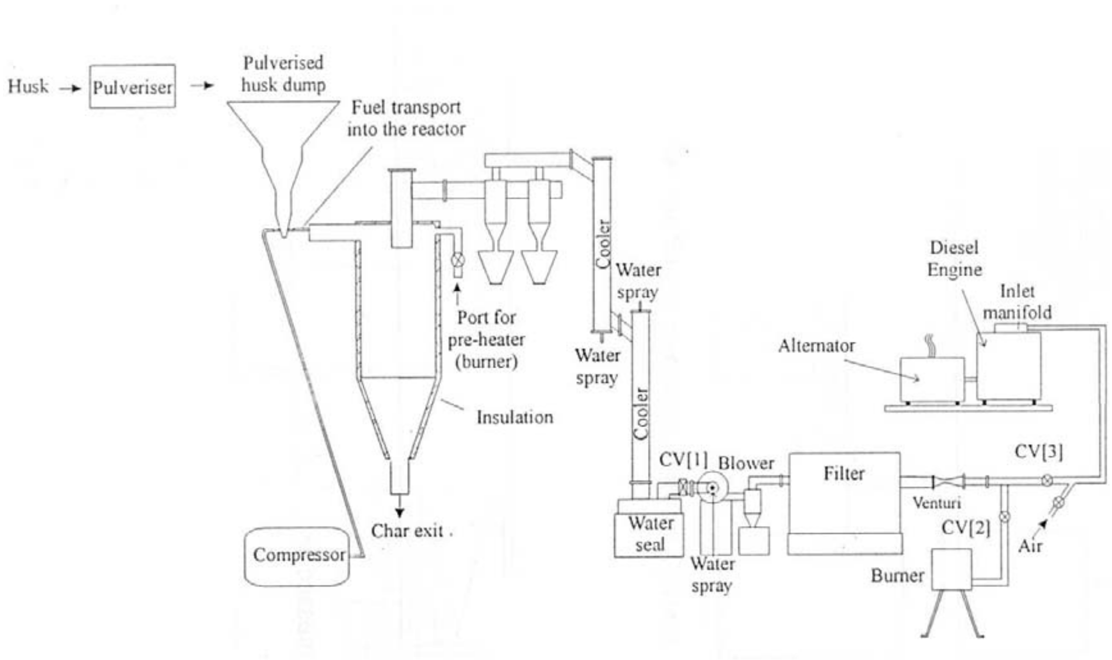


**Figure 3.18 Schematic of second generation Powdery Biomass Gasifier System**

### 3.4.1 The Reactor

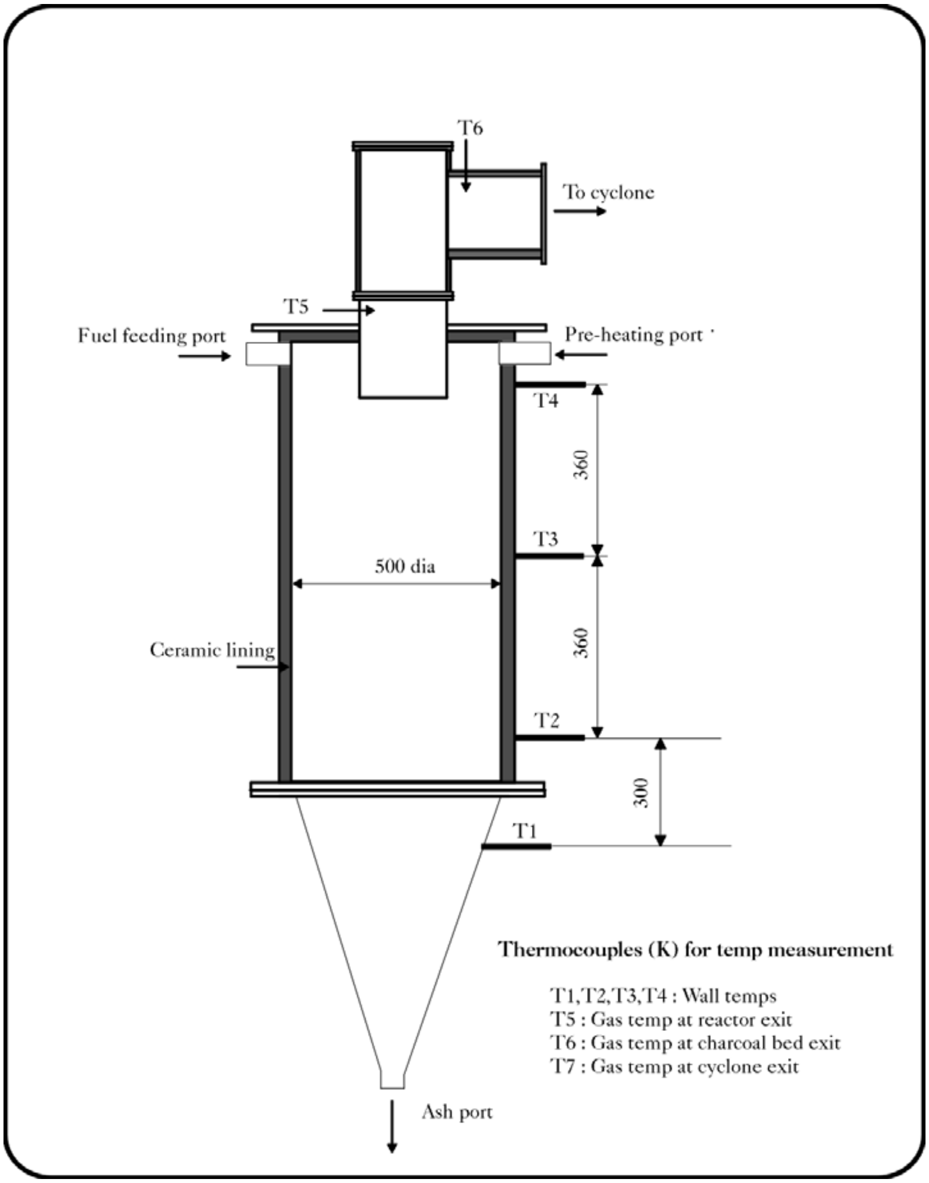


**Figure 3.19 Sectional view of ceramic cyclonic reactor**

Figure 3.19 shows the details of a 100 kWe reactor. It has tangential ports, one for heating the reactor as a part of the start-up system, another for introducing the pulverised fuel. It is also possible to have a single common port for heating and fuel feeding. The reactor has an outer mild steel shell, typically 3 to 6 mm thick of 0.62 m id, lined inside with 30 mm thick fire bricks (750 kg/m$^3$ density) and 30 mm thick rammed mass of whyteheat K of Associated Cement Company (2200 kg/m$^3$). This configuration is one of the several variants that could be successfully used for the inside. The top plate is also handled similarly with only the rammed mass. Typical qualification temperatures of these bricks are about 1000 C. Additional protection to the thermal environment is provided at the fuel entry location since the fuel-air mixture flows into the reactor along the tangential direction at fairly high speeds - 10 to 20 m/s. For a 100 kWe system the effective inner diameter of the reactor is about 0.5 m, height being 1.8 m including the conical region.

Normally the bottom of the reactor is open to the ambient atmosphere through a small exit duct as in a cyclone. 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. Typical exit gas velocities are restricted to about 1 to 2 m/s.

For a 2.7 MWth (625 kWe) system, diameter is about 2.0 m and height including the conical region about 3.5 m. For small power levels up to 100 kWe one tangential fuel feed port is considered satisfactory. At larger power levels it may be necessary to provide more ports provided the arrangement is consistent with rest of the system.

### 3.4.2 The Feed system

Amongst 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 kWe and beyond. The problems of the screw feed are that the material loaded into the hopper will not feed itself into the section containing the screw because of the low bulk density and wall friction allowing the material to remain stagnant even at large cross sections of the order of 400 mm. For this purpose a separate mechanical agitator is mounted on the top of the hopper to move the material towards the screw section. What is done is to disturb the material near the wall of the hopper and impart a motion towards lower region so that the pulverised material is helped to move down. Figure 3.13 shows the elements of the system. The system needs calibration 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 cyclone. The blower capacity in terms of pressure head should account for the above height difference and should have enough velocity so that the pulverised material can be carried into the reactor.

### 3.4.3 The Start-up system

Amongst many choices, a low grade fuel oil burner of the appropriate rating is to be used. Typically, it is of 40 kWth capacity (about 3.5 kg/hr of fuel oil) for a 100 kWe system and about 1.5 MWth (about 120 kg/hr of fuel oil) for 2.7 MWth gasifier system. These burners can be designed specially for this task or at higher power levels one can use commercially available burner systems. Figure 3.16 shows the elements of the system based on kerosene/diesel for the 100 kWe system. There is a atomiser provided to break the fuel into fine drops using compressed air. The atomiser is located centrally in a outer tubing measuring about 70 mm in diameter. There is tangential inlet, measuring 100 mm x 20 mm provided on the outer tube to obtain swirl effect. The fuel is pumped under pressure using a centrifugal pump and compressed air supplied from a pressure line. The atomiser demanded an additional requirement of compressed air at 2 bar pressure for adequate atomisation of the fuel. The burner is started by supplying heat externally in a form of a wick flame. The required air is drawn due to the suction effect caused by the blower downstream of the reactor. The system becomes self-sustainable once the atomised fuel got ignited with correct matching of A/Fs. Presently the burner is started by supplying heat in the form of a wick flame, it is possible to automate it by providing a LPG burner with an in-built ignition system.

### 3.4.4 Dust collection system

The hot gas exiting from the reactor top carry some amount of dust with it, which is largely char and ash. For engine application systems clean gas is a mandatory and this requires some form of dust collection device as a part of the system. A single cyclone was tried out as a dust collection device. Besides separating dust it provided additional surface area for heat dissipation and this in turn reduced load on the cooling system. But it was observed that the gas at the cyclone exit still had lot of finer particles, it was thought that multiple cyclones or multiclones would be helpful in the removal of finer particles by dividing the total flow among a set of cyclones. But the experiments proved the effectiveness of multiclones to be no different from a single cyclone in terms of dust collection and these are shown in Table 3.1. Hence the much simpler single cyclone has been accepted.

**Table 3.1 Dust collection in single & multiclone**

| Device | Dust collected (kg) | Amount of feed stock used (kg rice husk) |
|---|---|---|
| Single | 5 | 320 |
| Multiclone | 4.9 | 310 |

### 3.4.5 The Cooling System

For a 100 kWe system, the gas at the exit of the reactor has a thermal power of about 325 kW and a temperature of 750 to 800 $^0$C. This gas must be cooled to about within 5 $^0$C of the ambient temperature so that there will be no condensation of the moisture along the ducting or filter 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 externally convective and is intended to bring the temperature down to 200 to 250 $^0$C. The next step is to spray cool the gas flowing in the duct. Figure 3.20 shows the elements of the direct cooling system. Typical cooling water flow rates are 60 lpm at a head of about 30 m water. The cooling section is split into two parts one with a spray upwards and the next section with the spray downwards. The spray is of impinging type so arranged that spray holes of 3 mm diameter are large enough to pass wash water (being recirculated), yet atomisation being satisfactory. 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 should be adequate to run the system on a 10 to 12 hour/day basis without an active cooling system. The design of an external spray tower is called for if the availability of water is restricted.

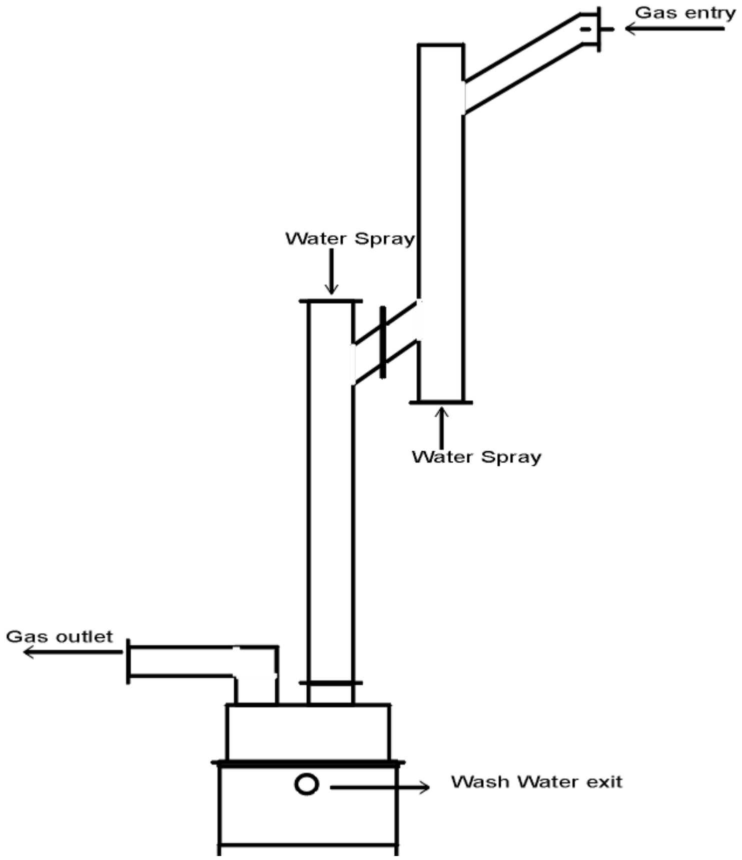


**Figure 3.20 The cooling system**

### 3.4.6 The Cleaning System

The direct cooling system is itself a major part of the cleaning system. About 80 % of the non-fine particulate matter and some tar related compounds will be taken away by the water due to intense contact with the gas. This is the reason for arranging both an upward and downward facing 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. Figure 3.21 shows the elements of this system. At the suction region of the blower, cooling water is arranged to be sprayed using a nozzle of about 6 mm diameter onto the hub of the rotor. The water spray gets finely atomised and agglomerate with the particulate matter. Due to the high rotational speed, the dirty mist hits the wall and flows with the water. When the layer thickness is reasonably large as may happen during the operation, the material gets washed out with the cooling water which 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 90 mm thick made up of sand particulates to size 1-2mm size and 2 $m^2$ cross section as shown in Figure 3.9 is usually sufficient to reduce the dust and tar content to less than 50 ppm each for a 100 kWe system with the pressure drop across the sand bed filter of less than 20 mm water gauge.

Typical operational times before which the sand bed filter is to be cleaned in about 250 hours. However, operation at off-design conditions and at mixture ratios more fuel rich compared to the designed value can call for the maintenance of this system at less than 100 hours.

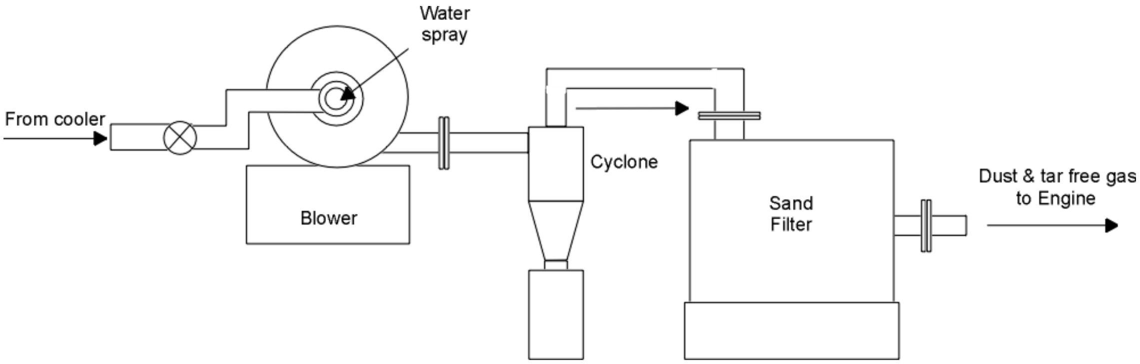


Figure 3.21 The blower clean-up system

### 3.4.7 Instrumentation

The system is provided with instrumentation for the measurement of reactor wall and gas temperatures at strategic locations. These instantaneous numbers are helpful in making judgement as to when to commence fuel feeding and when to changeover from combustion mode to gasification mode. A Chromel- Alumel (K type) thermocouple is used for sensing the temperature. The locations of these thermocouples are shown in Figure 3.17. The signal sensed by the thermocouple is conditioned and displayed digitally in degrees centigrade. There is also provision available for on-line data acquisition on a computer. Other than this, there is provision for gas flow measurement using a venturimeter in combination with manometer. It is also possible to display the flow in g/s using a flow transducer.

### 3.4.7 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 must be brought out that it is different from the control system needs of a wood gasifier where it is sufficient to control the gas flow rate. This is because the fuel feed is self-controlled in case of wood gasifier. The dual control in the case of 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 is generally ensured that the gasifier system operates close to the nominal working condition; for otherwise the temperatures in the cyclone system may stabilise at values at which the tar conversion will be inadequate. Load management is handled largely by bypassing the gas not required by the engine into a flare or a thermal system designed to use the waste heat from the engine exhaust.

### 3.4.8 The Engine-Alternator System

The power package is virtually unaltered except the air intake region. This is modified to accept the gas - air mixture. A large box acts as the air intake manifold in which two standard air filters reside. This forms the final part of the cleanup system. Valves on the air line and gas line are separately provided. A separate connection to a flare goes from the gas line to enable test check on gas quality as well as a ballast for receiving extra gas at the time of reduction in load or load trip.

### 3.5 Variants for thermal applications

In so far as the requirement of the gas for applications to internal combustion engines, the elements discussed above namely, the cooling and cleaning systems are essential. However, if the requirement is to generate heat - high grade for metal melting applications (1000 to 1300 $^0$C), medium grade heat for generating steam for power generation applications (> 600 $^0$C) or low grade heat for generating steam for process (> 300 $^0$C) - it is not necessary to cool the gas and in some cases not even be necessary to clean the gas. There are some applications like tea drying where it is essential that the combustion products which are used for drying food products like tea be clean if direct contact process is used as it happens in a part of the tea industry. To meet with the applications, two variants are suggested. Figure 3.22 shows the variant that is meant for boiler applications. The feed system with a blower to handle the pulverised fuel and the reactor are similar to the elements described earlier. The exit duct is connected to an ejector which can create enough suction to draw air through the tangential air inlet and account for the pressure drop in the cyclone reactor. The ejector is designed so as to pump the gas even in rich condition. This is to enable perform staged combustion to reduce the NOX emissions in the combustion process.

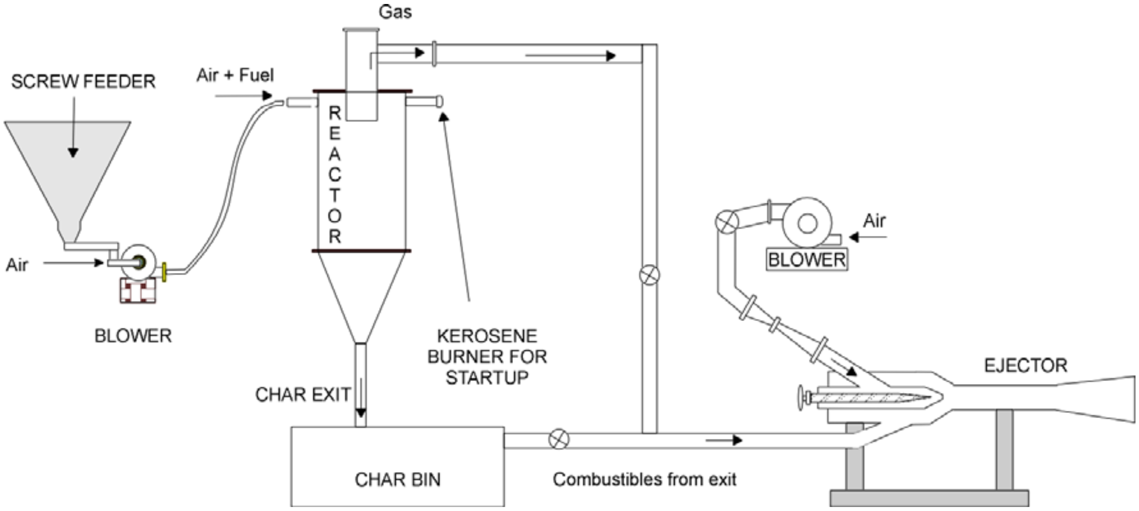


**Figure 3.22 Powdery Biomass Gasifier for thermal applications**

Figure 3.23 is the schematic of the system where the hot gas at the exit of the cyclone passes through a another cyclone to eliminate as much of fine dust as possible. This will reduce the dust loading from a typical 4 to 6 g/ m$^3$ to about 1 to 2 g/m$^3$. The rest of the elements are similar to the one described above.

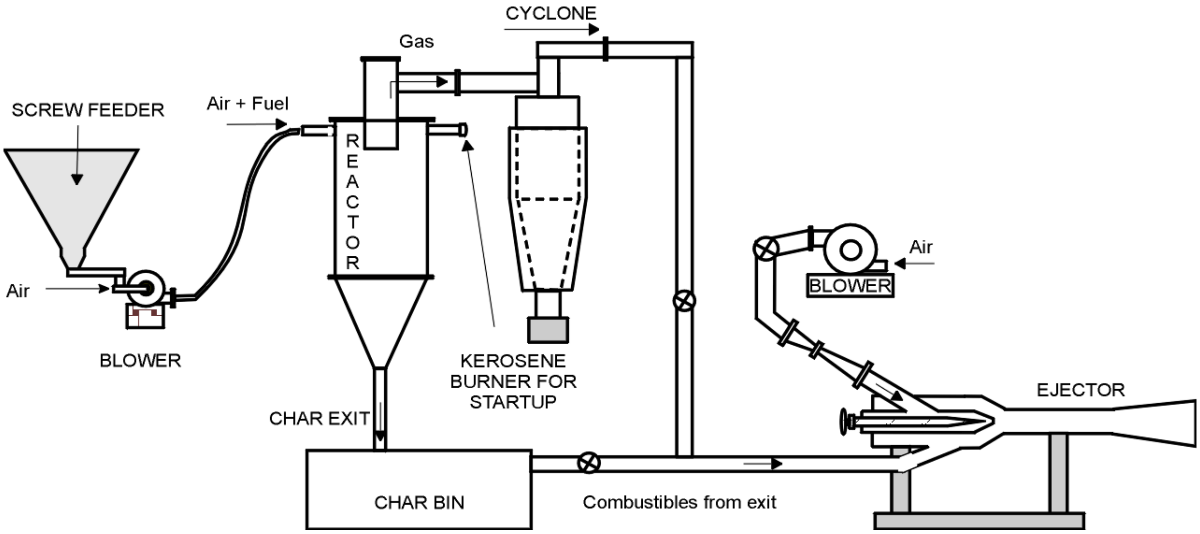


**Figure 3.23 Powdery Biomass Gasifier for thermal applications**

## 3.6 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 is the experience gained to determine the good performance of the system, experience has 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 are short duration tests involving measurements on part or whole of the system to understand the behaviour of the components. The hot tests where significant measurements have been made total about seventy hours with most useful data being obtained in about forty hours of test duration exclusive of the heating period. Most of the results are on pulverised rice husk; some data on sawdust has been acquired; limited experience on pulverised sugar cane trash also has been acquired.

### 3.6.1 Experience on Rice husk

One of the important questions to be asked is the size reduction which rice husk should be subjected to, as to whether size reduction is necessary at all. Initial experiments showed that rice husk per se either in the full form or half-piece form both of which were available (depending on the system adopted for the separation of the grain from the husk) were inadequate for the purpose of gasification as it was found that the gas quality from the system was inconsistent and inadequate. This question was specially important to be answered since it was known that the small 100 mm dia system needed pulverised fuel for proper functioning. Having decided that pulverising was required, the question was what would be the maximum size acceptable, since any further reduction would be both irrelevant and expensive.

A series of carefully constructed experiments in which the husk pulverised through different mesh sizes, 1.8, 2.0, and 2.2 mm were sieved to obtain their particle size distribution. Figure 3.24 shows the mass distribution of the pulverised mass. Experiments on gasification were performed with each of the samples in an otherwise similar condition for durations of one to

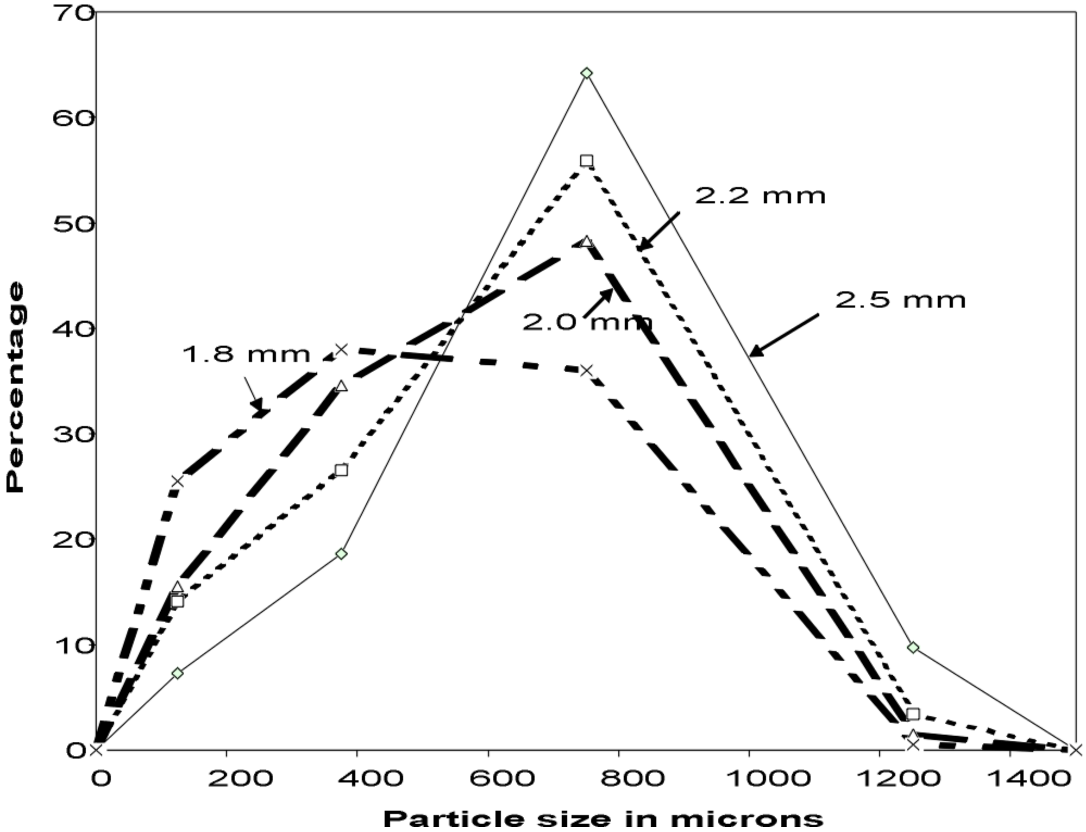


Figure 3.24 Particle size distribution of pulverised rice husk

one and a half hours. The wall temperature history from each of the experiments is put together in Figures 3.25 to 3.29. It seems clear that 1.8 mm and 2 mm pore size mesh fuels produce nearly same temperatures but 2.2 mm seems to be lower by 50 to 80 $^0$C all through. The gas temperature seems to have evened out in the process and all temperatures are nearly the same. It appears that 2 mm size mesh is essential and we may be putting more energy than required in pulverising the husk to below this size. Every unit of energy produces 16 kg pulverised husk with 2 mm mesh and 14 kg with 1.8 mm mesh. Another observation made during the test runs, namely, the residue from the bottom of the reactor appeared red hot in the case of 1.8 mm and 2.0 mm mesh fuels, but smoky in the case of 2.2 mm mesh fuel, indicates that larger size particles do not have enough residence time to undergo conversion and hence the pulverised fuel through the 2.2 mm mesh should not be used for gasification purposes.

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. Based on the tar and particulate analysis over a period of time (at the cold end just before the gas is led into the burner or engine), 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, 72 kWe 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 70 %. At this point the measured diesel replacement was 83 ± 2 % at a load of 50 kWe, 77 ± 2 % at 65 kWe. The change in air-to-fuel ratio for better operation on the engine

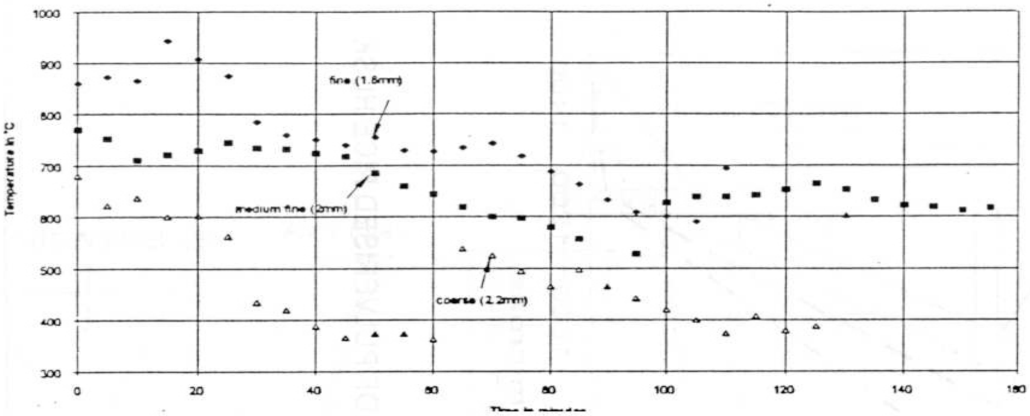


Figure 3.25 Variation of Reactor wall temperature [T1] with time

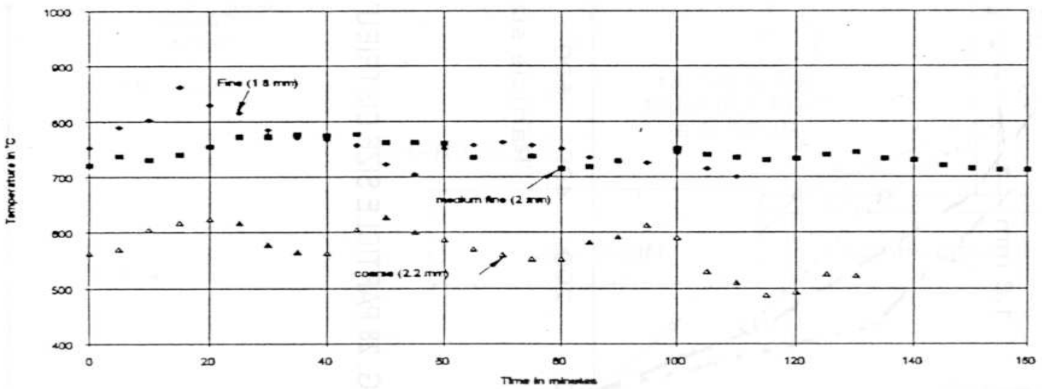
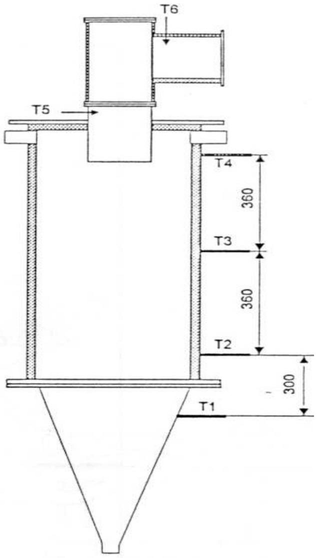


Figure 3.26 Variation of Reactor wall temperature [T2] with time



TEMPERATURE MEASUREMENT
POINTS ON THE REACTOR

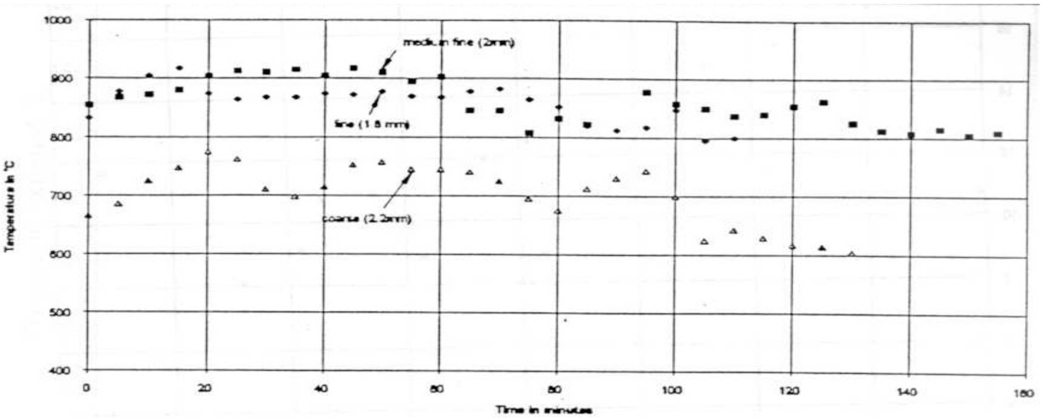


Figure 3.27 Variation of Reactor wall temperature [T3] with time

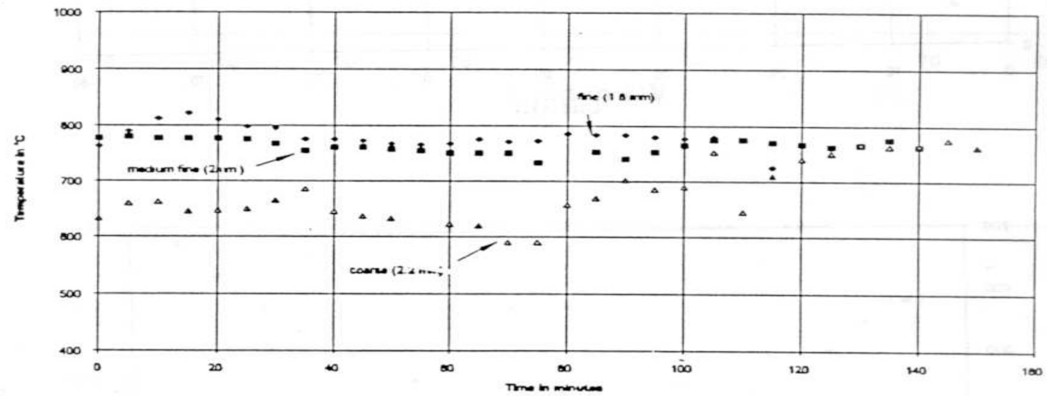


Figure 3.28 Variation of Reactor wall temperature [T4] with time

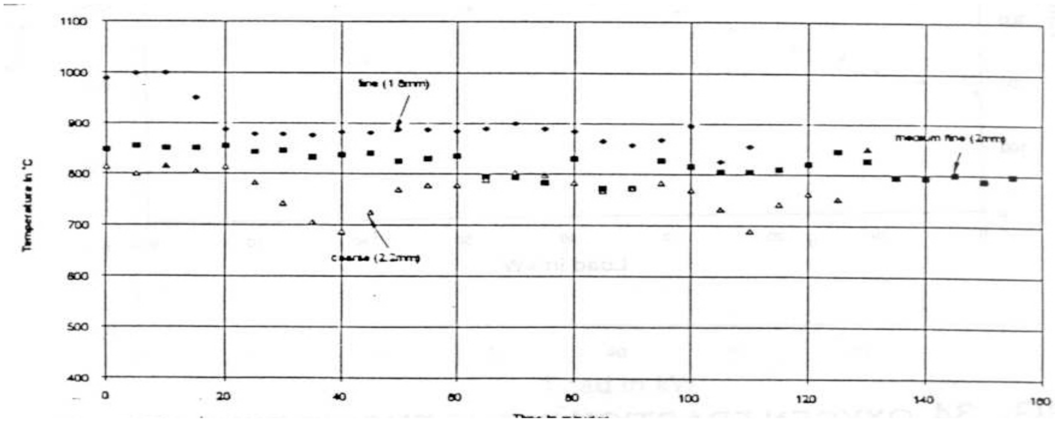


Figure 3.29 Variation of Gas temperature [T5] with time

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, this helping better the combustion efficiency. This explanation is tentative and needs to be reinforced by more careful measurements of the gas composition. The diesel substitution at varying loads is shown in Table 3.2. The worrisome point of the slightly more rich 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 the additional botheration. The reason for the higher tar load (typically 1000 mg/$m^3$) is thought to be 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 level to that comparable to wood gasifiers.

**Table 3.2 Diesel replacements achieved with load**

| Gasifier operating A/F | Load (kWe) | Diesel replacement (%) | Engine exhaust | |
|---|---|---|---|---|
| | | | Nox (ppm) | $O_2$ (ppm) |
| 0.9 - 1.1 | 19 | 78 | 165 | 9.9 |
| | 28 | 80 | 226 | 8.7 |
| | 38 | 77 | 249 | 8.2 |
| | 46 | 83 | 275 | 5.6 |
| | 57 | 81 | 361 | 4.0 |
| | 61 | 82 | 460 | 2.0 |
| | 65 | 67 | 677 | 1.3 |
| | 72 | 40 | 1143 | 1.0 |

### 3.6.2 Experience with Sawdust

Operation with sawdust was found straight forward with again good gas composition (leading to diesel replacements of in excess of 80 % at loads of 70 - 75 kWe) at air-to-fuel ratio of 1.5 ± 0.02. Problems of tar were observed to be much less than in the case of rice husk. Refer to Appendix -1 for test run details.

### 3.6.3 Experience with Sugar cane trash

Limited operation with sugar cane trash pulverised to 3 to 5 mm mesh size showed that the operation is straight forward with the problems of tar again, little as could be noticed at the exit of the blower drawing the cold gas through the system. The problems of sugar cane trash are that the rate of pulverisation in terms of kg/hr is much less than rice husk because of its density (typically 60 kg/hr instead of 200 kg/hr in the 11 kW motor powered pulveriser), and the material flow problems partly because of the low density. It was observed that lumps were getting formed in the stored mass and this would continue even in the bin of the screw feed system. The precise reasons for this phenomenon are not known; the strategy for taking care of this problem is thought to be to chaff cut and feed without having to pulverise.

A few tests were conducted using sugar cane trash (chaff cut and pulverised using 3mm mesh) after having initially run on sawdust . This procedure was adopted as trash was relatively new fuel and the A/F for cleaner operation was yet to be established. The tests were of short duration and conducted at a A/F around 1.25 to 1.5. Test on engine mode is yet to be conducted. Refer to Appendix -1 for test run details.

### 3.7 Measurements of Particulates and Tar

These were performed for rice husk with isokinetic sampling procedures perfected on the wood gasifier for Indo-Swiss test (Mukunda et al, 1994) only at the cold end after the sand bed filter. These measurements with showed the level of (P + T) to be less than 120 mg/m$^3$. Subsequent analysis showed that amount of particulates and tar were nearly equally distributed. Most of the (P + T) was otherwise trapped in the blower and the cyclone after the blower. They could be removed after dismantling the system elements. The amount of (P + T) so collected varied between 2000 to 4000 mg/m$^3$. The fine dust behaved in a manner not too different from tar and it took chemical analysis 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 thermo-chemical system involving a circulating bed system is currently under study. Limited observations have shown that either sugar cane trash or saw dust did not produce such amounts of tar. These are to be subjects of more careful study.

### 3.8 Measurements of Exhaust gas composition of engine

Measurements of exhaust gas for O2, CO2, and NOx were made. Figures 3.30 and 3.31 show the oxygen fraction in the exhaust with load in kWe for both diesel-alone and dual fuel mode. It can be seen that the oxygen fraction drops to about 4 % at 75 kWe for diesel-alone mode and to 1% at 72 kWe 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 it can be thought that 80 kWe is the maximum deliverable load at Bangalore ( 1Km. Altitude ) in diesel alone mode and 72 kWe is the peak delivered load in the dual-fuel mode for an engine rated at 96 kWe . Thus there is 10 % derating of the engine in the dual fuel-mode. This is simply 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.

A very important and interesting discovery was made at this point. It was uncovered that maximum diesel replacement always implied low concentration of $O_2$ in the exhaust gas - typically 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 on dual-fuel mode should

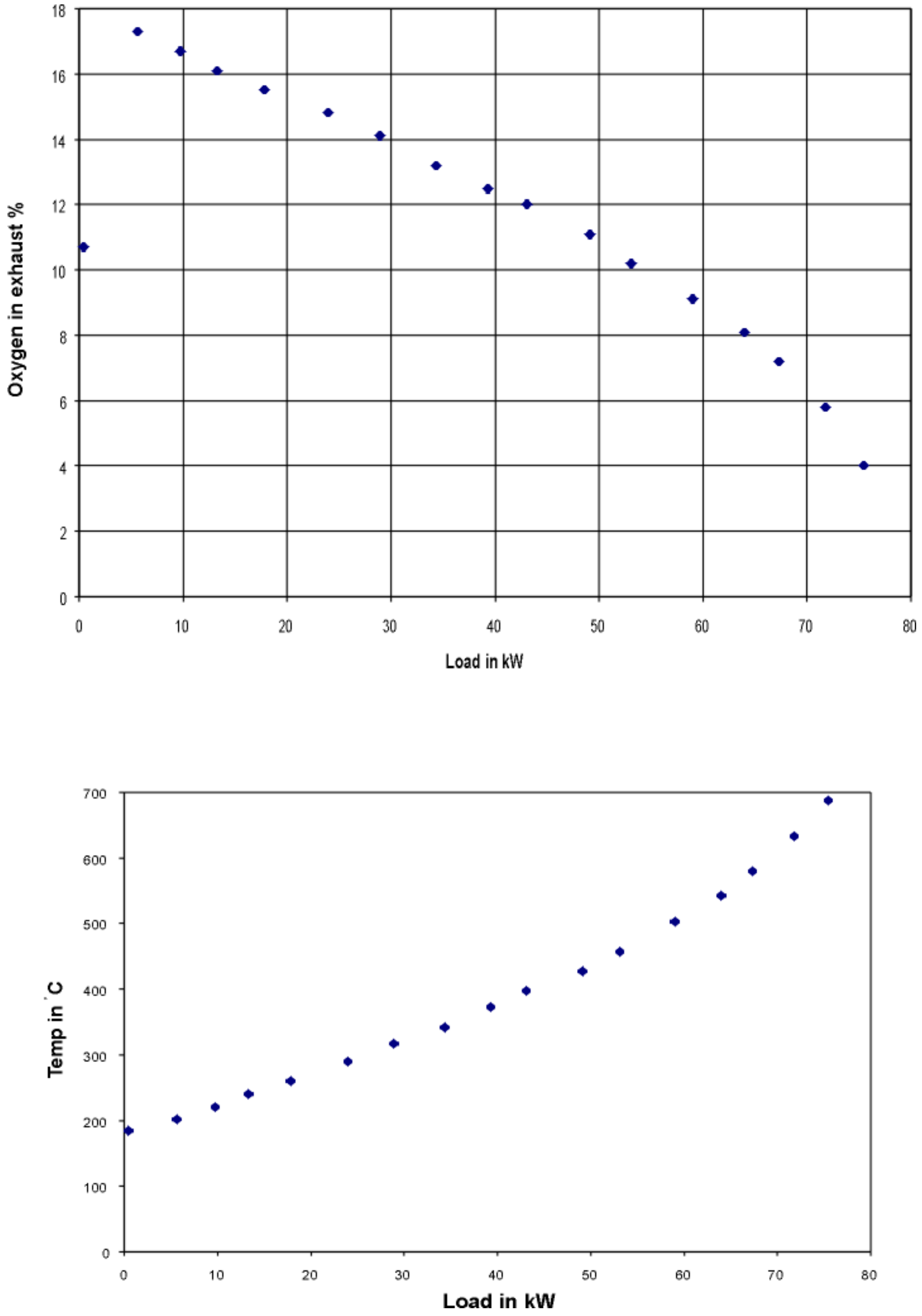
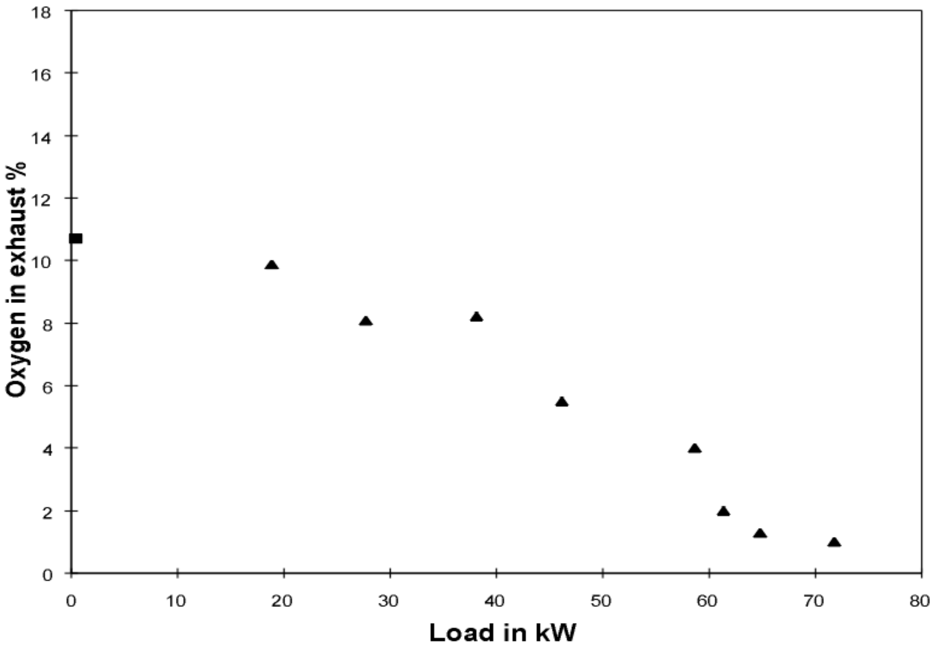


**Figure 3.30 Oxygen fraction in the engine exhaust and its temperature in diesel alone mode**



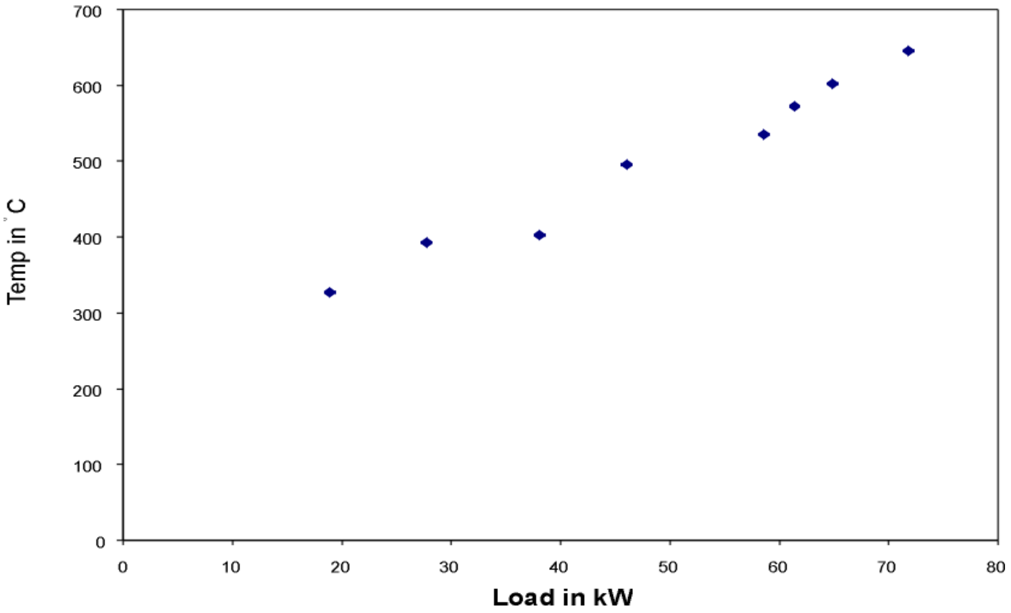


**Figure 3.31 Oxygen fraction in the engine exhaust and its temperature in dual-fuel mode of operation**

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 NOx are shown both for diesel-alone mode as well as dual fuel mode in Figure 3.32. It can be clearly seen that the NOx level is much lower - by a factor of five or so. These are 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.*

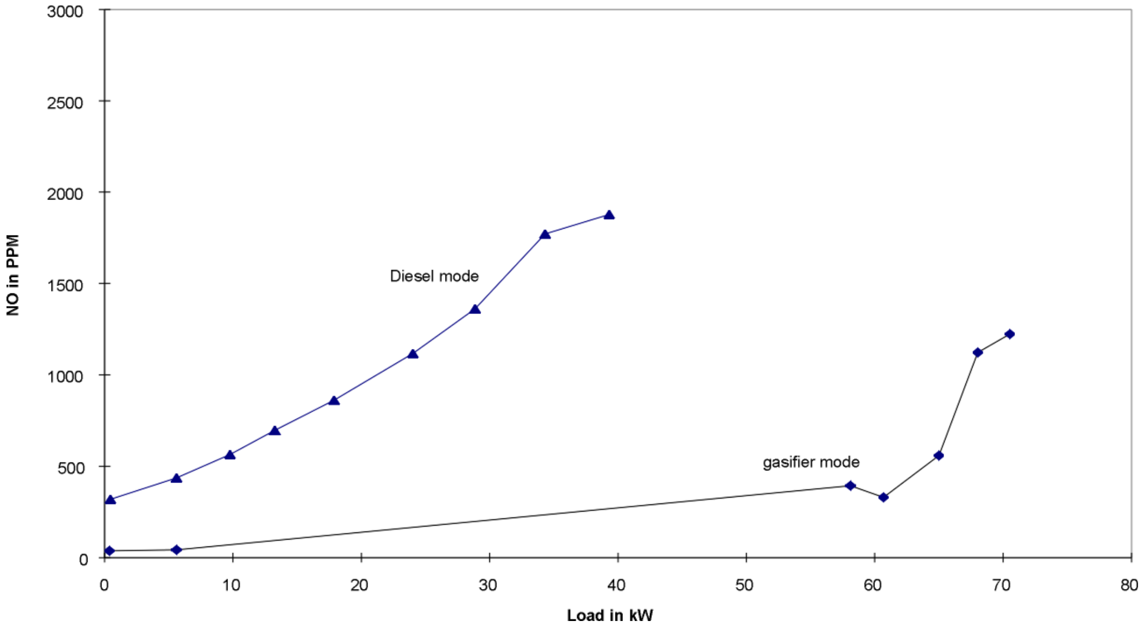


**Figure 3.32 $NO_X$ in the engine exhaust under diesel and aual-fuel mode**

### 3.9 Measures for tar reduction

From the experimental work carried so far in gasifying rice husk, the tar in gas seemed be a constant problem whenever the system is operated at A/F below 1.0 to 1.1. As better diesel replacements were achieved at lower A/F (around 0.9), elimination of tar from gas seemed to gain more prominence. This requirement is only meant for power generation application systems. As generation of tar in the reactor during gasification cannot be suppressed while operating at lower A/F's, reduction of tar downstream of the reactor seemed to be the only solution. This could have been done either by tar cracking using some cracking medium like charcoal or by removal of tar to acceptable level using an elaborate clean-up system. As tar cracking seemed to a better option in terms of ease of maintenance a tar cracking unit at the reactor exit was tried using charcoal as the cracking medium. The charcoal bed seemed to perform the job, tar measurement at cold end showed tar level up to 125 ppm. The consumption of charcoal was amounting to 5% of the total feed stock used (rice husk). As the tar reduction is dependent on use of charcoal which adds to the cost of operation, a cracking unit based on fluidised bed using the hot char exiting from the reactor was thought to be more appropriate. Therefore a circulating fluidised column was introduced between the reactor exit and the cyclone entry, allowing the hot gases to come in contact with the hot char and in the process allow the tar to get cracked. The final design of the fluidiser was arrived after making a series of experiments to find the appropriate velocities for fluidising by varying the char bed height. For the present fluidiser design, which accommodates a mean bed height of 100 mm, the fluidising velocity is typically around 0.55 m/s for a hot gas at a flow rate of 54 g/s. Table 3.3 shows the minimum fluidising velocity required as a function of mean bed height.

**Table 3.3 Fluidisation velocities using rice husk ash with varying bed height**

| Cold air flow rate, g/s | Pressure drop, mm | Fluidising velocity, m/s | Bed height, mm |
|---|---|---|---|
| 4.36 | 11 | 0.55 | 75 |
| 6.66 | 20 | 0.83 | 100 |

### 3.9.1 Circulating Fluidising Column

The fluidising column or fluidiser (see Figure 3.33) is a long vertical column of 600 dia made of SS 304 which consists of the following elements

(1) Opening for hot gas.
(2) Opening for hot char and ash mixture.
(3) Gas distributor or grid plate.
(4) Bin for dust collection.

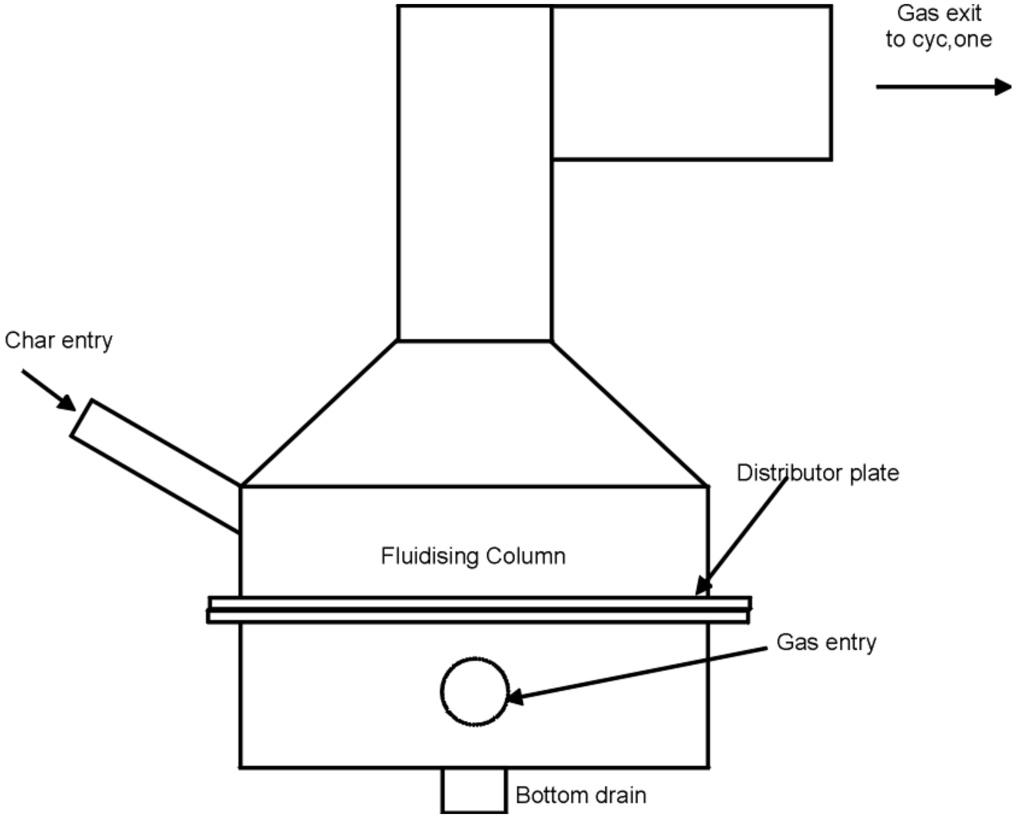


Figure 3.33 Fluidising column

The opening for the hot gas is of 150 mm dia, above which is the grid plate. The grid plate is a standard fluidising component and consists of arrays of holes which are 2mm dia and 2mm pitch. The plate is integrated in four halves wherein each portion has holes directed in one direction to give an overall swirl effect. The char exit tube from the reactor is 35 mm dia tube connected to fluidiser at 45o above the grid plate. This is located at 100 mm above the grid plate so that a char bed of 100 mm thick can be maintained. Below the gas entry is the bin for dust collection with a port for dust removal. The exit of the gas along with carry over of char and ash is connected to the existing cyclone. The residence time for gas with hot char in the column is typically around 1 sec during which hot char and ash mixture having temperature in excess of 500 oC helps in cracking the tar content in the gas. Overall schematic of the cyclone gasifier with fluidiser is shown in figure 3.34.

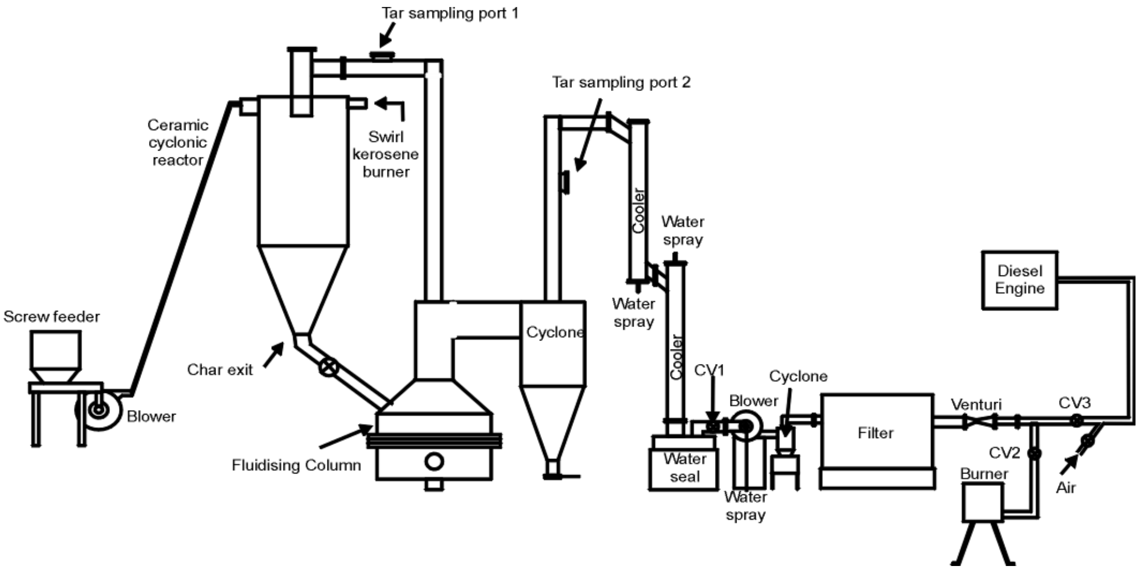


**Figure 3.34 Schematic of Powdery Biomass Gasifier System with fluidiser**

### 3.9.2 Tests with circulating fluidised bed

Initial tests with fluidiser were impressive, the qualitative checking of the wash waters from the coolers showed low tar levels in the gas when operated at A/F around 0.9. Further tests are being planned with slight modifications in the fluidiser based on experience from the earlier runs, with provision for iso-kinetic gas sampling both upstream and downstream of the fluidiser. This is being done in order the understand the effectiveness of the char bed fluidiser as a tar cracking unit. Figure 3.34 shows the gas sampling points on the system.

### 3.9.3 New gas sampling apparatus for tar measurement

To measure the tar content in the producer gas generated from powdery biomass gasifier, a tar measurement scheme is devised. The scheme is based on iso-kinetic sampling where a nozzle is designed to draw the gas for sampling at the same velocity as in the tube where the gas flows. The diameter of the nozzle upstream and downstream of the fluidiser is 17mm and 14 mm respectively for a gas sampling rate of $1m^3$/hr. These correspond to gas velocities of 3.95 & 3.5 m/s through the sampling nozzle. The gasifier system has to be operated at a flow rate of 54g/s to meet the iso-kinetic sampling requirement. The tar measurement system is shown in figure 3.35. The gas in hot condition is filtered and passed through a series of condensers, through which ice cold water is circulated to condense the tar. The gas is further bubbled through a bottle containing Methoxy benzene to trap any uncondensed tar before it is flared in the burner. Gas can be sampled at the required flow rate using a integrated flow meter.

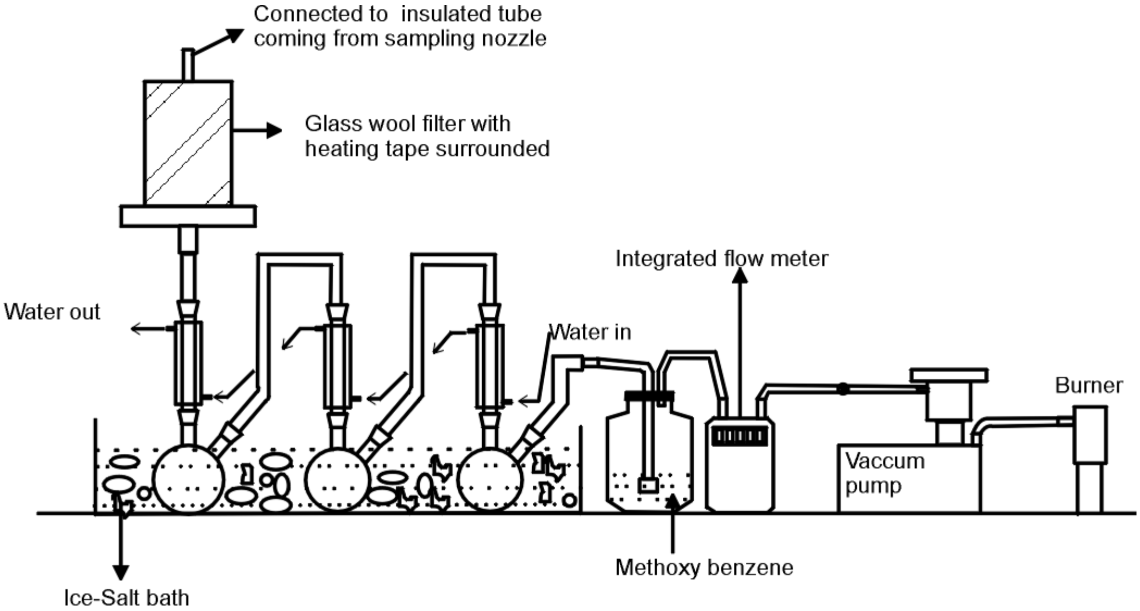


**Figure 3.35 Schematic of Tar measuring unit**

## 3.10 Summary

This chapter has outlined the experimental work that has been completed on the cyclone gasifier to gasify pulverised fuels in the state of pulverised condition. The essential issues which need to be tackled for ensuring a steady gasification process have been outlined. It must be brought out that the twin control on fuel feed and air implies that changes of one or the other will cause gas quality change either making it more fuel rich and thus filled with tar or a lean gas with acceptable tar but quality being poor preventing adequate diesel replacement. This implies that the corridor which needs to be traversed to obtain good, consistent quality gas calls for careful control system operation. Since this will turn out to be somewhat involved and capable of being done for relatively large systems, an alternate in terms of using briquetted fuels will be examined in the succeeding two chapters.

# Chapter 4

# Experiences on briquetting light agro residues

## 4.1 Introduction

In gasification of light agro residues like sugarcane trash, straw and coir pith, briquetting of the fuel helps in more than one way as under:

1. Handling of the biomass, in the sense the bulk density of the material increases by more than 7 times improvising handling and storage.
2. Briquetted fuels have moisture content, which is well suited for gasification (generally around 7%).
3. Sizing (particularly length) of the briquettes can be adjusted to the suit the gasifiers.
4. The briquettes can be used in open top down draft reburn gasifier without much problems of tunelling and bridging (a phenomenon which is usually observed when light agro residues are used as such).

In view of above, it was decided to study briquette formation of sugar cane trash, straw, rice husk, de-oiled rice bran, saw dust and coir pith. A cooperative entrepreneur who basically builds briquetting machine agreed to help us in the study. The industry agreed to arrange rice husk, saw dust and rice bran at their end and IISc was supposed to arrange straw, sugar cane trash and coir pith.

## 4.2 Preparations

The straw and sugarcane trash was pulverised in a hammer mill using 8 mm mesh. The coir pith was sun dried and screened to remove fibres from them. This was later filled in gunny bags and transported to the industry. The pulverised sugar cane trash weighed around 15 kgs/bag, pulverised straw weighed around 22 kg/bag and the coir pith was bagged in smaller plastic bags which weighed around 6 kgs/bag.

## 4.3 Tests

Briquetting machine type : Screw type with heater for forming bush
Make : Kannvarees Internationals Pvt. Ltd, Chennai.
Capacity : 500 – 750 kg/hr depending on the nature of biomass4

The above machine at the industry was set to initial heating for 400 $^0$C. Then the hopper was filled with rice husk and good briquette was achieved, same was tested for saw dust and good briquette was obtained. The industry had competence in briquetting rice husk and saw dust and hence the above two fuels were tried for very small time. Soon pulverised straw was loaded, the output was the material came out in as put condition or very loose briquette was formed which disintegrated after leaving the briquetting machine. The material movement was not uniform. To overcome this, the clearance between conveying screw and the surrounding walls was reduced by providing a U cup around the screw. Coir pith was tried and good briquettes were obtained. In total, 92 kgs of coir pith was fed and 72 kg of briquette obtained. The remaining 20 kg was lost during handling, as over burnt briquettes and semi-formed briquettes could not be fed back to hopper.

Sugar cane trash was initially tried at high temperature without success and later the heating coils were switched off. On cooling the material was recirculated causing preheating of the feed. At particular instance good briquettes was achieved for a short time which could not be repeated later. Later the heating coil was activated and various trials were conducted initially at lower temperatures than at above 400 $^0$C. The binding was not adequate and the briquettes disintegrated on exiting the forming bush. Even adding saw dust up to 1/3 rd volume did not bring much success. The same behaviour was observed with pulverised straw. In addition the pulverised straw demonstrated often violent release of moisture and volatiles throwing the material away from the forming bush. This however indicates that the temperature of the forming bush has to be reduced for smooth operations. How ever, reducing the area of the forming bush and reducing the taper angle of the taper spline bush may improve the performance of the system for the above material. The table below gives the chronological events of the test.

| Sl.NO | Start Time | End Time | Bio Mass Processed | Amps * | Volts | Actual Temp | Set Temp | Remarks |
|---|---|---|---|---|---|---|---|---|
| 1 | 10.41 am | 10.46 am | Grass | 45 | 380 | 435 to 415 | 427 | No briquette formation. |
| 2 | 10.52 - am | 10.59 am | Grass | 45 | 410 | 431 - 423 | 455 | No briquette formation. |
| 3 | 10.59 am | 11.05 am | Coir Pith | | | 450 - 457 | 485 | No briquette formation. |
| 4. | 11.16 am | 11.20 am | Grass | | | 445 - 376 | 483 | No briquette formation. |
| 5. | 11.23 am | 11.31 am | Grass | | | 502 - 450 | 494 | No briquette formation. |
| 6. | 12.35 | 12.51 | Coir Pith | 45 - 50 | 400 | 445 - 376 | 483 | Good Output. |
| 7. | 1.08 pm | 1.14 pm | Coir pith | 45 - 50 | 400 | 450 - 423 | 455 | Good output |
| 8. | 1.15 pm | 1.27 pm | Coir pith | 45 - 50 | 400 | 483 - 433 | 494 | Good output |
| 9. | 1.29 pm | 1.33 pm | Coir Pith | | | | | A: |
| 10. | 3.00 pm | 3.03 pm | Sugarcane Trash | 22 - 24 | | 470 - 420 | 465 | No briquette formation. |
| 11. | 3.04pm | 3.05 | Sugarcane trash | | | | | No briquette formation. |
| 12 | 4.10pm | 4.15pm | Sugarcane trash | 22 - 24 | | 180 | Removed heating coils | B |
| 13 | 4.35pm | 4.45pm | Sugarcane trash | 22 - | | 410 - 380 | 390 | C trash. |
| 14 | 5.15 | 5.25 | Sugarcane trash | 22 | | 337 - 290 | 399 | Output was good after 5 minutes of running the machine. |
| 15 | 5.43 | 6.20 pm | Sugarcane trash | 22 | | 415 - 390 | 400 | D |

A: Dry coir pith got over and tried feeding material with high moisture content. -this had more fibres in it. These fibres got jammed

B: No heat was supplied to the heating coil and the material was fed. There was a drop in temperature. The material was recirculated which acted like preheating and there was good output at 180 degrees with smoke from the central hole The approximate preheat temp could be 50 - 60 degrees . the color of briquettes were natural color without skin charring

C: Tried preheating the sugarcane trash and when fed into the hopper the material came out in the same form. .changed parts at forming to try to match the flow of sugarcane

D: Good forming  for 6 mts. Tried mixing saw dust with this to increase the flow of material.. inbetween tried adding grass to this and the material got jammed. .

# Chapter 5

## Tests with briquettes in Woody bioresidue gasifier

### 5.1 Introduction

The briquettes that were made in the above process were available for the tests. Before these could be tested, similar briquettes were made available to the laboratory through a Swiss test program essentially meant towards the evaluation of the gasification process for agro-residues. These required that tests be conducted on grass and powdered waste from furniture industry (restholz) from Switzerland for performance including P & T. The commitments led to the use of standard open top wood gasifier for tests on these bioresidues. These tests included measurements of gas composition, tar and particulates as well as NOx emission in the burnt gaseous fuel from a specifically designed hot water boiler.

### 5.2 The Fuels

Restholtz is a briquette made of sawmill refuse consisting of timber saw dust and some veneer wastes. These briquettes were made available in loosely compacted form of the size ranging from 150 to 175 mm by length and 100 mm in diameter. The density of these briquettes were estimated to be around 380 kg/$m^3$ (about one third as compared to high density briquettes). Another fuel called the energy grass (also called as switch grass) was despatched to India in bailed form. The grass varies in length from 100 to 200 mm and few much longer. In order to put these fuels into use along with meeting the emission standards, gasification was thought as an option and therefore these was expected to be tried in IISc design gasifier. The physical properties of the fuel are shown in Table 5.1

**Table 5.1 Gross properties of fuel**

| Feed stock | Density, kg/$m^3$ | Ash content, % |
|---|---|---|
| Grass | 50 – 55 | 8 |
| Restholtz | 350 | 2.5 |

### 5. 3 The Pre-tests:

While transitioning from cyclone system to open top downdraft reburn standard system, one of the concepts that was tried at the laboratory was a unique design called the Special Combined Updraft and Down draft (SCUD) gasifier for agro-residues like rice husk, sugar cane trash etc. This consisted of updraft gasifier for conversion of agro-residue to producer gas and further passing it through hot char bed for tar reduction. However, the cooling and cleaning systems remained the same as the earlier down draft version. Hence at the outset it was decided to try both of these fuels in this system. The restholtz briquettes were to be tried in as-received condition, however the grass required some processing. The grass was pulverised in a hammer mill to a size less than 8 mm. Use of grass led to several problems with respect to conveying the feed due to its low density and moreover there were problems related to material movement within the reactor. All these resulted in inconsistency in the quality of gas generated and moreover it was difficult to carry out the tests for longer duration. On the whole three tests were conducted with pulverised grass in SCUD system, the table 5. 2 below shows the test summary

**Table 5.2 Summary of tests on SCUD system**

| Date | Duration of run, min | Remarks |
|---|---|---|
| 21/1/98 | 125 | Flame Fluctuations observed, carry over high |
| 23/1/98 | 40 | Flame Fluctuations observed, carry over high |
| 26/1/98 | 120 | Flame Fluctuations observed, carry over high |

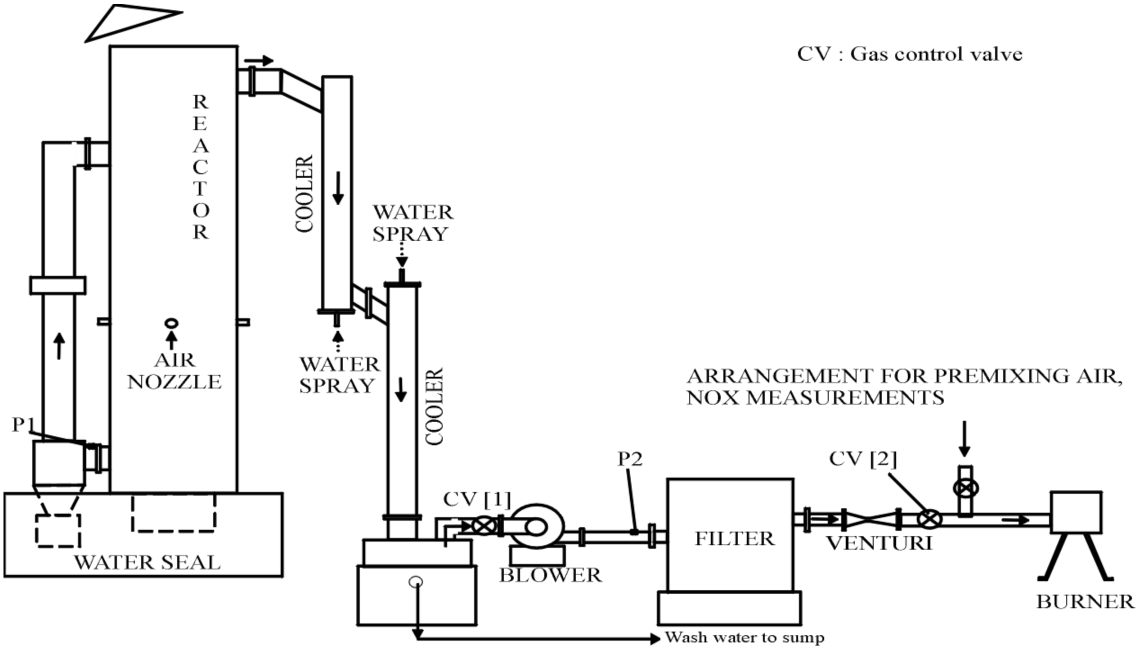


**Figure 5.1 Schematic of solid bioresidue gasifier used for tests on briquettes and grass**

Due to the problems encountered as above, it was felt that using these materials in downdraft version would be simpler and therefore open top down draft gasifier was adopted for these tests. To get a feel of how things will work, a test was conducted in down draft system with a mix of 70% pulverised grass and 30% wood chips. Grass was first chaff cut and then pulverized to less than 8 mm to enable movement downwards in the reactor. There were movement problems despite the hot wall reducing wall friction considerably. This was primarily because of the density of the material – in the range of 50 to 55 kg/$m^3$. The system was run for nearly 8 hours with varying flow rates. The system behaved pretty well for lower flow rates of 18 – 20 g/s. At 30 g/s flow rate needed to be adjusted periodically as the reactor pressure drop increased. By and large the operation was convenient and controllable. Periodic poking from top and from the air nozzles facilitated the material movement inside the reactor. On the whole the operation was much smoother compared to the SCUD experience.

The next test was conducted with pulverised grass alone. The operation was pretty smooth and gas of consistent quality was generated. Table 5.3 below shows the summary of these pre-tests.

**Table 5.3 Summary of the pre-tests on standard IISc gasifier**

| **Date** | **Duration of run, mins** | **Remarks** |
|---|---|---|
| 27/1/98 | 470 | Mixture used, gas quality good, poking helped in material movement |
| 5/2/98 | 225 | Pulverised grass alone used, gas quality good, poking helped in material movement |

Similarly, in the case of the as-received restholz briquettes were checked out. These had a density of 350 kg/$m^3$ and were somewhat fragile. It was not clear if the fragility was due to the process of making them or they could not be improved upon further. In any case they were close to the condition of use in a standard IISc design and hence were used directly. In a sense, it is the grass that posed problems in terms of operation. If the operation as a gasifier was simply possible, the questions of tar and particulate measurements could be undertaken. Hence the first task was to ensure smooth operation of the gasifier on grass. This was accomplished in a pre-test and it was determined that the operation as long as eight hours could be undertaken with the usual premise that initially one loads charcoal for startup. The charcoal in the bottom section would slowly get consumed and the question is what would happen later. It is possible that the char from the grass would constitute the reduction medium and this can be considered to be the intent in conducting the rigorous P & T tests.

## 5.4 The Tests, the results and the discussion

The two tests that were carried out on 18th and 19th Feb. 1998 were on Swiss grass and Restholz briquettes using the standard *open top downdraft reburn gasifier* built earlier for Swiss tests. These two tests were conducted with the participation of Dr. H Sharan and Mr Buhler. The tests followed the pattern of earlier tests made on wood chips in December 1994 under a separate Swiss grant. The standard 75 kg/hr gasifier with cooling and cleaning train was deployed. Figure 5.1 shows the arrangement of the gasifier and the principal P & T and gas sampling stations.

The tests were one each on pulverised grass and restholtz briquette at 18 g/s (33% load on a 75 kg/hr rated system). The run details is given in Table 5.4.

**Table 5.4 - Hours of run and Purpose**

| **Date** | **Feed stock** | **Run Time** | **Objective** |
|---|---|---|---|
| 18/02/98 | Energy grass | 5hrs 10 mins | Testing of Pulverised Energy grass |
| 19/02/98 | Restholtz | 5hrs 45 mins | Testing of Restholtz briquettes |

The parameters measured included the system behaviour like the temperatures, static pressure and gas flow rate. The gas quality was assessed in terms of composition ($H_2$, CO, $CH_4$, $CO_2$, $N_2$ & $O_2$) and particulate and tar content both at the hot and cold ends. Also flue gas analysis in terms of CO, NOx, excess $O_2$ was done. The parameters measured are summarised in Table 5.5.

**Table 5.5 - Overall Data Acquisition status**

| **Feed stock** | **Data Recorded** | | | | |
|---|---|---|---|---|---|
| | **Temp Data** | **Pressure Data** | **Gas & Fuel Flow Rates** | **Gas Comp.** | **P&T Analysis** |
| Energy grass | ♦ | ♦ | ♦ | ♦ | ♦ |
| Restholtz | ♦ | ♦ | ♦ | ♦ | ♦ |

The system had been operated on the previous days on SGF briquettes and therefore the same was to be consumed prior to changeover to the current test fuel. Therefore the system was run for about one hundred and thirty minutes (without further loading i.e partly empty condition) for the material inside the reactor to get exhausted to a level just above the air nozzle. Later the reactor was filled with energy grass and further loaded according to normal mode of operation. This was done in order to get to a stage of grass alone being gasified in the reactor for true measurements of tar and particulates. The procedure of iso-kinetic sampling and further treatment is same as carried out in the 1994 standard tests. The start-up details as given in Table 5. 6.

**Table 5.6 Operational details**

| **Feed stock** | **Sampling duration, mins** | **Amount of fuel burnt during sampling** | **Time for flame in the burner, min** |
|---|---|---|---|
| Energy grass | 129 | 100 | 10 |
| Restholtz | 196 | 105 | 8 |

On the whole the system was run for about 200 min on pulverised grass. The P&T analysis was commenced after about 60 min of changeover to grass. The sampling was conducted for about 2 hours duration as shown in Table 5.7.

**Table 5.7 Tar sampling details**

| **Feed stock** | **Duration, min** | | **Gas sampled, m$^3$** | |
|---|---|---|---|---|
| | Hot | Cold | Hot | Cold |
| Energy grass | 122 | 119 | 3.136 | 3.871 |
| Resthotlz | 116 | 191 | 3.348 | 6.586 |

During this period the system pressure drop increased from 30 mm to 160 mm wg and the same was brought down by prudent grate shaking. This had to be done to order to maintain the gas flow rate around 18 g/s. The gas composition was measured during the latter part of P & T analysis for about 60 min due to problems with the gas measuring systems. Data pertaining to reactor wall and gas temperatures were acquired on a computer. The exhaust gas composition was measured at the burner exit both in pre-mixed and diffusion mode. As per established procedure, sampling was conducted with a iso-kinetic sampling probe through a water and anisole collection train ending with a fine dust filter all being maintained at < 0 $^{o}$C. The samples so collected at the end of the sampling period were sent to M/s COSMIC industrial laboratories Ltd. for analysis. In addition to tests on the gas quality, an arrangement was made to connect the gas to a fire-in-tube boiler at the bottom of which was arranged a burner with a separate air supply from a blower for the combustion of the gas. Measurements

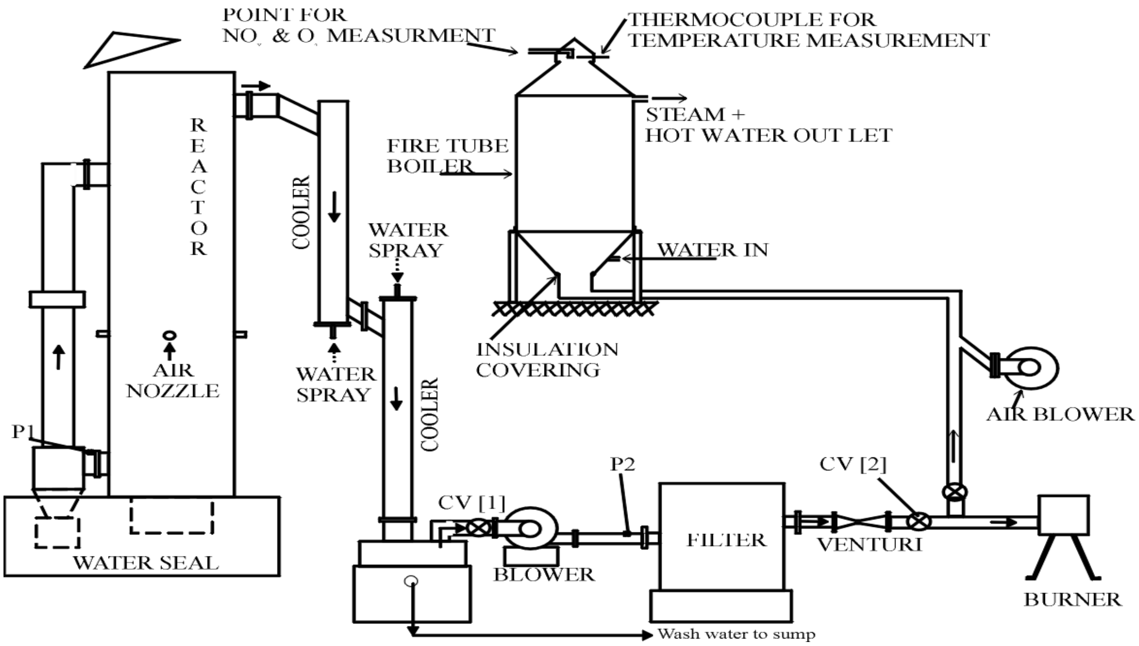


**Figure 5.2a Schematic of solid bioresidue gasifier along with fire tube boiler for tests on On SGF briquettes**

of temperature, oxygen and nitric oxide fractions in the exhaust stream were also made periodically to determine the NOx fraction in the exhaust (it was assumed that all of NOx is NO, a feature considered accurate for the present purposes). The arrangements for this are shown in Figure 5.2. Figure 5.2a shows the arrangements made for an earlier test using SGF briquettes which was carried out under a separate project given by Mr. Reudi Buhler.

Figure 5.2b Shows the arrangements made for the tests on restholz and grass.

The variation of reactor wall and gas temperatures with time is shown in Figure 5.3

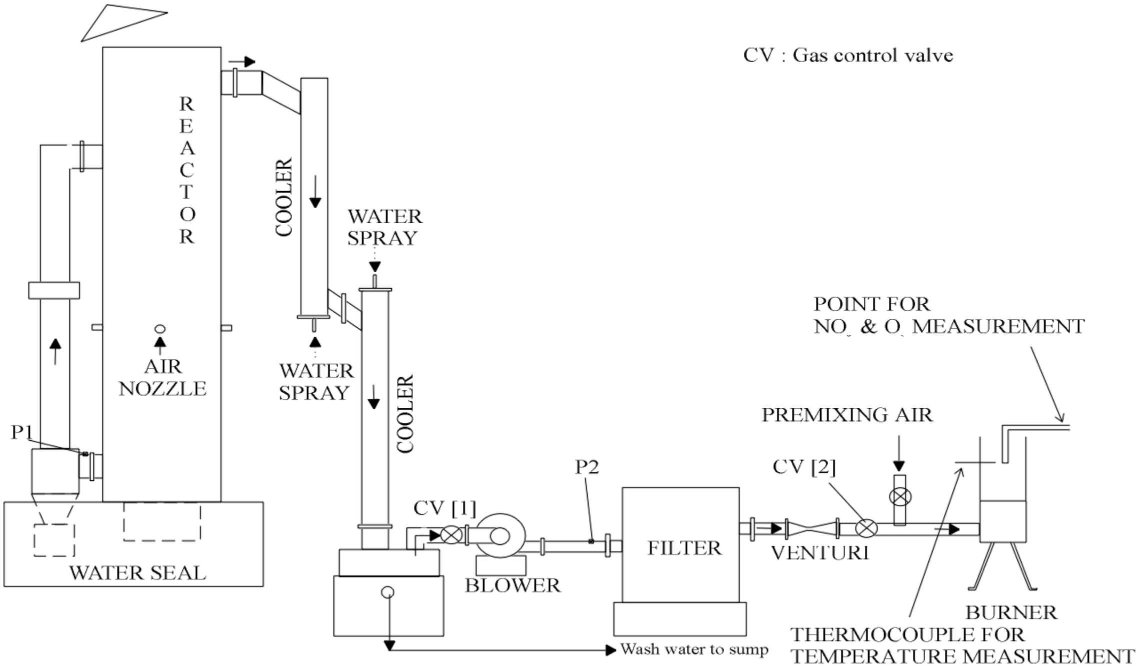


**Figure 5.2b Schematic of solid bioresidue gasifier used for $NO_x$ tests on briquettes and grass**

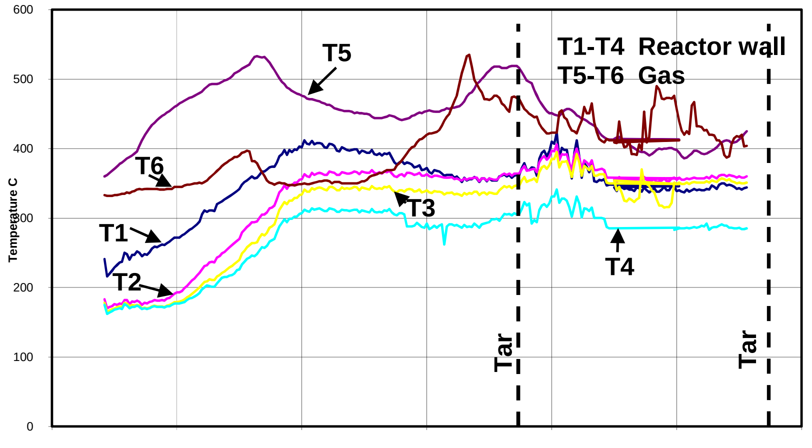


**Figure 5.3 – Reactor wall and Gas temperature profile with energy grass on 18/2/98**
**Note – Sudden raise in wall temperatures denotes partial burning of the gas inside due to void formation.**

The Thermocouple positions have been indicated in sketch 5.4.

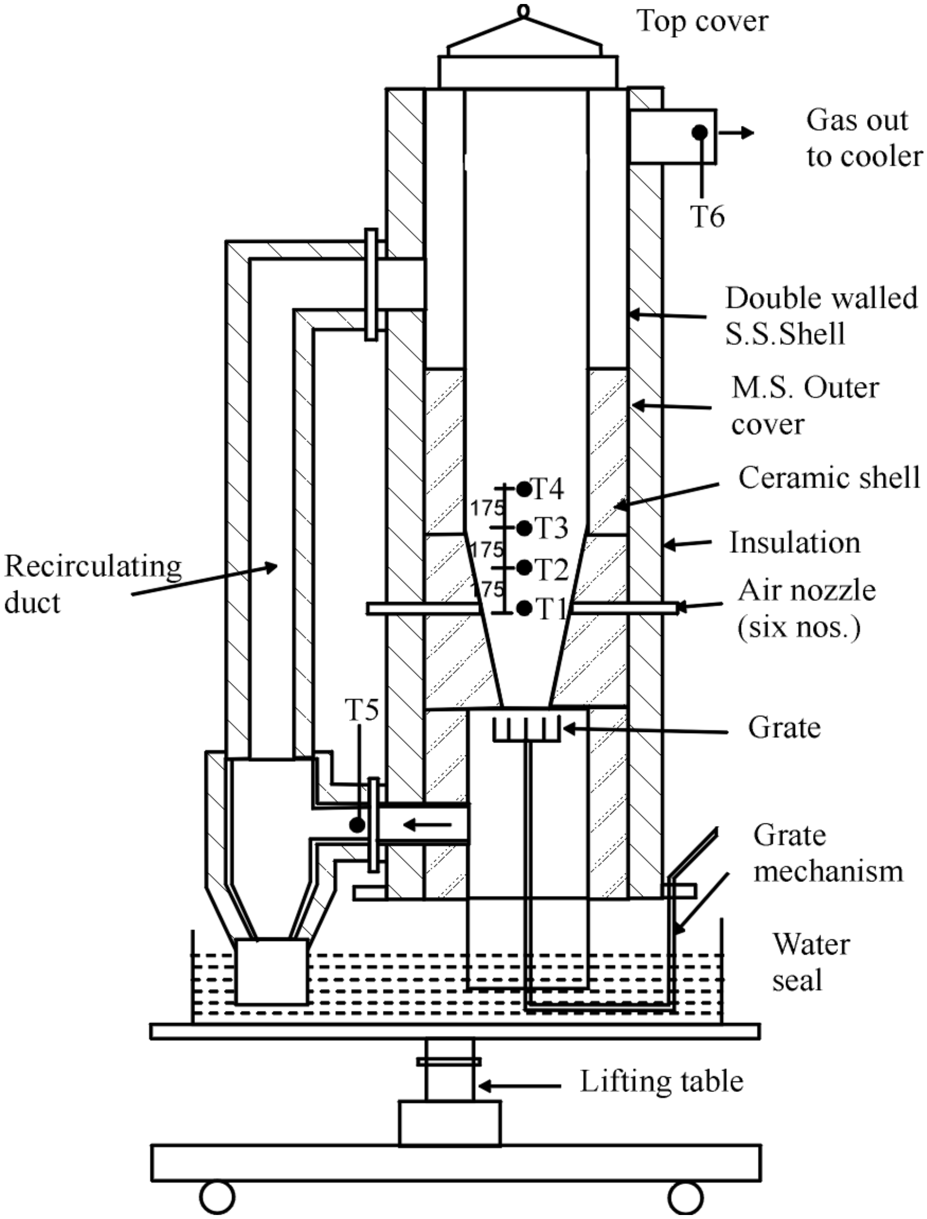


Figure 5.4  Thermocouple positions

Table 5.8 - Wall temperatures at the start of tar sampling

| **Feed stock** | **% Load** | **Start and stop of P&T sampling from time of gasifier start** | **T1, $^0$C** | **T2, $^0$C** | **T3, $^0$C** |
|---|---|---|---|---|---|
| Energy grass | 33 | 187 mins, 316 mins | 362 | 364 | 347 |
| Restholtz | 33 | 150 mins, 346 mins | 400 | 410 | 340 |

The wall temperatures during P & T sampling have been clearly indicated. The wall temperatures stabilised around 350 C prior to the P & T sampling as shown in Table 5.8.

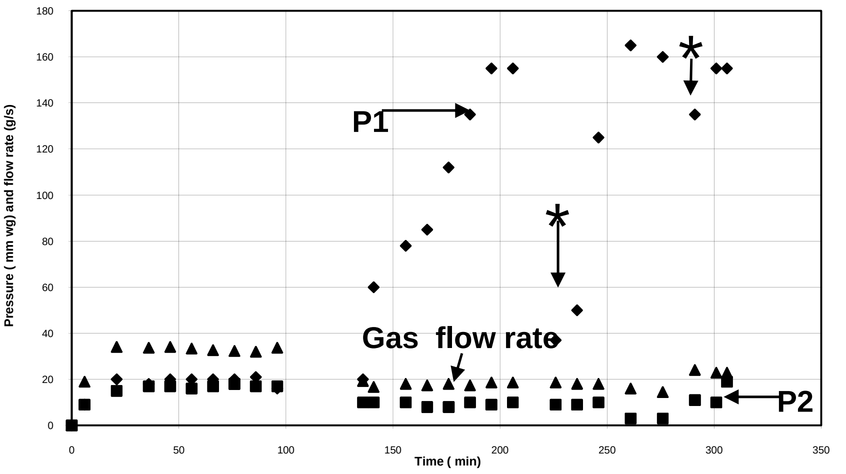


Figure 5.5 Pressure drop and gas flow profile with energy grass on 18/2/98
Note – P1 denotes suction pressure and P2 the positive pressure of the blower.

Denotes point of grate shaking. The reactor pressure drop reduces significantly with grate shaking and builds up after sometime.

The variation of system static pressures with time is shown in Figure 5.5. The system pressure drop increased from 30 mm to over 160 mm wg. The same was restricted to about 160 mm wg by resorting to grate shaking. The variation of gas composition with time is shown in Figure 5.6.

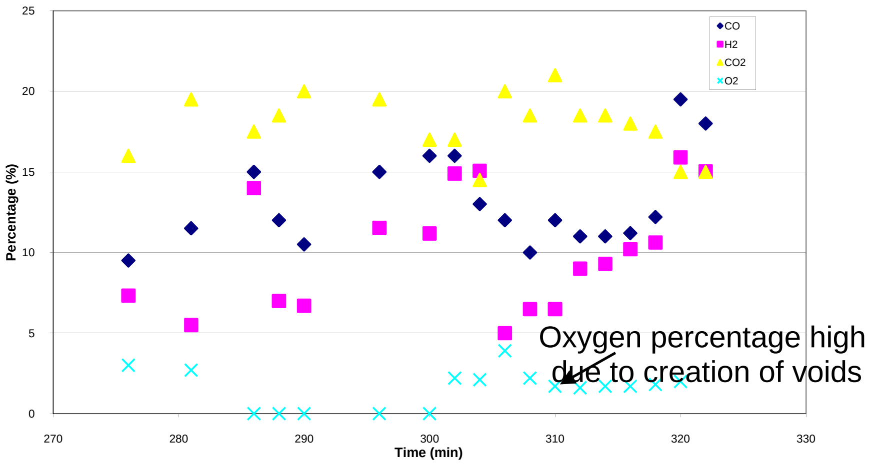


Figure 5.6 Variation of gas composition with time during tar sampling period, Feed stock – Energy grass.

The average gas composition is shown in Table 5.9, accordingly the gross calorific value averaged around 2.9 MJ/kg.

**Table 5.9 Summary of steady gas composition in various tests**

| Feed stock | CO | $H_2$ | $CH_4$ | $CO_2$ | $N_2$ | $O_2$ | µ | Q MJ/kg |
|---|---|---|---|---|---|---|---|---|
| Energy grass | 15 ± 2 | 15 ± 2 | - | 18 ± 2 | rest | 1.5 | 27.3 | 2.9 |
| Restholtz | 19 ± 1 | 15 ± 1 | 0.5 | 12 ± 1 | rest | 1.5 | 26 | 3.62 |

Table 5.10 gives the results of tar and particulates. It is clear that the values of P & T for grass are very high and nowhere near what may be expected for applications to engines. Restholz as a fuel provides much lower levels of P & T and seems to provide near acceptable gas quality for engine operations. The higher level of particulates even in this case can indeed be controlled by modifications to the design of the reactor. The cold tar in the case of restholz seems low enough for use in naturally aspirated engines.

**Table 5.10 Particulate and Tar details**

| Feed stock | Particulate, $mg/m^3$ | | Tar, $mg/m^3$ | |
|---|---|---|---|---|
| | Hot | Cold | Hot | Cold |
| Energy grass | 19571 | 408.2 | 3489 | 422.0 |
| Resthotlz | 5087.6 | 125.95 | 689.9 | 70.5 |

The Exhaust gas analysis is shown in Figure 5.7

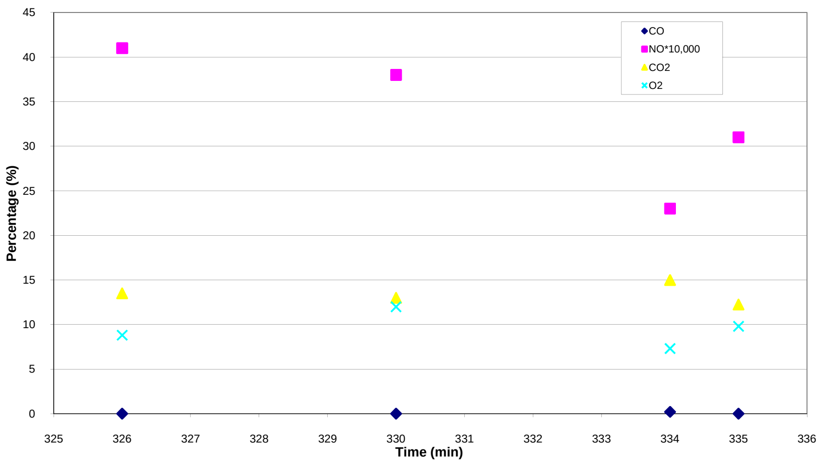


**Figure 5.7 – Exhaust gas composition in the premixed flame burner, Feed stock – Energy grass.**

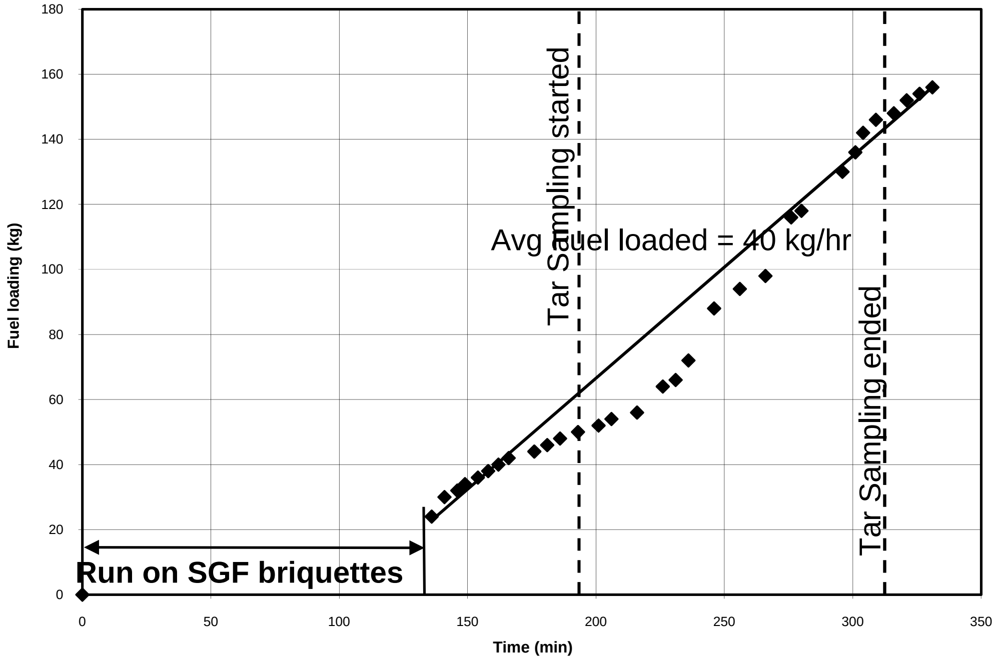


Figure 5.8 Cumulative loading of energy grass.

Notice variations in fuel loading with time. This variation is due to periodic poking action for helping material movement.

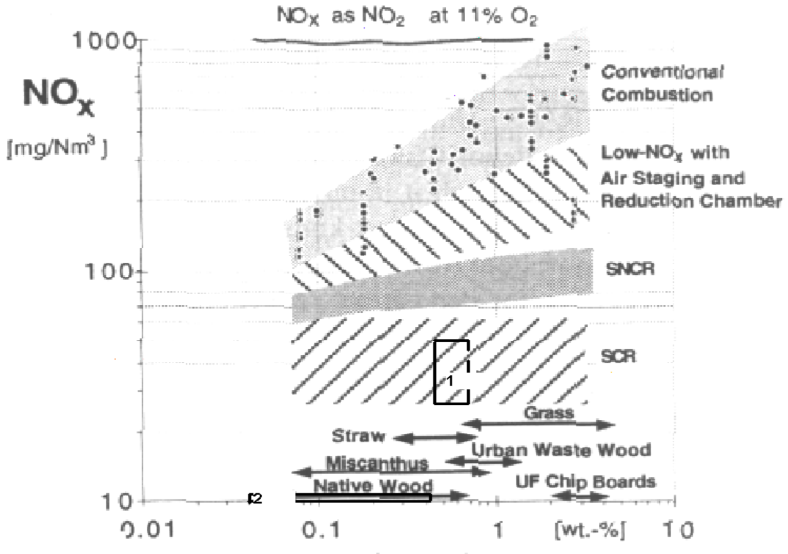
The trend of fuel loading is shown in Figure 5.8, which averaged around 40 kg/hr. The results of nitric oxides measured in the tests are presented in Table 5.11.

**Table 5.11 – NOx measurements**

| **Test date** | **Feed stock** | **Solid throughput Kg/hr (g/s)** | **Gas flow rate g/s** | **% $O_2$in combustion products** | **T, K** | **Measured ppmV** | **ppmV @ 11% $O_2$** | **mg/kg $NO_x$ on dry fuel basis** |
|---|---|---|---|---|---|---|---|---|
| 18/02/98 | Energy grass | 56 (15.5) | 39 | 8.8 | 1073 | 41 | 32 | 490 |
| | | | | 12.0 | | 38 | 43 | 650 |
| | | | | 7.3 | | 23 | 16 | 240 |
| | | | | 9.8 | | 31 | 27 | 407 |
| 19/02/98 | Restholtz | 26 (7.2) | 18 | 4.4 | 823 | 4 | 2.2 | 31 |
| | | | | 1.6 | 823 | 4 | 1.87 | 30.5 |
| | | | 37 | 6.3 | 1433 | 10 | 6.37 | 103 |
| | | 53 (14.8) | | 1.6 | 1523 | 10 | 9.17 | 76 |

[ Sample calculation: ppmV @ 11% $O_2$ = measured ppmV * [(1-(0.11* $MO_2$/0.23 * M)/ (1-($XO_2$* $MO_2$/0.23 * M))] ; mg/kg $NO_x$ = measured ppmV * [(1 + S)/(1-($XO_2$ * $MO_2$/0.23 * M))]; $O_2$ = 8.8% and $NO_x$ = 41 ppmV
Therefore, ppmV @ 11% $O_2$ = 41 * [(1-(0.11*32/0.23*27)/(1-(0.088*32/0.23*27))] = 32
mg/kg $NO_x$ = 41 * [(1+5.5)/(1-(0.88*32/0.23*27))] = 490]

Comparison with standard is shown in figure 5.9 below. These indicate that the NOx obtained from the combustion of the gas in the range of 10 to 40 mg/m$^3$ at 11 % oxygen in the exhaust stream for both restholz and grass are comparable to the best



Comparison of $NO_x$ emissions versus fuel nitrogen for different measures.

**Figure 5.9 – NOx from present results and comparison with standard reported (Source – NOx reduction in biomass combustion : primary and secondary measures, Th. Nussbaumer, Swiss Federal Institute of Technology)1 – Grass results from the present tests.**

3– Restholtz results from the present tests that can be obtained through NOx control techniques like SCR. The values work out to 0.2 to 0.65 g NOx /kg dry fuel and.compare with 0.5 to 1.8 g/kg dry fuel reported with classical combustion techniques. Thus, these measurements clearly indicate to the superiority of the gasification technique as a clean and environmentally friendly approach to thermo-chemical conversion of wastes and fuels in a manner which also generates electrical energy at low power levels.

In so far as the tests for restholz are concerned, the system was unloaded after the previous days run on grass and the reactor was loaded with charcoal till air nozzle and further with restholtz. The test procedure was similar to one conducted on 18/02/98. The variation of reactor wall and gas temperatures with time is shown in Figure 5.10

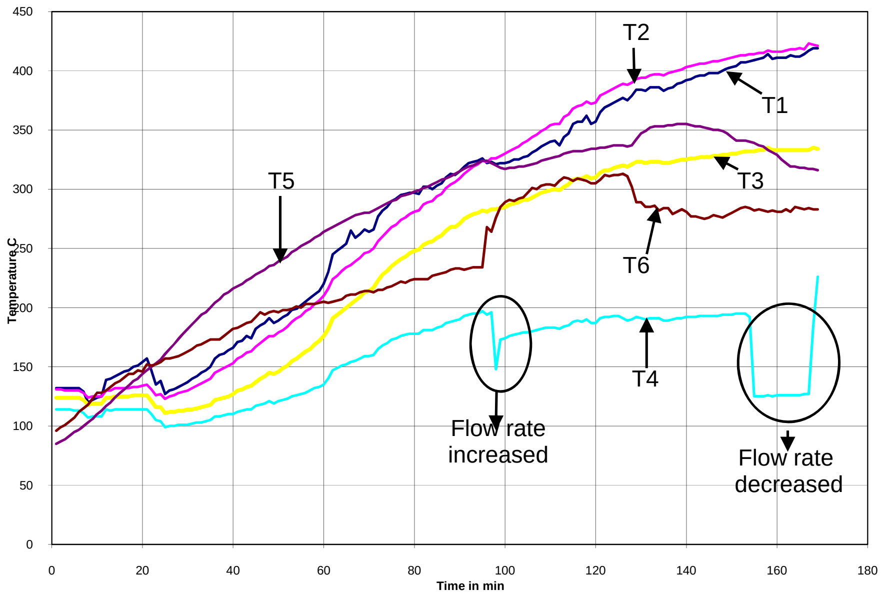


Figure 5.10 Reactor wall and Gas temperature profile with Restholtz on 19/2/98
Note – This plot does not cover the entire duration of test run due to corruption of the remaining data file. (the thermocouple positions have been indicated earlier)

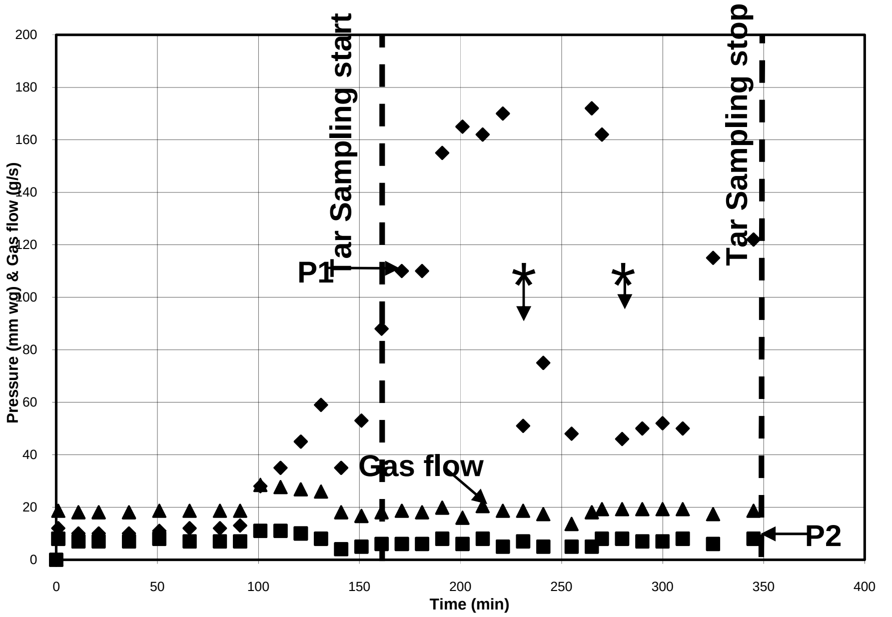


Figure 5.11 Pressure drop and gas flow profile with Restholtz on 19/2/98
Note – P1 denotes suction pressure and P2 the positive pressure of the blower.

Denotes point of grate shaking. The reactor pressure drop reduces significantly with grate shaking and builds up after sometime.

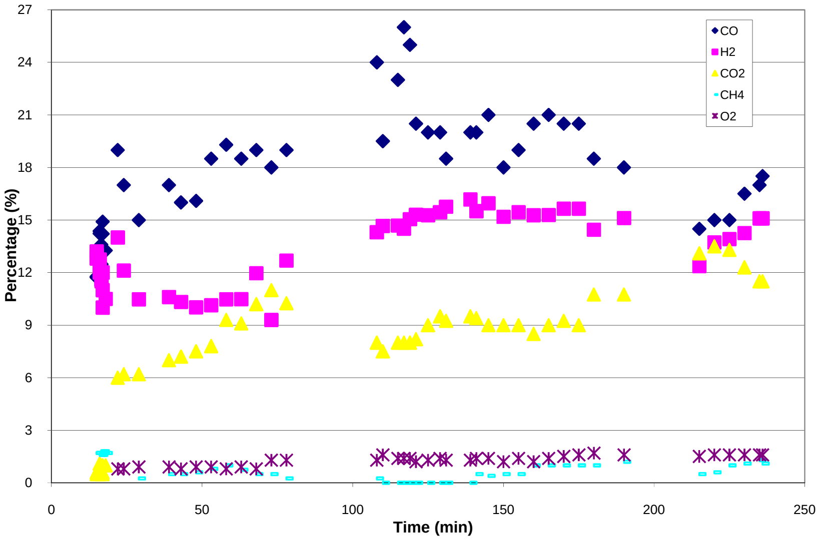


Figure 5.12 Variation of gas composition with time during the run, Feed stock – Restholtz

.

The wall temperatures was around 400 - 350 $^0$C prior to the P & T sampling as shown in Table 5.8.

The variation of system static pressures with time is shown in Figure 5.11

The system pressure drop increased from 40 mm to over 170 mm wg. The same was restricted to about 160 mm wg by resorting to grate shaking.

The variation of gas composition with time is shown in Figure 5.12, the average gas composition is shown in Table 5.9, the gross calorific value averaged around 3.62 MJ/kg. The P & T analysis results are shown in Table 5.10. The Exhaust gas analysis is shown in Figure 5.13

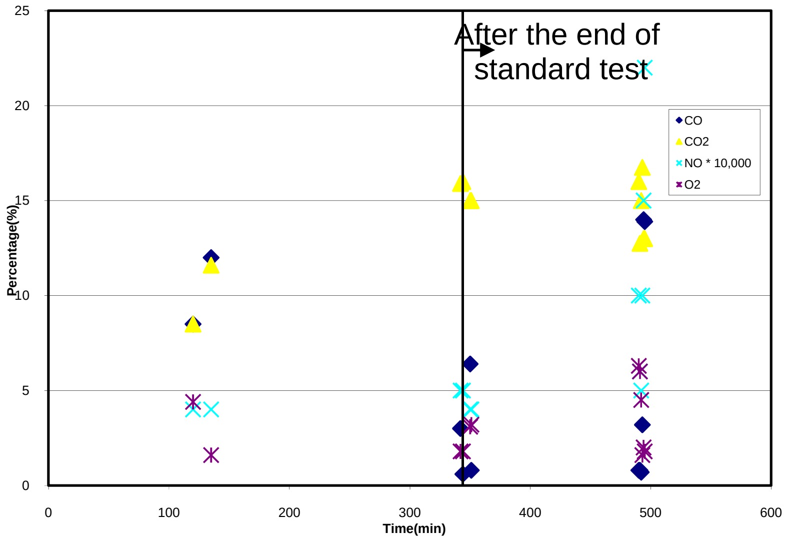


Figure 5.13 Exhaust gas composition in the premixed flame burner, Feed stock – Restholtz

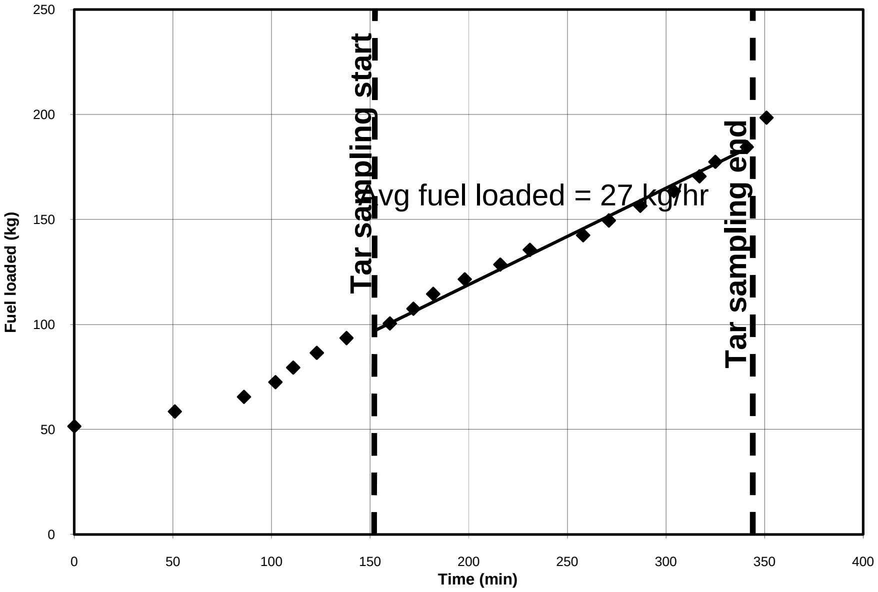


Figure 5.14 Cumulative loading of Restholtz.

The trend of fuel loading is shown in Figure 5.14, which averaged around 27 kg/hr.

## 5.5 Summary

The present chapter deals with the experiments that have led the investigators to get back to standard open top system for handling agro-residues through the briquetting route, a route that was not considered valid earlier by them themselves. This reversal of their position has arisen from the positive experience in dealing with restholz and Swiss grass. In fact, the problems normally expected with ash fusion in these residues with high ash content like for grass including the problematic salts of potassium with low ash fusion temperature were not faced. Perhaps, part of the answer was in the low fluxes used in the tests – about a third of the nominal flux. Nevertheless, this interesting feature was a sufficient incentive to pursue the idea of using the open top downdraft system for such light agro-residues. At this time the thesis of Dr. Kaupp (already alluded to in the literature review section (actually published in 1972) came to the attention of the investigators. A careful study of this excellent piece of research contained many remarks several of these based on research of an earlier period of time supporting the persistent observations made during the experiments at CGPL. Briefly stated again in the present context, for circumstances in which small particles sizes and heating rates are prevalent in the cyclone reactor, rapid pyrolysis is a natural consequence (particle sizes of 250 microns to a millimeter diameter and particle temperature rise rates of 400 to 1000 C / s). Rapid pyrolysis implies greater generation of tar (in fact liquid bio-fuel generation strategies are essentially based on this thought) or liquid components. For gasification processes, one must aim at enhancing gas output and reducing substantially the liquid components. Thus by using a cyclone gasifier, we may be, by design, causing greater generation of tar which is to be cracked subsequently. One can make a conceptual statement on the reactor behavior: we are creating a larger fraction of liquid components which are cracked in a suspended state in which high temperature and oxidative conditions in part and reducing reactions in part also are encouraged to reduce the high molecular compounds. Thus while the performance of the reactor as a tar reducing device may be good, the fact that small particle sizes are used leads to the creation of a larger amount of tar, a feature which is against the aims of a gasifier design.

The arguments made above show that cyclone reactor may not be the best device to generate tar free cold gas. It may not also be the best thermal system since pulverizing the fuel leads to a fair fraction of fine particles in the feed stock which will find their way out of the reactor as char/ash particles and therefore need a good cyclone to remove them. Perhaps it would be better to use solids of larger size so that the fraction of small particles will be low in the feed stock itself and thus help reduce the carry over of fine particulate matter. It is entirely possible that even here a cyclone may be needed to reduce particle carryover which may occur during operations like grate rotation or grate shaking performed once in a while to reduce the pressure drop through the reactor. It is these set of thoughts combined with the fact that briquetting agro-residues is an industry in itself, currently gaining prominence in the country (due to lack of firewood resources) that led to the motivation to use the standard solid bio-residue gasifier for light agro-residues as well. A further feature thought to make this strategy all the more viable is the fact that transportation of light agro-residues using petroleum fuels is expensive and enhancing the density near the source of these fuels helps in reducing the transportation costs (density increase can be as much as ten to twenty times the actual density). In fact, this feature in positively affecting the economy of fuel availability costs at the power station may be a strong driver to use briquetting approach in the design of power stations.

# Chapter 6

# Reciprocating engines : Aspects of dual fuel operation

## Introduction

During the project development phase, one of the important questions that came up again and again is the loss of peak power in dual fuel operation. Even though this question is somewhat incorrectly posed, one invariably expects answer to it. The "incorrectness" in the posing of the question is that dual fuel operation as a term is somewhat incomplete – 85 % diesel replacement is dual fuel operation; so also 15 % diesel replacement. Technically, at 0 % diesel replacement one will get the full diesel power. Also, in power plant operations, one demands base load and on specific occasions, the peak load. If one were to assume that peak load can be obtained at low diesel replacements, the question will then become: what is the diesel replacement at the base load operating point, which is typically 80 % of the rated load. If one has a design of the gasification system with high diesel replacement at the base load operational point, then the attainment of the peak power will not be affected. While on naturally aspirated engines, the points made above are valid, in the case of turbo-supercharged engines, the diesel replacements generally recommended are about 70 %. Discussions with engine manufacturers gave several possibilities for the limit indicated. One of these is that the diesel injectors will overheat at low diesel flow rates and therefore, one should restrict the diesel replacement. However, it is also possible that there is an inherent limit posed by the amount of air flow that can be ingested. Hence it was thought worthwhile exploring the reasons for such a limit.

Reciprocating engines has derived benefits for improving the overall efficiencies and cost per unit power installed over the last few decades. The major thrust has been in the area of design of combustion chamber, fuelling system and turbo charging. These have seen the benefits in the size reduction, fuel efficiency and the output per unit weight of the hardware.

While examining these aspects (from the technical brochures provided by the manufacturers), the following facts are evident - An increase in output by 36 percent from a naturally aspirated engine by turbocharging. An increase in output by 86 percent from a naturally aspirated engine by turbocharging and aftercooling. These have resulted in some reduction in the specific fuel consumption on the engine. In the case of ALU 680 engine, the increase in power from a turbo charged system is about 15 % over the naturally aspirated engine.

Analysing the data from the specifications provided on different engine capacities by different manufacturers it is clear that the cylinder displacement volume per unit power output in naturally aspirated mode is nearly constant; 8.5 kW/lts (0.118 lts/kW). This implies that the air available for diesel combustion is roughly same in most of these engines; i.e., the excess air factor is same.

Table 6.1 gives the details of different models available.

**Table 6.1 Cubic capacity of different engine per unit rated load for various power levels in naturally aspirated mode**

| Engine Model | No. of | Cubic | Rated load kW | Load/cubic |
|---|---|---|---|---|

| | cylinders | capacity, lts | | Cap. kWs/lt |
|---|---|---|---|---|
| RB 22 | 2 | 2.205 | 18.6 | 8.4 |
| RB 33 | 3 | 3.307 | 28 | 8.5 |
| RB 44 | 4 | 4.410 | 37.2 | 8.4 |
| RB 66 | 6 | 6.614 | 56 | 8.5 |
| ALU 680 | 6 | 11.1 | 94 | 8.5 |
| 3YD MK2 | 3 | 3.695 | 32 | 8.7 |
| 4YD MK2 | 4 | 4.928 | 43 | 8.7 |
| N 495 G | 4 | 8.1 | 68.8 | 8.5 |
| AV 1 | 1 | 0.551 | 3.7 | 6.7 |

Typical diesel engine efficiencies are in the range of 35 to 39 % (175 - 160 g/hph or 236 g/kWh - 216 g/kWh) and 42.7 MJ/kg for diesel) in the power range of 10 kW to about 1200 kW.

**Table 6.2 Derating of the power output while running on the dual fuel mode with natural gas**

| Model | Mode | Rated output, kW | Cubic capacity, lts | Aspiration | Derating (@ 70% saving) |
|---|---|---|---|---|---|
| N 495 G | Diesel | 68.8 | 8.1 | NA | |
| DG 495 G | Dual | 62.9 | 8.1 | NA | 9% |
| N 743 G | Diesel | 125.8 | 12.2 | NA* | |
| DG 743 G | Dual | 96.2 | 12.2 | NA | 23 % |
| N 855 G | Diesel | 166.5 | 14.0 | NA* | |
| DG 855 G | Dual | 107.3 | 14.0 | NA | 36 % |
| VT 1710 G | Diesel | 287.9 | 28.0 | NA* | |
| DG 1710 G | Dual | 222.0 | 28.0 | NA | 23 % |
| NTA 855 G | Diesel | 281.2 | 14.0 | TA | |
| DGTA 855 G | Dual | 203.5 | 14.0 | TA | 28 % |
| KTA 855 G | Diesel | 333.0 | 19.0 | TA | |
| DGTA 1150 G | Dual | 299.7 | 18.9 | TA | 10 % |
| VTA 28 G3 | Diesel | 518.0 | 28.0 | TA | |
| DGTA 1710 G | Dual | 407.0 | 28.0 | TA | 21 % |
| KTA 2300 G | Diesel | 658.6 | 38.0 | TA | |
| DGTA 2300 G | Dual | 592.0 | 37.8 | TA | 21 % |
| KTA 3067 G | Diesel | 873.2 | 50.0 | TA | |
| DGTA 3067 G | Dual | 784.4 | 50.3 | TA | 11 % |

Commercially, dual fuel engines are available in the market to run on natural gas or biogas. A diesel substitution of 70 % is suggested. A comparison of performance of these engines and the derating with respect to the diesel engine is presented in the Table 6.2 (here for some model the naturally aspirated power is estimated by using the ratio of 1:1.36 is the power gain in turbocharged engine). The natural aspiration output is derived from the available data by using the ratio of 1 : 1.36 power ratio between naturally aspirated and turbocharged output. From Table 6.2, it is clear that except for N495G, the derating in power output from the engine is between 23 to 36 %, compared with the diesel mode with natural aspiration and about 10 to 20 % in the turbo charged after cooled.

From the data available (Kirloskar Cummins) for similar engine cylinder capacity, the following are the details at 200 kW output;

**Table 6.3 Fuel consumption is diesel and dual fuel mode using natural gas (source : Kirloskar Cummins)**

| Engine model | Mode | Diesel lt/hr | Gas $m^3$/hr |
|---|---|---|---|
| NTA-855-G | Diesel | 57.8 | - |
| DGTA-855-G | Dual fuel | 22.5 | 45.5 |

The engine model indicated in the above Table 6.3 on the diesel mode can deliver a maximum of 340 - 380 BHP (251 - 281 kW) at 1500 rpm. Assuming that 200 kW is the maximum output from the engine, it is evident that the diesel saving is only 61% while the efficiency fall from 34.8 % in diesel mode to 29 % in the dual fuel mode. Even assuming that the deliver output in diesel mode is 251 kW the derating in dual fuel mode is about 20 %.

**We will now estimate the air flow rate in the turbocharged after cooled mode.**

Typical ratio of power between turbocharged after cooled to naturally aspirated engine is 1.8 : 1. Assuming that the air flow rate also increases in the same ratio we have for the NTA 855 G we have the air flow rate = 1500x8.1x60/2 x1.8 = 656.1 $m^3$/hr.

From the above table if an oxygen balance (air) is established, we have 22.5x0.85x16 + 45.5x0.5 (kg/$m^3$) x 14 = 624.5 $m^3$/hr

The difference is about 32 $m^3$/hr, which amounts to 1.0 % oxygen in the engine exhaust. This seems a reasonable estimate.

Based on the above analysis the derating in dual fuel mode is a limiting condition forced due to the air drawn into the engine cylinder. Further, the increase in the exhaust temperature limit due to dual fuel operation is an additional feature which sets the limit on the power delivered by the engine.

## Dual fuel operation using producer gas

Experiments performed on diesel engine in dual fuel mode were described earlier. The air inlet was fixed with a box where gas and air is allowed into the engine manifold. Optimisation of diesel replacement is performed by changing the resistances on the gas/air line to increase the gas flow rate. The existing governor is used for maintaining the frequency/rpm of the engine.

The system is instrumented for gas quality, gas flow rate, air flow rate, load measurement and engine exhaust oxygen level. Tests have been conducted on the naturally aspirated and turbocharged mode. The gas and air is premixed in the turbo charged mode.

The diesel replacement at each load is computed knowing the diesel consumption in the diesel mode. The diesel replacement is optimised by monitoring the oxygen content in the engine exhaust. At higher loads it has been found that the around 2 % oxygen level in the engine exhaust the best diesel substitution occurs. All the measured data is enclosed in the Appendix A.

The following sections will present the analysis of the tests on the engine.

### Mass and energy balances in dual fuel mode

Consider first the naturally aspirated mode of operation of the ALU680 engine with a cubic capacity of 11.1 liters at an engine speed of 1500 rpm. Its rated output is 128 hp at MSL = 94.7 kW. Calculations show the following features.

Theoretical air flow rate is equal to1500 x 11.1 x 60/2 = 499.5 $m^3$hr; At Bangalore, maximum output in Diesel mode (9.5 % derating) = 94.7x0.905 = 86 kW ; Radiator fan power input (5 %) = 4.3 kW ; Net engine output = 81.4 kW ; With an alternator efficiency of 91.3 %, the electrical output = 81.4 x 0.913 = 74 kW. ***Therefore the expected electrical output from an ALU 680 natural aspirated engine at Bangalore is 74 kW***

Consider the same engine fitted with a *turbocharger.* From the manual we have the rating = 143 hp = 106 kW. Thus from the manual the power output from the turbocharged engine is 18 % more than the natural aspirated engine. The following are the actual measurements on the ALU 680 engine in the diesel mode and the dual fuel mode using producer gas in natural aspirated and turbocharged mode.

## With Natural Aspiration :

### Diesel mode

Maximum electrical output is 72 kW. The fuel consumption at this load is 5.9 g/s (25 lt/hr) This amounts to the specific fuel consumption of 295 g/kWh in electrical mode and 269 g/kWh at the engine shaft. The measured oxygen content in the exhaust gas is 5.8 %. The overall efficiency works out to 28.6 % (electrical); 31.2 % (engine)

### Dual fuel mode

Maximum electrical output is 61 kW. The diesel replacement at this load is 74 %. The measured oxygen in the exhaust is 2 %. Thus the overall efficiency works out to 27% in electrical mode and 29 % at the engine shaft. The derating in dual fuel mode is 15 %.

## With Turbocharger :

### Diesel mode

Maximum electrical output is 93 kW. The fuel consumption at this load is measured as 6.8 g/s (28.8 lt/hr). The specific fuel consumption therefore works out to 261 g/kWh in electrical mode and 239 g/kWh at the engine shaft. The oxygen content in the gas is measured as 6.0 %. The overall efficiency becomes 32 % in electrical mode and 35.3 % at the engine shaft.

### Dual fuel mode

Maximum electrical output is measured as 64 kW. The diesel replacement at this load is measured as 74 %. The oxygen in the exhaust is measured as 2 %. The overall efficiency works out to 24 % in electrical mode and 26.2 % at the engine shaft. The derating in dual-fuel mode is 31 %.

### Analysis

From the measurements on the air, gas and the diesel flow rates the following mass and energy balance will determine the limiting condition on the diesel replacement or the power derating of the engine on the dual fuel mode.

### Natural Aspiration :

At Bangalore 115 g/s of air is ingested into the engine; implying about 85 % suction efficiency. The oxygen balance on the naturally aspirated engine can be assessed as follows. The diesel flow rate at nominal diesel operation is 4.2 g/s. At 74 % diesel replacement this implies a diesel flow rate of 4.2x0.26 = 1.1g/s. The air quantity required at stoichiometry is therefore 1.1x16.0 =17.6 g/s. The gas flow rate is given as 38 g/s. The amount of air required for burning up the gas is 38x1.3 = 49.4 g/s. At 2 % excess oxygen, the excess air in the exhaust is 11 g/s. Therefore, the sum of air and gas is (17.6 + 49.4 + 11) + 38 = 116 g/s

*From these data, it is clear that the amount of gas that could be replaced is limited due to the excess air capacity for this particular engine.*

On making the energy balance (gas cal value 4.7 MJ/kg) we have;

Energy balance on the naturally aspirated engine

Energy input from diesel is 47 kW and Energy input from gas is 178.6 kW and therefore, the overall efficiency is 61/(47+178.6) = 27 %

There is a drop in efficiency from 34 % to 27 % between the diesel mode and the dual fuel mode. This is consistent with the commercial engines available for dual fuelling on natural gas. The inefficiency in the dual fuel mode both in the producer gas mode and the in the natural gas is attributed to the combustion inefficiencies; related to the flame speeds of the gaseous fuel used.

**From the above it is clear that one can expect about 15 % derating in the dual fuel mode compared with the normal diesel run.**

### Turbocharge Aspiration :

Measurements on the system with turbocharging indicate that about 148 g/s of air can be injected in the engine at 93 kWe load. Tests on the dual fuel mode has indicated that a maximum of 64 kWe can be realised with 70 % diesel substitution. With 2 % oxygen in the gas, the total gas air mixture available is 148 - 14 = 134 g/s. At 93 kW the diesel consumption is 6.82x0.3= 2.046. Air requirement is 2.046 x 16 = 32.7 g/s. Gas air mixture amounting to 101 g/s is available. As indicated earlier for stoichiometric combustion we have 44 g/s of gas and 57 g/s of air.

Using the above mass balance, the energy balance is 2.046x42.7 + 44 x 4.7 = 294 kJ/s, amounts to an overall efficiency of 32 %. As per our earlier measurements, the overall efficiency in the dual fuel mode is around 27 %, thus full load realization is not possible on the turbo charged mode.

Measurements in the lab have indicated that at 64 kWe, an average diesel replacement of 70 % is achieved. At 64 kWe the air ingested is about 138 g/s. Repeating the above procedure, we have the energy balance, 4.5x0.3x42.7 + 45 x 4.7 = 269 kJ/s, amounting to
24 % overall efficiency.

Measurements on the engine exhaust temperature indicates that the loss of efficiency in the dual fuel mode is reflected in an increase in temperature. The energy carried by the exhaust is almost same as that loss on efficiency. These are attributed to the combustion inefficiency which is further related to the flame speeds of the mixture of gases. Further examination of these are necessary to relate the combustion efficiencies to the injection timing of the diesel fuel. The other point which is currently unanswered is the turbo charge efficiency being lower than the natural aspiration in the dual fuel mode.

Based on the above it is clear that a derating of about 30 % is unavoidable in the turbo charged mode while using the diesel engine in dual fuel mode.

Further tests on the engine fitted with turbocharger to obtain a 1:1.36 power output needs to be conducted to establish the performance in dual fuel operation with producer gas.

### Dual fuel engine rating for gasifier operation

The following Table 6.4 gives the power rating on the existing diesel engine on the dual fuel mode with producer gas operation. Here the rating is obtained by taking into account the generator efficiency, radiator power loss, typically about 5 % of the rated output and a factor for maximum power output in dual fuel mode (derating), in this case being 0.75 (25 % derating).

**Table 6.4 Power output while running on the dual fuel mode with producer gas**

| Model | Mode | Rated diesel output, kW | Dual fuel rating, kVA | Aspiration |
|---|---|---|---|---|
| N 495 G | Diesel | 68.8 | 57 | NA |
| NTA 495 G | Diesel | 128 | 104 | TA |
| NT 743 G | Diesel | 170 | 140 | T |
| NTA 743 G | Diesel | 189 | 155 | TA |
| NT 855 G | Diesel | 226 | 186 | T |

|  |  |  |  |  |
|---|---|---|---|---|
| NTA 855 G2 | Diesel | 252 | 206 | TA |
| KT 1150 G | Diesel | 281 | 230 | T |
| KTA 1150 G | Diesel | 333 | 273 | TA |
| VT 1710 G | Diesel | 288 | 236 | T |
| VTA 28 G3 | Diesel | 518.0 | 424 | TA |
| KT 2300 G | Diesel | 555 | 456 | T |
| KTA 2300 G | Diesel | 658.6 | 540 | TA |
| KTA 3067 G | Diesel | 873.2 | 715 | TA |
| KTA 50 G3 | Diesel | 1088 | 890 | TA |

The dual fuel output in KVA is obtained by assuming a generator efficiency of 92 %, radiator fan loss of 5 %, derating of 25 % compared with the diesel output along with a power factor of 0.8.

## Summary

The chapter highlights the performance of the commercial available engines in diesel and dual fuel mode based on the specifications provided on the technical brochures. The energy and mass balance have indicated that the dual fuel power output is limited by the air availability for the combustion. These analysis is consistent with the results obtained at the laboratory on a dual fuel engine using producer gas. The results are also consistent with engine ratings provided by the engine manufacturers for diesel and dual fuel power outputs. Further, it is clear that the overall engine efficiency is comprised during dual fuel operation.

# Chapter 7

# Computational Studies on cyclone gasifiers and combustors

## Introduction

This chapter is concerned with a computational study of the aero-thermo-chemistry of cyclone gasifiers and combustors. The reason for doing this task as a part of the project is that the flow inside the cyclone gasifier being complex, it would be of advantage to obtain some appreciation of the way the fluid behaves inside. In order to do this the conservation equations are solved using what is known as SIMPLE algorithm in the literature on computational fluid dynamics. The conservation equations are solved including turbulence and radiation on a geometry for which experimental results are available. The calculations for a range of flow rates and stoichiometries with premixed natural gas – air mixture are used to obtain the movement of the flame and other flow variables inside a cyclone reactor. Comparison with experiments on the movement of the flame and in some cases the velocity and temperature profiles along with streamlines is provided. The flame is generally located in the upper zone of the cyclone between the vortex finder and the outer wall in a region where the local normal velocities are about 0.5 m/s or less. The influences of throughput at a fixed stoichiometry and vice versa are similar on the flame structure in accordance with the experimental observations. Comparisons with the experimental results for temperature and axial velocity are satisfactory, but for swirl velocity. One of the interesting features, namely multiple steady solutions for the same parameters but different starting conditions is brought out and discussed.

The operation of a cyclone involves swirl. Swirl as a method of stabilizing flames has been known for a long time and swirl burners for combusting gaseous / particulate fuels have been studied extensively[refs. 9-11]. Using swirl in confined environment in a geometry like that of a cyclone for combusting solid fuels like pulverised coal or biofuels is also known but not investigated adequately. Combustion at stoichiometric conditions in swirl mode is performed in cyclones which can separate solid residues from gaseous products so that clean heat is generated. An even better method would be to perform gasification in the same reactor so that one can nearly double the power level. This is possible because with the same airflow into the cyclone, one has to increase the fuel feed at a fuel equivalence ratio of 3.0 so that combustible gases can be generated. Burning the gas so generated downstream is relatively simple and is advantageous in controlling emissions – NOX and others, a feature which is more difficult to achieve in direct combustion techniques. While there are commercially operating technologies for cyclone combustion of coal, and cyclone combustors are discussed even in text books [refs 12, 13], the physics of the combustion process is inadequately described and understood. Sridhar et al [ref. 14] have reported developmental studies on a cyclone gasifier for agricultural residues. There are no other studies on gasifiers reported in the literature. With regard to understanding the combustion behaviour in cyclones, the experimental studies of Najim et al [ref. 15], Styles et al [ref. 16], and O'Doherty et al [ref. 17] constitute an important body of knowledge. References [ref. 15,16] report many interesting results on a cylindrical cyclone combustor with methane-air premixed mixture. The studies are made with a constant fuel flow rate (3.1 kg/hr) but varying air flow rates to obtain varying richness in a 152.5 mm diameter stainless steel chamber of sufficient thickness. They have identified three modes of combustion corresponding to rich, stoichiometric and lean conditions. The flame movement between the three modes is traced to heat release rate variation primarily; aerodynamics of flow specially affects the lean flame behaviour. These results remain to be supported by computational studies to provide insight into the flame structure in the complex fluid flow environment of the cyclone. These experiments are particularly attractive for simulation since they do not involve two phase flow as will happen in most practical systems where cyclone is considered useful.

The present work is therefore concerned with a computational study of the reacting flow field inside the cyclone with two objectives - (1) make parametric studies to identify the flame movements and (2) calculate and compare with as much of experimental data as possible.

### 7.1 The Geometry and Computational domain

The geometry used in the present calculations is shown in Fig. 7.1. The premixed gaseous mixture of methane and air at different mixture ratios and flow rates enters tangentially with axisymmetry. This is very close to the experimental feature in which the gas enters at eight tangential ports around the periphery.

### 7.2 Governing Equations

The steady state Reynolds averaged equations of conservation of mass, momentum, energy and species have been used to describe the flow in a cyclone combustor/gasifier. The challenging problem in combustion modeling is a suitable choice of turbulence model. The main criteria for the selection are good description of flow problem considered and at the same time the model not being computationally expensive. In view of these considerations, the standard k-ε model has been used to account for turbulence in the present work. While there are questions about the choice of the model since turbulence loses isotropic behavior in a significant way in swirling flows recommendations have been made on the choice of this model for the present flows [ref. 18, 19]. The above governing equations are expressed in cylindrical polar co-ordinates–best suited to the geometry under consideration. Additional information on thermodynamics and chemical kinetics is provided for the closure of the system. It is assumed that the flow in the cyclone is axisymmetric, the fluid is Newtonian and ideal. Further assumptions of Ficks law of diffusion, equal diffusivities and equal specific heats of all species and Lewis number unity help in simplifying the mathematical description and reduces the computational effort and yet retaining the essential physics of the problem. All the governing equations have been cast in standard form found in literature [ref. 20]

### 7.3 Boundary Conditions

The boundary condition assumed for the set of above mentioned governing equation are :
No slip condition for velocities and zero gradient condition for the scalars (Wall temperature $T_w$ is specified for the non-adiabatic case) is enforced at cyclone walls (including vortex finder), Inlet has Dirichlet boundary condition where velocities and scalars are specified. The axis has symmetry conditions and zero gradient condition is imposed on far field boundary. Pressure at the far field boundary is specified as $p = p_{ref}$ , if mass flux is out of the flow domain and $p_{ref} - \rho v^2/2$, if mass flux is into the flow domain, here p is the static pressure, '$p_{ref}$'

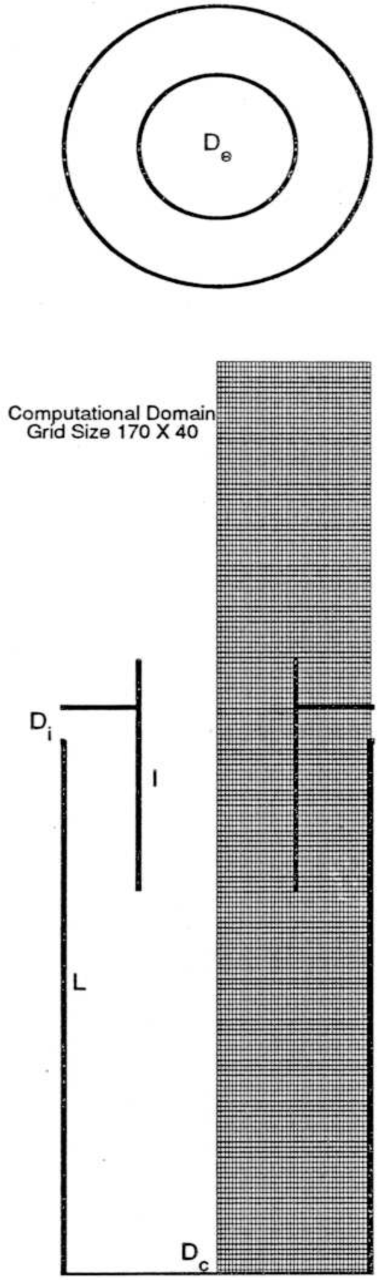


**Figure 7.1 Schematic diagram of cyclone combustor used by Najim et.al.**

is the ambient pressure taken as 1 atm here, ‘v’ is the total velocity of the fluid and ‘ρ’ is the density of the gas.

## 7.4 Radiation and Heat Loss

Radiative heat transfer is an important mode of heat transfer in combustion systems. Modeling of radiative transfer requires both the use of an accurate and efficient numerical technique and specification of radiative properties. The radiative energy balance for an absorbing emitting medium results in radiative transfer equation. This governing equation for gaseous combustion in discretized form is solved using discrete transfer method [ref. 21]. The computation domain was divided into 60 zones and total of 8×8 rays were used. The gas is assumed to be gray. The absorption and emission coefficients as a function of composition and temperature are calculated from total emissivity model [ref. 22, 23]. Heat loss by radiation and natural convection through the cylindrical wall has been considered.

Convective heat loss is modeled by an outside heat transfer coefficient for a vertical semi-infinite cylinder [ref. 23].

## 7.5 Combustion Model

A simple model of Eddy Breakup [ref. 24] with finite chemistry (Arrhenius model) is used to account for effect of turbulence on the local reaction rate. The idea is that the slower of the two processes, the laminar reaction and turbulent fluctuation control the reaction rate. The laminar reaction is given by Arrhenius mechanism and the turbulent reaction rate is assumed to be of the form

$$\omega_T''' = C_{EBU}\, \rho\, (\varepsilon/k) \min[\, Y_i\,]_{i=1\ldots n}$$

where $C_{EBU} = 23.6\,(\,\mu\varepsilon / \rho k^2\,)^{0.25}$

## 7.6 Choice of Chemical Kinetic Scheme

A simplified approach with single step overall reaction, has been considered. The kinetic parameters for the single step chemistry are chosen so as to match the heat release rate versus temperature profile and the flame speed of the one dimensional flame. The adequacy of an overall reaction model obtained from the above mentioned approach for one dimensional premixed laminar flame has been investigated [ref. 25, 26] and has been found to give accurate results close to that of detailed chemistry model. The kinetic model for the present study is a single step, second order reaction for premixed $CH_4$ - Air system.

$$\omega_{CH4}''' = A_f\, Y_{CH4}\, Y_{O2}\, \rho^2 \exp(-E/(R\,T))$$

The values of activation energy (E) and laminar one dimensional flame speed ($S_u$) for varying mixture ratios were obtained from literature [refs. 25, 26, 27]. One dimensional premixed laminar flame code [ref. 25] was used for determining the frequency factor $A_f$. With activation energy (E) as input `$A_f$' was tuned to obtain the desired value of flame speed ($S_u$) for corresponding equivalence ratios. Some of the typical values of $A_f$, activation temperature (E/R) and flame speed ($S_u$) used are given in table 7.1 below:

**Table 7.1: Kinetic parameters**

| φ | Activation Temmperature E/R (K) | Pre-exponential Factor A ($m^3$/Kmole.s) | Flame Speed (cm/s) |
|---|---|---|---|
| 0.7 | 16770 | 2.07e12 | 21 |
| 0.9 | 14350 | 1.17e12 | 35 |
| 1.5 | 18125 | 1.62e 11 | 08 |

## 7.7 Solution Procedure and Computational details

The finite difference equation is derived from differential equation integrated over a computational cell is solved using SIMPLE algorithm [ref. 28, 29]. The finite difference grid consists of a set of orthogonal lines in axial and radial directions of cylindrical polar co-ordinates. Grid refinement studies were carried out with refinement in both axial and radial directions to check for grid invariance. Typical grids of size 0.004, 0.003, 0.002 in axial direction (normalised to the length of cyclone ($L_0$)) and 0.002, 0.0015, 0.001 in radial direction (normalised to the radius of cyclone ($d_0/2$)) were tried and a normalised grid of size 0.003 in axial direction and 0.001in radial direction corresponding to a mesh of 170×40 was used for the present calculations. The grids are shown in Figure 7.1. Single iteration takes 7.1 cpu seconds on IBM590 and converged solution is obtained in about 8000-10000 iterations. Calculations have been made using both a code developed at the laboratory (based on staggered grids), tested over a period of ten years and a commercially available code CFX-F3D (based on collocated grids)

## 7.8 Results and Discussion

Calculations have been made over a range of equivalence ratio, $\phi$ from 0.65 (lean) to 1.5 (rich) and input power levels of 15 to 62 kWth (1 to 6 kg/h of $CH_4$). The results of Najim et al [ref. 15] correspond to fuel flow rate of 3.1 kg/h and air flow rates of 35 ($\phi$ = 1.5), 60 ($\phi$ = 0.9) and 89 ($\phi$ = 0.6) kg/h respectively. It must be noted that their experiments carry two simultaneous changes - changes in stoichiometry and flow rates. All the solutions were obtained as follows. Firstly, the case of $\phi$ = 1.5 was considered. The cold flow including the species distribution was developed including turbulence model. The reaction was turned on in an artificial manner by lowering the activation energy so as to have appreciably high reaction rate even at low temperatures inside the cyclone till about a temperature of 1500 K was developed in some region after which the formal reaction terms were used. Convergence was assured through the reduction of residuals of at least 5 orders and settling down of temperature distribution to within 0.2 %. It may be noted that the flame structure was captured in about 2000 iterations and remained steady while convergence on temperature took about 10000 iterations. The results of calculations with varying stoichiometry are shown in Figure 7.2 where contour plots of reaction rates of fuel inside the cyclone are presented. The flame is sharp on the inflow side and is located close to the inlet port area around the vortex finder. As air flow is increased, the flame becomes less rich first and therefore thinner till $\phi$ = 1 is reached and then it becomes elongated and broad at leaner conditions. The bottom portion of the reactor is virtually inactive in so far as the dynamics of reaction is concerned. In all cases except near $\phi = 1$, the flame edge is anchored on the wall at about the same location.

In order to distinguish between the roles of stoichiometry and throughput, calculations were made at $\phi = 1.5$ and flow rates of (1 *f* + 11.5 *a*), (2 *f* + 23 *a*), (3.1 *f* + 35.5 *a*) and (6 *f* + 69 *a*) kg/h, where *f* and *a* refer to fuel and air flow rates. Also calculations were made with total flow rate of 38.5 kg/h but varying stoichiometry by changing the relative flow rates of fuel and air. A comparison of these two is shown in Figure 7.3. The right part of the figure (7.3e-h) is dominated by the change in stoichiometry and is similar to the left part of Figure 7.2 (a-d) characterized by change in stoichiometry and throughput (from 41 kg/h at $\phi = 1.4$ to 56 kg/h at $\phi = 1.0$). It thus appears that in this range stoichiometry dominates the flame structure compared to flow rate. The left part of Figure 7.3 (a-d) is similar to the right part of Figure 7.2 (e-h). This implies that the flame structure on the lean side seen in Figure 7.2 is essentially a flow effect. Calculations made at $\phi = 1$ with increasing throughput (not presented here) show that the flame structure moves from what is seen in Figure 7.2d to 7.2e and remains about same for a range of throughput from 3 to 8 kg/h of fuel (45 to 120 kWth).

Figure 7.4 shows a comparison of the distribution of axial velocity and stream lines between experiment and calculations for $\phi = 1.5$. This comparison can be termed moderate and is affected by the swirl distribution. Yet in some segments of the reactor – particularly near the entry to the vortex finder – the comparison is fair. The differences seen in the exit zone are due to the inaccuracies of the swirl distribution which is very strong near the central zone. The velocities normal to the flame shown in the figure are about 0.5 m/s. These velocities are larger than laminar burning velocities for the mixture ratio considered – 0.08 m/s. The fact that the velocities around the turbulent flame are only about 0.5 m/s, much smaller than 5 to 7 m/s observed by Ishizuka [ref. 30] implies that concepts of vortex burst mechanism are not needed to explain the flame structure here.

In order to examine the discrepancy that even though the flame locations matched reasonably well, the swirl velocity did not match well particularly in the lower portions of the cyclone, laminar flow calculations were made. The flame structure in comparison to the turbulent flame is shown in Figure 7.5. The laminar flame is thinner, but longer. A part of the fuel escapes the inside of the reactor, but is brought in by the central vortex core for consumption inside. The flame behavior appears straightforward in the sense that the longer and thinner laminar flame is substituted by a shorter but thicker turbulent flame. On the whole laminar flow calculations gave a bad prediction of flame location; but swirl velocity predictions were better. This shows that the turbulence model is over estimating the viscosity in the lower portions.

A comparison of the temperature distribution shown in Figure 7.6 indicates that experimental peak temperatures are around 1200 C and calculated values including radiation and wall heat losses is 1500 C. This comparison of peak temperatures may be taken as fair in view of the fact that radiation corrections have not been made to the measured values. The flame in the

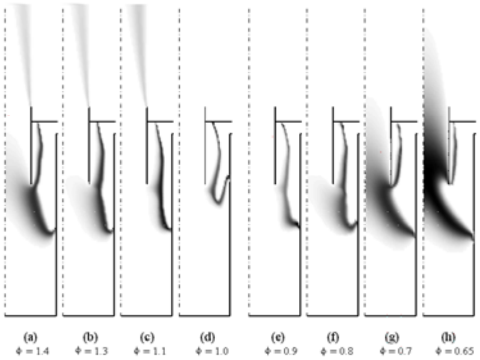


**Figure 7.2 Location of reaction zone at a constant fuel loading of 3.1 Kg/hr for different equivalence ratio**

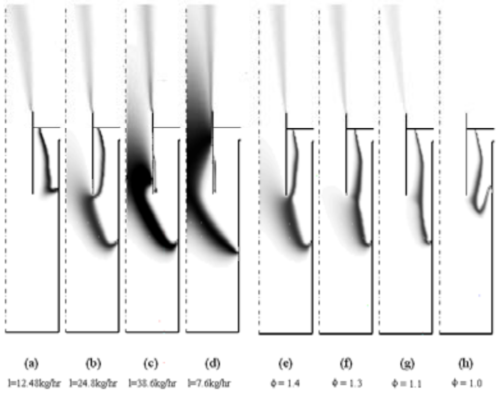


**Figure 7.3 Location of reaction zone (a,b,c,d) at equivalence ratio of 1.5 for different thoroughput and (e,f,g,h) at a constant thoroughput (38.6 kg/hr) for different equivalence ratio**

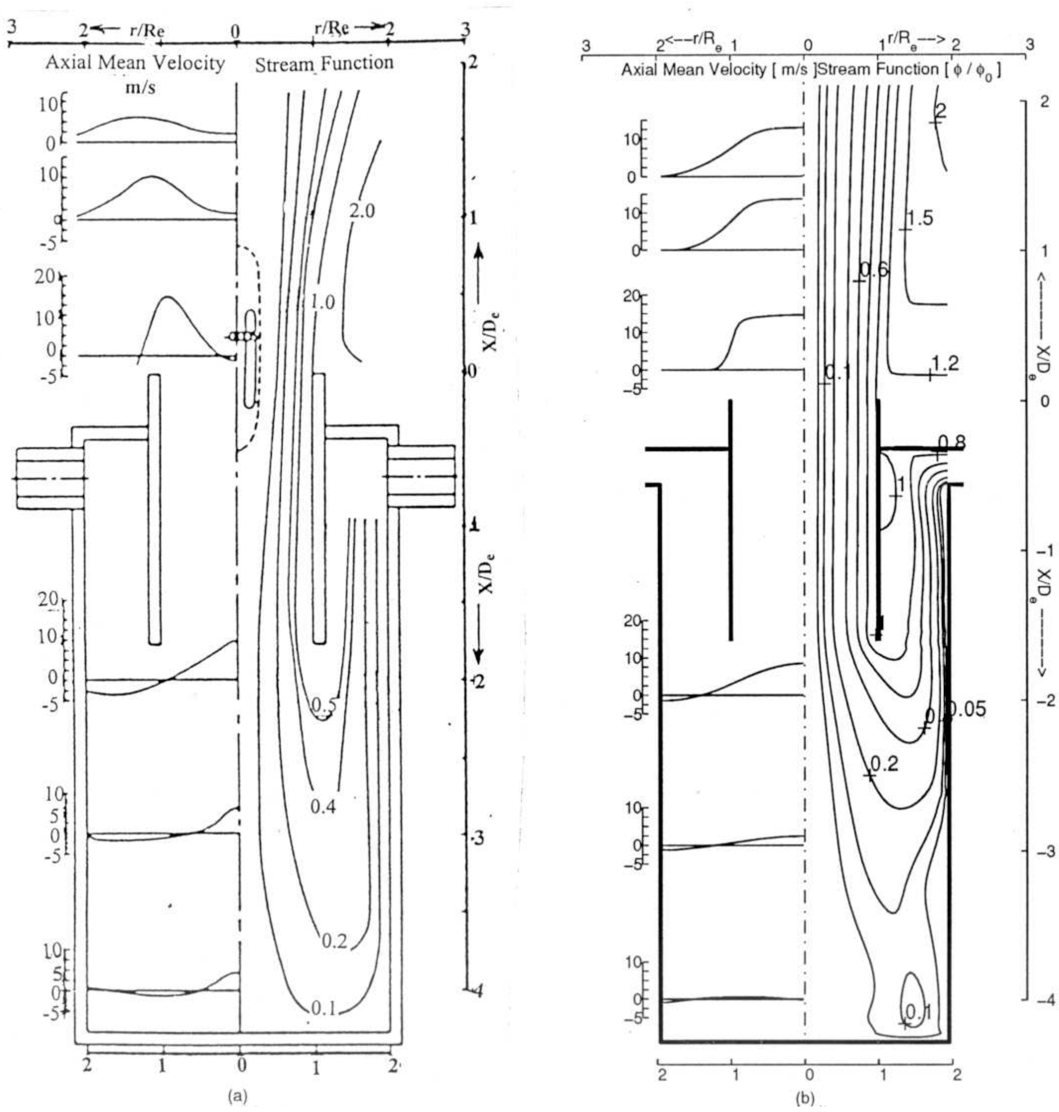
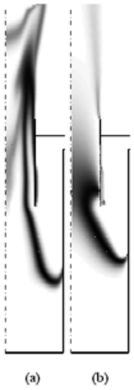


**Figure 7.4 Spatial distribution of streamlines and axial velocity for Φ=1.5 (Mode I), (a) Experiment (b) Computed**

Figure 7.5  (a) Laminar flame and (b) Turbulent flame at equivalence ratio of 1.5



Fuel flow rate of 3.1 kg/hr

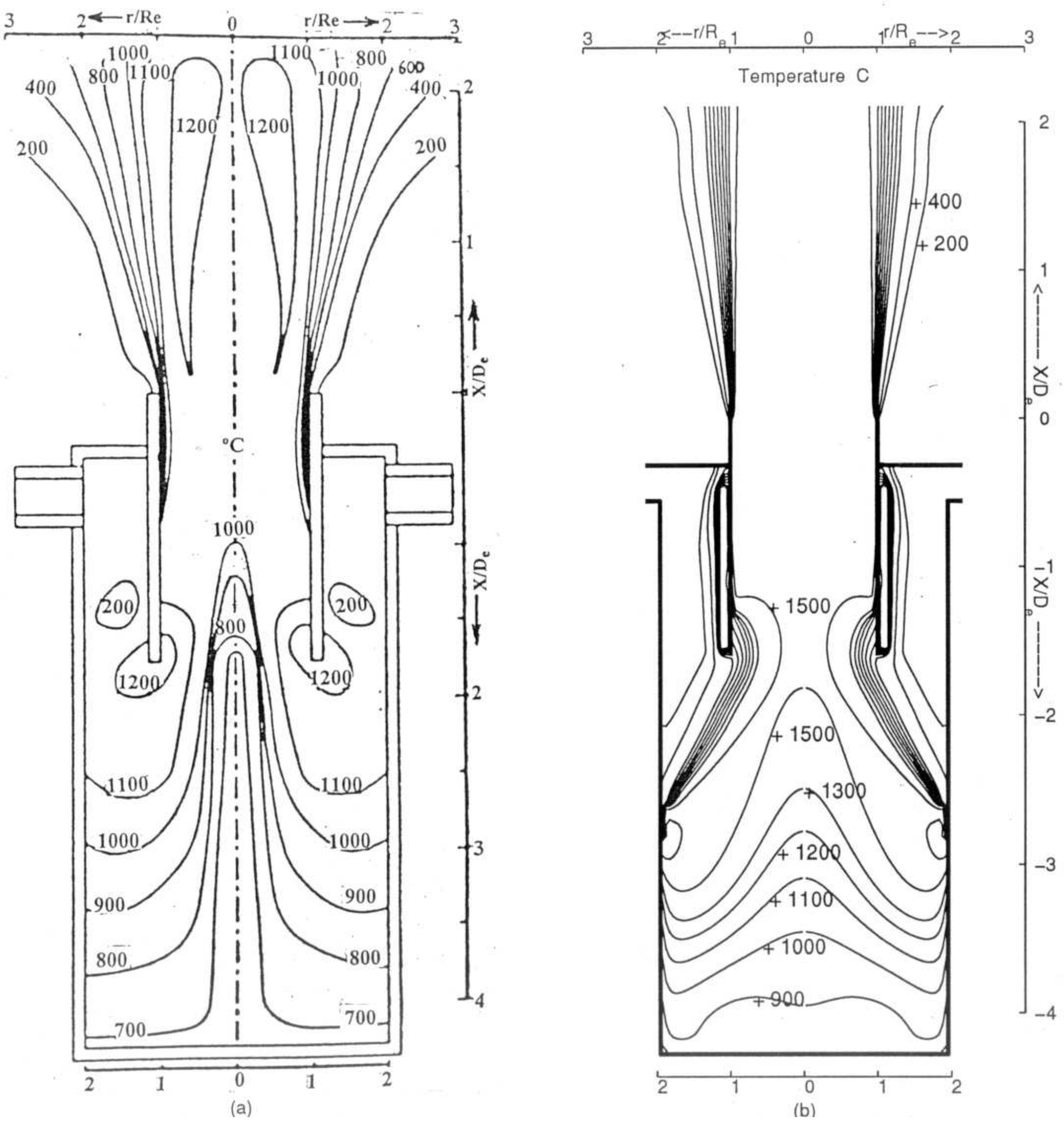


**Figure 7.6 Comparison of the temperature distribution**

experiment seems shorter compared to that from calculation, even though there is qualitative agreement of the distributions.

## 7.9 Multiple solutions

During the computations, it was found that in some cases, convergence took place to different solutions depending on the structure of the initial conditions. After several studies, the convergence behavior was mapped. Figure 7.7 b,d,e show the reaction rate contours obtained for cases presented in Figure 7.2 d,e,f. In Figure 7.2, the initial conditions were those corresponding to converged solutions for $\phi$ = 1.5. In Figure 7.7 b,d,e, the solution was generated as follows: Flow was developed with initial condition of reaction products at adiabatic conditions for $\phi$ = 1. The difference between the two solutions is very significant. The flame location described by Najim et al [ref. 15] at $\phi$ = 0.9 corresponds to what is shown in Figure 7.7b and not what is seen in Figure 7.2e. Further, computations were made for $\phi$ = 1 by approaching the steady state from steady solutions of rich and lean sides as well. The drop in residuals by one order from the earlier solutions is inferred to indicate acquisition of steady solutions in the new condition. It is argued that greater drop in residual may not be expected in view of most parts of the solution being already near the correct one. These results are shown in Figure 7.7a,c. As can be noticed Figure 7.7a,b,c show three solutions for $\phi$ = 1. The flame location in the flow field can be explained in terms of certain anchoring points. In Figure 7.7a the solution was started from cold reactants and ignition was achieved by decreasing activation energy. The reaction started downstream and propagated upstream. One anchoring point is provided by the hot combustion products trapped in the corner between upper wall and the vortex finder and the second anchoring point is on the side wall. Figures 7.7a and 7.7c are different in the part of flame close to the side wall. In this region, the velocity direction is predominantly downwards as can be seen in Figure 7.8a,b. In either case, the velocity component normal to the flame matches the flame speed (0.3-0.4 m/s) in the regions (cylindrical portion) where Karlovitz number is low (0.1–0.2), the lower portion of the flame towards the vortex finder is under negative stretch (Karlovitz number between –0.3 and –1.4) and hence thicker flame where as he flame portion near the anchor points are under positive stretch [Karlovitz number of 1.0]. For the case shown in Figure 7.7b the flame is initiated at the inflow boundary and remained attached close to the inlet slit, as the initial condition given is that of hot combustion products in the entire cyclone.

It is valuable to recognize that even in the experimental results of Najim et. al. [15], the stream line pattern for $\phi$ = 1.0 and 1.5 are not very different. Thus it appears that there are a few solutions – three found here, perhaps could be more which are steady and refer to the same inflow conditions. The state of inner conditions to start with will decide which solution will be reached.

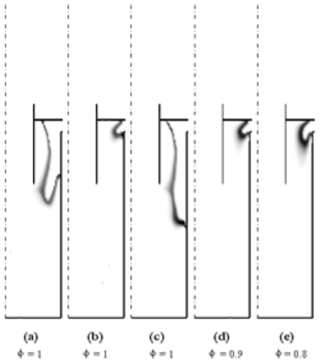
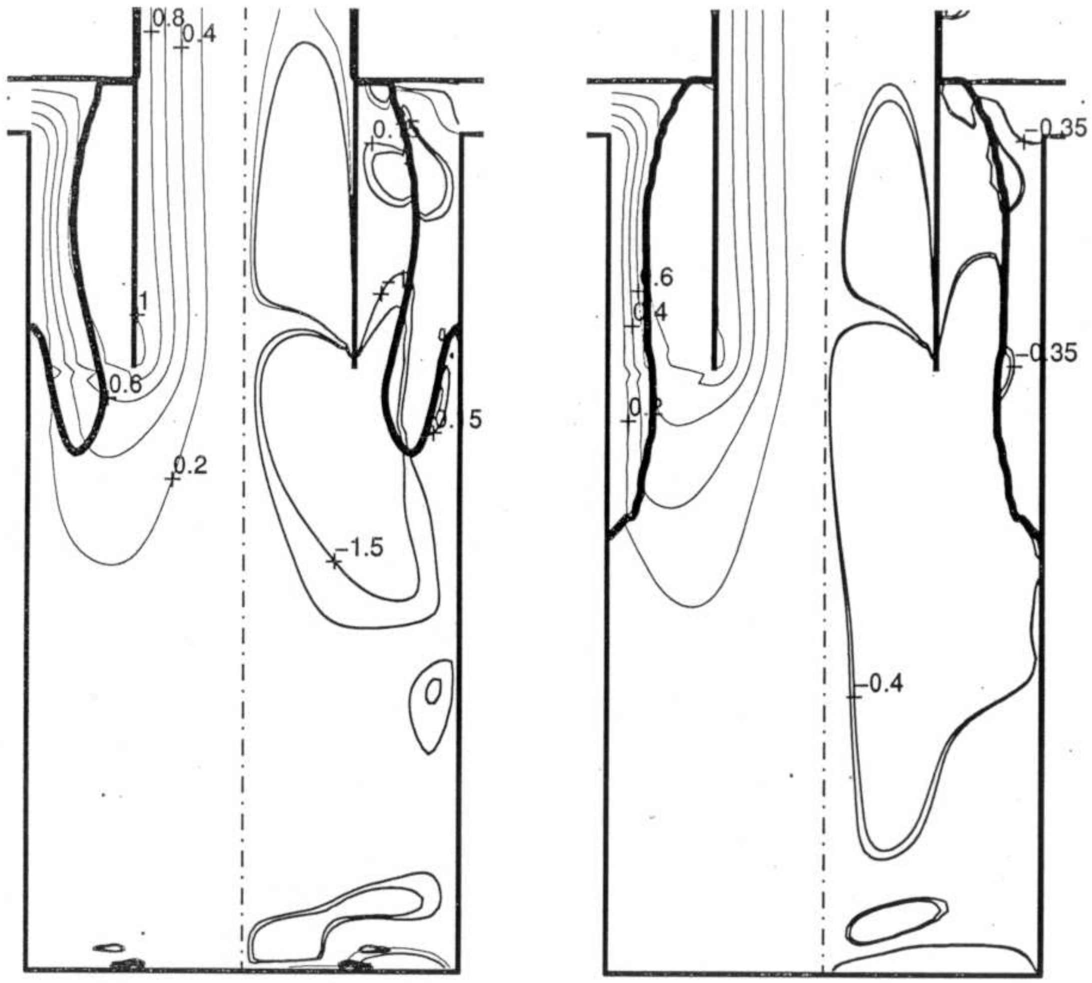


**Figure 7.7 Location of reaction zone corresponding to solution obtained with different distribution of species and fuel flow rate of 3.1 kg/hr.**



(a) (b)

Figure 7.8 Streamlines and Radial velocity contours for two solutions at $\Phi$=1.0

## 7.10 Concluding Remarks

This paper has treated computation of premixed reactive flow in a cyclone. The flame structure is largely limited to the upper region near the vortex finder. While for $\phi = 1$ it is very close to the entry zone, the flame moves out into the vortex finder as the incoming mixture moves away from stoichiometry. Limited comparison of temperature, velocity and stream lines with experiments appears encouraging; better comparison can be obtained by the choice of a more appropriate turbulence model, albiet with greater computational effort. The more interesting part of the work relates to multiple solutions. The calculated flame structure can depend on the initial conditions set out in the field. There are at least three solutions found for $\phi = 1$ with startup conditions rich, lean or stoichiometric condition. There is no experimental analogue for this, but these are not difficult to conceive. These results are interesting enough for more careful and well designed experiments to be pursued.

# Chapter 8

# Overview of the work

This report is a consolidation of the theoretical, experimental and developmental studies made on the systems for gasifying loose agro-residues. The environment in the late eighties when the project was conceived and early nineties when it was sanctioned, the bioresidue position in terms of availability indicated that it would be advantageous to use it without having to upgrade the quality significantly. At that time it was thought that if one were to pulverise the agro-residue, it would suffice for gasification. Transportation over a few kilometres did not seem too expensive in the loose form. The situation in ten years has changed so much that loose agro-residue cost has gone up for several residues, and the cost of transportation also has gone up due to price rise in diesel. These implied that a superior strategy would be to locally densify the fuel and then transport the material. This approach implied that one should try and adopt the classical wood gasifier to operate on agro-residues. This was what that has later emerged as a possible solution. The experimental work on using straw and sawdust briquettes in conventional downdraft open top reburn gasifiers has strengthened the confidence in using the standard gasifiers for this purpose. Modifications to the ash extraction system need to be dealt with in order to take away 5 to 20 % ash in agro-residues instead of 0.5 to 1 % ash in woody biomass. Tests carried out to determine the tar and particulate content of the gas has given promise to the possibility of the new approach. This has also produced great simplicity in the operation of the gasifier since the only control required is on the gas flow rate and the automatic O/F control which is the strong feature of wood gasifiers is still preserved in these operations as well.

It was an extremely tortuous journey to go all out and discover that the final solution resides in the early work itself. There have been no indications in the literature concerning such a conclusion. The only guidance available from the Chinese work was not adequate for generalising to other agro-residues. And even in the case of rice husk, it appears that briquetting helps better performance compared to the classical approach. These and related features need further exploration and are the tasks ahead.

# Chapter 9

# References

1. Anon, 25 MWe Floyd Myers Marsh rice husk (+rice straw) based power plant in California, USA reported in Power, p. S.15, **1983**
2. Anon, Alkali deposits found in biomass boilers" NREL/TP-433-8142, SAND96-8225, Vol. II, Feb **1996** (available to the public from NTIS, US department of commerce, 5285, port Royal Road, Springfield, VA 22161).
3. Company brochure, Gasification system developed and marketed by PRM systems, **1982+**
4. Editor, Chinese rice husk based gasification system (RAPA Bulletin on Rural Energy, p. 25, 1/85;p. 18, 2/**1987**
5. Anon, Indian rice husk based gasification system, **1980**
6. R. M. Jorapur, C. M. Gadgil, and A. K. Rajvanshi., Performance of a 15 kVA genset-gasifier system running on loose sugarcane leaves, Third national meet on Recent Advances in Biomass Gasification, GEDA, Baroda, **1991**
7. A. Kaupp , Gasification of rice hulls, Theory and Praxis, Friedr. Vieweg and Sohn, Braunschweig, **1984**
8. V. M. Tiangco, B. M. Jenkins, and J. R. Goss., Optimum specific gasification rate for static bed rice hull gasifiers, Biomass and Bioenergy, v. 11, pp. 51-62, **1996**; also see V. M. Tiangco, B. M. Jenkins, J. R. Goss, W. J. Chancellor, and I. R. Camacho, Variation of engine performance with reactor size for a rice hull fuelled gasification system, Paper No. 90-6076, American Society, **1990**
9. Lilley, G. D., AIAA Jl., Vol.15, No.8, pp 1063-1078, August **1997**
10. Syred, N. and Beer, J.M., *Combust. Flame* 23:143-201, **1974**
11. Weber, R. and Dugué, *Prog. Energy Combust. Sci.* 18:349-367,. **1992**
12. Thring, M. W., The science of flames and furnaces, Chapman and Hall Ltd, **1962**
13. Lilley, G. D., Gupta, A. K. and Syred, N., Swirl flows, Abacus Press,**1984**
14. Sridhar, G., Sridhar, H. V., Dasappa, S., Paul, P. J., Rajan, N. K. S., Shrinivasa, U. and Mukunda, H. S., Technology for gasifying pulverised bio-fuels including agricultural residues, to appear in Energy for sustainable development, **1997**
15. Najim, S.E., Styles, A.C. and Syred, N., *Eighteenth Symposium (International) on Combustion*, The Combustion Institute,Pittsburgh,PA,pp 1949-1957 , **1981**
16. Styles, A.C. and Syred, N., Najim, S.A., *J. Inst. of Energy* 1(405):159-168, **1979**
17. Doherty, T., Biffin, M. and Syred, N., *J. Inst. of Energy,* 66:110-118, **1993**
18. Khalil, E.E, Modeling of furnaces and combusters, Chapter 3, Editors: A.K. Gupta and D.G. Lilley, Abacus Press, **1982**
19. Sloan, D.G., Smith, P.J. and Smoot, L.D., *Prog. Energy Combust. Sci.* 12:163-250, **1986**

20 Gupta, A. K. and Lilley, D. G., Flowfield Modeling and Diagnostics, Abacus Press, p 42, **1985**

20. Lockwood, F.C. and Shah, N.G., *Eighteenth Symposium (International) on Combustion*, The Combustion Institute, Pittsburgh, PA, pp 1405-1414, **1981**,
21. Viskanta, R. and Mengle, M. P., *Prog. Energy Comb. Sci*., 13: 97-160, **1987**
22. Coppalle, A. and Verisch, P., *Combust. Flame* 49:101-108, **1983**
23. Holman, J.P.,White, P.R.., *Heat Tranfer,* McGraw-Hill Book Company, **1992**
24. Spalding, D.B., S*ixteenth Symposium (International) on Combustion,* The Combustion Institute, Pittsburgh, PA, pp 1657-1663, **1976**

25. Lakshmisha, K. N.,"Computational Studies on the Flammability Limits of Premixed Gases",Ph.D.Thesis, Indian Institute of Science, India, January, **1991**
26. Coffee, T. P., Kotlar, A. J., Miller, M. S., Combustion and Flame 54:154-169, **1983**
27. Gunther, R. and Janisch, G., *Combust. Flame* 19:275-288, **1972**
28. Patankar S. V., Numerical Heat Transfer and Fluid Flow, Hemisphere, **1980**.
29. Raithby, G. D. and Schneider, G.E., Handbook of Numerical Heat Tranfer Ed: Minkowycz, Sparrow, E.M., Schneider, G.E. and Pletcher, R.H., John Wiley, New York, **1988**.
30. Ishizuka, S., *Combust. Flame* 82:176-190, **1990**

# Appendix II

### Relevant Refereed Publications from the laboratory during the project period

1. K. N. Lakshmisha, P. J. Paul, H. S. Mukunda, On the flammability limit and heat loss in flames with detailed chemistry, Proceedings of the 23rd symposium (international) on Combustion, pp 433--440, 1990.

2. D. P. Mishra, P. J. Paul and H. S. Mukunda, Flame speed of wood gas at ambient and engine operating conditions, Third National Conference on Biomass Gasification, Baroda, Nov 1991

3. G. Goyal, P. J. Paul, H. S. Mukunda, One Dimensional Flame Studies on $H_2$–NO Flames, Combustion and Flame, p 160+, V.87, 1991

4. S. Dasappa, P. J. Paul, H.S. Mukunda and U. Shrinivasa, On the modeling of gasification of char spheres with Carbon dioxide, Carbon monoxide and Nitrogen, third National Conference on Biomass Gasification, Baroda, Nov 1991

5. H.S. Mukunda, P. J. Paul, U. Shrinivasa, S. Dasappa and A. E. Krishna Kanth, Development of Powdery Biomass Gasifiers, Third National Conference on Biomass Gasification, Baroda, Nov 1991

6. S. N. Srinivas, N. H. Ravindranath, S. Dasappa and H.S. Mukunda, A gasifier based rural power generation system: Performance and Problems, Third National Conference on Biomass Gasification, Baroda, Nov 1991

7. H. V. Sridhar, S. Dasappa, P. J. Paul, H. S. Mukunda and U. Shrinivasa, On the combustion of wood-char spheres in vitiated air-Analysis and Experiments, Fourth National Conference on Biomass Gasification, Baroda, Jan 1993

8. B. N. Baliga, S. Dasappa, U. Shrinivasa, and H. S. Mukunda., Gasifier-based Power Generation: Technology and Economics, Sadhana, v. 18, pp 57--75, March 1993

9. H. S. Mukunda, S. Dasappa, S. Bhogle, U. Shrinivasa, Studies on Stove for Powdery biomass, Int. J. Energy Research, v. 17, pp 281--291, June 1993

10. S. Dasappa, P.J. Paul, H. S. Mukunda, and U Shrinivasa, Gasification of wood-char spheres in CO$_2$-N$_2$ mixtures—Analysis and Experiments, Chemical Engineering Science, v. 49, No. 2, pp. 223--232, 1993

11. H. S. Mukunda, S. Dasappa, U Shrinivasa, Open Top Wood Gasifiers, pp 699-728, A Chapter in “Renewable Energy, sources for fuels and electricity”, Island Press, 1993

12. Purandar Chakrvarthy, D. P. Mishra, P. J. Paul and H.S. Mukunda, The theoretical calculations of the limits of flame propagation for producer gas mixture, Fourth National Conference on Biomass Gasification, Baroda, Jan 1993

13. Shrikant Kanitkar, Purandar Chakravarthy, P. J. Paul and H.S. Mukunda, The flame speeds, temperature and limits of flame propagation for producer gas - air mixtures - experimental results, Fourth National Conference on Biomass Gasification, Baroda, Jan 1993

14. Sangeeta Kohli, J. Srinivasan and H. S. Mukunda, Analysis of buoyancy-induced flow and heat transfer in a biomass stove, Fourth National Conference on Biomass Gasification, Baroda, Jan 1993

15. A. V. Manjunath, Colin M. Crasta, V. Gayathri, N. K. S. Rajan and H. S. Mukunda, Biomass utilisation via combustion and gasifiers - A computer based video presentation, Fourth National Conference on Biomass Gasification, Baroda, Jan 1993

16. S. Dasappa, H. V. Sridhar, P. J. Paul, and H. S. Mukunda, On the combustion of wood char spheres in O$_2$/N$_2$ mixtures - Experiments and Analysis, Proceedings of the 25th symposium (international) on Combustion, pp 569--576, 1994.

17. H. S. Mukunda, S. Dasappa, P. J. Paul, N. K. S. Rajan, and U. Shrinivasa., Gasifiers and combustors for biomass - technology and field studies, Energy for Sustainable Development, v. 1, pp 27--38, 1994.

18. H. S. Mukunda, P. J. Paul, S. Dasappa, U. Shrinivasa, N. K. S. Rajan, H. Sharan, R. Beuhler, P. Hasler and H. Kaufmann., Results of an Indo-Swiss Programme for Qualification, and Testing of an 300 kW IISc-Dasag Gasifier, Energy for Sustainable Development, v. 1, pp 46-49, 1994.

19. H. S. Mukunda, P. J. Paul., Fundamental combustion and gasification problems of biomass and biomass derived gaseous fuels, Invited paper, pp. 109--117, Proceedings of the First ISHMT-ASME Heat and Mass Transfer Conference, Jan 1994.

20. K. N. Lakshmisha, P. J. Paul and H. S. Mukunda., Computational studies of Hydrogen/air flames near rich flammability limits, pp. 763--769, Proceedings of the First ISHMT-ASME Heat and Mass Transfer Conference, Jan 1994.

21. D. P. Mishra, P. J. Paul, and H. S. Mukunda., Computational studies on the flame propagation in producer gas-air mixture and experimental comparisons, pp. 256--262, Proc. 13th National conference on IC engines and combustion, Jan 1994.

22. D. P. Mishra, P. J. Paul, and H. S. Mukunda., Computational studies of the effects of ambient parameters on stretched H$_2$/air premixed flames with detailed kinetics, pp. 277--283, Proc. 13th National conference on IC engines and combustion, Jan 1994.

23. S Dasappa, H V Sridhar, P J Paul, H S Mukunda, U Shrinivasa, Wood char sphere conversion with $H_2O$ and its mixtures with $CO_2$, $O_2$ & $N_2$ - Experiments and modelling, 26th International symposium on Combustion held at Naples, Aug 1996.

24. G. Sridhar, H. V. Sridhar, S. Dasappa, P. J. Paul, N. K. S. Rajan, U. Shrinivasa, H. S. Mukunda., Technology for gasifying pulverised biofuels including agricultural residues, Energy for Sustainable Development, pp. 9--18, v.III, no. 2, 1996.

25. H. S. Mukunda, S. Dasappa, P. J. Paul, N. K. S. Rajan, U. Shrinivasa, G. Sridhar, and H. V. Sridhar., Fixed bed gasification for electricity generation, Biomass Gasification and Pyrolysis, State of the art and future prospects, pp. 105--116, European Commission, CPL Press, 1997

26. H. Sharan, H. S. Mukunda, U. Shrinivasa, S. Dasappa, P. J. Paul, N. K. S. Rajan IISc--DASAG Biomass Gasifiers: Development, Technology, Experience and Economics, Developments in Thermochemical Biomass Conversion, pp 1045--1057, Blackie Academic and Professional (Pub), 1997.

27. H. S. Mukunda, S. Dasappa, P. J. Paul, N. K. S. Rajan, U. Shrinivasa, G. Sridhar, and H. V. Sridhar Fixed bed gasification for electricity generation, Biomass Gasification and Pyrolysis, State of the art and future prospects, pp. 105--116, CPL Press, 1997.

28. M. Jayamurthy, S. Dasappa, P. J. Paul, G. Sridhar, H. V. Sridhar, H. S. Mukunda, N. K. S. Rajan, C Barge, T Liliedahl, K. Sjostrom., Tar characterisation in new generation agro-residue gasifiers--cyclone and downdraft open top twin air entry systems, Biomass Gasification and Pyrolysis, State of the art and future prospects, pp. 235--248, CPL Press, 1997.

29. H. S. Mukunda., Some non-conventional ventures in Combustion Research, pp. 56--68, Proc. XVth national conference on I.C. Engines and Combustion, Allied Publishers, 1997.

30. Amit Kumar, P. J. Paul and H. S. Mukunda., Computational study of premixed gas fired cyclone combustor, pp. 701--711, Proc. XVth National conference on Internal Combustion engines and Combustion, Allied Publishers, 1997.

# Appendix I

## Test record - 1

| Parameter | Description |
|---|---|
| Date of test | 11.3.94 |
| Reactor version | Stainless steel |
| Mode of test | Burner |
| Feed stock | Pulverised rice husk using pneumatic feeder |
| Purpose | To generate tar free gas using a elaborate cleaning train |
| Preparations | An elaborate cleaning train consisting of one coarse and one fine filter |
| Run details | Pre-heating time: 30 min<br>Run time: 60 min<br>Rice husk consumed: 26 kg |
| Observations and results | Due to sudden increase in pressure drop across coarse filter the test couldn't be continued for longer time. The sudden raise in pressure drop in the filter is attributed to particulates and tar depositing on the sand bed. |
| Modifications for future test | Few changes contemplated in the coarse filter design |

## Test record - 2

| Parameter | Description |
|---|---|
| Date of test | 22.3.94 |
| Reactor version | Stainless steel |
| Mode of test | Burner |
| Feed stock | Pulverised rice husk using pneumatic feeder |
| Purpose | To generate tar free gas using a elaborate cleaning train |
| Preparations | An elaborate cleaning train consisting of one coarse and one fine filter. Coarse filter modified (1- 2mm sand size) |
| Run details | Pre-heating time: 33 min<br>Run time: 30 min<br>Rice husk consumed: 38 kg |
| Observations and results | Due to sudden increase in pressure drop across coarse filter the test couldn't be continued for longer time. The sudden raise in pressure drop in the filter is attributed to particulates and tar depositing on the sand bed. |
| Modifications for future test | Size of sand particles to be increased to 3 - 4 mm |

## Test record - 3

| Parameter | Description |
|---|---|
| Date of test | 15.4.94 |
| Reactor version | Stainless steel |
| Mode of test | Burner |
| Feed stock | Pulverised rice husk using pneumatic feeder |
| Purpose | To generate tar free gas using a elaborate cleaning train |
| Preparations | An elaborate cleaning train consisting of one coarse and one fine filter (30 mm large sand particles and 60 mm fine sand particle ranging from 250 - 600 microns).<br>Rice husk particle distribution:<br>1000 < RH> 1400 μ - 7%<br>500 < RH> 1000μ - 62%<br>500 < RH> 250 μ - 20%<br>250 < RH> 150 μ – 7.5 %-<br>RH<150 μ - 3.5% |
| Run details | Pre-heating time: 32 min<br>Run time: 18 min<br>Rice husk consumed: 20 kg |
| Observations | Large pressure drop across coarse filter but gas generated was clean. Peculiar odour smelt in the gas. Blower clean. |
| Results | Due to sudden increase in pressure drop across coarse filter the test couldn't be continued for longer time. The sudden raise in pressure drop in the filter is attributed to particulates and tar depositing on the sand bed. |

## Test record - 4

| Parameter | Description |
|---|---|
| Date of test | 19.4.94 |
| Reactor version | Stainless steel |
| Mode of test | Burner |
| Feed stock | Pulverised rice husk using pneumatic feeder |
| Purpose | To generate tar free gas using a elaborate cleaning train |
| Preparations | An elaborate cleaning train consisting of one coarse and one fine filter (30 mm large sand particles and 60 mm fine sand particle ranging from 250 - 600 microns).<br>Rice husk particle distribution:<br>1000 < RH> 1400 μ - 7%<br>500 < RH> 1000 μ - 62%<br>500 < RH> 250 μ - 20%<br>250 < RH> 150 μ - 7.5%<br>RH < 150 μ - 3.5% |
| Run details | Pre-heating time: 20 min<br>Run time: 60 min<br>Rice husk consumed: 82 kg<br>Gas flow rate : 40 g/s |
| Observations | Large pressure drop across fine filter but gas generated was clean. |
| Results | Due to sudden increase in pressure drop across coarse filter the test couldn't be continued for longer time. The sudden raise in pressure drop in the filter is attributed to particulates and tar depositing on the sand bed. |
| Modifications for future test | To introduce a scrubber instead of sand filters for gas clean-up |

## Test record - 5

| **Parameter** | **Description** |
|---|---|
| Date of test | 21.4.94 |
| Reactor version | Stainless steel |
| Mode of test | Burner |
| Feed stock | Pulverised rice husk using pneumatic feeder |
| Purpose | To generate tar free gas using a scrubber in addition to cooler (with out security filter). |
| Preparations | A scrubber having 25 mm thick pebbles was integrated with the system removing the filters.<br>Rice husk particle distribution:<br>1000 < RH> 1400 μ - 7%<br>500 < RH> 1000 μ - 62%<br>500 < RH> 250 μ - 20%<br>250 < RH> 150 μ - 7.5%<br>RH<150 μ - 3.5% |
| Run details | Pre-heating time: 30 min<br>Run time: 140 min<br>Rice husk consumed: 111 kg<br>Gas flow rate :- 38 ⌖ 2 g/s |
| Observations | Tar deposition found in the blower, pebble bed in the scrubber eroded. |
| Results | Lot of tar generated during the run probably due to low A/F. |
| Modifications for future test | To conduct future runs with higher A/F, fine sand filter to be used to prevent tar deposition in blower and venturi. |

## Test record - 6

| **Parameter** | **Description** |
|---|---|
| Date of test | 23.4.94 |
| Reactor version | Stainless steel |
| Mode of test | Burner |
| Feed stock | Pulverised rice husk using pneumatic feeder |
| Purpose | To generate tar free gas and understand the performance of the clean-up system. |
| Preparations | An elaborate cleaning train consisting of one scrubber and one fine filter being used. In the scrubber, pebble bed height increased to 40 mm and in sand filter, 30 mm coarse sand and 60 mm fine sand. Provision made for bypassing the sand filter. |
| Run details | Pre-heating time: 25 min<br>Run time: 110 min<br>Rice husk consumed: 55 kg<br>Gas flow rate : 40 - 45 g/s |
| Observations | Gas quality good based on flame. |
| Results | Tar deposition found in the blower and venturi. This was due to some local disturbance in the sand filter causing a leakage path for the gas. A variation in the Fuel feeding observed. |
| Modifications for future test | Pneumatic feeder to be recalibrated, scrubber and filter to be set right. |

## Test record - 7

| **Parameter** | **Description** |
|---|---|
| Date of test | 4.5.94 |
| Reactor version | Stainless steel |
| Mode of test | Burner |
| Feed stock | Pulverised rice husk using pneumatic feeder |
| Purpose | To generate tar free gas and understand the performance of the clean-up system. |
| Preparations | An elaborate cleaning train consisting of one scrubber and one fine filter being used. In the scrubber, pebble bed height increased to 40 mm and in sand filter, 30 mm coarse sand and 60 mm fine sand. Provision made for bypassing the sand filter. Cyclone, blower, venturi cleaned. A tar indicating equipment in the form of one inch glass tube filled with ice devised to condense tar if produced. |
| Run details | Pre-heating time: 15 min<br>Run time: 93 min<br>Rice husk consumed: 105 kg<br>Gas flow rate : ~32 g/s |
| Observations | The tar indicating device worked showing traces of brown color. |
| Results | Tar deposition found in the blower and venturi. No short circuiting in sand filter. Pebble bed disturbed in scrubber. |
| Modifications for future test | Problem with the load indicator for feed stock measurement to be set right. |

## Test record - 8

| **Parameter** | **Description** |
|---|---|
| Date of test | 11.5.94 |
| Reactor version | Stainless steel |
| Mode of test | Burner |
| Feed stock | Pulverised rice husk using pneumatic feeder |
| Purpose | To generate tar free gas and understand the performance of the clean-up system. |
| Preparations | An elaborate cleaning train consisting of one scrubber and one fine filter being used. In the scrubber, pebble bed height increased to 40 mm and in sand filter, 30 mm coarse sand and 60 mm fine sand. Provision made for bypassing the sand filter. Cyclone, blower, venturi cleaned. A tar indicator (fitted upstream of the blower) in the form of one inch glass tube filled with ice to condense tar on its outer surface, if produced. |
| Run details | Pre-heating time: 15 min<br>Run time: 95 min<br>Rice husk consumed: 105 kg<br>Gas flow rate : 32 g/s |
| Observations | The tar indicating device was a useful indicator in judging the quality of the gas. Traces of tar found to have condensed on the tube. |
| Results | Tar deposition found in the blower and venturi. No short circuiting in sand filter. Pebble bed disturbed in scrubber. Problem in the estimation of the fuel feed rate due to sudden failure of load indicator. |
| Modifications for future test | To resolve the fuel feed issue and to get a better estimation of fuel feed rate . This will be useful in operating the system at slightly higher A/F and in turn reduce tar generation. |

## Test record - 9

| Parameter | Description |
|---|---|
| Date of test | 10..5.94 |
| Reactor version | Stainless steel |
| Mode of test | Burner |
| Feed stock | Pulverised rice husk using pneumatic feeder |
| Purpose | To generate tar free gas and understand the performance of the clean-up system. |
| Preparations | Slight modifications done in the scrubber which includes increase in the mesh size and introduction of partitions to reduce sand/pebbles erosion. Provision made for bypassing the sand filter. Cyclone, blower, venturi cleaned. Fuel feed system corrected. Finer size rice husk to be used to establish a better thermal environment. Use of tar indicating device to be continued.<br>Rice husk particle distribution:<br>500 < RH> 1000 μ - 21%<br>500 < RH> 250 μ - 41%<br>250 < RH> 150 μ - 28%<br>RH < 150 μ - 10% |
| Run details | Pre-heating time: 30 min<br>Run time: 90 min<br>Rice husk consumed: 85 kg |
| Observations | Reactor wall temperatures found be higher than 850 $^0$C through out the run. Traces of tar found to have condensed on the tar condensing tube. Char conversion in the reactor 11-14%. There was a reduction in gas flow rate with time despite pressure drops being normal. Nominal flow rate couldn't be maintained. it was felt that the blower efficiency dropped with time as it was getting coated with tar. |
| Results | Tar deposition found in the blower and venturi. No short circuiting in sand filter. |
| Modifications for future test | Trouble with load indicator to be set right. |

## Test record - 10

| Parameter | Description |
|---|---|
| Date of test | 14..5.94 |
| Reactor version | Stainless steel |
| Mode of test | Burner |
| Feed stock | Pulverised rice husk using pneumatic feeder |
| Purpose | To generate tar free gas and understand the performance of the clean-up system. |
| Preparations | Scrubber tested by connecting it to discharge end of blower.<br>Sand changed in fine filter 290+ kg filled. Venturi fitted down stream of the blower. |
| Run details | Pre-heating time: 20 min<br>Run time: 140 min<br>Rice husk consumed: 130 kg |
| Observations | The run was smooth with feed rate adjusted based upon wall temperatures and flame quality. Operated at A/F of 1.2 to 1.4 Scrubber performance was doubtful. System shutoff as cooling water temperature increased 12$^0$ above the room temperature. |
| Results | Tar and dust deposition found in the blower and fine filter amounting to 90 gm. Tar level about 200 mg/m$^3$. |

## Test record - 11

| Parameter | Description |
|---|---|
| Date of test | 27.5.94 |
| Reactor version | Stainless steel |
| Mode of test | Burner |
| Feed stock | Pulverised rice husk using pneumatic feeder |
| Purpose | To generate tar free gas and understand the performance using coarse sized Pulverised rice husk. This test is planned with the intention that by increasing the average particle size the pyrolysis rate could be brought and hence the amount of tar generated. It also has to be observed whether limiting the particle size to larger ones could lead to reduction in dust level in the gas. |
| Preparations | As the earlier blower was performing inefficiently, the same was replaced. However the other elements in the cleaning circuit remains the same The reactor insulation was stripped and checked for leakage. Insulation and cladding was redone. |
| Run details | Pre-heating time: 17 min<br>Run time: 45 min<br>Rice husk consumed: 37 kg |
| Observations | The char flow was not smooth, pyrolysis incomplete. The wall temperatures were relatively low. Also there was increase in pressure drop across filter. Problems in conveying coarse sized feed into the reactor. |
| Results | Tar and dust deposition found in the blower and fine filter. |

## Test record - 12

| Parameter | Description |
|---|---|
| Date of test | 29.6.94 |
| Reactor version | Stainless steel |
| Mode of test | Burner |
| Feed stock | Pulverised rice husk using pneumatic feeder |
| Purpose | To generate tar free gas and understand the performance using coarse sized pulverised rice husk. |
| Preparations | There is change attempted in the cleaning train where in there is water spray arrangement provided in the blower to wash the dust/tar sticking to the impeller and outer casing. There on the gas and water mixture is to be led to a cyclone to separate the clean gas from the water. |
| Run details | Pre-heating time: 16 min<br>Run time: 90 min<br>Rice husk consumed: 80 kg |
| Observations | The wall temperatures were relatively low. Operated at A/F of around 1.05. Problems in conveying coarse sized rice husk using pneumatic conveyor. |
| Results | Venturi had light traces of tar. Blower found virtually clean. |

## Test record - 13

| Parameter | Description |
|---|---|
| Date of test | 4.7.94 |
| Reactor version | Stainless steel |
| Mode of test | Burner |
| Feed stock | Pulverised rice husk using pneumatic feeder |
| Purpose | To generate tar free gas and understand the performance using coarse sized pulverised rice husk. |
| Preparations | To continue using blower with a water spray arrangement as a part of cleaning circuit. In addition a sand filter juxtaposed between the cyclone exit and the venturi. |
| Run details | Pre-heating time: 19 min<br>Run time: 120 min<br>Rice husk consumed: 110 kg |
| Observations and results | The system was for operated for 2 hrs without much hurdles. However, there was lot of tar generated in the process and was found to have collected in the blower. This happened despite maintaining reasonable A/F (around 1:1). The inadequate cyclonic action of the reactor seemed to be the reason behind high tar generation. Calculation of inlet air entry velocity to the cyclone proved to be too low (around 3.4 m/s, for a flow of 36 g/s). As a minimum air velocity of around 10 m/s is required for adequate cyclonic action, the air inlet port is to be modified accordingly. |
| Modifications for future tests | The inlet air entry area to the cyclone to be reduced from 50 sq. cm to 20 sq. cm to get adequate air velocities for cyclonic action. |

## Test record - 14

| Parameter | Description |
|---|---|
| Date of test | 15.7.94 |
| Reactor version | Stainless steel |
| Mode of test | Burner |
| Feed stock | Pulverised rice husk using pneumatic feeder |
| Purpose | To generate tar free gas and understand the performance using coarse sized pulverised rice husk. |
| Preparations | The tangential inlet area to cyclone reduced to 20 sq. cm from 50 sq. cm. |
| Run details | Pre-heating time: 16 min<br>Run time: 105 min<br>Rice husk consumed: 173 kg |
| Observations and results | The system was for operated for nearly 2 hrs without much hurdles at A/F of 1.1 to 1.2. There were problems related to char flow and moreover it was not fully pyrolysed. The reactor wall temperature seemed to slightly low and this could be due to less percentage of finer particles in the feed. Tar deposition found in the blower and venturi. |

## Test record - 15

| **Parameter** | **Description** |
|---|---|
| Date of test | 15.7.94 |
| Reactor version | Stainless steel |
| Mode of test | Burner |
| Feed stock | Pulverised rice husk using pneumatic feeder |
| Purpose | To generate tar free gas and understand the performance using pulverised rice husk having lesser percentage of coarse particles (max. 1.4 mm). |
| Preparations | Rice husk particle distribution:<br>1000 < RH> 1400 μ - 5%<br>500 < RH> 1000 μ - 54%<br>500 < RH> 250 μ - 23%<br>250 < RH> 150 μ - 6.5%<br>RH < 150 μ - rest |
| Run details | Pre-heating time: 23 min<br>Run time: 105 min<br>Rice husk consumed: 111 kg |
| Observations and results | The system was operated for nearly 2 hrs at A/F around 1.25 without much hurdles. The char flow was smooth with the reactor wall temperature being reasonable. In the later stage there was a dip in the wall temperatures. Traces of tar was found to have deposited in the blower. It was felt that the percentage of finer particles was still low and an increase in fines could improve the performance. |

## Test record - 16

| **Parameter** | **Description** |
|---|---|
| Date of test | 1.8.94 |
| Reactor version | Stainless steel |
| Mode of test | Burner |
| Feed stock | Pulverised rice husk using pneumatic feeder |
| Purpose | To generate tar free gas and understand the performance using pulverised rice husk having lesser percentage of coarse particles (more fines). |
| Preparations | Rice husk particle distribution:<br>RH> 1000 μ - 5%<br>500 < RH> 1000 μ - 48%<br>500 < RH> 250 μ - 29%<br>250 < RH - 18% |
| Run details | Pre-heating time: 19 min<br>Run time: 30 min<br>Rice husk consumed: 19 kg |
| Observations and results | The test could not be conducted beyond 30 min due to large pressure drop across the coolers. The increase in pressure drop is due to continuous accumulation of dust from the earlier tests |

## Test record - 17

| Parameter | Description |
|---|---|
| Date of test | 3.9.94 |
| Reactor version | Ceramic reactor |
| Mode of test | Burner |
| Feed stock | Pulverised rice husk using pneumatic feeder |
| Purpose | To generate tar free gas using the new ceramic reactor.<br>Also to understand the effectiveness of the charcoal bed as a tar cracking medium. To estimate the dust and tar level in the cooled and cleaned gas. |
| Preparations | 1) A new ceramic reactor constructed from mild steel, with an inner lining of fire brick and white heat-k measuring 30 mm each formed the top of the reactor. A stainless steel cone formed the bottom of the reactor. A charcoal bed (10 kg) provided at the exit of the reactor for tar cracking.<br>2) A multiclone to be used instead of a single cyclone to collect finer dust particles.<br>3) Two powdery biomass stoves of 20 and 40 kWth to be used for initial heating of the reactor.<br>4) Provision made for particulate and tar sampling downstream of the fine filter. Gas to be sampled at the rate of 0.5 $m^3$/hr.<br>5) The rice husk particle size distribution is similar to that of the previous run. |
| Run details | Pre-heating time: 60 min<br>Run time: 150 min<br>Rice husk consumed: 193 kg |
| Observations | Entered into gasification mode after 35 min of commencement of fuel feeding. Initial the system was run at a gas flow rate of 42 $\pm$ 2 g/s, at A/F of 1.2. Then the gas flow was increased to 50 g/s, with the A/F being around 1.15. Gas sampling was done for tar and particulate measurement at the cold end (downstream of the filter) for one hour at a rate of 0.5 $m^3$/hr. The charcoal bed seemed to be<br>functioning as a cracking media. |
| Results | Dust collected In the multiclone : 2.5 kg<br>Tar level in the cold gas : 125 ppm; Dust level : 125 - 150 ppm.<br>Charcoal consumption: 5% of the total feed used. |

## Test record - 18

| Parameter | Description |
|---|---|
| Date of test | 19.9.94 |
| Reactor version | Ceramic |
| Mode of test | Burner and Engine |
| Feed stock | Pulverised rice husk using pneumatic feeder |
| Purpose | To generate tar free gas using slightly finer rice husk powder and to understand if the newly designed kerosene burner would suffice the initial heating requirement. Also to operate diesel engine on dual-fuel mode and obtain the diesel replacements at different loads. |
| Preparations | Rice husk particle distribution:<br>RH> 1000 μ - 0.5%<br>500 < RH> 1000 μ - 36.2%<br>500 < RH> 250 μ - 38.5%<br>250 < RH - 25.5%<br>A new heating device in the form of kerosene burner, with the power level around 60 kW to be used. Charcoal bed used for tar cracking. |
| Run details | Pre-heating time: 60 min<br>Run time: 142 min<br>Rice husk consumed: 151 kg |
| Observations and results | It was a steady run with good flame quality, A/F being 1.2 to 1.4. Reactor wall temperatures relatively high due to larger amount of fines in the powder. Test after inspection showed not much tar deposition in the blower. Venturi virtually clean. About 4.5 % charcoal of the total feed material consumed. Test on engine in dual-fuel mode showed 45% diesel replacement at 40 kW electrical load. |

## Test record - 19

| Parameter | Description |
|---|---|
| Date of test | 24.9.94 |
| Reactor version | Ceramic |
| Mode of test | Burner |
| Feed stock | Pulverised rice husk using pneumatic feeder |
| Purpose | To gain experience in generation of clean gas (without charcoal bed for tar cracking) using slightly finer rice husk powder. |
| Preparations | Rice husk particle distribution is same as that of the previous run. |
| Run details | Pre-heating time: 30 min<br>Run time: 90 min<br>Rice husk consumed: 75 kg |
| Observations and results | It was a steady run with good flame quality, A/F being around 1.2. Reactor wall temperatures relatively high due to larger amount of fines in the powder. Test after inspection showed traces of tar deposition in the blower. |

## Test record - 20

| Parameter | Description |
|---|---|
| Date of test | 28.9.94 |
| Reactor version | Ceramic |
| Mode of test | Burner |
| Feed stock | Pulverised rice husk using pneumatic feeder |
| Purpose | To gain experience in generation of clean gas (without charcoal bed for tar cracking) using slightly finer rice husk powder. |
| Preparations | Rice husk particle distribution is same as that of the previous run. |
| Run details | Pre-heating time: 45 min<br>Run time: 155 min<br>Rice husk consumed: 130 kg |
| Observations and results | it was a steady run with reactor wall temperatures relatively high due to larger amount of fines in the powder. Problems in getting correct gas flow measurement (probably due to venturi having got coated). Test after inspection showed traces of tar deposition in the blower. |

## Test record - 21

| Parameter | Description |
|---|---|
| Date of test | 01.10.94 |
| Reactor version | Ceramic |
| Mode of test | Burner and Engine |
| Feed stock | Pulverised rice husk using pneumatic feeder |
| Purpose | To gain experience in generation of clean gas (without charcoal bed for tar cracking) using slightly finer rice husk powder. Also to operate diesel engine on dual-fuel mode and obtain the diesel replacements at different loads. |
| Preparations | Rice husk particle distribution is same as that of the previous run. |
| Run details | Pre-heating time: 30 min<br>Run time: 135 min<br>Rice husk consumed: 158 kg |
| Observations and results | A steady run with good flame quality, A/F being around 1.3. Operation on dual-fuel mode showed diesel replacement around 65% at 45 kWe load. |

## Test record - 22

| Parameter | Description |
|---|---|
| Date of test | 04.10.94 |
| Reactor version | Ceramic |
| Mode of test | Burner and Engine |
| Feed stock | Pulverised rice husk using pneumatic feeder |
| Purpose | To gain experience in generation of clean gas (without charcoal bed for tar cracking) using slightly finer rice husk powder. Also to operate diesel engine on dual-fuel mode and obtain the diesel replacements at different loads. |
| Preparations | In order to reduce the cooling load, an evaporative cooling system has been employed, this involves spraying water on the multiclones continuously. |
| Run details | Pre-heating time: 50 min<br>Run time: 205 min<br>Rice husk consumed: 290 kg |
| Observations and results | A steady run with good flame quality, A/F being around 1.3. Operation on dual-fuel mode recorded a diesel replacement of 79% at about 40 kWe load. |

## Test record -23

| Parameter | Description |
|---|---|
| Date of test | 06.10.94 |
| Reactor version | Ceramic |
| Mode of test | Burner |
| Feed stock | Pulverised rice husk using pneumatic feeder |
| Purpose | To gain experience in generation of clean gas (without charcoal bed for tar cracking) using slightly finer rice husk powder. |
| Preparations | Rice husk particle distribution being same as that of the previous run. All system elements like multiclone, coolers & blower cleaned . |
| Run details | Pre-heating time: 54 min<br>Run time: 180min<br>Rice husk consumed: 240 kg |
| Observations and results | A steady run with good flame quality with A/F being around 1.2. |

## Test record - 24

| Parameter | Description |
|---|---|
| Date of test | 18.10.94 |
| Reactor version | Ceramic |
| Mode of test | Burner and Engine |
| Feed stock | Pulverised rice husk using pneumatic feeder |
| Purpose | To gain experience in generation of clean gas (without charcoal bed for tar cracking) using slightly finer rice husk powder. Also to operate diesel engine on dual-fuel mode and obtain the diesel replacements at different loads. |
| Preparations | Rice husk particle distribution being same as that of the previous run. |
| Run details | Pre-heating time: 42 min<br>Run time: 115 min<br>Rice husk consumed: 121 kg |
| Observations and results | Initial 45 min was a steady run with good flame quality. There was some error in flow measurement probably due to venturi getting coated with dust. Moreover, in the latter part the gas flow rate continuously reduced despite further opening the control valve. Due to the above reason the operating A/F was not clearly known. Therefore the test wasn’t conducted on engine mode. After test inspection showed the control valve completely covered with dust. |

## Test record - 25

| Parameter | Description |
|---|---|
| Date of test | 07.11.94 |
| Reactor version | Ceramic |
| Mode of test | Burner and Engine |
| Feed stock | Initially saw dust and later on sugar cane trash. These were conveyed using a combination of screw feeder and blower. |
| Purpose | To gain experience in generation of clean gas using sugar cane trash. This particular test involves operating the system on saw dust till the system reaches steady state and later on switching to sugar cane trash. This procedure is being adopted as trash is relatively new fuel and the A/F for cleaner operation is yet to be established. Also to run the engine on dual-fuel mode by supplying gas derived from saw dust. |
| Preparations | The pneumatic feeder performed satisfactorily in conveying feeds like saw dust and pulverised rice husk. However, the same couldn't convey lighter materials like sugar cane trash mainly due to material characteristics. Therefore a new feeding system had to evolved which could cater to different types of feed stocks. Therefore a screw feeder and blower combination was evolved to resolve the problem and the system performed exceedingly well. |
| Run details | Pre-heating time: 45 min<br>Run time on saw dust : 50 min<br>Run time on trash : 15 min |
| Observations and results | A steady run with good flame quality, A/F being around 1.5 to 1.7 (for saw dust). Operation on dual-fuel mode using producer gas derived from saw dust recorded a diesel replacement of 76% at 42 kW electrical load. The change over to sugar cane trash was smooth and run for 15 min at A/F around 1.5. The test couldn't be continued for longer time as there were problems related to consistent fuel feeding. |

## Test record - 26

| Parameter | Description |
|---|---|
| Date of test | 11.11.94 |
| Reactor version | Ceramic |
| Mode of test | Burner |
| Feed stock | Pulverised sugar cane trash |
| Purpose | To gain experience in generation of clean gas using sugar cane trash. |
| Preparations | Sugar cane trash was chopped and pulverised to about 3 mm size. Screw feeder and blower combination used for conveying the feed. |
| Run details | Pre-heating time: 120 min<br>Run time: 75 min<br>Trash consumed: 70 kg |
| Observations and results | Initial heating time high due to trouble with the kerosene pump. Change over smooth, operated at A/F around 1.25. There was problems in char exiting due to char being too light, kept floating in the reactor. It had to be physically extracted on a continuous basis to keep the system in operation. |

## Test record - 27

| **Parameter** | **Description** |
|---|---|
| Date of test | 23.11.94 |
| Reactor version | Ceramic |
| Mode of test | Burner |
| Feed stock | Pulverised rice husk conveyed using pneumatic feeder. |
| Purpose | To gain experience in generation of clean gas using pulverised rice husk. |
| Run details | Pre-heating time: 60 min<br>Run time: 210 min<br>Rice husk consumed : 166 kg |
| Observations and results | There were problems during the run related to the blower failure.<br>The system had to be restarted a number of times therefore no precise conclusion could be arrived from the test. |

## Test record - 28

| **Parameter** | **Description** |
|---|---|
| Date of test | 9.12.94 |
| Reactor version | Ceramic |
| Mode of test | Burner and Engine |
| Feed stock | Saw dust conveyed using vibratory feeder and blower |
| Purpose | To gain experience in generation of clean gas using saw dust. Also to operate diesel engine on dual-fuel mode and obtain maximum diesel replacements at different loads. |
| Run details | Pre-heating time: 60 min<br>Run time on trash : 30 min<br>Saw dust consumed: 49 kg |
| Observations and results | The test couldn't be continued for a longer time mainly due to problems related to the feeding system. Therefore the test couldn't be conducted on engine mode. |

## Test record - 29

| **Parameter** | **Description** |
|---|---|
| Date of test | 10.12.94 |
| Reactor version | Ceramic |
| Mode of test | Burner and Engine |
| Feed stock | Saw dust conveyed using vibratory feeder and blower |
| Purpose | To gain experience in generation of clean gas using saw dust. Also to operate diesel engine on dual-fuel mode and obtain maximum diesel replacements at different loads. |
| Run details | Pre-heating time: 40 min<br>Run time on trash : 80 min<br>Saw dust consumed: 122 kg |
| Observations and results | It was a steady run with good flame quality. Operated at A/F around 1.5 to 1.7. Run on engine in duel-fuel mode recorded a diesel replacement of 68% at 70 kWe load. |

### Test record - 30

| Parameter | Description |
|---|---|
| Date of test | 12.12.94 |
| Reactor version | Ceramic |
| Mode of test | Burner and Engine |
| Feed stock | Saw dust conveyed using vibratory feeder and blower. |
| Purpose | To gain experience in generation of clean gas using saw dust. To operate diesel engine on dual-fuel mode and obtain maximum diesel replacements at various loads. Also to measure the No$_x$ level in the engine exhaust. |
| Run details | Pre-heating time : 45 min<br>Run time on trash : 190 min<br>Saw dust consumed: 225 kg |
| Observations and results | A normal run with good quality flame. Operated at A/F around 1.3 to 1.5. The producer gas when fed to the engine recorded a maximum diesel replacement of 79% at 58 kW electrical load. The NOx content in the engine exhaust was typically 250 ppm around 58 kWe load in dual-fuel mode as against over 1800 ppm in diesel alone mode. |

### Test record - 31

| Parameter | Description |
|---|---|
| Date of test | 12.12.94 |
| Reactor version | Ceramic |
| Mode of test | Burner and Engine |
| Feed stock | Saw dust conveyed using vibratory feeder and blower. |
| Purpose | To gain experience in generation of clean gas using saw dust. To operate diesel engine on dual-fuel mode and obtain maximum diesel replacements at various loads. Also to measure the Nox level in the engine exhaust. |
| Run details | Pre-heating time : 45 min<br>Run time on trash : 190 min<br>Saw dust consumed: 225 kg |
| Observations and results | A normal run with good quality flame. Operated at A/F around 1.3 to 1.5. The producer gas when fed to the engine recorded a maximum diesel replacement of 79% at 58 kW electrical load. The NOx content in the engine exhaust was typically 250 ppm around 58 kWe load in dual-fuel mode as against over 1800 ppm in diesel alone mode. |

### Test record - 32

| Parameter | Description |
|---|---|
| Date of test | 28.12.94 |
| Reactor version | Ceramic |
| Mode of test | Burner |
| Feed stock | Pulverised sugar cane trash conveyed using screw feeder and blower. |
| Purpose | To gain experience in generation of clean gas using sugar cane trash. |
| Preparations | Sugar cane trash chopped and pulverised using 5 mm size mesh. Screw feeder was calibrated using the above material. |
| Run details | Pre-heating time : 46 min<br>Run time on trash : 100 min<br>Trash consumed: 87 kg |
| Observations and results | The system was run on saw dust for about 30 min after initial pre-heating, for the wall temperatures to build up. The change over to sugar cane trash was smooth, operated at A/F around 1.5. Initially the char flow from the reactor exit was smooth, but in the latter part of the run there was obstruction to the char flow probably due to ash fusion. Post test inspection showed the char/dust weighing about 3 kg to have collected in the multiclones. Tar in the range of 1200 ppm found deposited in the blower. |

## Test record - 33

| Parameter | Description |
|---|---|
| Date of test | 17.1.95 |
| Reactor version | Ceramic |
| Mode of test | Burner |
| Feed stock | Rice husk pulverised to coarse size, conveyed using screw feeder and blower. |
| Purpose | To gain experience in generation of clean gas using pulverised rice husk. Also to measure the amount of air flow required for gasification for precise control of A/F. |
| Preparations | Screw feeder was calibrated for the above feed stock and an arrangement was made at the reactor inlet port, where by the entire air flow through the inlet port would be pumped from the blower and could be measured more precisely. |
| Run details | Pre-heating time : 60 min<br>Run time: 120 min<br>Rice husk consumed: 176 kg |
| Observations and results | The system was run for about nearly 120 min after initial pre-heating. Operated initially at A/F around 1.0 and in the latter stages at 0.65. There were problems with respect to char flow from the reactor exit, however, the test was continued. Post test inspection showed the char to have collected in the multiclones, weighing about 11kg. A careful examination based on post cold flow test revealed that there was insufficient air being pumped by the blower than required for gasification. This was resulting in remaining air being drawn from the char exit port, causing hindrance to char flow and getting carried to the multiclones. Tar in the range of 2000 ppm found deposited in the blower. |

## Test record - 34

| Parameter | Description |
|---|---|
| Date of test | 31.1.95 |
| Reactor version | Ceramic |
| Mode of test | Burner |
| Feed stock | Rice husk pulverised to coarse size using 2.2 mm mesh size, conveyed using screw feeder and blower. |
| Purpose | To gain experience in generation of clean gas using coarse pulverised rice husk. To operate the diesel engine on dual-fuel mode and obtain optimum diesel replacement. |
| Preparations | Rice husk particle distribution:<br>1000 <RH> 2000 $\mu$ - 5%<br>500 < RH> 1000 $\mu$ - 46%<br>500 < RH> 250 $\mu$ - 32%<br>250 < RH> 150 $\mu$ - 17%<br>In the previous run, with the arrangement made at the inlet port to the reactor, the char from the reactor wasn't exiting due to suction effect and getting carried to the multiclones. In order to overcome this problem a modification is contemplated at the burner port, (180 $^0$C apart from the fuel feeding port) whereby a part of the burner port is to be kept open (after pre-heating) for air entry, with inlet velocities in the range of 10m/s. |
| Run details | Pre-heating time : 50 min<br>Run time on : 40 min<br>Rice husk consumed: 40 kg |
| Observations and results | After the initial pre-heating for 50 min, the feed was commenced by keeping a part of burner port open for air intake. However, the air stream entering at the burner port had a negative effect on the wall temperatures due to cooling effect. The condition didn't improve despite supplying external heat from the burner port. As the reason for the above was obvious, the system was stopped and restarted after adopting the original configuration of air intake at the feeding port itself. The test was conducted with the above modification for some time but couldn't be continued for longer duration due to trouble in the fuel conveying line. |

## Test record - 35

<table>
<tr><th>Parameter</th><th>Description</th></tr>
<tr><td>Date of test</td><td>2.2.95</td></tr>
<tr><td>Reactor version</td><td>Ceramic</td></tr>
<tr><td>Mode of test</td><td>Burner & Engine</td></tr>
<tr><td>Feed stock</td><td>Rice husk pulverised to coarse size using 2.2 mm mesh size, conveyed using screw feeder and blower.</td></tr>
<tr><td>Purpose</td><td>To gain experience in generation of clean gas using coarse pulverised rice husk. To operate the diesel engine on dual-fuel mode and obtain optimum diesel replacement.</td></tr>
<tr><td>Preparations</td><td>Rice husk particle distribution is similar to that of the earlier test.<br>The problem of conveying the feed was resolved by increasing the diameter of the conveying tube from 30 mm to 36 mm to prevent material getting packed at higher feed rates. The problem of leakage of diesel in the fuel injection system of the diesel engine was rectified and the same was calibrated and SFC's checked.</td></tr>
<tr><td>Run details</td><td>Pre-heating time : 40 min<br>Run time on : 155 min<br>Rice husk consumed: 270 kg</td></tr>
<tr><td>Observations and results</td><td>It was a steady run, operated at A/F of 0.9. But there was problem with respect to char being smoky, probably due to incomplete pyrolyisis. This could be due to lesser amount of fines in the feed resulting in wall temperatures being relatively lower. The diesel substitution obtained in dual-fuel mode are as follows:
<table>
<tr><th>S.No.</th><th>Load (kWe)</th><th>Diesel replacement (%)</th><th>$O_2$ (%)</th></tr>
<tr><td>1</td><td>50</td><td>83</td><td>7.0</td></tr>
<tr><td>2</td><td>60</td><td>80</td><td>4.5</td></tr>
<tr><td>3</td><td>65</td><td>77</td><td>3.0</td></tr>
<tr><td>4</td><td>70</td><td>54</td><td>1.9</td></tr>
</table>
At higher loads part of the gas was fed to the engine and rest burnt in the burner. Higher diesel replacement couldn't be obtained at higher loads mainly due to limitation from the engine side. This is being due to insufficient amount of oxygen available for combustion at higher loads (70 kWe & above). Higher amount of gas supply at these loads was resulting in exhaust becoming smoky and engine stalling.</td></tr>
</table>

## Test record - 36

<table>
<tr><th>Parameter</th><th>Description</th></tr>
<tr><td>Date of test</td><td>22.2.95</td></tr>
<tr><td>Reactor version</td><td>Ceramic</td></tr>
<tr><td>Mode of test</td><td>Burner & Engine</td></tr>
<tr><td>Feed stock</td><td>Rice husk pulverised using 2.0 mm mesh size, conveyed using screw feeder and blower.</td></tr>
<tr><td>Purpose</td><td>To gain experience in generation of clean gas using finer pulverised rice husk. To operate the diesel engine on dual-fuel mode and obtain optimum diesel replacement.</td></tr>
<tr><td>Preparations</td><td>Rice husk particle distribution:<br>RH> 1000 μ - 1.5%<br>500 < RH> 1000 μ - 48.3%<br>500 < RH> 250 μ - 34.6%<br>250 < RH> 150 μ - 15.5%</td></tr>
<tr><td>Run details</td><td>Pre-heating time : 42 min; Run time : 180 min; Rice husk consumed: 275 kg</td></tr>
<tr><td>Observations and results</td><td>It was a steady run, operated at A/F of 0.9:1 to 1:1. No problems in char exiting from the reactor. Reactor wall temperatures relatively higher compared to the earlier run on coarse rice husk. The diesel substitution obtained in dual-fuel mode are as follows:
<table>
<tr><th>Load (kWe)</th><th>Diesel replacement (%)</th><th>O<sub>2</sub> (%)</th><th>NOx (ppm)</th></tr>
<tr><td>19</td><td>78</td><td>9.9</td><td>165</td></tr>
<tr><td>28</td><td>80</td><td>8.7</td><td>226</td></tr>
<tr><td>38</td><td>77</td><td>8.2</td><td>249</td></tr>
<tr><td>46</td><td>83</td><td>5.6</td><td>275</td></tr>
<tr><td>57</td><td>81</td><td>4.0</td><td>361</td></tr>
<tr><td>61</td><td>82</td><td>2.0</td><td>460</td></tr>
<tr><td>65</td><td>67</td><td>1.3</td><td>677</td></tr>
<tr><td>72</td><td>40</td><td>1.0</td><td>1143</td></tr>
</table>
Higher diesel replacement couldn’t be obtained at higher loads mainly due to limitation from the engine side. This is being due to insufficient amount of oxygen available for combustion at higher loads (70 kWe & above). Higher amount of gas supply at these loads was resulting in exhaust becoming smoky and engine stalling.<br>Post inspection showed little tar deposition in the blower.</td></tr>
</table>

## Test record - 37

| Parameter | Description |
|---|---|
| Date of test | 13.3.95 |
| Reactor version | Ceramic |
| Mode of test | Burner & Engine |
| Feed stock | Rice husk pulverised using 2.0 mm mesh size, conveyed using screw feeder and blower. |
| Purpose | To gain experience in generation of clean gas using finer pulverised rice husk. To operate the diesel engine on dual-fuel mode and obtain optimum diesel replacement at higher loads. |
| Preparations | Rice husk particle distribution:<br>RH> 1000 μ - 1.5%<br>500 < RH> 1000 μ - 48.3%<br>500 < RH> 250 μ - 34.6%<br>250 < RH> 150 μ - 15.5% |
| Run details | Pre-heating time : 60 min;<br>Run time : 170 min;<br>Rice husk consumed: 225 kg |
| Observations and results | It was a steady run, operated at A/F of 1.0. No problems in char exiting from the reactor. A diesel substitution of 81% was recorded in dual-fuel mode at 60 kWe. Post inspection showed little tar deposition in the blower. |

## Test record - 38

<table>
<tr><th>Parameter</th><th>Description</th></tr>
<tr><td>Date of test</td><td>22.3.95</td></tr>
<tr><td>Reactor version</td><td>Ceramic</td></tr>
<tr><td>Mode of test</td><td>Engine</td></tr>
<tr><td>Feed stock</td><td>Rice husk pulverised using 2.0 mm mesh size, conveyed using screw feeder and blower.</td></tr>
<tr><td>Purpose</td><td>To gain experience in generation of clean gas using finer pulverised rice husk and to operate the diesel engine on dual-fuel mode for long duration and obtain optimum diesel replacement.</td></tr>
<tr><td>Preparations</td><td>Rice husk particle distribution:<br>RH > 1000 μ - 1.5%<br>500 < RH> 1000 μ - 48.3%<br>500 < RH> 250 μ - 34.6%<br>250 < RH> 150 μ - 15.5%<br>Until the previous experiments, a multiclone was used as a dust collection device with the intention that it would collect the finer dust particles and reduce pressure drop problems down stream of the system. But a careful analysis of the earlier tests revealed that the performance of multiclones was no better than a single cyclone. As the single cyclone used in the early stages of experiments had larger surface area compared to multiclones, it was felt that single cyclone would serve the purpose better in terms of heat dissipation (reducing the load on coolers) in addition to dust separation. Therefore the multiclones was replaced by a single cyclone with an outer cooling jacket.<br>Also a flow measurement indicator in addition to manometer provided.</td></tr>
<tr><td>Run details</td><td>Pre-heating time : 60 min;<br>Run time : 345 min;<br>Rice husk consumed: 515 kg</td></tr>
<tr><td>Observations and results</td><td>It was a steady run, operated at A/F of 0.9:1 to 1:1. No problems in char exiting from the reactor. Reactor wall temperatures relatively higher compared to the earlier run on coarse rice husk. The diesel substitution obtained in dual-fuel mode are as follows:
<table>
<tr><th>Load (kWe)</th><th>Diesel replacement (%)</th><th>$O_2$ (%)</th><th>NOx (ppm)</th></tr>
<tr><td>19</td><td>78</td><td>9.9</td><td>165</td></tr>
<tr><td>28</td><td>80</td><td>8.7</td><td>226</td></tr>
<tr><td>38</td><td>77</td><td>8.2</td><td>249</td></tr>
<tr><td>46</td><td>83</td><td>5.6</td><td>275</td></tr>
<tr><td>57</td><td>81</td><td>4.0</td><td>361</td></tr>
<tr><td>61</td><td>82</td><td>2.0</td><td>460</td></tr>
<tr><td>65</td><td>67</td><td>1.3</td><td>677</td></tr>
<tr><td>72</td><td>40</td><td>1.0</td><td>1143</td></tr>
</table>
Higher diesel replacement couldn’t be obtained at higher loads mainly due to limitation from the engine side. This is being due to insufficient amount of oxygen available for combustion at higher loads (70 kWe & above). Higher amount of gas supply at these loads was resulting in exhaust becoming smoky and engine stalling.<br>Post inspection showed little tar deposition in the blower.</td></tr>
</table>

## Test record - 39

| Parameter | Description |
|---|---|
| Date of test | 27.3.95 |
| Reactor version | Ceramic |
| Mode of test | Burner |
| Feed stock | Rice husk pulverised using 2.0 mm mesh size, conveyed using screw feeder and blower. |
| Purpose | To gain experience in generation of clean gas using finer pulverised rice husk and to operate the diesel engine on dual-fuel mode for long duration and obtain optimum diesel replacement. |
| Preparations | Rice husk particle distribution:<br>RH> 1000 μ - 1.5%<br>500 < RH> 1000 μ - 48.3%<br>500 < RH> 250 μ - 34.6%<br>250 < RH> 150 μ - 15.5% |
| Run details | Pre-heating time : 51 min; Run time : 126 min; Rice husk consumed: 170 kg |
| Observations and results | The A/F of around 1:1.1 was maintained. No problems in char exiting from the reactor. The drop in gas temperature as it passed through cyclone without and with water in cooling jacket was observed to be $180^o$ and $226^o$ respectively. However, during the course of run the heat loss in the cyclone dropped. Run on engine wasn't possible as there was leakage detected in the fuel line of the engine. |

## Test record - 40

| Parameter | Description |
|---|---|
| Date of test | 04.04.95 |
| Reactor version | Ceramic |
| Mode of test | Burner and Engine |
| Feed stock | Rice husk pulverised using 2.0 mm mesh size, conveyed using screw feeder and blower. |
| Purpose | To gain experience in generation of clean gas using finer pulverised rice husk and to operate the diesel engine on dual-fuel mode for long duration and obtain optimum diesel replacement. |
| Preparations | Water in the cooler water seal and sump changed. Cyclone cleaned. |
| Run details | Pre-heating time : 69 min;<br>Run time : 205 min;<br>Rice husk consumed: 310 kg |
| Observations and results | The A/F was maintained around 1:1. No problems in char exiting from the reactor. The diesel substitution obtained in dual-fuel mode are as follows:<br>**Load (kWe)** / **Diesel replacement (%)** / **$O_2$ (%)**<br>62 / 83 / 2<br>65 / 74 / 1.2<br>Post test analysis showed about 2 kg dust to have collected in the cyclone. The tar collected in the blower was of the order of 1700 ppm. |

## Test record - 41

| Parameter | Description |
|---|---|
| Date of test | 10.11.95 |
| Reactor version | Ceramic with fluidising char bed for tar cracking |
| Mode of test | Burner |
| Feed stock | Rice husk pulverised using 2.0 mm mesh size, conveyed using screw feeder and blower. |
| Purpose | To experiment the concept of using fluidised bed column as a tar cracking media. The hot char from the reactor exit to be used as the fluidising media, where on, the hot gas from the cyclone reactor is fluidised through the char bed. To qualitatively check the extent of tar in gas by checking the quality (extent of tar) of wash water from the cooler and cyclone. |
| Preparations | 1) Preliminary studies were conducted to find out critical fluidising velocities and related pressure drops with varying char bed height.<br>2) Fluidising column introduced between reactor and cyclone with necessary ductings. The fluidiser consists of a 2mm dia and 2mm pitch distributor plate. The char exits from reactor through a 65 mm dia tube above the distributor plate (100 mm height) into the fluidiser. Where as, the gas enters from the reactor below the distributor plate.<br>3) The bottom of the fluidiser and cyclone connected to a common dump.<br>4) Kerosene swirl burner developed for reactor preheating purpose.<br>5) The dump of fluidiser and cyclone packed with ash to prevent short circuiting of gas without fluidising from fluidiser to cyclone |
| Run details | Pre-heating time :60 min; Run time : 40 min; Rice husk consumed: 66 kg |
| Observations and results | The changeover from pre-heating was smooth, but there was tar visible in the wash water from coolers. There were two problems during the course of run, firstly as the char exit tube from the reactor was large, the pyrolysis gases were sucked directly into the fluidiser (above the fluidiser plate) and tar was visible in the gas downstream of it. The second problem was related to char extraction from the dump. As the dump was packed with ash prior to the start of test, char extraction was almost impossible. |

## Test record - 42

| Parameter | Description |
|---|---|
| Date of test | 7.12.95 |
| Reactor version | Ceramic with fluidising char bed for tar cracking |
| Mode of test | Burner |
| Feed stock | Rice husk pulverised using 2.0 mm mesh size, conveyed using screw feeder and blower. |
| Purpose | To continue using hot char fluidised bed column for tar cracking. |
| Preparations | 1. Two separate dumps for fluidiser and cyclone fabricated.<br>2. View ports at two location in fluidiser and one in char exit pipe fabricated.<br>3. A slide gate at char exit provided to vary the tube area. |
| Run details | Pre-heating time : 60 min; Run time : 75min; Rice husk consumed: 85 kg |
| Observations and results | It was a smooth run except for small hindrance in char removal. Traces of tar was observed in the wash water during the initial part of the run, however the wash water was relatively cleaner in the latter part as the wall temperatures had increased. Post test inspection showed fluidisation had not occurred as there was leakage paths around the grid plate. The ash was formed in a heap at the center and depleted towards the wall. The tar collected in the blower was of the order of 142ppm. |
| Modifications for future run | Leakage path around the distributor plate to the plugged. |

## Test record - 43

| Parameter | Description |
|---|---|
| Date of test | 25/01/96 |
| Reactor version | Ceramic with fluidising char bed for tar cracking |
| Mode of test | Burner |
| Feed stock | Rice husk pulverised using 1.8 mm mesh size, conveyed using screw feeder and blower. |
| Purpose | To continue using hot char fluidised bed column for tar cracking. Gas sampling for tar measurement to be done both upstream and down stream of fluidiser. This is being done to understand the effectiveness of char bed as a tar cracking medium. |
| Preparations | 1. The volume of the dump below the fluidiser was reduced.<br>2. The grid plate was welded to a flange and fixed to avoid any gas leakage paths.<br>3. A new slide valve provided at char exit pipe to vary the tube area<br>4. It was initially planned to have a screw extractor to continuously extract the char from cyclone bottom. As the design allowed large leakage path the idea has been discarded and a slide valve has been incorporated.<br>5. Provision for isokinetic gas sampling for tar measurement provided upstream and downstream of the fluidiser |
| Run details | Pre-heating time :45 min; Run time : 130min; Rice husk consumed: 224 kg<br>Gas sampling done at the reactor exit, total gas sampled was 0.7485 $m^3$ in 50 min. |
| Observations and results | It was a smooth run with good flame quality. Gas sampling could be done only at the reactor exit i.e upstream of the fluidiser. There was problem of leakage with slide valve on the char exit tube. The slide valve at the cyclone bottom had to be opened 25% of the total area to prevent ingress of air.<br>Tar level in the gas upstream of the reactor was found to be of the order of 757 ppm. |

## Test record - 44

| Parameter | Description |
|---|---|
| Date of test | 16/02/96 |
| Reactor version | Ceramic with fluidising char bed for tar cracking |
| Mode of test | Burner |
| Feed stock | Rice husk pulverised using 1.8 mm mesh size, conveyed using screw feeder and blower. |
| Purpose | To continue using hot char fluidised bed column for tar cracking. Gas sampling for tar measurement to be done both upstream and down stream of fluidiser. This is being done to understand the effectiveness of char bed as a tar cracking medium. |
| Preparations | 1. The slide plate in char exit pipe was replaced by control valve mechanism<br>2. The cyclone bottom slide valve was replaced by control valve mechanism.<br>3. The cooler sprays which had blocked was cleaned (the first spray directing upwards was worse among the two). |
| Run details | Pre-heating time : 65 min; Run time : 180min; Rice husk consumed : 285 kg |
| Observations and results | The flame appeared to be lean despite A/F being around 0.9 to 1.0. Leakage was suspected to be the reason. Gas sampling couldn’t be carried for the same reason. |

## Test record - 45

| Parameter | Description |
|---|---|
| Date of test | 22/02/96 |
| Reactor version | Ceramic with fluidising char bed for tar cracking |
| Mode of test | Burner |
| Feed stock | Rice husk pulverised using 1.8 mm mesh size, conveyed using screw feeder and blower. |
| Purpose | To continue using hot char fluidised bed column for tar cracking. |
| Preparations | No modifications done. |
| Run details | Pre-heating time :36 min; Run time : 40min; Rice husk consumed: 60 kg |
| Observations and results | The test couldn't be successfully carried due to following reasons :<br>1) In order to bring down the heating time, the flow rate was limited to 20 g/s and burner power level increased. The hot gases tried to vent out through feed inlet pipe and in the process the feed inlet pipe was cut. This was however rectified.<br>2) The control valve in char exit pipe got struck in close position hindering the char flow to fluidiser.<br>3) The control valve at the cyclone bottom got struck in the open position and this called for sealing it externally to avoid air leakage into the system. |

## Test record - 46

| Parameter | Description |
|---|---|
| Date of test | 05/04/96 |
| Reactor version | Ceramic with fluidising char bed for tar cracking |
| Mode of test | Burner |
| Feed stock | Rice husk pulverised using 1.8 mm mesh size, conveyed using screw feeder and blower. |
| Purpose | To continue using hot char fluidised bed column for tar cracking. Gas sampling for tar measurement to be done both upstream and down stream of fluidiser. This is being done to understand the effectiveness of char bed as a tar cracking medium. |
| Preparations | 1) The char exit tube diameter leading to fluidiser reduced from 65 mm to 35 mm without any other restriction.<br>2) The fuel inlet port has been modified to accommodate preheating burner.<br>3) Water seal has been provided at the cyclone bottom and a water spray a water spray arrangement provided to facilitate char removal.<br>Rice husk particle distribution:<br>1000 < RH> 2000 μ - 0.5%<br>500 < RH> 1000 μ - 33%<br>500 < RH> 250 μ - 45%<br>250 < RH> 150 μ - 16.3%<br>RH < 150 μ - rest |
| Run details | Pre-heating time : 28 min; Run time : 135min; Rice husk consumed : 198 kg;<br>Gas sampled: 0.7m$^3$ in 1hr 12 min down stream of the fluidiser. |
| Observations and results | The run was smooth, at A/F 0.9 - 0.97, the water spray arrangement to extract char worked well with char flowing out smoothly into the water sump. The tar sampling was only carried at a single point i.e down stream of the fluidiser and the tar level in the hot gas was found to be around 2029 PPM. |

## Test record - 47

| Parameter | Description |
|---|---|
| Date of test | 03/05/96 |
| Reactor version | Ceramic with fluidising char bed for tar cracking |
| Mode of test | Burner |
| Feed stock | Rice husk pulverised using 1.8 mm mesh size, conveyed using screw feeder and blower. |
| Purpose | To continue using hot char fluidised bed column for tar cracking. Gas sampling for tar measurement to be done both upstream and down stream of fluidiser. This is being done to understand the effectiveness of char bed as a tar cracking medium. |
| Preparations | Rice husk particle distribution:<br>1000 < RH> 2000 μ - 0%<br>500 < RH> 1000 μ - 14%<br>500 < RH> 250 μ - 42%<br>250 < RH> 150 μ - 26%<br>RH < 150 μ - 18%<br>The other preparations remains the same as done in the previous run. |
| Run details | Pre-heating time : 30 min; Run time : 185min; Rice husk consumed : 192 kg;<br>Gas sampled: 1.057m$^3$ in 1hr 25 min up stream of the fluidiser; 0.739m$^3$ in 1hr down stream of the fluidiser. |
| Observations and results | The run was smooth, at A/F 0.95 - 1.0, the wall temperatures were relatively high due to larger percentage of fines. The water spray arrangement to extract char worked well with char flowing out smoothly into the water sump. The tar sampling was conducted both upstream and downstream of the fluidiser and was found to be 737 and 334 PPM respectively. |

## Test record - 48

| Parameter | Description |
|---|---|
| Date of test | 13/05/96 |
| Reactor version | Ceramic with fluidising char bed for tar cracking |
| Mode of test | Burner |
| Feed stock | Rice husk pulverised using 1.8 mm mesh size, conveyed using screw feeder and blower. As the percentage of fines were large, the same was mixed with slightly coarse particles. |
| Purpose | To continue using hot char fluidised bed column for tar cracking. Gas sampling for tar measurement to be done both upstream and down stream of fluidiser. This is being done to understand the effectiveness of char bed as a tar cracking medium. |
| Preparations | Rice husk particle distribution:<br>1000 < RH> 2000 μ - 0%<br>500 < RH> 1000 μ - 19%<br>500 < RH> 250 μ - 40%<br>250 < RH> 150 μ - 24%<br>RH < 150 μ - 17%<br>Arrangement was made for gas analysis (CO, $CO_2$,$CH_4$ & $O_2$) at the filter exit. |
| Run details | Pre-heating time : 30 min; Run time : 167min; Rice husk consumed : 175 kg;<br>Gas sampled: 0.7212m$^3$ in 45 min up stream of the fluidiser; 0.8234m$^3$ in 54 min down stream of the fluidiser. |
| Observations and results | It was not a steady run mainly due to reduction in gas flow rate with time. It happened due to blockage at the entry of the fluidiser. However, the tar sampling was pursued both upstream and downstream of the fluidiser and was found to be and PPM respectively.<br>Gas analysis showed CO content in gas to increase with slight reduction in A/F. The producer gas contained CO : 12.5 $\pm$ 0.5; $CO_2$ : 9.0 $\pm$ 0.5 & $O_2$ : 2.0 $\pm$ 0.5. The indication of $O_2$ in gas implies there was some leakage in the gas path. $CH_4$ couldn't be measured due to some error in the initial settings of that particular measurement unit. |