DEVELOPMENT OF DESIGN PARAMETERS FOR GASIFICATION OF MAIZE (*ZEA MAYS* L.) COBS IN THROATLESS GASIFIER

Dissertation

Submitted to the Punjab Agricultural University
in partial fulfilment of the requirements
for the degree of

DOCTOR OF PHILOSOPHY
in
ENERGY SCIENCE AND TECHNOLOGY
(Minor Subject: Processing and Food Engineering)

By

Sangeeta Chopra
(L-2004-AE-67-D)

School of Energy Studies for Agriculture
College of Agricultural Engineering

PUNJAB AGRICULTURAL UNIVERSITY
LUDHIANA-141 004
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CERTIFICATE I

This is to certify that the dissertation entitled, "Development of Design Parameters for Gasification of Maize (*Zea mays* L.) Cobs in Throatless Gasifier" submitted for the degree of Ph.D., in the subject of Energy Science and Technology (Minor subject: Processing and Food Engineering) of the Punjab Agricultural University, Ludhiana, is a bonafide research work carried out by Sangeeta Chopra (L-2004-AE-67-D) under my supervision and that no part of this dissertation has been submitted for any other degree.

The assistance and help received during the course of investigation have been fully acknowledged.

18/12/07
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CERTIFICATE II

This is to certify that the dissertation entitled "Development of Design Parameters for Gasification of Maize (*Zea mays* L.) Cobs in Throatless Gasifier" submitted by Sangeeta Chopra (L-2004-AE-67-D) to the Punjab Agricultural University, Ludhiana in partial fulfillment of the requirement for the degree of Ph.D. in the subject of Energy Science and Technology (Minor subject: Processing and Food Engineering) has been approved by the Student's Advisory Committee after an oral examination on the same.

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ABSTRACT

Biomass is a renewable source of energy. It can be converted into gaseous fuel through gasification. Maize cobs (*Zea mays* L.) is an important biomass. The volatile matter, fixed carbon, ash content and higher heating value of maize cobs was 83.01, 15.16, 1.83 % and 18.2 $\text{MJ}\cdot\text{kg}^{-1}$, respectively. The gasification of shelled maize cobs was conducted in throatless gasifiers having 15, 22.5, 30 and 36 cm diameter reactors. The maize cobs could be successfully gasified in all the experimental runs. The experimental runs were conducted over a range of gas flow rates in each reactor, resulting in specific gasification rate (SGR) in the range of 120-270 $\text{kg}\cdot\text{h}^{-1}\cdot\text{m}^{-2}$. The optimum SGR was 165 $\text{kg}\cdot\text{h}^{-1}\cdot\text{m}^{-2}$. The combustible gases were observed to be 31-38 % of the producer gas at optimum SGR. Average amount of CO, CH_4 and H_2 in producer gas was observed to be 18, 12.5 and 3 % respectively. The lower heating value of producer gas was 4.2-5.22 $\text{MJ}\cdot\text{Nm}^{-3}$. Maximum gasification efficiency obtained was 66.8-68.9 % at optimum SGR. The char produced was 12.6-14.4 % of the fuel and its average calorific value was 20.5 $\text{MJ}\cdot\text{kg}^{-1}$. The average equivalence ratio was 0.47. The effect of diameter of reactor on efficiency of gasification was not significant, whereas the specific gasification rate (SGR) had a significant effect on gasification efficiency. The cost of energy obtained from producer gas was 25.5 $\text{paisa}\cdot\text{MJ}^{-1}$. The chemical energy of producer gas at optimum SGR was 66.4-68.7 % of the energy of maize cobs. The SGR value of 165 $\text{kg}\cdot\text{h}^{-1}\cdot\text{m}^{-2}$ may be used as design parameter for gasification of maize cobs in throatless gasifier.

Key words: Maize cobs, specific gasification rate, gasification efficiency, throatless gasifier, combustible gases, reactor

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Signature of Major Advisor

Sangeeta Chopra

Signature of the Student

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Symbols

η	Efficiency, %
ρ	Density, $kg \cdot m^{-3}$
λ	Latent heat of vaporization of water, $MJ \cdot kg^{-1}$
M	Molecular weight
N	Nitrogen content
R	Universal gas constant, $kJ \cdot (kgmol)^{-1} \cdot K^{-1}$
Vo	Volume of ideal gas at NTP, Nm^3
V	Velocity, $m \cdot s^{-1}$
F	Flow rate or feed rate, $Nm^3 \cdot h^{-1}$ or $kg \cdot h^{-1}$
A	Area, m^2
d	Diameter, m
l	Length, m
T	Temperature, °C
Δh	Pressure drop, inch water column
X	Mole fraction
Cp	Heat capacity, $kJ \cdot (kgmol)^{-1} \cdot K^{-1}$
SGR	Specific gasification rate, $kg \cdot h^{-1} \cdot m^{-2}$
VM	Volatile matter, %
FC	Fixed carbon, %
AC	Ash content, %
HHV	Higher heating value, $MJ \cdot kg^{-1}$
LHV	Lower heating value, $MJ \cdot kg^{-1}$ or $MJ \cdot Nm^{-3}$
NTP	Normal temperature and pressure
BD	Bulk density, $kg \cdot m^{-3}$
CE	Chemical energy, MJ
SE	Sensible energy, MJ
WC	Water column

Subscripts

m	maize cobs
g	producer gas
r	residue
a	air
es	engine system
gs	gasifier system
c	containment tube
rc	reactor
n	nitrogen
p	pipe
o	orifice
i	ith component of air or producer gas

CHAPTER 1

INTRODUCTION

The primary energy consumption of India is dependent on coal, oil and natural gas up to the level of 54.5, 31.75 and 7.69 % respectively (Anonymous 2005b). The total commercial energy consumption has increased considerably in India during the past two decades, due to the growing economy. Various estimates indicate that India needs to increase its primary energy supply by 3 - 4 times of the 2003-04 levels by 2031. Presently the country is facing energy shortage, which is reflected by an increase in fuel imports. India's oil import was 76 % of its requirement in 2005-06. Thus there is an increasing gap between demand and supply of energy (Anonymous 2007). India therefore faces a formidable challenge in meeting its energy needs and providing adequate and affordable energy in a sustainable manner. Nearly 80 % of the world's energy consumption is fossil based and projections show that the energy demand growth is also dependent on fossil fuels. The utilization of fossil fuels is also causing environmental and health concerns due to increased emissions of CO_2, NO_x and SO_2 into environment. These emissions are also responsible for global warming. The Kyoto Protocol agreement stipulated that by 2010, the developed countries should reduce their total emissions of greenhouse gases by at least 5 - 5.2 % from the level of 1990 (Carlos 2005). The renewable energy technologies have an important role to play in helping India realize its challenge of achieving energy independence. Intensive efforts are therefore being made to develop alternative renewable sources of energy.

One such source of energy is biomass. It absorbs the same amount of CO_2 in growing as it releases when burnt as a fuel. Therefore its contribution to global warming is zero. In addition it contains negligible amount of sulphur thus contributing minimally to acid rain. Biomass is the fourth largest source of energy (after coal, oil and natural gas) supplying about 15 % of the world's energy consumption and about 38 % of that in the developing countries. Furthermore, biomass often accounts for more than 90 % of the total rural energy supplies in the developing countries. The estimated potential of agro residues in India is 16000 MW of which 913.53 MW have been achieved (Anonymous 2007). Since 90 % of the world's population is expected to reside in developing countries by 2050, biomass energy is likely to remain a substantial energy feedstock (Demirbas 2004).

Biomass resources such as agricultural residues, agro-industrial residues and forest and other residues, which can be used for energy production, are listed in Table 1.1. Biomass has variable moisture content and a fibrous structure consisting of lignin, carbohydrates and ash. It is made up of carbon, hydrogen, oxygen, and nitrogen. Sulphur is also present in lesser proportions. The ash content is from 0.17 - 24.4 % on dry weight basis. In comparison to solid fossil fuels, biomass contains much less carbon, more oxygen and has a lesser heating value The volatile matter (VM) in biomass varies from 62.3 - 83.6 % on dry weight basis and is higher than that in coal, which is around 40 %. The fixed carbon content of biomass is very low (13.3 - 30 %) compared to that of coal (40 - 55 %) on dry weight basis (Ebeling and Jenkins 1985). The heating value of biomass ranges from 12 - 16 MJ·kg^{-1}. The lower end belongs to rice husk and straw and the higher end belongs to wood and bagasse. The heating value of coal (having high ash content of 30 - 40 %) found in India and a few other parts of the world is 15 - 20 MJ·kg^{-1}. The heating value of biomass is comparable to such coals (Mukunda *et al* 1994).

Table 1.1 Biomass materials, which can be used for energy production

Agricultural Residues	Agro-Industrial residues	Forest and other residues
Paddy Straw	Rice Husk	Deadwood from existing forests
Pearl Millet	Bagasse	Wood from specially grown plantations
Sorghum Stalks	De-oiled Cakes	Saw mill wastes
Maize Stalks	Groundnut Shells	Pulp wood wastes
Maize Cobs	Cashew nut Shells	Road side bushes
Coconut Shells	Coconut Fibre	Wood from wastelands
Cotton Stalk	Tea/ coffee wastes	
Jute and Mesta Sticks		
Oilseed Straw		

Source: Upadhyay *et al* (2005)

While coal has to be mined and transported over long distances causing economic problems, biomass can be grown in places near to where it is to be utilized. The estimated production of crop and agro industrial residues in Punjab and India is 38 and 620 million metric tonnes respectively. These estimates are based on the production of cereals, pulses, oilseeds and cash crops in the year 2001-02 (Anonymous 2005a, Upadhyay *et al* 2005).

Maize (*Zea Mays* Linn.) cobs is an important agricultural crop residue. The annual area and production of maize in India and Punjab is shown in Table 1.2. Major maize producing states in India are Andhra Pradesh, Bihar, Karnataka, Madhya Pradesh, Rajasthan and Uttar Pradesh.

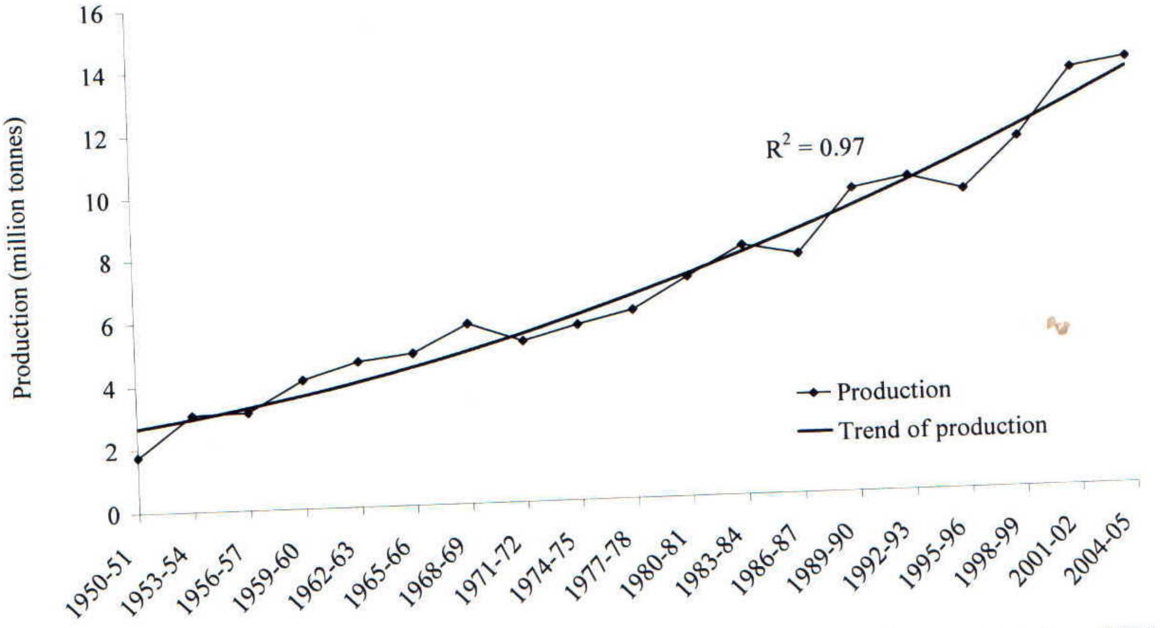
Punjab ranks 9th among the states in India in terms of its production and 3rd in terms of its yield (Anonymous 2005a). The all India production of maize is increasing steadily over the years (Fig.1.1). The grain to cob ratio is 2:1 for maize crop. The estimated production of maize cobs in India and Punjab is 4.4 million tonnes and 1.56 lakh tonnes respectively. A large amount of cobs is available on fields after shelling.

Table 1.2 Area and production of maize in India and Punjab

Year	India		Punjab	
	Area (million hectares)	Production (million tonnes)	Area (million hectares)	Production (million tonnes)
1994-95	6.14	8.88	1.73	0.322
1995-96	5.98	9.53	1.71	0.307
1996-97	6.26	10.77	1.66	0.352
1997-98	6.32	10.82	1.68	0.352
1998-99	6.20	11.15	1.57	0.360
1999-00	6.42	11.51	1.63	0.420
2000-01	6.59	12.04	1.64	0.458
2001-02	6.29	13.30	1.65	0.449
2002-03	7.42	10.30	1.53	0.312
2003-04	-	14.72	1.73	0.322

Sources: Anonymous (2004), Anonymous (2005a)

The production and collection cost of maize cobs is estimated to be around US $ 2 per tonne and US $ 0.7 per tonne respectively (Tripathi *et al* 998). Presently the cobs are being used inefficiently for domestic purposes cooking and heating) in rural areas or are being burnt in the open to clear fields for subsequent crop cultivation causing pollution.



Source: Anonymous 2004

Fig. 1.1 All India production and trend in maize

Biomass can be converted to solid, liquid or gaseous fuels by biochemical, chemical and thermo-chemical methods. Whereas only selected biomass can be converted into biogas, ethanol or bio-diesel through biochemical and chemical methods. Most of the biomass materials can undergo thermo-chemical conversion, thus making this method much more attractive than the others. The thermo-chemical conversion of biomass includes combustion, gasification and pyrolysis the major difference being the amount of oxygen used in the process. Combustion is a complete oxidation process resulting in heat. This process requires sufficiently high temperature, strong turbulence of air and a long residence time of the mixture in the fire chamber. Direct combustion of biomass is used for heat and electricity generation with an efficiency of 20 - 40 % (McKendry 2002b, Kucuk and Demirbas 1997). Pyrolysis, a non-oxidative thermal process results in gases, liquid and char. The product distribution depends on the process operating conditions i.e. temperature, heating rate and residence time. Pyrolysis or devolatilization is also the key process controlling the other thermo chemical processes i.e. combustion and gasification.

Gasification is a partial oxidation process that results in primarily producer gas, tar and particulate matter. Under controlled conditions, characterized by low oxygen supply and high temperatures, most biomass materials can be converted into a gaseous fuel known as producer gas. The producer gas consists of CO, H_2, CO_2, CH_4 and N_2 and has a low calorific value (4 - 6 $MJ \cdot Nm^{-3}$). It can be burnt with a high efficiency and good degree of control without emitting smoke. The producer gas can be used to generate heat (up to 1000 - 1200 °C) or used in engines or turbines after cleaning (McKendry 2002b). Biomass gasification has attracted highest interest of researchers among the thermo chemical technologies as it offers higher efficiencies (60-80 %) in relation to combustion.

Biomass gasification systems consist of a reactor / gasifier, in which the fuel is fed with limited supply of gasifying media, and a gas cleaning system. The gasifiers are of fixed bed (updraft, downdraft, open core/ throatless, crossdraft, two stage) or fluidised bed (bubbling fluidised bed, circulating fluidised bed, entrained bed and twin reactor) type. The gasifying media may be air, oxygen, steam or a mixture of these. If air is used as the oxidant, the producer gas has a very low heating value (4 - 5 $MJ \cdot Nm^{-3}$) due to the dilution with nitrogen; gasification with oxygen gives a gas with a net heating value of 10 - 15 $MJ \cdot Nm^{-3}$ and with steam 13 - 20

MJ·Nm^{-3} (McKendry 2002c). The gas cleaning and cooling system consists of filtration through cyclones, wet scrubbers and dry filters. The fluidised bed gasifiers are complex structures with large blowers for blowing air and augers for feeding biomass. In comparison the fixed bed gasifiers are of simple construction as the fuel naturally descends due to gravity. The downdraft gasifiers are classified as Imbert downdraft gasifiers and throatless gasifiers. The Imbert downdraft gasifier has a constriction or throat to allow for maximum mixing of gases. However the throat restricts the smooth flow of low-density biomass causing bridging and channelling leading to increased tar production. The design cannot be scaled up to larger sizes because air enters at the sides and is incapable of penetrating a large diameter fuel bed creating caves and high tar level in producer gas (Reed and Das 1988).

The throatless, stratified or open top gasifier overcomes the disadvantages of Imbert gasifier. It consists of a cylindrical reactor with a hearth at the bottom. This reactor is placed in another cylinder with annular space in between. The open top ensures uniform access of air and permits fuel to be fed easily and uniformly. The fuel flows down smoothly without causing bridging or channelling. The producer gas generated in the reactor travels up through the concentric containment tube, where a part of the heat of the gas is transferred to the cold fuel entering the reactor, improving the thermal efficiency of the system in addition to drying the fuel. The throatless gasifier is easy to construct and has good scale up properties. Because of its advantages the throatless gasifier was used in the present investigation. The throatless gasifiers have been tested for gasification of wood chips (Mukunda *et al* 1994), rice husk (Jain *et al* 2000), sugarcane leaves and bagasse (Jorapur and Rajvanshi 1997), coconut shells (Dasappa *et al* 2003), sawdust (Wander *et al* 2004, Altafini *et al* 2003), cashew nut shells (Singh *et al* 2006) and Jatropha seed husk (Vyas and Singh 2007). The design parameters and operating conditions depend on the properties of the fuel to be gasified and type of gasifier. These have been optimised for gasification of rice husk in throatless gasifier (Jain and Goss 2000, Tiangco *et al* 1996) and cashew nut shells (Singh *et al* 2006). The gasification of maize cobs in throatless gasifiers has not been studied. Very little is known about the operating conditions and design parameters for gasification of maize cobs in throatless gasifiers. Therefore the present study was addressed to the following specific objectives:

1. To evaluate the fuel related properties of maize cobs.
2. To evaluate the performance of gasifiers with diameter and air flow rate as variables.
3. To develop the parameters for designing gasifier reactor for gasification of maize cobs.

CHAPTER 2

REVIEW OF LITERATURE

The present chapter discusses historical development of gasification, its principle, characteristics of biomass, theory and developments of fixed bed gasification systems such as updraft, Imbert and throatless downdraft systems and their applications. The properties of producer gas and the commercial installations of fixed bed gasifiers have also been presented. The literature on gasification of biomass was reviewed from research papers published in journals namely Biomass and Bioenergy, Bioresource Technology, Fuel, Applied Energy, Energy Conversion and Management etc. during the period 1985-2007. The research papers were accessed from journals available in the libraries of PAU, Ludhiana and SLIET, Longowal. Reprints were also obtained from authors through correspondence.

2.1 History of gasification

The history of gasification dates back to seventeenth century. The process of gasification to produce combustible gases from organic feeds was used in blast furnaces, 180 years ago. The first commercial updraft (fixed bed) gasifier was installed in 1839, when Bischaf patented a simple process for gasifying coke. The first attempt to use producer gas to fire internal combustion engine was carried out in 1881 (Loewer *et al* 1982). The downdraft gasifiers (wood gas generators) were used for power generation and automotive applications before and during the Second World War. It is estimated that by 1945 around 9 million vehicles were running on producer gas all over the world. After the end of the Second World War, availability of cheap fossil fuels led to decline of producer gas industry. The interest in biomass gasification was renewed after the energy crisis of 1970s'. The technology began to be perceived as a relatively cheap indigenous alternative for small scale industrial and utility power generation, especially in developing countries that suffered from high petroleum prices and had sufficient sustainable biomass resources (Rajvanshi 1986, Stassen and Knoef 1995)

2.2 Principle of gasification

Biomass gasification is the conversion of biomass into producer gas consisting primarily of H_2, CO, CO_2, N_2 with lesser amounts of H_2O, CH_4, and higher hydrocarbons. Factors that affect the performance of the gasification reactor system are equivalence ratio (ER), gasification temperature and heating rate, kind of gasifying agent, pressure, residence time and feedstock properties. The gasification process is carried out at elevated temperatures, 500-1400°C and atmospheric, sub-atmospheric or elevated pressures. The gasifying agent used can be air (Jain *et al* 2000, Singh *et al* 2006, Pian and Yoshikawa 2001, Zainal *et al* 2002, Dogru *et al* 2002, Tiangco *et al* 1996, Vyas and Singh 2007, Wander *et al* 2004), steam (Franco *et al* 2003), carbon dioxide (Marquez *et al* 2002, Encinar *et al* 1998), pure oxygen (Na *et al* 2003) or a mixture of these gases (Lv *et al* 2004, Carlos 2005). Air-based gasifiers (or mixture of air and steam) produce fuel gas containing relatively high concentration of nitrogen with heating value between 4-6 $MJ \cdot m^{-3}$. Oxygen and steam-based gasifiers produce a gas containing a relatively high concentration of H_2 and CO with medium heating value between 12-18 $MJ \cdot m^{-3}$. Low heating value gas is used directly in combustion or in an engine, while medium/high heating value gases can be utilized as feedstock for subsequent conversion into basic chemicals, principally methane and methanol.

Gasification is a complex thermo chemical process involving several sequential and parallel reactions. The final gas composition of the gasification process is the result of a series of these complex reactions occurring to a varying degree (Demirbas 2004, Carlos 2005). Many of these reactions are endothermic and must be balanced by partial combustion or external heat source. The stages that occur during gasification at the same time in different parts of the gasifier are as follows:

Drying

Biomass fuels consist of moisture content ranging from 5-15 %. At temperatures above 100 °C the water is converted to steam but there is no decomposition of biomass in this zone.

Pyrolysis

Pyrolysis is the decomposition of biomass fuels heated to 300-500 °C in absence of oxygen. The biomass is pyrolysed to solid char, condensable hydrocarbons, tar and gases. The amounts of the products in this reaction is influenced by chemical composition of biomass and operating conditions but approximately 75-90 % is volatile material and remaining is char which is non volatile material containing high carbon content. The volatile hydrocarbons and char are subsequently converted to producer gas in the process of gasification.

Oxidation

The oxidation process takes place between 700-1000 °C. Heterogeneous reactions take place between oxygen, carbon and hydrogen in the biomass fuel to form CO_2 and H_2O as shown by reactions 2.1 and 2.2.

$$C + O_2 \rightarrow CO_2 \tag{2.1}$$

$$H_2 + 1/2\,O_2 \rightarrow H_2O \tag{2.2}$$

Reduction

In the reduction zone, a number of high temperature chemical reactions take place in the absence of O_2. In the reduction zone CO_2, volatile compounds and steam are reduced to CO and H_2 (2.3, 2.4, 2.5). Reaction 2.6 is the methane production reaction. The mixture of gases gets diluted with N_2 (air gasification) and unreduced CO_2 and is known as producer gas or fuel gas. The reactions 2.4, 2.5 and 2.6 are endothermic and the temperature of the gas reduces during this phase.

$$\text{Boudouard reaction, } CO_2 + C \leftrightarrow 2CO - 172.6\,\text{MJ/kgmol} \tag{2.3}$$

$$\text{Water gas reaction, } C + H_2O \leftrightarrow CO + H_2 - 131.4\,\text{MJ/kgmol} \tag{2.4}$$

$$\text{Water shift reaction, } CO_2 + H_2 \leftrightarrow CO + H_2O - 41.2\,\text{MJ/kgmol} \tag{2.5}$$

$$\text{Methane reaction, } C + 2H_2 \leftrightarrow CH_4 + 75\,\text{MJ/kgmol} \tag{2.6}$$

2.3 Impact of biomass properties on gasification

The biomass properties have a significant effect on the performance of the gasifier. The main properties of interest are size, moisture content, bulk density, angle of repose, volatile matter, fixed carbon, ash and energy content of biomass. The size of biomass affects the pressure drop across the gasifier. Larger particles tend to cause bridging and prevent the downward movement of feedstock in the gasifier reactor whereas smaller particles clog the available air voids leading to a high-pressure drop and subsequent shutdown of the gasifier. McKendry (2002c) reported that the particle size of feedstock should typically be 10-20 % of the reactor diameter.

The biomass moisture content affects both the operation and the quality of producer gas. Higher moisture content of biomass feedstock requires more air to maintain process temperature resulting in lower heating value of producer gas and lower gasification efficiency. The upper limit of moisture content for biomass to be used in a downdraft reactor is around 25 % wet basis. Biomass feedstock having moisture content below 15-18 % wet basis has been reported to be suitable for downdraft gasification (Dogru *et al* 2002, Bridgwater *et al* 1986).

The angle of repose of biomass determines its flow properties. With an angle of repose of biomass over 45°, the fuel may not flow even in a straight cylinder and will require either an inverted cone or some agitation (Reed and Das 1988).

Biomass with higher bulk density requires less reactor space for a given refuelling time. However, low bulk density fuels give rise to insufficient flow under gravity resulting in low heating value of gas. Biomass with bulk density in the range of 100-300 $kg{\cdot}m^{-3}$ gives rise to sufficient flow in the reactor (Jain 1997, Dogru *et al* 2002). The bulk density of hazelnut shells, cashew nut shells, rice husk and wood chips have been reported to be 319.14, 481.83, 105 and 250.28 kg·m^{-3} respectively. These biomass materials have been successfully gasified in throatless gasifiers (Dogru *et al* 2002, Singh *et al* 2006, Jain 1997, Stassen and Knoef 1995).

The proximate analysis determines the concentration of volatile matter and fixed carbon content, which provide a measure of the ease with which the biomass can be ignited and subsequently gasified. For biomass materials the concentration of volatile matter and fixed carbon ranges from 62.3-83.6 and 13.3-30.0 % on dry basis respectively (Ebeling and Jenkins 1985). The volatile matter of some biomass materials like rice husk, hazelnut shells, cashew nut shells and fuel wood are 71, 62.7, 79.5 and 82 % and their fixed carbon content is 12.5, 24.08, 18.9 and 17 % respectively (Jain 1997, Dogru *et al* 2002, Singh *et al* 2006). In comparison the volatile matter and fixed carbon of bituminous coal is 35 and 45 % respectively (McKendry 2002a).

The ash content of biomass affects the smooth running of the gasifier. Melting of ash in the reactor causes slagging and clinker formation. In general no slagging occurs with fuel having ash content below 5 %. Ash content varies from fuel to fuel. Ash contents of biomass ranges from 0.17 % to 24.36 % on dry weight basis (Ebeling and Jenkins 1985). The ash content of bituminous coal and lignite is 9 and 10.4 % respectively (McKendry 2002a). The ash content of wood, hazelnut shells, cashew nut shells and rice husk is 1, 0.77, 1.53 and 16.5 % respectively (Jain 1997, Dogru *et al* 2002, Singh *et al* 2006, Reed and Das 1988). Biomass with higher energy content is better for gasification.

Higher heating value (HHV) for biomass ranges from 14.56-23.28 MJ·kg^{-1} on dry basis with rice straw and rice hulls having lower HHV and forest residue (wood), bagasse and nutshells having HHV, towards the higher side (Ebeling and Jenkins, 1985). The HHV of rice husk, hazelnut shells, fuel wood and bagasse have been reported to be 15.5, 17.36, 19.6 and 20 MJ·kg^{-1} respectively. The HHV of anthracite is 30.9 MJ·kg^{-1}. The HHV of fossil fuel (coal) is higher than that of biomass because of lower proportion of oxygen in the former (Jain 1997, McKendry 2002a, Dogru *et al* 2002). The elemental composition of biomass shows that the oxygen content in biomass is more than that in fossil fuels. It is reported to be 40.05, 41.5, 44.4 and 45.83 wt % in rice husk, wood, bagasse and hazel nut shells respectively as compared to 8.7 wt % in bituminous coal (Jain 1997, McKendry 2002a, Dogru *et al* 2002, Jorapur and Rajvanshi 1997). High oxygen concentration in biomass is responsible for lesser heating value of biomass compared to coal and hydrocarbon fuels. The LHV of some biomass materials like cashew nut shells, rice husk and bagasse is 17.8, 14.36 and 18.61 MJ·kg^{-1} respectively (Jain 1997). The LHV of coal found in India and a few other parts of the world having high ash content (30-40 %) is 15-20 MJ·kg^{-1} and biomass is comparable in lower heating value to such coals (Mukunda *et al* 1994).

2.4 Theory of fixed bed gasification system

The fixed bed gasification system consists of a reactor / gasifier with a gas cooling and cleaning system. The fixed bed gasifier constitutes of a bed of solid fuel particles through which the gasifying media and gas move either up or down. The fuel bed moves slowly down as the gasification occurs. The fixed bed gasifiers are of simple construction and generally operate with high carbon conversion, long solid residence time, low gas velocity and low ash carry over (Carlos 2005, Reed and Das 1988). It consists of usually a cylindrical space for fuel and gasifying media with a fuel feeding unit, an ash removal unit and a gas exit. The gasifier is made up of firebricks, steel or concrete. In fixed bed gasifiers tar removal is a major problem, however recent progress in thermal and catalytic conversion of tar has given credible options. The fixed bed gasifiers are being considered to be of average strength for small-scale heat and power applications. The gas cleaning and cooling system normally consists of filtration through cyclones, wet scrubbers and dry filters (Carlos 2005, Rajvanshi 1986, Demirbas 2002, Riva 2006).

There are many types of fixed bed gasifiers with varying schemes for both reactor design and reaction media. The fixed bed gasifier can be classified according to the ways in which the gasifying agent enters the gasifier i.e. updraft, downdraft, crossdraft and two stage gasifier. The downdraft gasifiers are Imbert type (gasifier with throat) and open core type (throatless). The gasifying media may be air, steam, oxygen or a mixture of these and the producer gas may be used in thermal (heat gasifiers) or engine (power gasifiers) applications. The composition of producer gas and the level of contamination vary with the biomass, type of gasifier and operating conditions (Bridgwater *et al* 1999, Reed and Das 1988, Stassen and Knoef 1995).

2.5 Updraft gasification system

The updraft gasifier is the oldest and simplest form of fixed bed gasifier. It can handle biomass fuels with high ash (up to 15 %) and high moisture content (up to 50 %). It is more robust than other fixed bed gasifiers because it is less sensitive to variations in size and quality of biomass. In an updraft (counter current) gasifier, biomass fuel enters from the top of the reaction chamber and the gasifying media or agent (air, O_2 or mixture) enters from the bottom of the unit from below a grate. The fuel flows down slowly through the drying, pyrolysis, gasification and combustion zones. The ash is removed from the bottom. The updraft gasifier has high thermal efficiency as the sensible heat of the producer gas is recovered by direct heat exchange with the entering feedstock, which is dried, and pyrolysed before entering the gasification zone. The producer gas exits at low temperature (80-300 °C) and contains an abundance of oils and tar (10-20 %) since the products of the pyrolysis and drying zone are directly drawn into it without decomposition. The dust content in the producer gas is low due to low gas velocities and filtering effect of feed in drying and pyrolysis zones. (Carlos 2005, Reed and Das 1998, Anonymous 2002, Stassen and Knoef 1993).

2.5.1 Studies on updraft gasification systems

The high temperature (>1000 °C) agent gasification in updraft gasifiers permits the gasification of a wide range of feedstock including low rank biomass fuels and waste such as sludge. The higher temperatures of the preheated feed gas lead to a lower yield of tar, higher production of producer gas rich in H_2 content. Carlos (2005) investigated the high temperature air/steam gasification process for gasification of bark, charcoal, woodchips and wood pellets in a conventional batch type countercurrent updraft gasifier. Preheated air, steam and air/steam mixture were used as gasifying media. Preheating of air up to 830 °C kept the temperature in the oxidation zone of gasifier above 1000 °C, which promoted the thermal cracking of tar in one step in the gasifier. The lower heating value (LHV) of producer gas, cold gas efficiency and specific gas production rate (SGPR) increased from 4.6 to 7.3 $MJ{\cdot}Nm^{-3}$, 36.1 to 45.2 % and 744.9 to 916.6 $kg{\cdot}m^{-2}{\cdot}h^{-1}$ respectively as the temperature of the preheated feed gas was increased from 350 to 830 °C. With preheated air of 830 °C the LHV (7.3 $MJ{\cdot}Nm^{-3}$) of producer gas was well above that reported for downdraft gasifiers. When the feed gas used was mixture of steam and air, increase in the steam fraction with respect to the high temperature air favoured the water gas shift equilibrium and steam reforming of tars and hydrocarbons which led to increase in fraction of H_2 (10.4 to 29.9 %) and decrease in CO (29.4 to 18.4 %) in the producer gas. However use of steam lowered the temperature of gasification and the cold gas efficiency (43 to 37 %).

Yang *et al* (2006) investigated high temperature agent gasification (HiTAG) of wood pellets in a batch type updraft fixed bed gasifier (Fig. 2.1). The gasifier was a vertical cylindrical reactor consisting of wind box and gasifier bed. The feedstock bed was supported by a bed of ceramic balls placed on perforated disk inside the reactor. The gasification process became faster with increase in temperature of feed gas (650 to 830 °C). The higher feed gas temperature led to increase in concentration of CO (20.1 to 26.8 %) and H_2 (6.6 to 12.7 %) in producer gas. The critical feed gas temperature (at which the yield of gaseous products was maximum) was between ignition temperature of biomass and the melting temperature of the ash in the biomass.

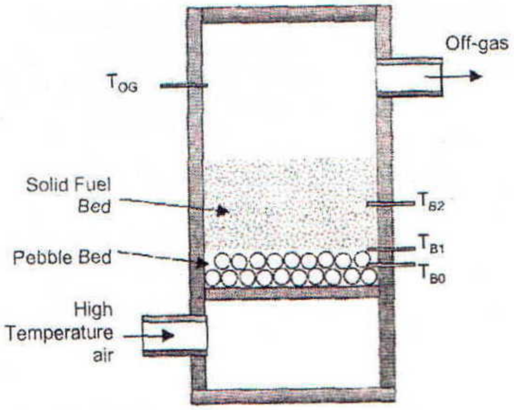


Fig. 2.1 Updraft gasifier for high temperature air gasification

The updraft gasifier was generally used for gasification of conventional biomass fuel like wood, wood chips, bark etc. However, Rao *et al* (2004) studied the gasification of non-conventional fuels like low-density refuse derived fuel (RDF) pellets in an updraft gasifier with an inclined grate.The grate inclination helped in crushing of large clinkers. An air-partitioner in the gasifier ensured uniform distribution of air in the combustion zone. The high heating value (HHV) and energy content of producer gas was 5.58 MJ·Nm^{-3} and 12.2 MJ·kg^{-1} respectively. The tar content from RDF pellets was 45 % less than that in gas generated from wood chips. The specific gasification rate of RDF pellets was within the range reported for updraft gasifiers with fixed grate i.e. SGR 100-200 kg·m^{-2}·h^{-1}. The cold gas efficiency obtained with RDF was 73 %, which was over 8 % higher than that obtained with wood chips.

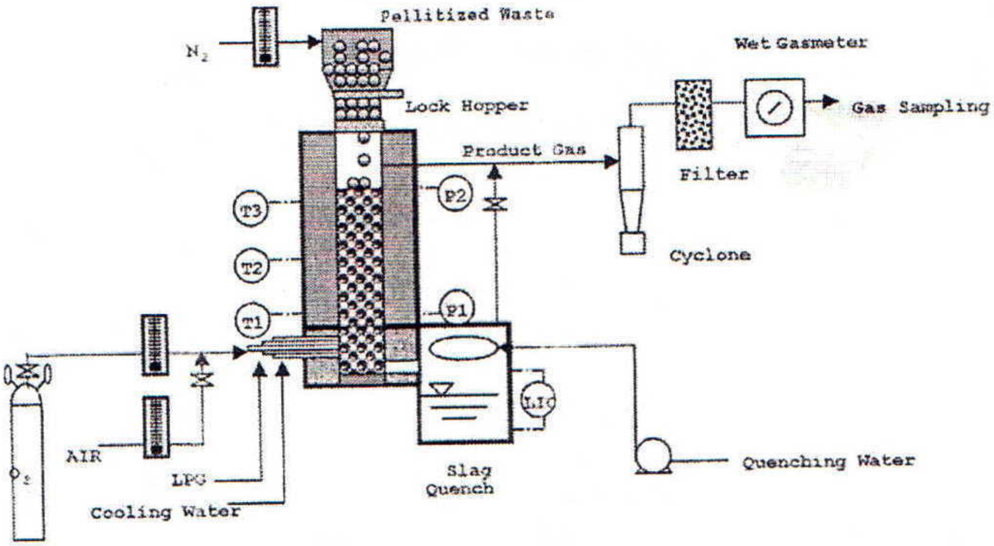


Fig. 2.2 Updraft gasifier using O_2 as gasifying medium

Na *et al* (2003) gasified combustible waste pellets in an updraft fixed bed gasifier lined with alumina refractory (Fig. 2.2) using O_2 as the gasifying medium. The composition of H_2 and CO in the producer gas was in the range 30-40 % and 15-30 % respectively depending on oxygen/waste ratio. As the bed height was increased the H_2 and CO content in producer gas increased whereas CO_2 content reduced. Gasification was difficult above a bed height of 700 mm because of pressure drop of O_2. The cold gas efficiency was around 61 % at O_2/waste ratio of 0.4-0.5 and the heating value of producer gas was

11.72-13.40 MJ·Nm^{-3}, which was more than heating value of producer gas generated by air gasification. The gas was cleaned of the particulate matter by a cyclone. O_2 gasification was reported to produce a medium heating value (MHV) gas (10-18 MJ·Nm^{-3}), which is suitable for limited pipeline distribution and as synthesis gas for conversion to methane and methanol.

2.5.2 Applications of updraft gasification systems

The producer gas from updraft gasifier has high amount of tar and is therefore mostly used in thermal applications i.e. close coupled steam boilers and crop dryers. Payne *et al* (1983) investigated the performance of an updraft gasifier (Fig. 2.3) used in conjunction with a combustor for grain drying. Maize cobs of varying moisture content (9-46 %) were gasified in the gasifier with primary air as the gasifying medium. The producer gas was then completely combusted with secondary air and the exhaust gas mixed with the ambient air and used directly for drying the grain. The total particulate emission was proportional to the second power of the gasification rate (amount of corncobs gasified per unit grate area per unit time), which in turn was dependent on the corncob moisture content and primary airflow rate.

The commercial use of an updraft fixed bed gasifier of 8 MW capacity (BIONEER) for thermal applications has been reported by Anonymous (2002). The gasifier consisted of a refractory lined vessel with a rotating cone shaped grate. The temperature of the combustion zone was controlled by humidification of gasification air. The gasifier was used to gasify a variety of feedstock (wood chips, forest wastes, peat, straw etc) and the gas was used for burning in a boiler to generate hot water. For successful operation the biomass fuel had moisture content less than 50 %, ash less than 10 % of dry matter with minimum softening point of ash above 1190 °C. Above 50 % moisture content the producer gas contained lot of tar aerosols. The producer gas generated from gasification of wood chips of 41 % moisture content consisted of 30 % CO, 11 % H_2, 3 % CH_4, 7 % CO_2, and 49 % N_2 with HHV of 6.2 $MJ{\cdot}Nm^{-3}$. The tar content of dry producer gas was in the range 50-100 $g{\cdot}Nm^{-3}$. The gasifier proved to be economically feasible for small heating systems.

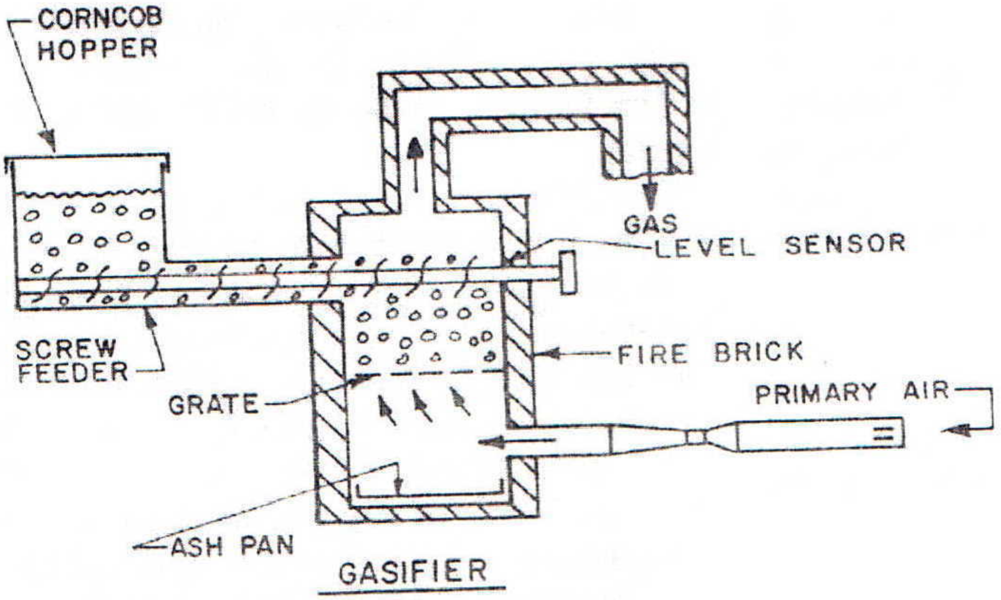


Fig. 2.3 Updraft gasifier for corn drying

Leung *et al* (2004) reviewed the gasification technologies being applied in China and surmised that the updraft gasifiers of capacity 2–30 kW were used for gasification of tree barks and timber blocks generating producer gas of lower heating value 4.1–5.3 MJ·Nm^{-3} at efficiency of 70-75 %. The producer gas was being used as boiler fuel commercially. The high amount of tar and pyrolysis products in the producer gas of updraft gasifier makes it highly unsuitable in engines and gas turbines. Barker *et al* (1996) reported that the updraft gasification between 2 – 20 MW was suitable for supplying fuel gas to reciprocating engines at efficiency of 30-35 % only, if the gas phase tars were cracked into smaller components, which do not condense at lower temperatures. This can be done by thermal cracking i.e. by raising temperature of gasifier over 1200 °C as in HiTAG (Carlos, 2005 and Yang *et al,* 2006)

2.6 Imbert downdraft gasification system

The Imbert downdraft gasifier or throated downdraft gasifier features a cocurrent flow of gases and solids through a descending packed bed, which is supported across a constriction or throat. The biomass fuel enters through the hopper and flows down, gets dried and pyrolysed before being partially combusted by the gasifying media (air) entering at the nozzles. The throat allows maximum mixing of gases in high temperature region, which aids tar cracking. Below the constriction or 'throat' the combustion gases along with tar pass through the hot char and are reduced to primarily CO and H_2. The gasifier can handle uniformly sized biomass fuels having moisture content and ash content less than 20 % and 5 % respectively. The throated (Imbert) downdraft gasifier is generally used for gasification of woody biomass of uniform sizes and shapes (blocks) as they flow smoothly through the constricted hearth. The producer gas from downdraft gasifier has lesser tar-oils (<1 %), higher temperature (around 700 °C) and more particulate matter than that from an updraft gasifier. The gasifier has lower overall efficiency since a high amount of heat content is carried over by the hot gas (Clarke 1981, Reed and Das 1988). The physical limitations of biomass particle size limit the capacity of the throated downdraft gasifiers to 500 kW. The throat of the downdraft gasifier presents a hazard to low-density biomass fuels. The biomass in form of twigs, sticks or bars does not flow down smoothly causing bridging and channelling leading to increased tar production. The throated downdraft gasifier operation is very sensitive to feedstock size and quality. Modifications have been made in the gasifier to successfully gasify the low and medium density fuels like stalks, shells etc.

2.6.1 Studies on Imbert downdraft gasification systems

Liinanki *et al* (1985) introduced a rotating grate and a double conical hopper in a downdraft gasifier for gasification of coir dust, cotton stalk and wheat straw. The fuel had lower density and higher ash content compared to that of wood and was densified into briquettes. The double conical hopper in the gasifier (Fig. 2.4) created space for the fuel briquettes to expand when they were heated up to avoid the bridging problem in the pyrolysis zone. A rotating grate fed out the slag particles before their agglomeration in the gasifier. The distance between the choke plate and the grate was also increased to increase the volume of the reduction zone to get better distribution of slag in the char bed. The gasification system consisted of a gasifier with a cyclone for coarse dust removal and a glass fibre-fabric for removal of fine material. The cold gas efficiency was 72-77 %. The tar content was below 1 g·Nm^{-3}. Wheat straw pellets were also tested but due to small particle size, streams of cold gas passed between the throat and air nozzles resulting in incomplete tar cracking and in producer gas with high tar content.

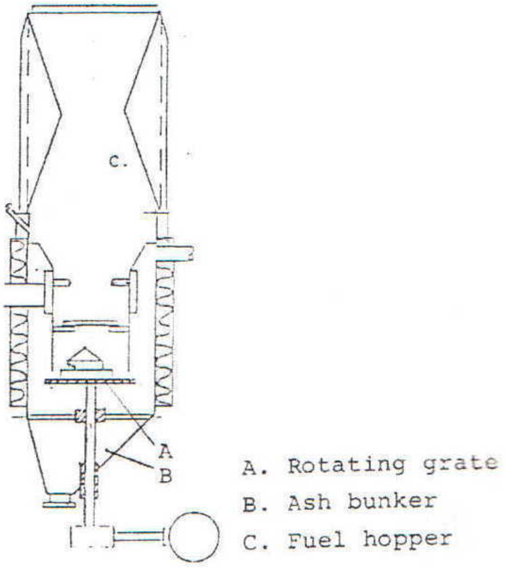


Fig. 2.4 Downdraft gasifier modified for non-woody biomass

Jayah *et al* (2003) investigated the gasification of chips of rubber wood of varying moisture content (12.5-18.5 %) and chip size (3.3-5.5 cm) in an 80 kW downdraft throated gasifier, which was double walled with an air gap in between. During the operation the gasifier was shaken to avoid bridging of fuel in throat. Small chips underwent faster char conversion increasing the conversion efficiency and therefore required smaller gasification zone length. Higher throat angle decreased temperature, reaction rate and conversion efficiency whereas smaller angles required a longer gasification zone length to reach optimum efficiency. For wood chip of moisture content 15 %, the optimum chip size was 5 cm, gasification zone length 22-33 cm, throat angle 61° and conversion efficiency 56 %. The tar, water vapour and ash content were 7-9 % of the producer gas output.

Sasidharan *et al* (1995) reported that downdraft gasifiers lined with ceramic material had greater life and lesser cost than downdraft gasifiers made of austenitic steel for biomass gasifier system below 500 kW. The gasifier made of steel failed at the throat and air nozzle region due to high temperature oxidation and corrosion mostly within 1500 hours of operation whereas the gasifier lined with ceramic material could withstand thermal shock. The composition of ceramic material was alumina (50-70 %), kaolin (16-20 %), feldspar (10-15 %) and talc (3-7 %).

Warren *et al* (1995) reduced the grate spacing and increased the grate height so that it does not block with char in downdraft-throated gasifier used for gasification of wood chips of coppice willow and poplar. The fine particles of the wood chips blocked the flow of air reducing the temperature in some areas of the throat. A fuel agitator was used to stir up the wood chip to allow free fuel flow but it was ineffective. The bridging of the fine fuel particles was not solved successfully so the fuel had to be removed of these particles prior to gasification. The throated downdraft gasifier was used for gasification of wood chips of coppice willow and poplar. The producer gas was passed through a twin cyclone, a pipe and fin cooler and a sawdust and foam filter to remove particulate matter and tar. It was mixed with air in a venturi before using in an engine to generate 30 kW of electricity.

Dogru *et al* (2004) and Midilli *et al* (2004) also used the throated downdraft gasifier to gasify briquetted-buffing dust leather (BDLW) residues of moisture content 11.23 % (d.b.). As the feed rate of BDLW increased from 2.09–5.04 $kg{\cdot}h^{-1}$, 0.08–0.21 $kg{\cdot}h^{-1}$ of ash, 0.04–0.06 $kg{\cdot}h^{-1}$ of tar and 0.60–1.39 $kg{\cdot}h^{-1}$ of condensate were obtained. The flow rates of wet gas increased almost linearly from 3.78 $Nm^3{\cdot}h^{-1}$ to 9.72 $Nm^3{\cdot}h^{-1}$, with the increase of the fuel feed rate. The combustible gases varied between 29 and 33 % of the total wet gas produced. The most productive region for the gasification of leather residues was between 486.39 and 584.36 $Nm^3{\cdot}m^{-2}{\cdot}h^{-1}$ of the specific gasification rate (SGR). The optimum efficiency of cold gas was 46.50 % at around 486.39 $Nm^3{\cdot}m^{-2}{\cdot}h^{-1}$ of the SGR. The large briquette sizes of the leather residues occasionally formed bridging in the throat zone of the gasifier.

Midilli *et al* (2001) gasified sewage sludge in a throated downdraft gasifier of 10 kW capacity and the producer gas generated had 19-23 % combustible gases and LCV of 2.55-3.2 $MJ{\cdot}Nm^{-3}$. Dogru *et al* (2002) investigated the gasification of hazelnut shells of moisture content 12 % (d.b.) in a 5 kW throated downdraft gasifier. The optimum operation of the gasifier was between 1.44 and 1.47 $Nm^3{\cdot}kg^{-1}$ of air fuel ratios and 4.06 and 4.48 $kg{\cdot}h^{-1}$ of wet feed rate. The high quality of producer gas of HHV (4.75-5.15 $MJ{\cdot}m^{-3}$) was due to high throat temperature (1015-1206 °C) and low char (0.201-0.228 $kg{\cdot}h^{-1}$) and low tar (0.023-0.025 $kg{\cdot}h^{-1}$) content. There was no sign of bridging or ash fusion at optimum throat temperature of 1000-1050 °C since the ash content of hazel nut shells was quite low i.e. 0.77 %. At higher flow rates of air (>1.5 $Nm^3 \cdot kg^{-1}$), the HHV of producer gas showed a significant decrease while tar output increased as more air resulted in more combustion. The producer gas was cleaned and cooled by passing through a packed bed scrubber and a dry filter with wood or charcoal.

Kutz *et al* (1983) used a downdraft-throated gasifier (830 $MJ \cdot h^{-1}$) in conjunction with a combustor for grain drying. The throat of the gasifier was made up of V shaped channels framed by triangular ducts, which were subdivided to separate primary air from secondary air. The gasifier was insulated with firebricks lined by mild steel shell. The air was preheated as it traveled through the ducts. The maize cobs having 8.1, 23.2 and 32 % moisture content were gasified with air. As the primary airflow rate increased the gasification rate increased linearly whereas as the moisture content of biomass increased the gasification rate decreased. The turn down ratio also decreased with the increase in moisture content of biomass and was 3:1 at 8.1 % moisture content. The particulate emission to energy input ratio was 134 $mg \cdot MJ^{-1}$, which was above the EPA standard for that from high capacity coal fired boilers.

The downdraft gasifier with throat is known to generate best quality producer gas with minimum tar for engines (Jain 2006). Sheng (1989) reported that the downdraft gasifiers with throat were commercially available in China (Fig. 2.5). These could operate on multi-fuels (wood, corncobs, hard nut shells,sawdust and hard coal) and the producer gas had 20-28 % CO and over 12 % H_2 content and was suitable to drive diesel engines.

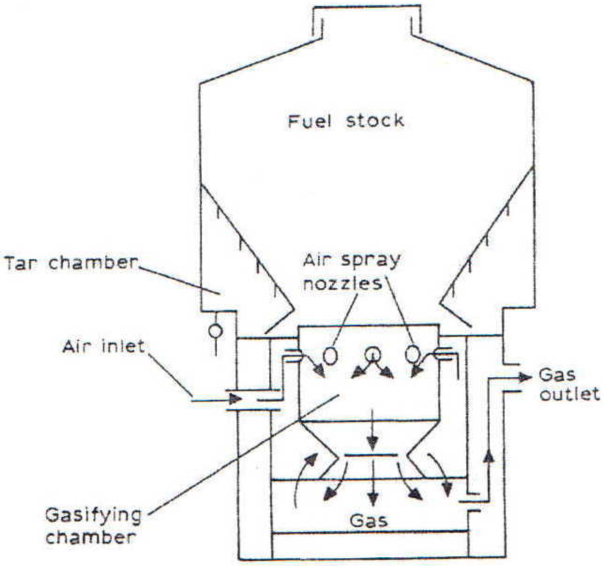


Fig. 2.5 Multifuel downdraft gasifier

A 10 kW downdraft throated gasifier was tested for various biomass fuels after their pre-treatment (size reduction and/or briquetting). The producer gas was used as a supplementary fuel in diesel engine pump set. The producer gas from the gasification of acacia auriculiformais, wood chips, fuel wood and sorghum stems replaced diesel in compression ignition (CI) engines by 70-76 %, 62.25 %, 22.5 % and 58.60 % respectively. In another trial of 3.75 kW downdraft throated gasifier, tamarindus and maize cobs were gasified and producer gas replaced 62.27 % and 48-52 % of diesel respectively (Jain, 1996).

2.6.2 Applications of Imbert downdraft gasification systems

Ghosh *et al* (2004) reported 5 x 100 kW downdraft gasifiers being used for electrification of 5 villages in Gosaba islands in West Bengal, India. Each 100 kW downdraft gasifier was equipped with a water sprayed gas cooling system, two-stage gas cleaning system, blower, an engine (165 hp) coupled to a 125 kVA alternator and pump sets for circulating water in the gas cooling tower and for removal of ash from the reactor. The average consumption of fuel wood and diesel per kWh of electricity generated was 0.822 kg and 0.135 litres. The diesel replacement by producer gas was 59 %. The overall efficiency of the Gosaba plant was 19 %.

Leung *et al* (2004) reported the use of downdraft gasifiers with efficiency of 75 % in China for gasification of straw for domestic cooking. The output of the gasifiers ranged from 60-200 kW and the heating value of producer gas was 3.8-4.6 $MJ \cdot m^{-3}$.

2.7 Throatless downdraft gasification system

The throatless (stratified or open top) downdraft gasifier was developed to overcome the problem of bridging and channeling in throated (Imbert) downdraft gasifiers. The gasifier consists of a cylindrical vessel with a hearth at the bottom. During operation the air and biomass move downwards through the four zones in the reactor. The open top ensures uniform access of air and permits fuel to be fed easily and uniformly, which keeps the local temperatures in control. The hot producer gas generated is drawn below the grate and up through the annulus of the reactor, where a part of the heat of the gas is transferred to the cold fuel entering the reactor, improving the thermal efficiency of the system (Reed and Das 1988, Mukunda *et al* 1994). The pyrolysis components are cracked in the oxidation zone, as gas traverses a long uniformly arranged bed of hot char without any low temperature zones, therefore the tar generated is low (0.05 kg tar per kg gas). The open top throatless gasifier is suitable for small sized biomass having high ash content up to 20 % (Stassen and Knoef 1995, Jain and Goss 2000). The gasifier is easy to construct and has good scale up properties. In order to improve the performance of throatless (stratified or open top) gasifier and use it for power and heat applications, changes were made in the design by allowing a varying air distribution in the gasifier, improving insulation of gasifier and re-circulating the gas within the gasifier.

2.7.1 Studies on throatless downdraft gasification systems

Mukunda *et al* (1994) developed an open top gasifier consisting of a vertical tubular reactor with an open top and a water seal at the bottom The lower two-thirds of the reactor was lined with a ceramic material to prevent high temperature corrosion. The upper part of the reactor was made of stainless steel with an annular jacket around it. The producer gas was drawn from below the grate and taken through an insulated pipe (re-circulating duct) to the upper annulus of the reactor where part of the sensible heat of the gas was transferred to the cold wood chips inside the reactor improving the thermal efficiency of the system. The entire reactor surface along with the re-circulating duct was insulated with aluminosilicate blankets.

Dasappa *et al* (2003) developed an open top downdraft reburn reactor, a cylindrical vessel made of mild steel, with an inner lining of ceramic. Air nozzles were provided around the combustion zone. Uniform air distribution across the section was established by locating these nozzles at two different heights. The dual air entry - from top and the nozzles - favoured a high residence time for gases at elevated temperatures, thus eliminating the tar. The top of reactor helped in loading of fuel. The fuel bed was supported on an ash extraction screw. The screw was operated based on the ash content of biomass and / or the pressure drop across the reactor. Two discharge outlets were provided for ash extraction.

Wander *et al* (2004) developed an open top stratified gasifier with internal gas recirculation, which could burn a part of the gas produced to raise the gasification temperature. The gasifier (Fig. 2.6) consisted of a cylinder with a cast iron grate fixed to a rotating shaft. Rods were fixed on the shaft to mix sawdust in the reduction zone and to extract the ash. In the center of the gasifier a device like a venturi aspirated part of the gases produced in it to be burnt in a chamber. The gasifier was used for gasification of 12 $kg{\cdot}h^{-1}$ of sawdust of moisture content (9-11 %). With no recirculation of gases, the air / sawdust ratio had to be kept above 1.5 to get cold gas efficiency of 60 %, whereas with re-circulation of gases, the ratio was lower i.e. 1.1-1.4. Gas re-circulation raised the gasification reaction temperature, helped in burning a part of the tar and improved efficiency of gasifier. Strong mixing of sawdust was required to avoid bridging and channeling. The gasifier was used with a cyclone to remove particulate matter from producer gas.

In another trial on the open core gasifier with gas re-circulation conducted by Altafini *et al* (2003) the feed rate of sawdust, temperature and pressure in the gasifier was 11.34 $kg{\cdot}h^{-1}$, 800 °C and 0.93 bar respectively. The moisture content of sawdust was varied from 0-30 %. It was observed that as the moisture content of the sawdust increased the air/sawdust ratio had to be increased to keep the temperature constant. The LHV of the producer gas reduced with the increasing moisture content of sawdust. Maximum cold gas efficiency (68 %) was achieved with sawdust having moisture content of 20 %.

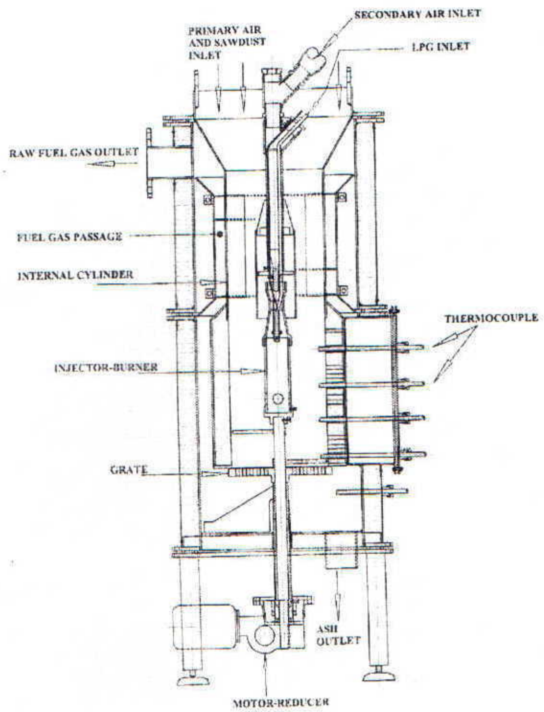


Fig. 2.6 Stratified gasifier with gas re-circulation

Barrio *et al* (2001) used a small-scale (30 kW) stratified downdraft gasifier (Fig. 2.7) to gasify wood pellets at a feed rate 5 kg·h^{-1}. The design of the gasifier allowed for variation in the point of air injection along the length of gasifier. The grate was a perforated plate with a crank, which could be shaken manually. The equivalence ratio was lower (0.3) when air was taken in from the top (80 %) and sides (20 %) of the gasifier. It was 0.4-0.45 when 100

% air was taken in from the top (traditional open core). The gasifier produced 12 $Nm^3 \cdot h^{-1}$ of producer gas with a calorific value of 5 $MJ \cdot Nm^{-3}$ and CO and H_2 content of 20 % each.

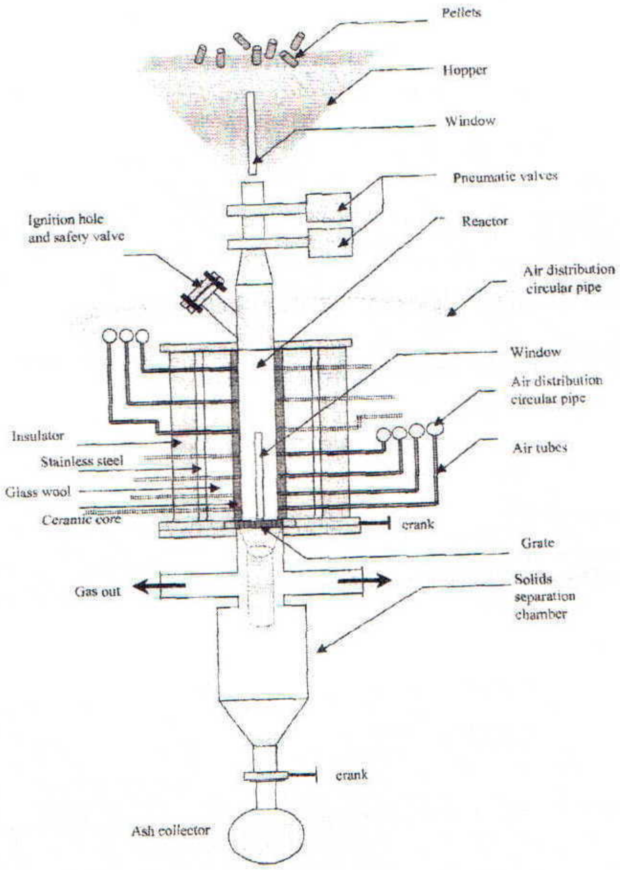


Fig. 2.7 Stratified downdraft gasifier

2.7.2 Optimization of operating parameters of throatless gasifiers

The specific gasification rate (SGR) i.e. rate of fuel consumption per unit area of reactor area has been optimized for throatless gasifiers. Knowing the optimal value of SGR, the size of the reactor can be computed from the energy demand of the gasification system. Tiangco *et al* (1996) gasified rice hulls in an open core or static bed gasifier of varying reactor diameters from

16-30 cm. The specific gasification rate was varied in the range of 100-400 $kg \cdot m^{-2} \cdot h^{-1}$ As the SGR increased, the producer gas flow rate and reaction airflow ratio increased. The cold gas efficiency increased up to an optimum value of SGR and then decreased. The highest cold gas efficiency was between 50-60 % at SGR of 200 $kg \cdot m^{-2} \cdot h^{-1}$. It was observed that the cold gas efficiency and optimum value of SGR were independent of the size of the reactor thus indicating that SGR could be used satisfactorily to upscale the reactor size.

Jain *et al* (2000) developed the design parameters for rice husk throatless gasifier for engine applications. The gasifier was made of two concentric cylinders of mild steel the inner one being reactor and the outer the containment tube. The grate was made of stainless steel wire mesh. The gas was passed through packed bed water scrubber and dry filter. SGR was varied in the range 110-240 $kg \cdot m^{-2} \cdot h^{-1}$. As the SGR increased the equivalence ratio increased from 0.33 to 0.44. The cold gas efficiency increased from 53 to 69 % up to SGR of 190 $kg \cdot m^{-2} \cdot h^{-1}$. Further increase in SGR reduced the efficiency. The optimum value of SGR, at which the gasification efficiency was maximum, was 190 $kg \cdot m^{-2} \cdot h^{-1}$. Jain and Goss (2000) conducted gasification of rice husk in open core throatless batch fed gasifiers of four different diameters to develop the up scaling parameters for gas production. For all the reactors the gasification efficiency was the maximum (65 %) between SGR values 190-195 $kg \cdot m^{-2} \cdot h^{-1}$. The specific gas production rate (SGPR) was 410-429 $Nm^3 \cdot h^{-1} \cdot m^{-2}$ and equivalence ratio was 0.4. The LHV of producer gas was 4 $MJ \cdot Nm^{-3}$. The optimum SGR and specific heat rate for 100

$kg \cdot h^{-1}$ rice husk gasifier system was 200 $kg \cdot m^{-2} \cdot h^{-1}$ and 2.7 $GJ \cdot m^{-2} \cdot h^{-1}$ respectively (Jain 2006).

Singh *et al* (2006) carried out gasification of cashew nut shells in open core downdraft gasifier of capacity 150,000 $kcal \cdot h^{-1}$ at varying gas flow rates. The maximum gasification efficiency was 70 % at SGR of 167 $kg \cdot m^{-2} \cdot h^{-1}$. The producer gas flow rate was 130 $m^3 \cdot h^{-1}$ and its LHV was 1081 $kcal \cdot m^{-3}$. The producer gas was used for thermal applications like boilers through direct combustion or for heating air using heat exchangers.

2.7.3 Applications of throatless gasification systems

Jorapur and Rajvanshi (1997) developed commercial (1080 $MJ \cdot h^{-1}$) low-density biomass gasification system for thermal applications at Nimbkar Agricultural Research Institute (NARI), India. The reactor was lined by high temperature resistant firebricks on the inner side. The gas conditioning system consisted of high temperature char/ash coarse settler and a high efficiency cyclone separator. The gasifier was operated on sugarcane leaves, bagasse and their mixture and the HHV of the gas was between 3.56-4.82 $MJ \cdot Nm^{-3}$. The system also produced char, (with gross calorific value of 18.9 $MJ \cdot kg^{-1}$) which was about 24 % by weight of the original fuel. The output was in the range of 288-1080 $MJ \cdot h^{-1}$. The temperature of the gas was greater than 300 °C and so there was no condensation of tars and particulate matter. The performance of the gasifier was excellent up to fuel moisture content of 15 %.

Dasappa *et al* (2003) used throatless reactors of capacity 500 $kg{\cdot}h^{-1}$ and 300 $kg{\cdot}h^{-1}$ were used for low (100 °C) and high (600 °C) temperature applications respectively. The low temperature application was drying of marigold flowers for which the coconut shells were gasified and gas from the gasifier system replaced diesel fuel in the range of 125–150 $l{\cdot}h^{-1}$. The high temperature application was for a heat treatment furnace in which biomass gasifier replaced 2000 l of diesel per day. The gas quality after cleaning and cooling through a cyclone and water scrubber was comparable to that which could be used in engines.

Mukunda *et al* (1994) reported that producer gas from throatless gasifier could be used for engine (power) applications as it contained low amount of tar. The gasifier was used for gasification of wood chips. The ratio of the cold gas flow rate to wood chips consumption rate was about 2.6. The composition of gas was 18 % H_2, 19 % CO, 1.25 % CH_4, 12 % CO_2 and rest N_2. The calorific value ranged from 4 $MJ{\cdot}kg^{-1}$ to 4.4 $MJ{\cdot}kg^{-1}$. The amount of tar and particulate matter in producer gas were 100 $mg{\cdot}m^{-3}$ and 700 $mg{\cdot}m^{-3}$. They were reduced to 20 $mg{\cdot}m^{-3}$ and 50 $mg{\cdot}m^{-3}$ respectively after cleaning through a sand filled coarse filter and a fine filter. The total efficiency of the system measured in relation to the final electric energy was 27 % in a 100 kW compression ignition engine with 85 % diesel replacement.

Sardar Patel Renewable Energy Research Institute (SPRERI), India tested a 3.5 kW throatless gasifier for gasification of paddy husk and the producer gas was used in a diesel engine pump set. The average diesel replacement and specific husk consumption was 61.1 % and 9.2 kg·h^{-1} respectively. Punjab Agricultural University, India tested a 10 kW throatless downdraft paddy husk gasifier coupled to a diesel engine. The gasifier efficiency, tar content and diesel replacement were 67 %, 75 mg·Nm^{-3} and 75 % respectively at 8 kW load (Jain 1996).

Leung *et al* (2004) reviewed the open core gasifiers (60-200 kW) being developed in China for electricity generation. These operated on rice husk and produce producer gas of lower heating value 3.8-4.6 MJ·m^{-3} with efficiency of 50 %. Dasappa *et al* (2004) tested the open top ceramic lined reactor for gasification of biomass with varying moisture contents up to 37 % and studied the variation of tar and particulate in the raw gas. The tar content in this reactor design was lower due to the high quality insulating material used for reactor and air distribution between the nozzle and the reactor top. The cracking of the tars improves the overall gasification efficiency. With increase in moisture content, the tar level in the gas increased and particulate matter reduced. The tar content in the raw gas was in the range of 50–250 mg·Nm^{-3} for fuel having moisture content less than 15 %, beyond which it increased to about 700 mg·Nm^{-3}. At a capacity of 75 kg·h^{-1} the cold gas efficiency was around 75 %, whereas the large capacity gasifier system of 650 kg·h^{-1} resulted in cold conversion efficiencies in the range of 85 %. The fraction of tar and particulate matter in the hot gas from open top reactor were observed to be lower than in the Imbert design. The gasification system consisted of the gasifier, high efficiency cyclone, and ejector scrubber to cool and clean gas before using it in the engine. Diesel savings of up to 70 % and an overall efficiency of 20 % were achieved.

2.8 Commercial installations of fixed bed gasifiers

Many countries have developed commercial biomass gasification technologies. Some of the commercially available fixed bed gasifiers are listed in Table 2.1

2.9 Critical analysis of literature review

Biomass has high potential to contribute to energy needs of modern society. The fixed bed gasifier is the most practical option for obtaining producer gas for use in small-scale power generation systems and thermal applications. The physical and chemical characteristics of biomass, capacity of gasifier and its application decides the choice of gasification system. The updraft gasifier can handle biomass fuels having high ash and moisture content and is suitable essentially for thermal applications. The heating value of producer gas has been improved by high temperature agent gasification (HiTAG) in updraft gasification systems. The downdraft gasifier is suitable for both thermal and engine applications. The introduction of features like rotating grate, double conical hopper, ceramic lining of gasifiers, reduced grate spacing etc. resulted in improved performance of Imbert downdraft gasifiers. The throatless gasifier is advantageous as it is simpler in design, construction and operation. The design parameters have been established for gasification of rice husk and cashew nut shells in throatless gasifiers.

Table 2.1 Few commercially available fixed bed gasifiers

Country	Type of fixed bed gasifiers	Fuel	Size	Organization / project
USA	Downdraft	Hogged wood, stumps	1 MW	CLEW
	Downdraft	Woodchips, corn cobs	40 kW	Stwalley Engg.
Denmark	Updraft	Hazardous, leather waste	2-15 MW	DTI
	Updraft	Straw, woodchips, bark	1-15 MW	VOLUND R&D Centre
	Downdraft	Wood residues	0.5 MW	Hollesen Engg.
New Zealand	Downdraft	Wood blocks, chips, coppice willow chips	30 kW	Fluidyne
France	Downdraft	Wood, agricultural residues	100-600 kW	Martezo
UK	Downdraft	Wood chips, hazel nut shells, MSW	30 kW	Newcastle University of technology
	Downdraft	Industrial agricultural wastes	300 kW	Shawton Engineering
Switzerland	Stratified	Woody and agricultural biomass	50-2500 kW	DASAG
	Downdraft	Wood, wood-waste	0.25-4 MW	HTV Energy
India	Downdraft	Wood chips, rice hulls	100 kg/h	Associated Engineering Works
	Downdraft	Wood stalks, cobs, shells, rice husk		Ankur Scientific Energy Technologies
Belgium	Small scale	Wood chips	160 kW	SRC Gazel
South Africa	Downdraft	Wood blocks, chips, briquettes	30-500 kW	SystBM Johansson gas producers
Finland	BIONEER updraft	Wood chips, straw, RDF pellets, peat	4-5 MW, 6.4 MW	Ahlstrom Corporation, VTT
Netherlands	Downdraft	Rice husk	150 kW	KARA Energy Systems
China	Downdraft	Sawdust	200 kW	Huairou wood equipment
	Downdraft	Crop residues	300 kW	Huantai Integrate Gas-supply System

Sources: Ciferno and Marano (2002) and Leung *et al* (2004)

Producer gas derived from biomass typically contains 18-20 % each of H_2 and CO, 2 % CH_4 and the rest inert gases such as CO_2 and N_2. The lower calorific value of the producer gas varies in the range of 4.5-5.5 $MJ \cdot kg^{-1}$. The commercial installations for fixed bed gasification systems have come up in many countries. Although gasification technologies have recently been successfully demonstrated at small scale by the researchers and several demonstration projects are under implementation they still face economic and other non-technical barriers when trying to compete in the energy markets. The development in efficient utilization of biomass to meet energy needs will have dual advantage of reducing our dependence on commercial energy and protecting our environment.

CHAPTER 3

MATERIALS AND METHODS

The study of gasification of shelled maize cobs in throatless gasifier was conducted in the School of Energy Studies, PAU, Ludhiana during the year 2006 - 2007. The methods adopted for investigating the fuel related properties of maize cobs and experimental runs on gasification of maize cobs in throatless gasifier are briefly described below.

3.1 Measurement of fuel related properties of maize cobs

Shelled maize cobs (Fig. 3.1) of *Paras* variety were procured from Department of Agronomy and Agro meteorology and Forestry, PAU. The maize cobs were stored in ventilated place in the laboratory. The physical, thermal and chemical characteristics of biomass influence its gasification. Size, bulk density, true density, moisture content, angle of repose, proximate composition (volatile matter, fixed carbon, and ash content), high heating value and elemental composition of maize cobs were determined experimentally. The lower heating value, stoichiometric air fuel

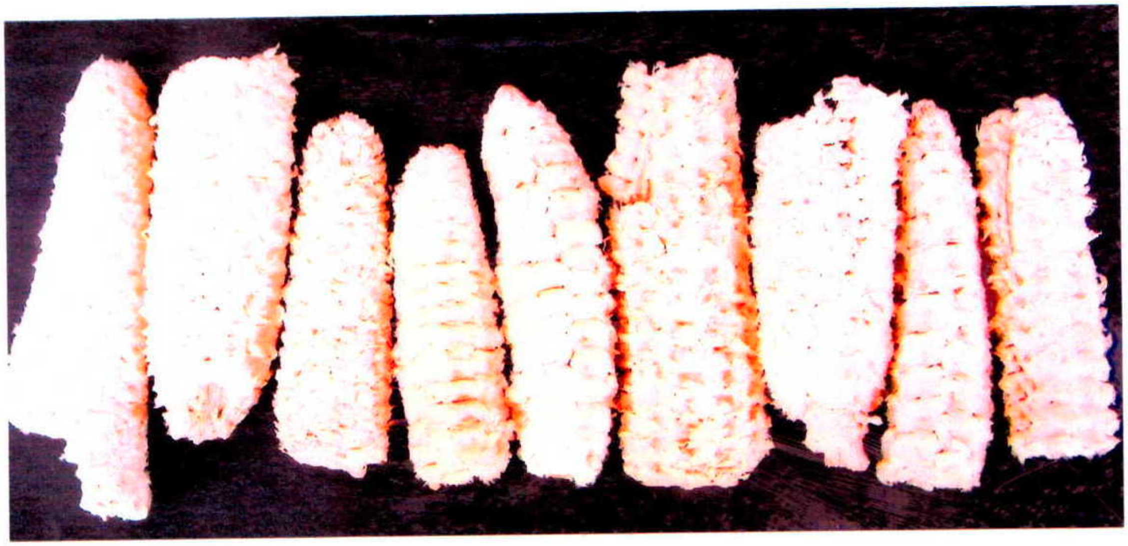


Fig 3.1 Shelled maize cobs

ratio and stoichiometric formula of maize cobs were computed. The methods used to determine the properties are described below:

3.1.1 Size

Size of feedstock is an important parameter, which affects gasification. Larger particles tend to cause bridging and prevent the downward movement of feedstock in the gasifier reactor, whereas smaller particles clog the available air voids leading to a high-pressure drop and subsequent shutdown of the gasifier. The shelled maize cobs are cylindrical in shape (Fig. 3.1). These are normally 10 to 15 cm long. These were reduced to a length of 4 to 7 cm manually, for gasification. The length and diameter of these maize cobs was measured using vernier calliper and average values have been reported.

3.1.2 Bulk Density

Bulk density has a considerable impact on gas quality as it influences the fuel residence time in gasifier, fuel velocity and gas flow rate. The bulk density is the ratio of the weight of the bulk of biomass material to the volume occupied by it. A cylindrical container having a volume of 18.4×10^{-3} m^3 was used for measuring bulk density of maize cobs. The maize cobs were filled into the cylinder from a height of around 60 cm and the container was tapped gently for settling and then the weight of maize cobs contained in the cylinder was measured.

3.1.3 True density

The true density of maize cobs is the weight per unit volume of a single piece of maize cob. It was determined using the Archimedes principle (Pathak and Jain, 1984).

3.1.4 Moisture content

The biomass moisture content affects both the operation and the quality of producer gas. Higher moisture content reduces the efficiency of the gasifier and results in low gas heating values. Moisture content of maize cobs was determined by drying maize cob samples to a constant weight in a hot air oven with temperature regulation between 104 to 110 °C as per ASTM D 3173-73 (Anonymous, 1983)

3.1.5 Angle of repose

It is the angle made by biomass from the horizontal to the sides of the pile under free falling conditions. It was determined by filling a large open-ended tube of diameter 15 cm with oven dried maize cobs, keeping the tube with its end on the ground. The tube was then lifted in such a manner that the maize cobs formed a pile on the ground. The angle made between the slant sides of the pile with the horizontal was measured as the angle of repose.

3.1.6 Elemental analysis

The ultimate elemental analysis for carbon, hydrogen, nitrogen and sulphur was done using the CHNS analyser (Vario EL III), Elementar, Germany.

3.1.7 Proximate analysis

The proximate analysis was done to estimate the volatile matter, fixed carbon and ash in maize cobs as per BS 1016 Part 3 and 4, 1965 (Anonymous, 1969). The concentration of volatile matter (VM) and fixed carbon (FC) content provide a measure of the ease with which the biomass can be ignited and subsequently gasified. The ash content (AC) of biomass has an impact on smooth running of the gasifier. Melting of ash in the reactor causes slagging and clinker formation. According to the procedure one gram of air dried and ground sample (-50 +100 mesh ASTM) was weighed in a tarred platinum crucible with a lid. A few drops of benzene were added to the contents of the crucible to replace air. The crucible containing the sample and covered with the lid was placed in furnace for 7 minutes at a constant temperature of 915 °C. The residue containing fixed carbon and ash was weighed after cooling. The volatile matter and moisture content of the sample accounted for the loss of weight during heating. Since the moisture content of the air-dried sample had been separately determined using standard oven method, the amount of volatiles was calculated by deducting the weight of the moisture from the total loss in weight. The residue containing fixed carbon and ash was then kept in the furnace for 3 hours at 650 °C. The resultant ash was cooled and weighed. The loss of weight represented the amount of fixed carbon. All quantities were expressed as percentage of the weight of the moisture-free sample.

3.1.8 Higher heating value

The higher heating value (HHV) of fuel is the total energy content released when the fuel is burnt in air, including the latent heat contained in the water vapor and therefore represents the maximum amount of energy potentially recoverable from a given biomass source. Higher energy content of fuel is better for gasification. For estimation of HHV the ASTM method D 2015-77 for gross calorific value of solid fuel by adiabatic bomb calorimeter (Anonymous 1983) was followed. The sample was prepared by grinding and sieving the maize cobs to powder (-50+100 mesh size ASTM).

It was combusted in adiabatic oxygen bomb calorimeter. The water formed during the process was condensed and the latent heat of vaporization (λ) of water was accounted for calculating HHV. The determinations of higher heating value of maize cobs (HHV_m) were made in triplicate and average values are reported. Parikh *et al* (2005) has correlated higher heating value of biomass with its proximate analysis as given in equation 3.1. The correlation is valid for fixed carbon (FC) in range of 1.0-91.5 %, volatile matter (VM) between 0.92-90.6 % and ash content (AC) between 0.12-77.7 % on dry basis.

$$HHV\ (MJ\cdot kg^{-1}) = 0.3536*FC + 0.1559*VM - 0.0078*AC \qquad (3.1)$$

3.1.9 Stoichiometric formula

Stoichiometric formula of maize cobs was calculated from elemental composition of biomass. The stoichiometric formula is required for conducting energy balance and material balance over the gasification process, calculating the lower heating value of biomass and estimating the stoichiometric air requirement. If C, H and O represent the weight per cent of carbon, hydrogen and oxygen of biomass as determined from the elemental analysis, then the stoichiometric formula is represented by CH_xO_y, where x and y are the molar ratios of H/C and O/C and are determined using equations (3.2) and (3.3) respectively.

$$x = H / (C/12) \qquad (3.2)$$

$$y = (O/16) / (C/12) \qquad (3.3)$$

3.1.10 Stoichiometric air fuel ratio

The stoichiometric air fuel ratio is the theoretical air required for complete oxidation of a unit weight of biomass. Combustion of a biomass material is represented by the equation (3.4). The moles of air in the reaction are represented by 'n' and are given by equation 3.5.

$$CH_xO_y + n(0.79N_2 + 0.21O_2) = CO_2 + \frac{x}{2}H_2O + 0.79n\,N_2 \qquad (3.4)$$

$$n = \frac{(2 + x/2 - y)}{0.42}\ \text{kgmol air / kgmol biomass} \qquad (3.5)$$

This is equivalent to, $n_1\ (\text{Nm}^3/\text{kg biomass}) = \frac{(2 + x/2 - y) \times Vo}{0.42 \times M} \times (1 - AC)$

where, n_1 = stoichiometric air fuel ratio in Nm^3/kg biomass.

3.1.11 Lower heating value

The LHV of maize cobs (LHV_m) was determined using the calculated HHV_m and elemental analysis according to equation (3.6)

$$LHV_m = HHV_m - (np - nr) \times R \times T - \lambda \times W \qquad (3.6)$$

np = no. of moles of products in combustion, eqn. 3.4

nr = no. of moles of reactants in combustion, eqn. 3.4

$R = 8.314\ kJ \cdot (kgmol)^{-1} \cdot K^{-1}$

$T = 273.15\ K$

$W = (x/2) \times 18 / M_m$ = water formed in combustion, eqn. 3.4

$\lambda = 2.542\ MJ \cdot kg^{-1}$ = latent heat of vaporization of water

3.2 Design of throatless gasifier for gasification of maize cobs

The throatless gasifiers are suitable for running diesel engines having capacities up to 25 hp. Farmers generally own small engines (up to 25 hp) for water pumping and other applications on the farm (Jain and Goss 2000, Mukunda *et al* 1994). Thus, the throatless gasifiers suitable for running small engines were designed. The dimensions of the throatless gasifiers were calculated by material and energy balance over the gasifier diesel engine alternator system (Fig. 3.2). The unit consists of gasifier system (gasifier and gas cleaning unit) and engine system (diesel engine and alternator). Reactor diameter is the most critical parameter for a throatless gasifier. Two different approaches are in use for estimation of the reactor diameter. Use of kinetic model is one approach (Jain *et al* 2001). The other approach is the use of specific gasification rate (SGR) (Jain *et al* 2000). The second approach was used to calculate the diameter of the reactor of throatless gasifier for the present study. The length of the reactor was calculated from bulk density of maize cobs so that the reactor can accommodate fuel for operating the system for 45-60 minutes. The length of containment tube was kept 15 cm more than that of the reactor to allow free space at the bottom of the reactor for producer gas to flow and move in the containment tube. The assumptions considered for the calculations are given in Table 3.1. The assumptions were based on the reported information. The material and energy balance calculations based on one-hour operation are as given below.

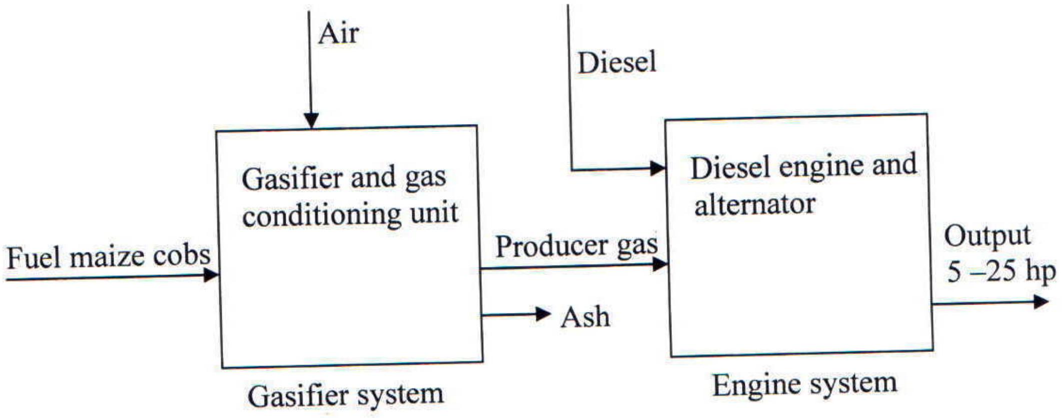


Fig. 3.2 Gasifier diesel engine alternator system

Table 3.1 Assumptions for calculating size of throatless gasifier

Assumptions	Symbol	Value
Efficiency of engine system in dual fuel mode[1]	η_{es}	22 %
Diesel replacement by producer gas to engine in dual fuel mode[1]	-	70 %
Efficiency of gasifier system[2]	η_{gs}	65 %
Lower heating value of producer gas[2]	LHV_g	4.5 MJ·Nm^{-3}
Nitrogen content in producer gas[2]	N_g	52.5 %
Lower heating value of maize cobs[3]	LHV_m	17 MJ·kg^{-1}
Nitrogen content in maize cobs[3]	N_m	0.60 %
Ash content in maize cobs[3]	AC_m	1.80 %
Bulk density of maize cobs[3]	BD_m	100 kg·m^{-3}
Velocity of producer gas in containment tube[2]	$V_{g,c}$	15 cm·s^{-1}
Specific gasification rate[2]	SGR	190 kg·h^{-1}·m^{-2}
Normal temperature and pressure of air and gaseous products[4]	NTP	0 °C and 1 atm
Volumetric / mole composition of air[4]	N_a, O_a	0.79, 0.21
Volume of 1kgmol of ideal gas[4]	Vo	22.414 N·m^3
Molecular weight of nitrogen[4]	M_n	28

Sources: [1]Reed and Das 1988, [2]Jain *et al* 2000, [3]Jain 1997, [4]Chadwick 1980

3.2.1 Calculations of dimensions of gasifier for a 5 hp engine system

The step-by-step design calculations for dimensions of throatless gasifier for a 5 hp engine system are as follows:

Output of engine system = 5 hp or 13.4 MJ·h^{-1}

Input of engine system = output of engine system / η_{es} = 13.4 / 0.22 = 60.95 MJ·h^{-1}

Energy contribution of diesel to engine system = 0.3* 60.95 = 18.29 MJ·h^{-1}

Energy contribution of producer gas to engine = 0.7*60.95 = 42.67 MJ·h^{-1}

Output of gasifier system = energy contribution of producer gas to engine

= 42.67 $MJ \cdot h^{-1}$

Input of gasifier system = output / η_{gs} = 42.67 / 0.65 = 65.64 $MJ \cdot h^{-1}$

Required flow rate of producer gas (F_g) = energy contributed by producer gas / LHV_g = 42.67 / 4.5 = 9.48 $Nm^3 \cdot h^{-1}$

Fuel required (F_m) by gasifier system = input of gasifier system / LHV_m = 65.64 / 17.4 = 3.77 $kg \cdot h^{-1}$

Flow rate of air (F_a) required by gasifier system was calculated by nitrogen balance over gasifier system as per equation 3.7.

$$F_a x N_a + F_m x N_m x Vo/M_n = F_g x N_g \qquad (3.7)$$

F_a= 6.28 $Nm^3 \cdot h^{-1}$ (by solving 3.7)

Area of the reactor (A_{rc}) = F_m / SGR = 3.77/190 = 0.020 m^2

Inner diameter of reactor (d_{rc}) = 15.9 cm

Inner diameter of containment tube (d_c) was calculated from equation 3.8 so that the velocity of producer gas in annular space is approximately 15 $cm \cdot s^{-1}$.

$$F_g / (\pi (d_c^2 - d_{rc}^2)/4) = 15 \ cm \cdot s^{-1} \qquad (3.8)$$

d_c = 21.8 cm (by solving equation 3.8)

Length of reactor, $l_{rc} = 0.75x\ F_m/(A_{rc}\ x\ BD_m)$ (3.9)

Length of reactor = 165 cm (solving 3.9)

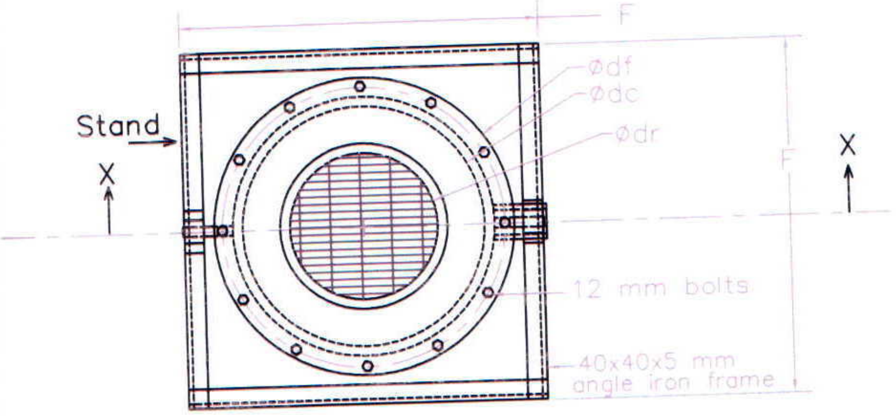
Length of containment tube = 180 cm.

Similarly, the size of gasifiers was calculated for higher capacity engine system in the range 5-25 hp. The capacity of gasifier, diameter and height of reactor and containment tube are given in Table 3.2.

Table 3.2 Capacity and corresponding sizes of gasifiers

Capacity of engine system, hp	Reactor diameter, cm	Containment tube diameter, cm	Reactor length, cm	Containment tube length, cm
5	15	21	165	180
10	22.5	31	165	180
18	30	40	165	180
25	36	50	165	180

The plan, elevation and side view of the throatless gasifier are shown in Fig. 3.3. A throatless gasifier of 30 cm reactor diameter tested for gasification of rice husk (Jain *et al* 2000) existed in Pathak energy laboratory. It was used for trials of gasification of maize cobs. The three other gasifiers of dimensions given in Table 3.2 were fabricated in the laboratory. The throatless gasifier consists of reactor and containment tube flanged at the top. The bottom of the containment tube was sealed with a flange. The reactor and containment tube (Fig. 3.4) were made from 3 mm thick mild steel sheet. The flanges were made of 6 mm thick mild steel sheet. The grate was positioned within the reactor at distance of 5 cm from the bottom of the reactor. The grate supports the fuel bed and allows the producer gas to flow through it. The grate was made from 15 ASTM stainless steel wire mesh fitted on a circular ring of 6 mm thick mild steel rod and was supported on three legs. It could be removed for cleaning purposes. The gasifier was mounted on hinges on an angle iron frame. The reactor could be tilted along the hinges for ash and char removal. The fabrications of three gasifiers of reactor diameters 15 cm, 22.5 cm and 36 cm were carried out in the Pathak Energy Laboratory, School of Energy Studies, PAU, Ludhiana.



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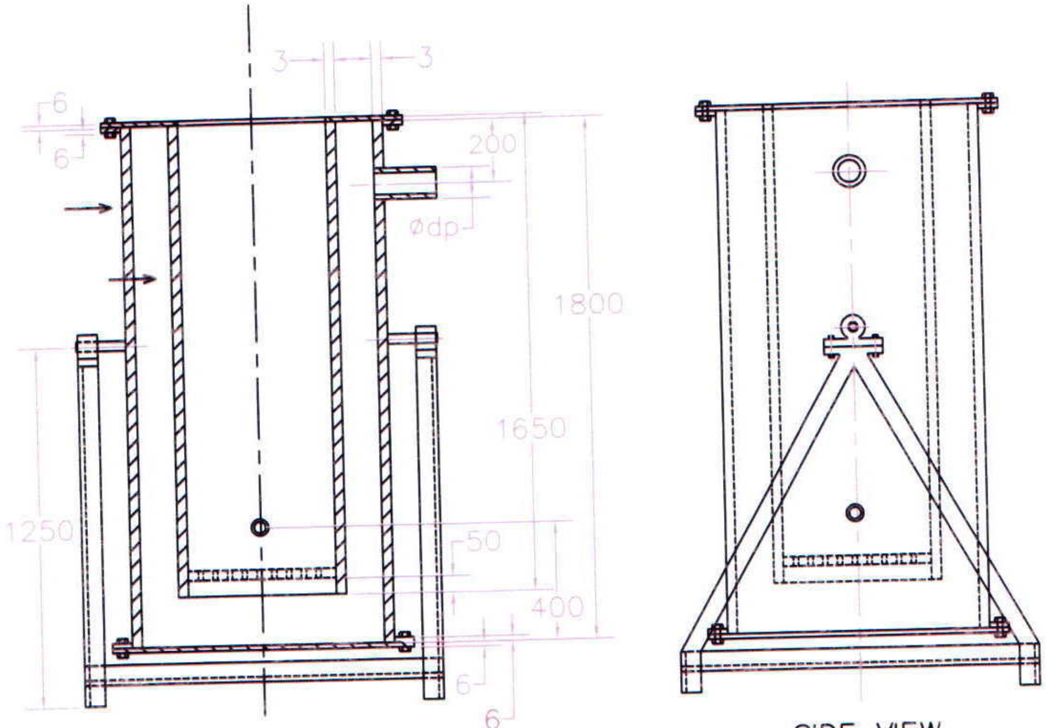


Section X X

SIDE VIEW

Fig. 3.3 Schematic drawing of throatless gasifier (all dimensions in mm)

Fig. 3.4 Reactor and containment tube of the gasifier

3.3 Experimental set-up of the gasifier system

The gasifier system used for the gasification of maize cobs consisted of a throatless gasifier, gas-cleaning system (consisting of a wet scrubber and dry filter), orifice meter, gas control valve and a suction blower connected in series. The schematic diagram and experimental set-up are shown in Figures 3.5 and 3.6. The gas control valve was used to control the gas flow rate, which was measured using the orifice meter. The temperature probes of chromel-alumel thermocouples (T1-T3) were connected at grate and exit of gasifier and wet scrubber to monitor the temperature of gas. The gas was driven through the whole system with a suction blower connected after the calibrated orifice meter. The gas from the suction blower was flared in the atmosphere using an electric burner. The cleaning system consisting of wet scrubber and dry filter (Fig. 3.7) reduced the particulate content of the gas. The gasifier was connected to the water scrubber and other components by 37 mm diameter plastic hose pipes. The wet scrubber had charcoal bed with a counter current contact of gas and water. Water was sprayed on top of the charcoal bed and the gas entered from the bottom and passed through the bed. The dry filter was packed with maize cob pieces, as these have high surface area, good physical strength and low commercial value. The gas entered from the top and exited from the bottom of the dry filter. The design details of the water scrubber and dry filter are reported in Jain *et al* (2000).

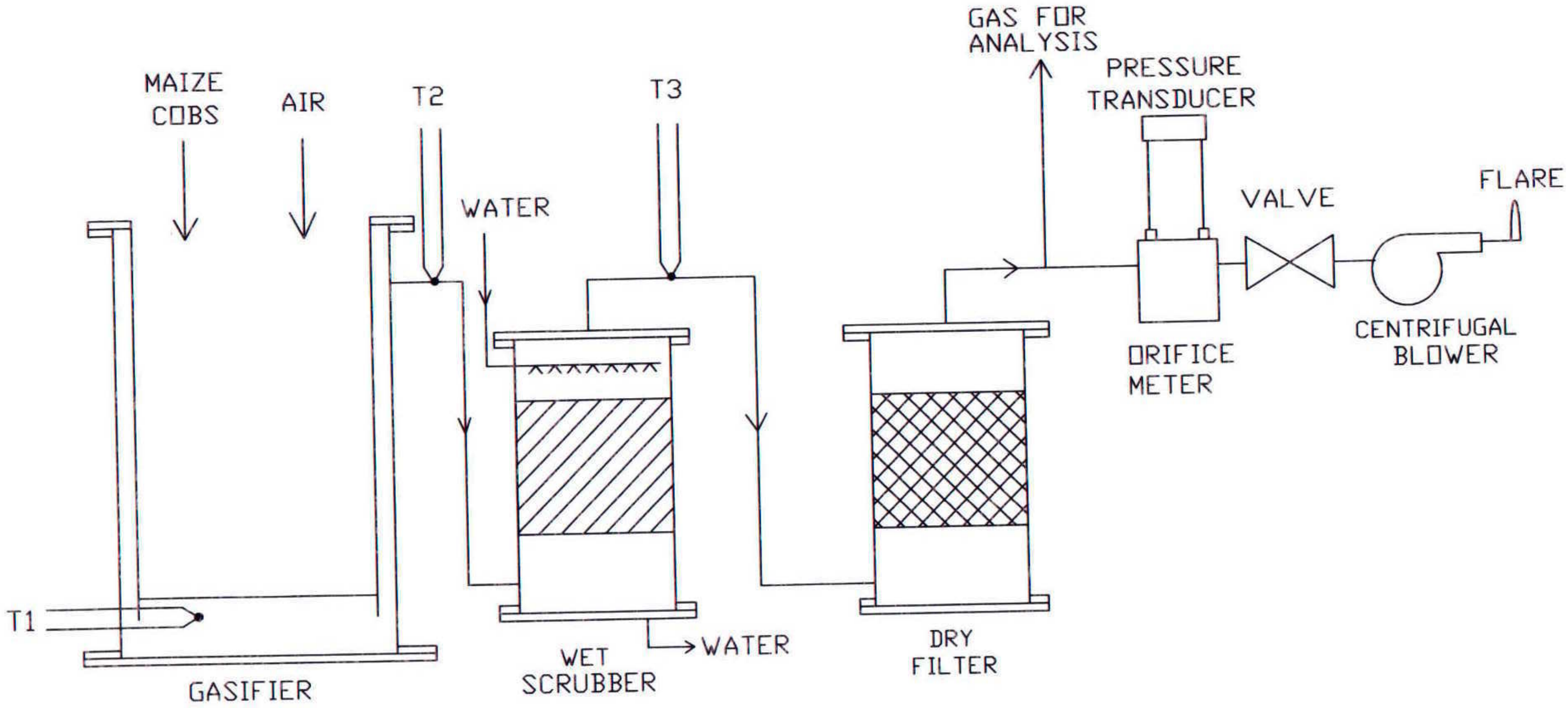


Fig. 3.5 Schematic diagram of the experimental set up for gasification of maize cobs

Fig. 3.6 Experimental set-up for gasification of maize cobs

Fig. 3.7 Gas cleaning system

3.4 Experimental procedure

Experimental trials were carried out for each reactor. Prior to each run of the gasifier, 0.5 kg char/ ash was fed into the reactor followed by 0.5 kg of maize cobs. The char was added to protect the grate from high temperature.

The maize cobs inside the reactor were ignited and suction blower was started. As the fire established, approximately one kg of maize cobs were added to the reactor. The gas flow was adjusted to preset / desired level using the gas control valve and other observations were started. When the fire reached the top layer of the maize cobs the gasifier was filled with measured quantity of maize cobs and the time was recorded as the time of start of run. As the level of the maize cobs descended in the gasifier during the run it was refilled with known weight of maize cobs to sustain the gasifier operation. When the fire reached the top layer of fuel inside the gasifier at the end of the operation, the time of completion of run was observed and the run was concluded. The gasifier was operated for duration of 60 to 110 minutes. Several runs at different gas flow rates were conducted for each gasifier. Nine to ten levels of gas flow rates were selected in such a way that a wide spectrum of SGR (120 to 300 $kg \cdot h^{-1} \cdot m^{-2}$) was covered. At each SGR runs in triplicate were conducted. The observations taken during each run were moisture content of maize cobs; amount of fuel consumed; operating time of run; thermocouple readings at grate, gasifier, water scrubber outlet and reading of pressure transducer. The gas samples were collected from the main gas line between orifice meter and dry filter every 10 to 15 minutes using 300 ml capacity airtight sampling bottles. The gas composition was analysed for CO, CO_2, H_2, O_2, N_2 and CH_4 content by gas chromatography. After the run was over the blower was turned off and the open top of the gasifier was closed properly to quench the combustion of un-burnt carbon in residual char. The weight of char residue obtained was measured after the gasifier cooled to room temperature. The calorific value of char residue (CV_r) was determined using adiabatic oxygen bomb calorimeter.

3.5 Evaluation of producer gas composition from gas chromatograph

The producer gas composition was determined by gas chromatography. The gas chromatograph (GC) (AIMIL-Nucon, series 5700) consisted of two columns Porapack Q, and molecular sieve 5-A, housed in a column oven, a top mounted injector, a thermal conductivity detector (TCD) and a temperature control module. The instrument is shown in Fig. 3.8. The columns are tubings packed with stationary phase. The TCD measures the difference in thermal conductivity between the carrier gas flowing through the reference cell and carrier gas/sample component mixture flowing through the measuring cell. The temperature control module consists of three independent heating systems for heating oven, injector and detector. The gas injection was done by a gas tight syringe. Argon was used as carrier gas. The GC was calibrated with standard samples.

Fig. 3.8 Gas chromatrograph

3.5.1 Calibration of gas chromatograph

The gas chromatograph was calibrated with standard samples and their mixtures. The standard samples of 30 % CO + 70 % N_2 and 1.8 % CH_4 + 98.2 % N_2 were used for calibration of GC for CO and CH_4, respectively. Standard sample of 20 % H_2+80 % N_2 was used for calibration for H_2 and N_2. Since the producer gas is typically a mixture of 40-50 % N_2, 15-20 % H_2, 10-15 % CO, 10-15 % CO_2, 3-5 % CH_4 (McKendry 2002c), the calibration of GC for CO_2 was done with a mixture of 1 part of 100% CO_2 and 9 parts of 30% CO.

Before operating the gas chromatograph the carrier gas was allowed to flow through the system for ten minutes and leakage of gas was tested by a soap solution. The flow of carrier gas was adjusted to 25 ml/min. After the carrier gas has flowed for at least ten minutes the GC was switched on and the temperatures of the column oven, injector, and detector were set to 50 °C each. The filament current was set to 100 mA. Initially 300 μl air samples were injected into the GC using airtight syringe and the chromatograms of air were observed. The areas of O_2 in the chromatograms were compared and the air was injected again till similar areas (within ± 10 %) were achieved. The base line was also checked to be straight. For calibration 300 μl of the standard gas or its mixture as stated above was taken in the syringe and injected in the GC. This was repeated until three similar areas (within ± 10 %) were achieved for each gas component, which was indicated by a peak. Typical calibration curves obtained for CO, CH_4 and CO_2 are given in Figures 3.9, 3.10 and 3.11 respectively. For H_2 and N_2 the typical calibration chromatogram is given in Fig. 3.12. The position of peak on the time scale indicated the time of retention and is characteristic of each particular gas component. The area under each peak indicated the volume of each gas present. The calibration of GC was done before the start of operation of each gasifier.

3.5.2 Calculation of producer gas composition from gas chromatograph

The calibration chromatograms of CO, H_2, N_2, CH_4 and CO_2 were taken as reference for measuring the per cent constituents of producer gas obtained during experimental runs. The chromatogram of the producer gas was obtained by injecting 300 μl of producer gas in the gas chromatograph. The O_2 found in the gas was attributed to air leak because the system was operated in suction mode. Whenever, O_2 was found in the gas chromatogram, the composition of gas was converted to air free basis by subtracting the O_2 and corresponding ratio of N_2 (the N_2/O_2 ratio in air is 79/21) (Reed and Das, 1988). The chromatogram of producer gas and calibration chromatogram were compared. The retention times of the peaks of gaseous components in the two chromatograms were matched and used to identify the gas components of producer gas. The area of the gas components in producer gas chromatogram was observed. The quantity of the gas components in producer gas was then calculated using the calibration chromatograms.

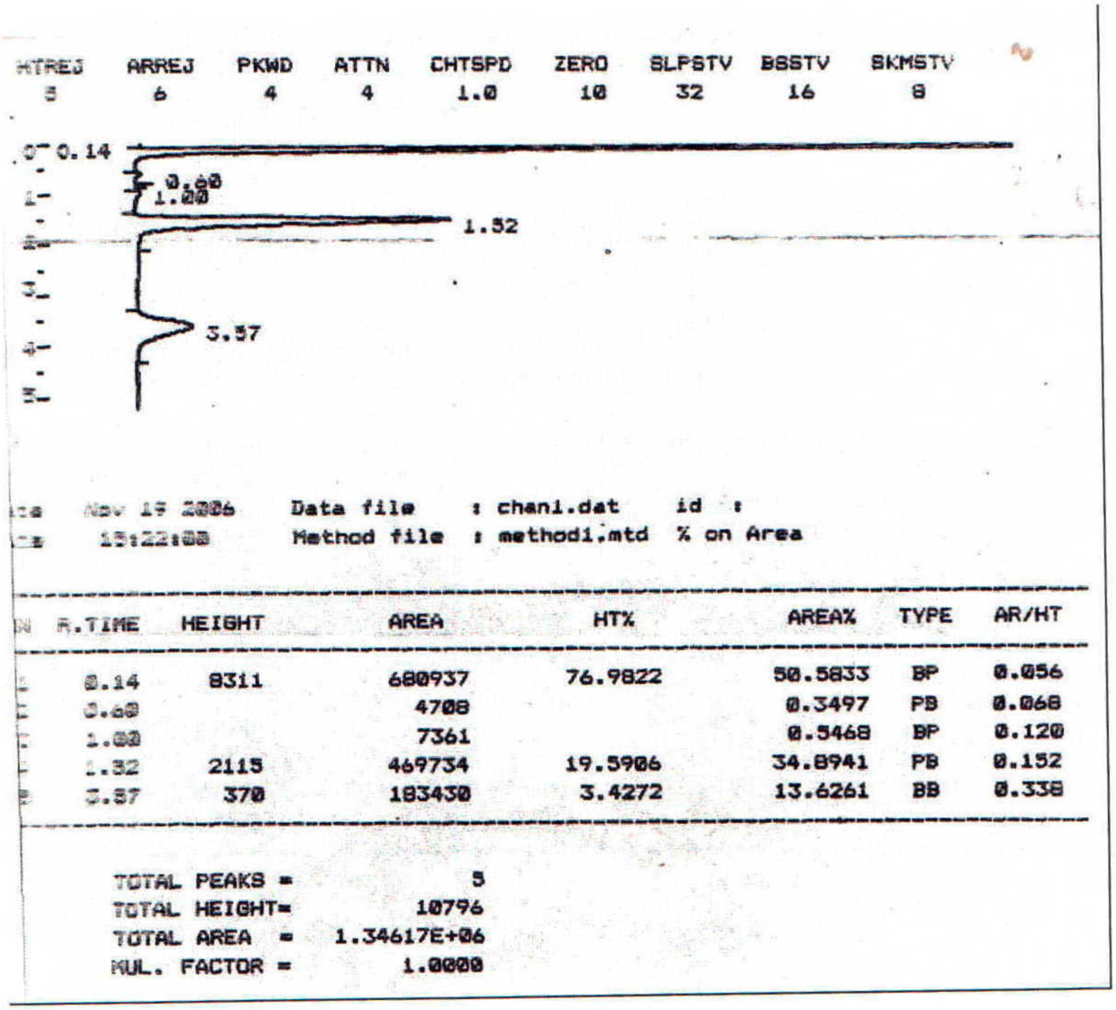
3.6 Operating parameters of the gasifier

The quantity of maize cobs used, operating time, gas flow rate, composition of producer gas, gas temperature at gasifier, wet scrubber outlet; pressure drop across the gasifier, wet scrubber and dry filter were measured during each trial run. Feed rate of maize cobs, lower heating value of producer gas, specific gasification rate and gasification efficiency were evaluated for each run as per the equations given below:

3.6.1 Feed rate of maize cobs

Feed rate of maize cobs (F_m) is the weight of dry maize cobs gasified per unit time. It was calculated according to equation (3.10).

$$F_m = \frac{\text{Weight of dry maize cobs used}}{\text{operating time of run}} \qquad (3.10)$$



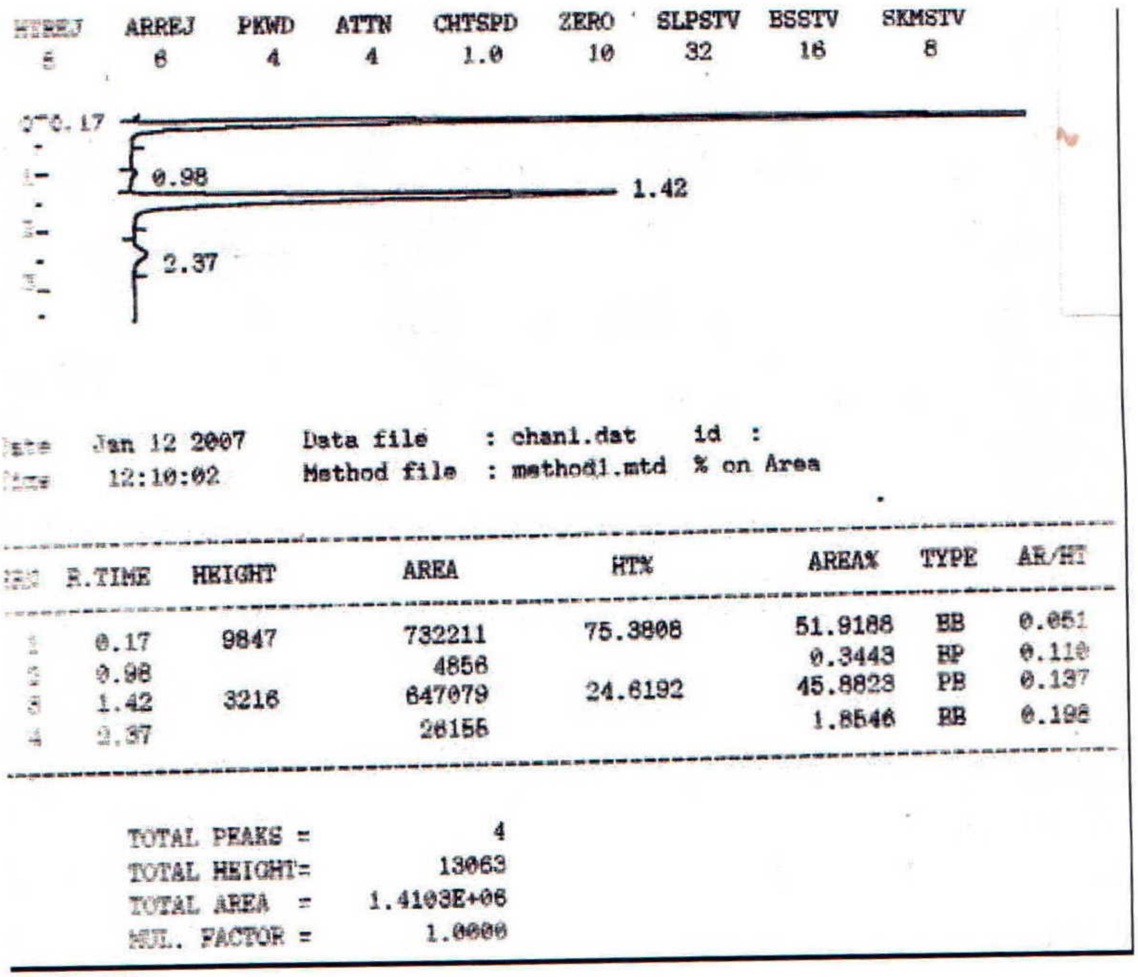
```
HTREJ   ARREJ   PKWD   ATTN   CHTSPD   ZERO   SLPSTV  BSSTV   SKMSTV
  5       6       4      4      1.0     10      32      16       8

      Nov 19 2006     Data file     : chani.dat    id  :
       15:22:08       Method file   : methodi.mtd  % on Area

-----------------------------------------------------------------------------
  R.TIME    HEIGHT          AREA            HT%           AREA%   TYPE   AR/HT
-----------------------------------------------------------------------------
   0.14      8311          680937         76.9822        50.5833   BP    0.056
   0.60                      4708                          0.3497   PB    0.068
   1.00                      7361                          0.5468   BP    0.120
   1.32      2115          469734         19.5906        34.8941   PB    0.152
   3.57       370          183430          3.4272        13.6261   BB    0.338
-----------------------------------------------------------------------------

        TOTAL PEAKS =               5
        TOTAL HEIGHT=           10796
        TOTAL AREA  =     1.34617E+06
        MUL. FACTOR =          1.0000
```

Fig. 3.9 Calibration chromatogram for carbon monoxide

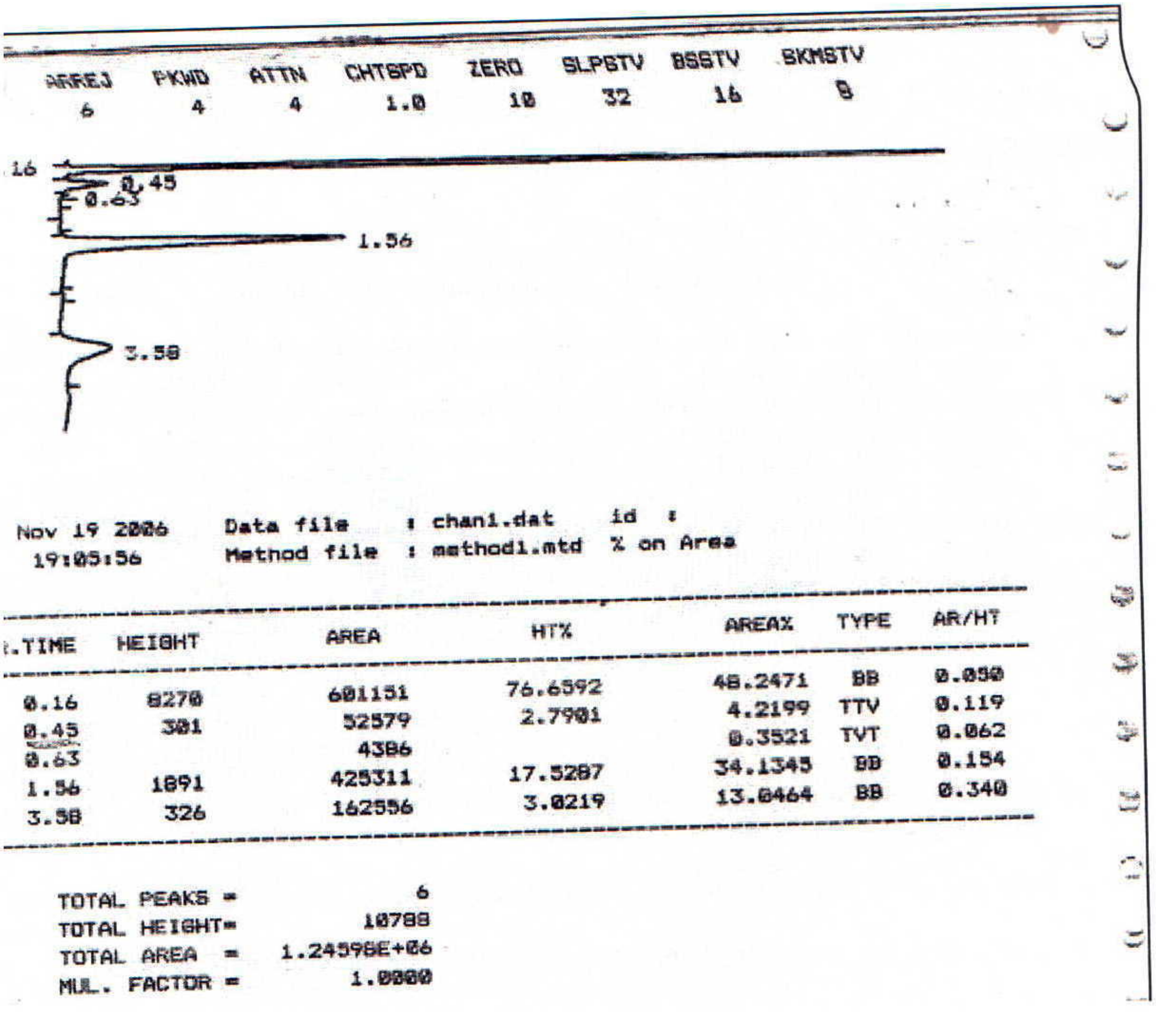


```
HTREJ   ARREJ   PKWD   ATTN   CHTSPD   ZERO   SLPSTV   BSSTV   SKMSTV
  5       6       4      4      1.0      10      32       16       8

ate    Jan 12 2007     Data file     : chani.dat      id  :
ime     12:10:02       Method file   : method1.mtd   % on Area
------------------------------------------------------------------------------
    R.TIME   HEIGHT          AREA            HT%           AREA%   TYPE   AR/HT
------------------------------------------------------------------------------
1    0.17     9847          732211         75.3808        51.9188   BB     0.051
2    0.98                     4856                          0.3443   BP     0.110
3    1.42     3216          647079         24.6192        45.8823   PB     0.137
4    2.37                    26155                          1.8546   BB     0.198
------------------------------------------------------------------------------

         TOTAL PEAKS =             4
         TOTAL HEIGHT=         13063
         TOTAL AREA  =    1.4103E+06
         MUL. FACTOR =        1.0000
```

Fig. 3.10 Calibration chromatogram for methane



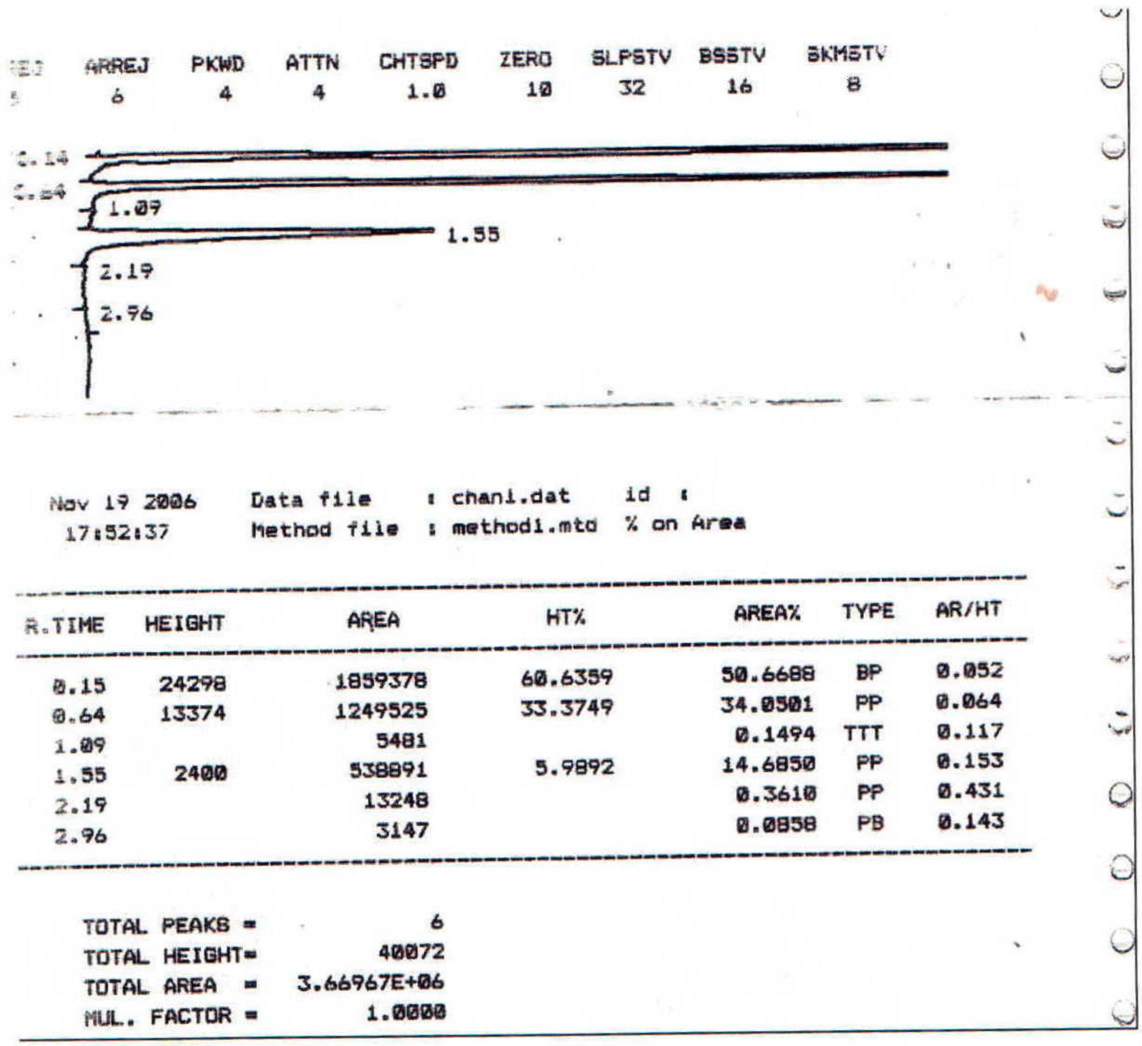
```
 ARREJ   PKWD   ATTN   CHTSPD   ZERO   SLPSTV   BSSTV   SKMSTV
   6       4      4      1.0     10      32       16       8

Nov 19 2006     Data file    : chani.dat     id  :
 19:05:56       Method file  : methodi.mtd   % on Area

------------------------------------------------------------------------------
.TIME    HEIGHT          AREA             HT%           AREA%   TYPE   AR/HT
------------------------------------------------------------------------------
                                                       48.2471   BB    0.050
 0.16     8270          601151          76.6592         4.2199   TTV   0.119
 0.45      301           52579           2.7901         0.3521   TVT   0.062
 0.63                     4386                         34.1345   BB    0.154
 1.56     1891          425311          17.5287        13.0464   BB    0.340
 3.58      326          162556           3.0219
------------------------------------------------------------------------------

   TOTAL PEAKS =             6
   TOTAL HEIGHT=         10788
   TOTAL AREA  =   1.24598E+06
   MUL. FACTOR =        1.0000
```

Fig. 3.11 Calibration chromatogram for carbon dioxide



```
ARREJ   PKWD   ATTN   CHTSPD   ZERO   SLPSTV  BSSTV   BKMSTV
  6       4      4      1.0     10      32      16       8

Nov 19 2006     Data file     : chani.dat     id  :
 17:52:37       Method file   : method1.mtd   % on Area

------------------------------------------------------------------------------
R.TIME   HEIGHT        AREA            HT%             AREA%   TYPE   AR/HT
------------------------------------------------------------------------------
 0.15    24298       1859378         60.6359          50.6688   BP    0.052
 0.64    13374       1249525         33.3749          34.0501   PP    0.064
 1.09                   5481                           0.1494   TTT   0.117
 1.55     2400        538891          5.9892          14.6850   PP    0.153
 2.19                  13248                           0.3610   PP    0.431
 2.96                   3147                           0.0858   PB    0.143
------------------------------------------------------------------------------

    TOTAL PEAKS =              6
    TOTAL HEIGHT=          40072
    TOTAL AREA  =    3.66967E+06
    MUL. FACTOR =         1.0000
```

Fig. 3.12 Calibration chromatogram for hydrogen and nitrogen

3.6.2 Specific gasification rate

Specific gasification rate (SGR) is defined as the rate of fuel gasified per unit area of the reactor. It was calculated according to equation (3.11) in which A_{rc} is cross sectional area of the reactor. The specific gasification rate (SGR) is an indicator of the size of the gasifier for a given throughput and depends on the type of the gasifier and the fuel

$$SGR = F_m / A_{rc} \tag{3.11}$$

Tiangco *et al* (1996) concluded that SGR is an important parameter for designing gasifier reactors as the gasification efficiency (η_g) varies as a general function of SGR according to equation (3.12).

$$\eta_g = f\,((SGR)/(A_{rc}{*}LHV)) \tag{3.12}$$

3.6.3 Chemical energy of maize cobs

The chemical energy of maize cobs (CE_m) was computed from the lower calorific value of maize cobs and feed rate of the maize cobs (equation 3.13).

$$CE_m = F_m \times LHV_m \tag{3.13}$$

3.6.4 Temperature of producer gas

Chromel–alumel thermocouples were used for measuring the temperature of producer gas, below the reactor grate (thermocouple T1), gasifier outlet (thermocouple T2) and outlet of water scrubber (thermocouple T3). The e.m.f across the thermocouples was measured using a precision digital voltmeter. The e.m.f was converted into temperature using the standard calibration table for determining the temperature of producer gas (Table 3.3). The data on ambient temperature was taken from Department of Agronomy, Agro meteorology and Forestry, PAU.

Table 3.3 Standard calibration table for chromel-alumel thermocouple (°C)

°C	0	10	20	30	40	50	60	70	80	90
-190	-5.60	-5.43	-5.24	-5.03	-4.81	-4.58	-4.32	-4.06	-3.78	-3.49
-90	-3.19	-2.87	-2.54	-2.20	-1.86	-1.50	-1.14	-0.77	-0.39	0.00
0	0.00	0.40	0.80	1.20	.1.61	2.02	2:43	2.85	3.26	3.68
100	4.10	4.51	4.92	5.33	5.73	6.13	6.53	6.93	7.33	7.73
200	8.13	8.54	8.94	9.34	9.75	10.16	10.57	10.98	11.39	11.80
300	12.21	12.63	13.04	13.46	13.88	14.29	14.71	15.13	15.55	15.98
400	16.40	16.82	17.24	17.67	18.09	18.51	18.94	19.36	19.79	20.22
500	20.65	21.07	21.50	21.92	22.35	22.78	23.20	23.63	24.06	24.49
600	24.91	25.34	25.76	26.19	26.61	27.03	27.45	27.87	28.29	28.72
700	29.14	29.56	29.97	30.39	30.81	31.23	31.65	32.06	32:48	32.89
800	33.30	33.71	34.12	34.53	34.93	35.34	35.75	36.15	36.55	36.96
900	37.36	37.76	38.16	38.56	38.95	39.35	39.75	40.14	40.53	40.92
1000	41.31	41.70	42.09	42.48	42.87	43.25	43.63	14.02	44.40	44.78
1100	45.16	45.54	45.92	46.29	46.67	47.04	47.41	47.78	48.15	48.52
1200	48.89	49.25	49.62	49.98	50.34	50.69	51.05	51.1	51.76	52.11
1300	52.46	52.81	53.16	53.51	53.85	54.20	54.54	54.88	.....	.....

3.6.5 Gas flow rate

The calibrated orifice meter was used to measure gas flow rate (F_g). The diameters of the pipe (d_p) and orifice (d_o) were 35 and 21 mm respectively. The pressure drop across the orifice was measured using a pressure transducer (Setra Systems Inc., Model 239, 0-30 inch WC). The gas flow rate at NTP was computed from the observation of pressure transducer (Δh_w) in inch water column (WC) using equations (3.14) and (3.15).

$$F_g = C_d \times \sqrt{(2 \times g \times \Delta h_g)} \times A_p \times A_o/(A_p^2 - A_o^2) \quad (3.14)$$

$$\rho_g \times g \times \Delta h_g = \rho_w \times g \times \Delta h_w \quad (3.15)$$

where F_g = Flow of the gas through the pipe at NTP

C_d (coefficient of discharge) = 0.6

A_p = cross sectional area of pipe

A_o = cross sectional area of orifice

g (acceleration due to gravity) = 9.81 $m^2 \cdot s^{-1}$

$\rho_g = \sum X_i \times \rho_i$, density of producer gas

ρ_i = density of i^{th} component of producer gas

X_i = mole fraction of i^{th} component of producer gas

ρ_w(density of water at NTP) = 999.839 $kg \cdot m^{-3}$

Δh_w = Pressure drop across orifice in inch water column

Δh_g = Equivalent pressure drop of gas in inch water column

3.6.6 Lower heating value of producer gas

The lower heating value of producer gas (LHV_g) was determined using its composition and standard lower heating value of combustible constituents of gas (equation 3.16). The lower heating values of H_2, CO and CH_4 at NTP are 10.789 $MJ \cdot Nm^{-3}$, 12.626 $MJ \cdot Nm^{-3}$ and 35.795 $MJ \cdot Nm^{-3}$, respectively (Perry 1984).

$$LHV_g = \sum X_i \times LHV_i \quad (3.16)$$

where X = mole fraction

i = i^{th} component of producer gas

3.6.7 Airflow rate

Airflow rate (F_a) was computed by conducting nitrogen balance over the gasifier process using the expression 3.17.

$$F_a \times N_a + \frac{F_m \times N_m \times V_o}{M_n} = F_g \times N_g \qquad (3.17)$$

where N_m = Nitrogen content *of* maize cobs (%)

N_g = Nitrogen content *of* producer gas (%)

N_a = Nitrogen content of air (%)

V_o = Volume of 1 kgmol of gas at NTP (22.414 Nm^3)

M_n = Molecular weight of nitrogen

6.8 Air fuel ratio

Air fuel ratio (AF) is the ratio of airflow rate to the fuel feed rate d was calculated using expression, AF = F_a/F_m.

6.9 Equivalence ratio

Equivalence ratio (ER) is the ratio of air fuel ratio to the toichiometric air fuel ratio, and is calculated using equation (3.18).

$$ER = \frac{AF}{\text{Stochiometric air fuel ratio}} \qquad (3.18)$$

3.6.10 Char residue rate

Char residue rate (F_r) is the weight of char residue obtained per unit operating time of run (3.19). Char production rate was char residue rate per unit feed rate of maize cobs and was expressed in per cent.

$$F_r = \frac{\text{Weight of char residue obtained}}{\text{Operating time}} \qquad (3.19)$$

3.6.11 Chemical energy of producer gas

Chemical energy of producer gas (CE_g) was computed from the gas flow rate and lower heating value of the gas by using equation (3.20)

$$CE_g = F_g \times LHV_g \qquad (3.20)$$

3.6.12 Gasification efficiency

Gasification efficiency (η_g) is a measure of per cent chemical energy of maize cobs, which is converted to chemical energy of producer gas. It depends on cold gas energy and chemical energy of dry fuel and was calculated by equation (3.21).

$$\text{Gasification efficiency} = \frac{CE_g}{CE_m} \tag{3.21}$$

3.6.13 Energy of char residue

The chemical energy (CE_r) and sensible energy (SE_r) of char residue were computed using equations (3.22) and (3.23). The calorific value of char (CV_r) was observed by burning char in adiabatic constant volume bomb calorimeter. The specific heat of char was taken from the specific heat of charcoal assuming that char contains 70 % charcoal. The temperature of producer gas at the exit of gasifier was considered as temperature of char residue.

$$CE_r = F_r \times CV_r \tag{3.22}$$

$$SE_r = F_r \times S_r \times (T_g - T_a) \tag{3.23}$$

3.6.14 Sensible energy of producer gas

The sensible energy of producer gas (SE_g) was computed from equation (3.24). The heat capacities of the different constituents of producer gas (Cp_i) reported by Smith *et al*, 1996 (Table 3.3) were taken for the calculation of SE_g.

$$SE_g = F_g \int_{273.15}^{T_g} \sum X_i \times Cp_i \, dT \tag{3.24}$$

where, X = mole fraction

$i = i^{th}$ component of producer gas

T_g = temperature of gas and Cp = heat capacities of gases

3.6.15 Sensible energy of air

Sensible energy of air (SE_a) was computed from the airflow rate and the heat capacities of N_2 and O_2 (Table 3.4) from the equation (3.25)

$$SE_a = F_a \int_{273.15}^{T_g} \sum X_i \times Cp_i \, dt \qquad (3.25)$$

where X = mole fraction, $i = i^{th}$ component of air, and T_a = temperature of air

Table 3.4 Heat capacities of gases in ideal gas state

Constituent of producer gas	Cp / R
H_2	$3.249 + 0.422 \times 10^{-3} \times T$
CO	$3.376 + 0.557 \times 10^{-3} \times T$
CH_4	$1.702 + 9.081 \times 10^{-3} \times T$
CO_2	$5.457 + 1.045 \times 10^{-3} \times T$
N_2	$3.280 + 0.593 \times 10^{-3} \times T$
O_2	$3.639 + 0.506 \times 10^{-3} \times T$

Source: Smith *et al*, 1996

3.7 Energy balance over the gasification process

Using the basic data energy balance calculations were carried out over the gasification process to estimate how the input energy to the gasifier was distributed in its products during gasification process. The chemical energy of fuel (CE_m) and sensible energy of air (SE_a) were considered as the input energy to the gasifier (equation 3.26). Since maize cobs fed to the gasifier were at ambient temperature, its sensible energy was low compared to its chemical energy and was thus neglected. The sensible and chemical energy of producer gas (CE_g and SE_g) and that of char residue (CE_r and SE_r) were considered as output energy, equation

3.27. The difference between the input and output energy was considered as loss, equation 3.28 (Jain *et al* 2002).

$$\text{Input Energy} = CE_m + SE_a \tag{3.26}$$

$$\text{Output Energy} = CE_g + SE_g + CE_r + SE_r \tag{3.27}$$

$$\text{Loss} = \text{Input Energy} - \text{Output Energy} \tag{3.28}$$

CHAPTER 4

RESULTS AND DISCUSSION

The results obtained from experiments regarding fuel related properties of shelled maize cobs and performance of the throatless gasifiers for maize cobs are presented and analysed in this chapter.

4.1 Fuel related properties of maize cobs

The fuel related properties of shelled maize cobs such as size, bulk density, true density, moisture content, angle of repose, elemental and proximate composition, stoichiometric air fuel ratio, higher and lower heating value are given in Table 4.1.

4.1.1 Physical characteristics

The average length and diameter of size-reduced maize cobs used in the investigation were observed to be 5.85 and 1.92 cm respectively. The average moisture content of maize cobs was observed to be in the range of 6.07-8.05 % wet basis. The angle of repose and bulk density of maize cobs were observed to be 29.2^0 and 160 $kg \cdot m^{-3}$ at 6 % moisture content (w.b.) respectively. The low angle of repose and medium bulk density of maize cobs indicate its free flow properties. The moisture content of maize cobs was within the reported range for downdraft gasifier application so there was no need to dry the maize cobs.

4.1.2 Elemental composition

The elemental composition of maize cobs was observed to be C (46.18 %), H (4.93 %), O (46.43 %), N (0.6 %) and S (0.03 %) on dry basis. The concentration of nitrogen and sulphur was observed to be low in maize cobs.

Table 4.1 Fuel related properties of maize cobs used for gasification

Characteristic		Value
Physical characteristics	Length (cm)	5.85 (±1.38)
	Diameter (cm)	1.92 (±0.9)
	Shape (description)	Cylindrical
	Angle of repose (^{0})	29.2 (±0.5)
	Bulk density ($kg \cdot m^{-3}$)	160 (±3.18)
	True density ($kg \cdot m^{-3}$)	300 (±2.5)
	Moisture content (%, w.b.)	6.07-8.05
Ultimate analysis	C (%)	46.18
	H (%)	4.93
	O (%)	46.43
	N (%)	0.60
	S (%)	0.03
Proximate analysis	Volatile matter (%, d.b)	83.01
	Fixed carbon (%, d.b)	15.16
	Ash (%, d.b)	1.83
Energy content	Higher heating value ($MJ \cdot kg^{-1}$, d.b.)	18.2
	Lower heating value ($MJ \cdot kg^{-1}$, d.b.)	17.09

4.1.3 Stoichiometric formula of maize cobs and stoichiometric air fuel ratio

The molar ratio of hydrogen to carbon (H/C) and oxygen to carbon (O/C) of maize cobs was calculated from the elemental analysis as 1.27 and 0.77 respectively. Thus the stoichiometric formula of maize cobs is $CH_{1.27}O_{0.77}$. The stoichiometric air fuel ratio of maize cobs was 3.844 $Nm^3 \cdot kg^{-1}$. On ash free basis it was 3.91 $Nm^3 \cdot kg^{-1}$.

4.1.4 Proximate analysis

The volatile matter, fixed carbon and ash content of maize cobs was observed to be 83.01, 15.16 and 1.83 % on dry basis respectively. Low ash content of maize cobs facilitated the operation of the gasifier, as there was no slagging and clinker formation.

4.1.5 Higher and lower heating value

The higher heating value (HHV_m) of maize cobs was experimentally determined. It was observed to be 18.2 $MJ \cdot kg^{-1}$ on dry basis. HHV_m was also calculated theoretically from proximate analysis of maize cobs and was found to be 18.28 .$MJ \cdot kg^{-1}$ (Parikh *et al* 2005). However, the experimental value was used in all the calculations. The lower heating value (LHV_m) of maize cobs was observed to be 17.09 $MJ \cdot kg^{-1}$ on dry basis.

The low ash content, high energy content, cylindrical shape, low angle of repose, ultimate and proximate analysis of maize cobs indicated that it can be used as a fuel for gasification in a throatless gasifier. The properties of maize cobs agree well with the data reported by Jain (1997) and Ebeling and Jenkins (1985).

4.2 Performance evaluation of gasifiers for gasification of maize cobs

Four throatless gasifiers with reactors having diameters 15, 22.5, 30 and 36 cm were evaluated for gasification of maize cobs and 8-10 experimental runs were carried out with each reactor. All the four gasifiers operated quite well during the trials. The producer gas yielded a bright flame in almost all the runs. However the flame was better visible after sunshine hours (Fig.4.1). Maize cobs could be gasified in bigger sized gasifiers without any problem of fuel restriction. However in the smallest reactor (15 cm), the problem of bridging of fuel was observed during the gasifier operation, which was removed by tapping the sides of the reactor.

The weight and moisture content of fuel, reading of pressure transducer (Δh_w), e.m.f across thermocouples, weight and calorific value of char residue are reported for each run in Tables 4.2, 4.5, 4.8 and 4.11 for the 15, 22.5, 30 and 36 cm diameter reactors respectively. The run time varied from 60 to 110 minutes. During each run, the gas composition was evaluated every 10-15 minutes. The average composition of the producer gas obtained during the experimental runs on 15, 22.5, 30 and 36 cm diameter reactors are presented in Tables 4.3, 4.6, 4.9 and 4.12 respectively.

The gasification parameters such as dry fuel feed rate (F_m), specific gasification rate (SGR), gas flow rate (F_g), lower heating value of producer gas (LHV_g), air fuel ratio (A/F), equivalence ratio (ER), superficial velocity of gas (V_g), temperature of gas at grate (T_g), char residue rate (F_r), per cent combustible gases, char production rate and gasification efficiency (η_g) were calculated and are presented in Tables 4.4, 4.7, 4.10 and 4.13.

The effect of specific gasification rate (SGR) was seen on the per cent combustible gases and lower heating value of producer gas (LHV_g), air fuel ratio, char production rate, superficial velocity and gasification efficiency (η_g). The optimum operational point for each gasifier was determined on the basis of quality of producer gas and gasification efficiency.

Fig. 4.1 Throatless gasifier in operation

Table 4.2 Operating data recorded for experiments on 15 cm diameter reactor

Run no	wet wt. of fuel (kg)	m.c. (%w.b.)	dry wt.of fuel (kg)	Δhw (inch WC)	Char residue (kg)	CV_r ($MJ \cdot kg^{-1}$)	T_a (°C)	e.m.f T_1 (mV)
1	4.2	7.32	3.9	0.10	0.93	21.14	16.4	8.54
2	4.5	7.24	4.1	0.14	0.97	21.07	14.4	8.74
3	4.7	7.46	4.4	0.18	0.96	20.90	16.3	8.94
4	4.9	7.32	4.5	0.24	0.91	20.63	12.8	9.14
5	4.9	7.54	4.5	0.27	0.86	20.46	15.1	9.55
6	5.0	7.65	4.7	0.31	0.87	20.35	13.8	9.96
7	5.3	7.81	4.9	0.37	0.89	20.26	17.1	10.32
8	5.4	7.23	5.0	0.42	0.90	20.23	13.7	10.65
9	5.6	7.83	5.1	0.52	0.88	20.07	16.2	11.19

Table 4.3 Composition of producer gas from maize cobs for 15 cm diameter reactor

Run no	Producer gas composition (%)					
	CO_2	H_2	O_2	N_2	CH_4	CO
1	9.00	13.81	0.42	62.02	1.96	12.79
2	7.91	14.59	0.46	61.36	1.27	14.41
3	8.58	14.82	0.30	59.48	1.07	15.75
4	7.86	13.66	0.42	59.11	1.81	17.15
5	8.01	14.36	0.47	59.83	1.71	15.62
6	8.31	15.45	0.60	60.39	1.15	14.10
7	8.16	14.08	0.57	62.49	1.40	13.30
8	8.13	14.26	0.54	62.34	1.04	13.69
9	9.41	14.07	0.50	61.97	1.24	12.82

Table 4.4 Gasification parameters for 15 cm diameter reactor

Run No.	F_m ($kg \cdot h^{-1}$)	SGR ($kg \cdot h^{-1} \cdot m^{-2}$)	F_g ($Nm^3 \cdot h^{-1}$)	LHV_g ($MJ \cdot Nm^{-3}$)	Fa ($Nm^3 \cdot h^{-1}$)	A/F	ER	V_g ($m \cdot s^{-1}$)	T_g (^oC)	Fr ($kg \cdot h^{-1}$)	Combustible gases (%)	Char production rate (wt. % of fuel)	Gasification Efficiency (%)
1	2.34	132.4	5.30	3.808	4.14	1.77	0.461	0.08	210	0.374	28.6	16.0	50.45
2	2.56	144.9	6.32	3.847	4.89	1.91	0.497	0.10	215	0.399	30.3	15.6	55.58
3	2.78	157.3	7.19	3.971	5.39	1.94	0.505	0.11	220	0.409	31.6	14.7	60.10
4	3.00	169.9	8.25	4.286	6.15	2.05	0.533	0.13	225	0.405	32.6	13.5	68.96
5	3.21	181.6	8.71	4.134	6.58	2.05	0.533	0.14	235	0.411	31.7	12.8	65.68
6	3.45	195.2	9.34	3.858	7.12	2.06	0.537	0.15	245	0.428	30.7	12.4	61.16
7	3.85	217.9	10.22	3.700	8.06	2.09	0.545	0.16	254	0.466	28.8	12.1	57.49
8	4.22	238.8	10.92	3.638	8.59	2.04	0.530	0.17	262	0.506	29.0	12.0	55.11
9	4.80	271.6	12.11	3.580	9.47	1.97	0.513	0.19	275	0.552	28.1	11.5	52.88

Table 4.5 Operating data recorded for experiments on 22.5 cm diameter reactor

Run no	Wet wt. (kg)	m.c. (% w.b.)	Dry weight (kg)	Δh_w (inch WC)	T_a (°C)	Emf T_1 (mV)	Char residue (kg)	CV_r $MJ \cdot kg^{-1}$
1	10.6	7.10	9.8	0.58	13.9	9.10	1.53	21.06
2	10.6	7.13	9.8	0.63	12.4	9.34	1.45	20.91
3	11.0	6.97	10.2	0.87	12.2	9.42	1.42	20.71
4	11.1	7.24	10.3	0.97	15.4	9.55	1.41	20.68
5	11.3	7.25	10.5	1.00	18.7	9.96	1.39	20.57
6	11.4	7.15	10.6	1.04	15.0	10.32	1.37	20.50
7	11.6	7.43	10.7	1.29	15.5	10.57	1.33	20.34
8	11.7	6.89	10.9	1.43	16.6	11.31	1.31	20.23
9	11.9	7.65	11.0	1.93	18.8	11.96	1.27	20.08
10	11.8	7.24	11.0	2.21	18.0	12.21	1.21	19.90

Table 4.6 Composition of producer gas from maize cobs for 22.5 cm diameter reactor

Run no	Producer gas composition (%)					
	CO_2	H_2	O_2	N_2	CH_4	CO
1	8.38	12.02	0.86	63.79	2.79	12.16
2	6.29	12.46	0.58	63.66	2.33	14.68
3	7.76	14.97	0.55	60.02	1.31	15.39
4	8.80	14.50	0.46	59.02	1.85	15.37
5	9.60	14.55	0.59	57.93	2.80	14.53
6	10.06	10.67	0.53	58.13	3.55	17.06
7	8.78	12.65	0.54	61.88	2.83	13.33
8	10.09	12.77	0.51	60.68	1.96	14.00
9	7.01	11.42	0.56	66.67	1.54	12.80
10	8.62	11.49	0.57	66.18	1.89	11.26

Table 4.7 Gasification parameters for 22.5 cm diameter reactor

Run No.	F_m ($kg \cdot h^{-1}$)	SGR ($kg \cdot h^{-1} \cdot m^{-2}$)	F_g ($Nm^3 \cdot h^{-1}$)	LHV_g ($MJ \cdot Nm^{-3}$)	Fa ($Nm^3 \cdot h^{-1}$)	A/F	ER	V_g ($m \cdot s^{-1}$)	T_g (^oC)	Fr ($kg \cdot h^{-1}$)	Combustible gases (%)	Char production rate (wt. % of fuel)	Gasification Efficiency (%)
1	5.36	134.8	12.68	3.83	10.21	1.90	0.495	0.09	224	0.83	26.97	15.54	53.05
2	5.67	142.5	13.22	4.03	10.62	1.87	0.488	0.09	230	0.84	29.47	14.74	55.09
3	6.08	152.9	15.53	4.03	11.76	1.93	0.503	0.11	232	0.84	31.68	13.83	60.23
4	6.25	157.1	16.40	4.17	12.21	1.96	0.509	0.11	235	0.86	31.69	13.70	64.03
5	6.50	163.5	16.65	4.41	12.17	1.87	0.487	0.12	245	0.86	31.88	13.23	66.08
6	6.67	167.7	16.98	4.58	12.45	1.87	0.486	0.12	254	0.86	31.28	12.95	68.21
7	7.01	176.3	18.91	4.06	14.77	2.11	0.548	0.13	260	0.87	28.81	12.38	64.14
8	7.33	184.4	19.91	3.85	15.25	2.08	0.541	0.14	278	0.88	28.72	12.00	61.12
9	7.76	195.2	23.13	3.40	19.47	2.51	0.653	0.16	294	0.90	25.76	11.53	59.31
10	8.33	209.6	24.75	3.34	20.68	2.48	0.646	0.17	300	0.92	24.64	11.00	58.03

Table 4.8 Operating data recorded for experiments on 30 cm diameter reactor

Run no	wet wt. (kg)	m.c. (% w.b.)	dry wt. (kg)	Δhw (inch WC)	Char residue (kg)	CVr (MJ·kg^{-1})	T_a (°C)	e.m.f at T_1 (mV)
1	19.1	6.06	17.9	1.82	2.88	21.15	23.3	9.34
2	19.8	6.56	18.5	2.17	2.92	21.10	22.8	9.79
3	20.7	6.23	19.4	2.73	2.88	20.92	21.7	10.41
4	21.4	6.42	20.0	3.32	2.89	20.84	19.6	10.61
5	22.1	6.67	20.6	3.65	2.87	20.73	19.8	11.31
6	22.8	6.58	21.3	4.75	2.80	20.55	18.8	11.51
7	23.4	6.02	22.0	5.82	2.62	20.20	14.9	11.96
8	26.3	6.78	24.5	6.37	2.66	19.84	12.5	12.79
9	26.9	6.24	25.2	6.85	2.73	19.82	19.3	13.25

Table 4.9 Composition of producer gas from maize cobs for 30 cm diameter reactor

Run no	Producer gas composition (%)					
	CO_2	H_2	O_2	N_2	CH_4	CO
1	14.15	10.69	0.62	56.00	1.70	16.84
2	16.35	8.87	0.71	53.72	2.12	18.23
3	15.96	10.17	0.69	53.78	2.07	17.33
4	15.23	10.89	0.54	53.12	2.05	18.17
5	16.30	8.52	0.66	52.74	2.24	19.54
6	17.11	7.48	0.60	55.02	2.20	17.60
7	17.25	6.73	0.65	57.48	2.12	15.78
8	15.99	6.81	0.63	59.45	2.00	15.10
9	13.23	7.21	1.01	63.41	2.00	13.13

Table 4.10 Gasification parameters for 30 cm diameter reactor

Run No.	F_m (kg·h^{-1})	SGR (kg·h^{-1}·m^{-2})	F_g (Nm^3·h^{-1})	LHV_g (MJ·Nm^{-3})	Fa (Nm^3·h^{-1})	A/F	ER	V_g (m·s^{-1})	T_g (^{o}C)	Fr (kg·h^{-1})	Combustible gases (%)	Char production rate (wt. % of fuel)	Gasification Efficiency (%)
1	9.34	132.1	23.30	3.888	16.46	1.76	0.46	0.09	230	1.50	29.23	16.06	56.8
2	10.08	142.6	25.43	4.018	17.23	1.71	0.44	0.10	241	1.59	29.22	15.77	59.3
3	10.80	152.8	28.53	4.027	19.36	1.79	0.47	0.11	256	1.60	29.57	14.81	62.3
4	11.43	161.7	31.51	4.204	21.11	1.85	0.48	0.12	261	1.65	31.11	14.44	67.8
5	12.01	170.0	33.03	4.188	21.98	1.83	0.48	0.13	278	1.67	30.30	13.90	67.4
6	12.75	180.4	37.66	3.817	26.15	2.05	0.53	0.15	283	1.68	27.28	13.17	66.0
7	14.21	201.0	41.69	3.475	30.25	2.13	0.55	0.16	294	1.69	24.62	11.90	59.7
8	16.33	231.1	43.62	3.360	32.73	2.00	0.52	0.17	314	1.77	23.92	10.84	52.5
9	17.41	246.3	45.23	3.153	36.20	2.08	0.54	0.18	325	1.88	22.34	10.80	47.9

Table 4.11 Operating data recorded for experiments on 36 cm diameter reactor

Run no	wet wt. (kg)	m.c. (w.b.)	dry wt. (kg)	Δhw (inch WC)	Char residue (kg)	CV_r ($MJ \cdot kg^{-1}$)	T_a (°C)	e.m.f at T_1 (mV)
1	24.5	7.56	22.7	2.33	3.40	20.96	27.0	9.83
2	25.5	7.89	23.5	2.72	3.42	20.87	29.5	10.37
3	27.1	8.02	24.9	3.50	3.42	20.69	30.2	10.69
4	27.9	7.69	25.8	4.11	3.38	20.54	30.8	11.35
5	29.7	7.54	27.4	4.70	3.47	20.41	33.3	11.39
6	30.0	7.65	27.7	5.66	3.46	20.37	29.2	11.60
7	31.8	7.81	29.3	6.51	3.48	20.20	30.8	12.13
8	34.3	8.05	31.6	8.89	3.54	19.97	30.3	13.04
9	36.2	7.83	33.4	9.84	3.75	19.99	28.5	13.38

Table 4.12 Composition of producer gas from maize cobs for 36 cm diameter reactor

Run no	Producer gas composition (%)					
	CO_2	H_2	O_2	N_2	CH_4	CO
1	9.11	11.37	0.66	62.76	2.27	13.84
2	10.78	11.46	0.53	58.72	2.97	15.55
3	9.84	10.50	0.51	58.44	3.19	17.53
4	11.15	12.02	0.50	56.34	3.76	16.23
5	8.57	17.29	0.38	53.20	3.26	17.30
6	9.47	12.94	0.51	56.56	3.65	16.87
7	10.12	13.79	0.43	57.15	3.18	15.33
8	9.30	11.39	0.51	61.78	2.68	14.34
9	10.55	10.80	0.68	60.92	2.62	14.42

Table 4.13 Gasification parameters for 36 cm gasifier reactor

Run No.	F_m (kg·h^{-1})	SGR (kg·h^{-1}·m^{-2})	F_g (Nm^3·h^{-1})	LHV$_g$ (MJ·Nm^{-3})	Fa (Nm^3·h^{-1})	A/F	ER	V_g (m·s^{-1})	T_g (^{o}C)	Fr (kg·h^{-1})	Combustible gases (%)	Char production rate (wt. % of fuel)	Gasification Efficiency (%)
1	12.37	121.5	25.36	3.785	20.07	1.62	0.422	0.07	242	1.86	27.47	15.00	45.4
2	13.15	129.2	27.41	4.264	20.29	1.54	0.401	0.07	255	1.92	29.98	14.58	52.0
3	14.23	139.8	31.05	4.489	22.88	1.61	0.418	0.08	263	1.95	31.22	13.73	57.3
4	15.15	148.8	33.66	4.693	23.91	1.58	0.411	0.09	279	1.99	32.01	13.12	61.0
5	16.46	161.7	36.00	5.216	24.14	1.47	0.382	0.10	280	2.08	37.85	12.64	66.8
6	16.94	166.4	39.51	4.834	28.18	1.66	0.433	0.11	285	2.12	33.46	12.50	66.0
7	18.49	181.7	42.38	4.560	30.55	1.65	0.430	0.12	298	2.20	32.30	11.90	61.2
8	21.04	206.7	49.50	3.999	38.58	1.83	0.477	0.14	320	2.36	28.41	11.21	55.1
9	23.02	226.2	52.08	3.924	40.02	1.74	0.452	0.14	328	2.59	27.85	11.25	52.0

4.2.1 Effect of gas flow rate on rate of fuel consumption and SGR

During the trials on gasification of maize cobs on the four throatless gasifiers the gas flow rates were observed in the range of 5.3 to 12.11, 12.68 to 24.75, 23.3 to 45.23 and 25.36 to 52.08 $Nm^3 \cdot h^{-1}$ for 15, 22.5, 30 and 36 cm diameter reactors, respectively. All these gas flow rates resulted in stable operation of gasifier and yielded combustible producer gas. As expected the rate of consumption of dry maize cobs increased with increase in size of the reactor and with the increase in gas flow rate. The feed rate was observed to be from 2.34 to 4.8 $kg \cdot h^{-1}$, 5.36 to 8.33 $kg \cdot h^{-1}$, 9.34 to 17.41 $kg \cdot h^{-1}$ and 12.37 to 23.02 $kg \cdot h^{-1}$ for 15, 22.5, 30 and 36 cm diameter reactors respectively.

The SGR increased linearly with the increase in gas flow rate and was observed to be in the range of 120-272 $kg \cdot h^{-1} \cdot m^{-2}$ in the throatless gasifiers for gasification of maize cobs. The trend of increase in SGR with gas flow rate is linear as is shown in Fig. 4.2. The SGR varied from 132 to 272, 135 to 210, 132 to 246, and 121 to 226 $kg \cdot h^{-1} \cdot m^{-2}$ for the 15, 22.5, 30 and 36 cm diameter reactors, respectively. SGR is a universal parameter and has been reported by many researchers. The range of SGR in throatless gasifier for gasification of rice husk in throatless gasifier was observed to be 105-264 $kg \cdot h^{-1} \cdot m^{-2}$ with gas flow rate variation of 6.6-13.0 $Nm^3 \cdot h^{-1}$ (Jain and Goss 2000) and 100-300 $kg \cdot h^{-1} \cdot m^{-2}$ with gas flow rate variation of 5.0-40.0 $Nm^3 \cdot h^{-1}$ (Tiangco *et al* 1996). Singh *et al* (2006) reported an SGR of 70-170 $kg \cdot h^{-1} \cdot m^{-2}$ for gasification of cashew nut shells in open core gasifier. Vyas and Singh (2007) have reported an SGR of 270 $kg \cdot h^{-1} \cdot m^{-2}$ at

5.5 $Nm^3 \cdot h^{-1}$ gas flow rate for gasification of Jatropha seed husk in an open core gasifier.

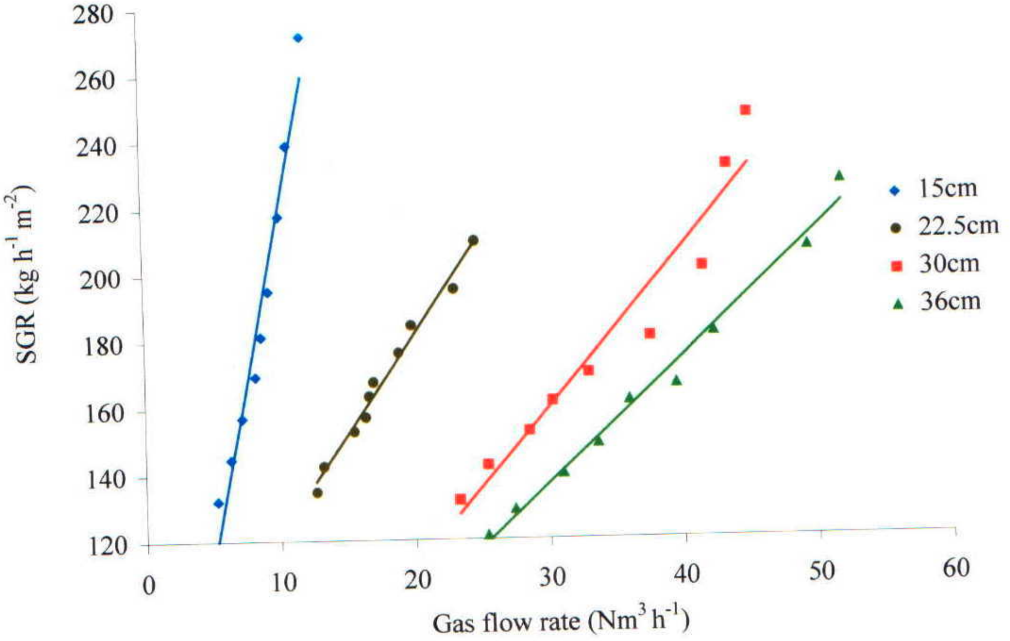


Fig. 4.2 Effect of gas flow rate on SGR for 15, 22.5, 30 and 36 cm diameter reactors

4.2.2 Effect of SGR on per cent combustible gases in producer gas

The composition of producer gas obtained by gasification of maize cobs in 15, 22.5, 30 and 36 cm diameter reactors are presented in Tables 4.3, 4.6, 4.9 and 4.12 respectively. The combustible gases in producer gas were H_2, CO_2 and CH_4, while the non-combustible gases were N_2 and CO_2. A typical chromatogram of producer gas obtained from gasification of maize cobs is presented in Fig. 4.3. It depicts the various peaks of the components of producer gas. The peaks were identified by the retention times of the individual gaseous components. The retention times for CO_2, H_2, O_2, N_2, CH_4 and CO were 0.43, 0.64, 1.0, 1.47, 2.45, and 3.16 minutes respectively.

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;  ARREJ   PKWD   ATTN   CHTSPD   ZERO   SLPSTV   BSSTV   SKMSTV
     6       4      4      1.0     10      32       16       8
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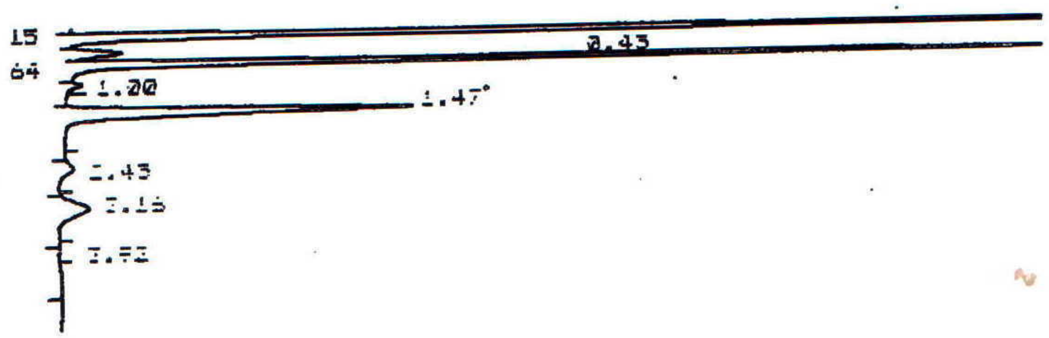

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Dec 25 2006     Data file    : chani.dat     id  :
 00:24:48       Method file  : methodi.mtd   % on Area

-----------------------------------------------------------------------
.TIME   HEIGHT         AREA          HT%           AREA%   TYPE   AR/H
-----------------------------------------------------------------------
0.15    15337        1292806       61.2892        50.6814   BV     0.2
0.43      276          44440        1.1029         1.7422   TTT    0.1
0.64     7140         700268       28.5326        27.4524   VP     0.0
1.00                    9125                       0.3577   TTT    0.0
1.47     2090         417416        8.3520        16.3636   PB     0.1
2.45                   16485                       0.6463   BB     0.1
3.16      181          70307        0.7233         2.7562   BB     0.2
-----------------------------------------------------------------------

   TOTAL PEAKS =          6
   TOTAL HEIGHT=      25024
   TOTAL AREA  = 2.55085E+06
   MUL. FACTOR =     1.0000
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Fig. 4.3 Typical chromatogram of producer gas obtained from gasification of maize cobs

The per cent combustible gases and lower heating value of the producer gas are presented in Tables 4.4, 4.7, 4.10 and 4.13. The per cent combustible gases were 28.1-32.6, 24.6-31.9, 22.3-31.1 and 27.5-37.8 % of the producer gas for 15, 22.5, 30 and 36 cm diameter reactors, respectively. The variation in per cent combustible gases with SGR is presented in Fig. 4.4. The combustible gases were observed to increase with initial increase in SGR up to 170 $kg \cdot h^{-1} \cdot m^{-2}$ and then reduced with further increase in SGR. The highest proportion of combustible gases in producer gas was observed to be 31.1-37.8 % at SGR values in the range of 161.7 to 169.9 $kg \cdot m^{-2} \cdot h^{-1}$ for all the reactors. Similar, findings have been reported by Singh *et al* (2006) and Dogru *et al* (2002), for downdraft gasification of cashew nut and hazelnut shells respectively. Singh *et al* (2006) reported per cent combustible gases of 30.88 % at SGR of 167 $kg \cdot m^{-2} \cdot h^{-1}$ during gasification of cashew nut shells in open core downdraft gasifier. The per cent combustible gases were observed to be 24.8-36.2 % of total producer gas during the gasification of hazelnut shells (Dogru *et al* 2002).

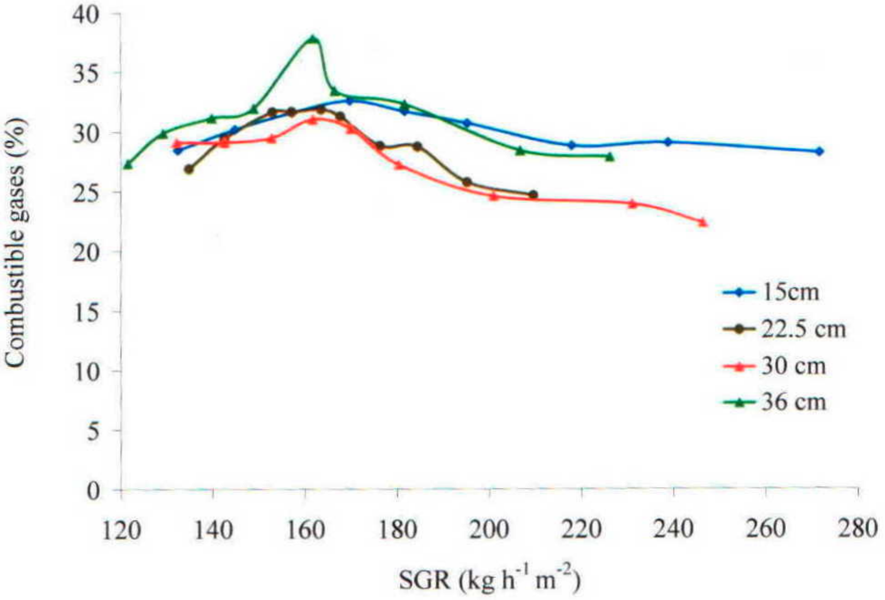


Fig.4.4 Effect of SGR on per cent combustible gases in producer gas for 15, 22.5, 30 and 36 cm diameter reactors

4.2.3 Effect of SGR on heating value of producer gas

The variation in lower heating value of producer gas (LHV_g) as a function of SGR is given in Fig 4.5. It gives an idea about the optimum operating point of the gasifier. The LHV_g increased with initial increase in SGR up to 170 $kg \cdot h^{-1} \cdot m^{-2}$ due to increase in the per cent combustible gases in producer gas. With further increase in SGR beyond 170 $kg \cdot h^{-1} \cdot m^{-2}$, the LHV_g reduced due to reduction in combustible quality of producer gas. This may be due to increased airflow and improved oxidation of pyrolysis products with increasing temperature in the oxidation zone. The maximum values of lower heating value of producer gas were observed to be in the range of 4.20-5.22 $MJ \cdot Nm^{-3}$ for all the reactors in the SGR range of 161.7-169.9 $kg \cdot h^{-1} \cdot m^{-2.}$ This range of SGR was observed to be the optimum operating point for gasification of maize cobs in throatless gasifier because the per cent combustible gases in producer gas and the lower heating value of producer gas were highest for all the reactors. Singh *et al* (2006) reported the maximum heating value of producer gas as 4.53 $MJ \cdot Nm^{-3}$ for gasification of cashew nut shells at SGR of 167 $kg \cdot m^{-2} \cdot h^{-1}$. Jain *et al* (2000) reported maximum value of calorific value of gas at 4.74 $MJ \cdot Nm^{-3}$ at SGR of 189 $kg \cdot h^{-1} \cdot m^{-2}$ for gasification of rice husk in throatless gasifier of reactor diameter 30 cm.

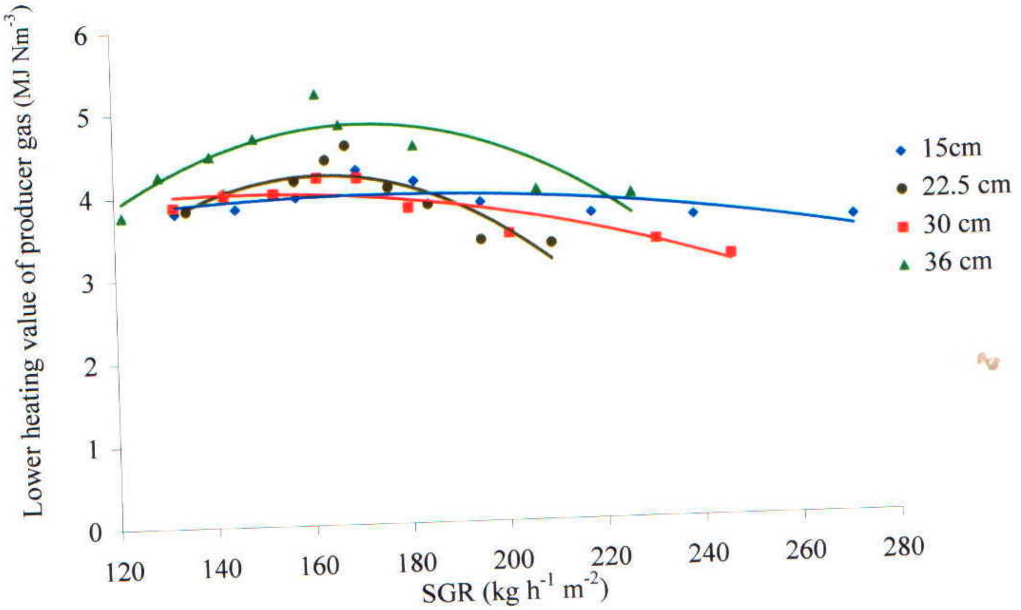


Fig. 4.5 Effect of SGR on lower heating value of producer gas obtained in 15, 22.5, 30 and 36 cm diameter reactors

4.2.4 Effect of SGR on char production rate

The char production per unit weight of dry maize cobs consumed was observed to reduce with increase in SGR (Fig. 4.6). It indicated better utilization of maize cobs at higher SGR. The char production rates were observed to reduce from 16-11.5 %, 15.5-11.0 %, 16.1-10.8 % and 15.0-11.2 % of input dry maize cobs in 15, 22.5, 30 and 36 cm reactors over the range of variation of SGR. The char production rate decreased with increase in SGR and became almost constant at SGR above 240 kg·h^{-1}·m^{-2}. At optimum SGR the char production was 12.6-14.4 % of input dry maize cobs in the reactors. The average calorific value of char was 20.5 MJ·kg^{-1}. Jorapur and Rajvanshi (1997) obtained char as 24 % of input biomass (bagasse) and calorific value of char was in the range of 18.9-23 MJ·kg^{-1}.

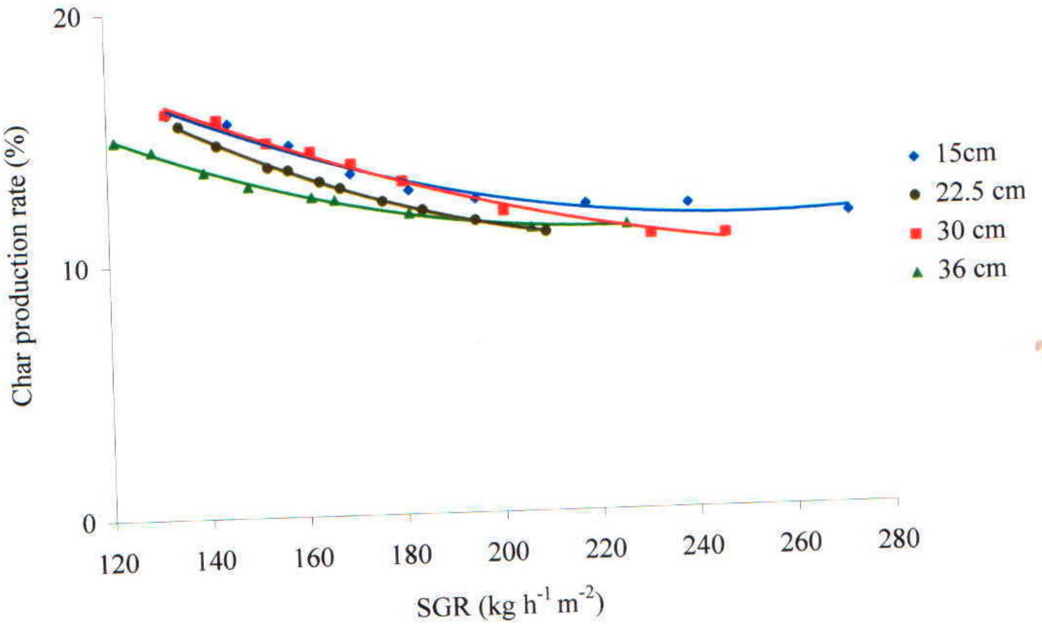


Fig. 4.6 Effect of SGR on char production rate for 15, 22.5, 30 and 36 cm diameter reactors

4.2.5 Effect of SGR on air fuel ratio

The effect of SGR on air fuel ratio for gasification of maize cobs in various reactors is shown in Fig.4.7. The air fuel ratios varied from 1.77-2.09, 1.9-2.51, 1.76-2.13 and 1.62-1.83 Nm^3·kg^{-1} for 15, 22.5, 30 and 36 cm reactors respectively for the variation in SGR from 120 – 272 kg·h^{-1}·m^{-2}. In this range of air fuel ratio, the temperatures in the gasifier did not increase high enough to induce slag and clinker formation, which were therefore not observed. At optimum values of SGR between 161.7-169.9 kg·h^{-1}·m^{-2} at which per cent combustible gases and lower heating value of producer gas were maximum, the air fuel ratios obtained were 2.05, 1.87, 1.85 and 1.47 Nm^3·kg^{-1} for 15, 22.5, 30 and 36 cm diameter reactors respectively. The air fuel ratio has a vital effect on gasifier performance because it regulates the fuel consumption rate and the temperature in the gasifier. It is suggested that the gasifier should be operated within these values to yield producer gas of maximum heating value. Jain and Goss (2000) obtained an air fuel ratio of 1.33-2.27 at SGR of 117-264 kg·h^{-1}·m^{-2} for gasification of rice husk in throatless gasifier.

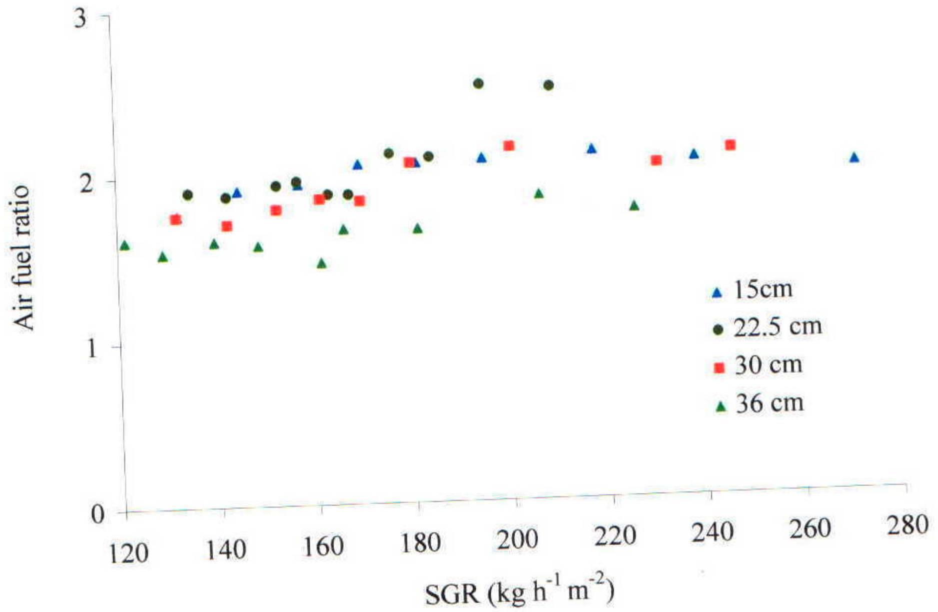


Fig. 4.7 Effect of SGR on air fuel ratio

4.2.6 Effect of SGR on superficial velocity

The superficial velocity of gas in a gasifier is an important measure of its performance controlling the gas production rate, gas energy content, fuel consumption rate and char production rate. The superficial velocity in general increased directly with increase in SGR for the trials on all the gasifiers (Fig.4.8). The variation in superficial velocity was from 0.07-0.19 m·s^{-1} for the full range of variation in SGR in the four reactors. In each reactor as the superficial velocity increased the char production rate reduced as more fuel was gasified. The lower heating value of the gas reduced (3.15-3.58 MJ·Nm^{-3}) at superficial velocities nearing 0.17-0.19

m·s^{-1}. The superficial gas velocity at optimum SGR varied between a narrow range of 0.10 to 0.13 m·s^{-1}. Reed *et al* (1999) reported that a low superficial velocity in downdraft gasification causes relatively slow pyrolysis conditions and produces higher yields of char (20-30 %) and gas with high hydrocarbon content.

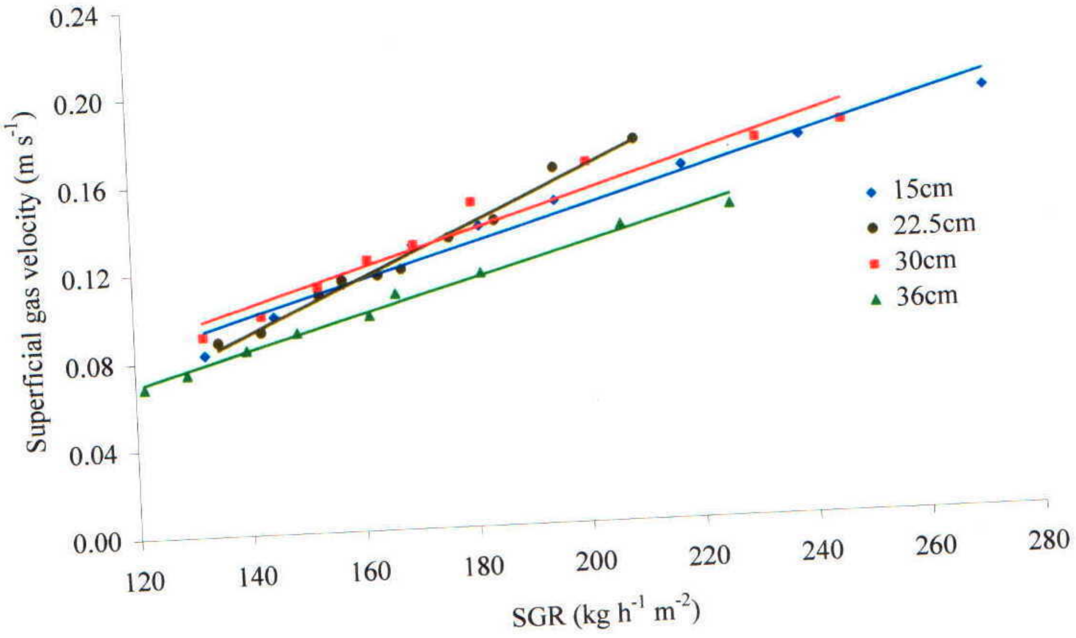


Fig. 4.8 Effect of SGR on superficial velocity

4.2.7 Equivalence ratio

The maximum gasifier efficiency corresponded to equivalence ratio of 0.53, 0.49, 0.48 and 0.38 for 15, 22.5, 30 and 36 cm diameter reactors respectively. An average equivalence ratio of 0.47 may be selected for making material and energy balance calculations over the gasifier engine systems and their design work.

4.2.8 Temperature of producer gas

The hot gas temperature leaving the reactor grate was found to vary from 210 to 328 °C during the trials on the four reactors. The temperature of the producer gas was observed to be dependent on the gas flow rate. As the gas flow rate increased the temperature of the producer gas at the grate increased (Tables 4.4, 4.7, 4.10, 4.13). The temperature of producer gas entering the water scrubber varied from 90 to 140 °C. The higher temperature of producer gas accounted for higher temperature of gas entering the water scrubber. The temperature of gas leaving the water scrubber was 40 – 65 °C. Singh *et al* (2006) observed the raw producer gas temperature between 200 – 500 °C for gasification of cashew nut shells in open core gasifier and the higher temperature of 500 °C was observed at gas flow rate of 130 $m^3 \cdot h^{-1}$.

4.2.9 Pressure drop

The pressure drop across the gasifier, wet scrubber and dry filter was measured. The average pressure drop was observed to be 10.07, 3.27 and 5.2 mm of Hg across gasifier, wet scrubber and dry filter respectively. The total maximum pressure drop across the whole system was observed to be 18.54 mm of Hg. This is important to decide the size and suction capacity of the blower required for the system. Dogru *et al* (2002) observed a pressure drop of 5.07 mm of Hg across a downdraft gasifier, during gasification of hazelnut shells.

4.2.10 Producer gas composition as a function of run time

The producer gas composition was plotted as a function of the run time. The experimental runs at optimum SGR for 15, 22.5, 30 and 36 cm diameter reactors were selected for the plots. These are presented in Figures 4.9, 4.10, 4.11 and 4.12 respectively. In all the reactors there was a variation in the gas composition with run time but no definite trend could be observed. The variation in gas composition during the experimental runs could be due to reloading of the biomass, pressure variations in the reactor and change in the flow behaviour of biomass in the gasifier. CO_2, H_2, CO and CH_4 in producer gas were 7.86 ± 1.2 %, 13.66 ± 1.1 %, 17.15 ± 5.1 %, 1.8 ± 0.6 %, respectively for 15 cm diameter reactor. These were 10.06 ± 1.5 %, 10.6 ± 1.9 %, 17.06 ± 2.6 % and 3.4 ± 1.2 % for respectively for 22.5 cm diameter reactor. Similarly CO_2, H_2, CO and CH_4 in producer gas were 15.7 ± 1 %, 10.89 ± 2.1 %, 18.17 ± 0.6 % and 3.4 ± 1.2 % and 8.7 ± 1.2 %, 17.3 ± 1.4 %, 17.5 ± 0.8 % and 3.3 ± 0.3 % for 30 and 36 cm diameter reactors respectively.

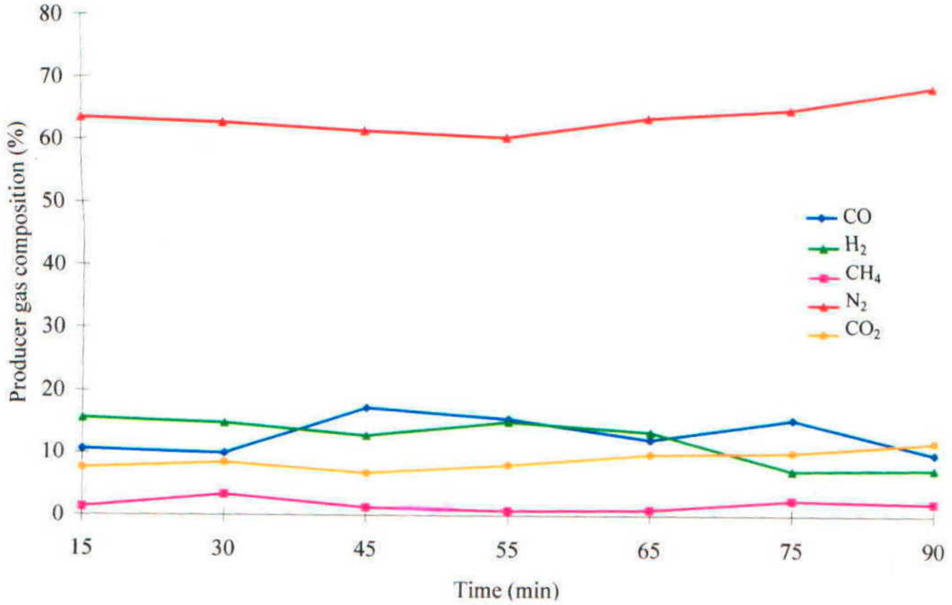


Fig. 4.9 Producer gas composition vs. run time for 15 cm diameter reactor at optimum SGR

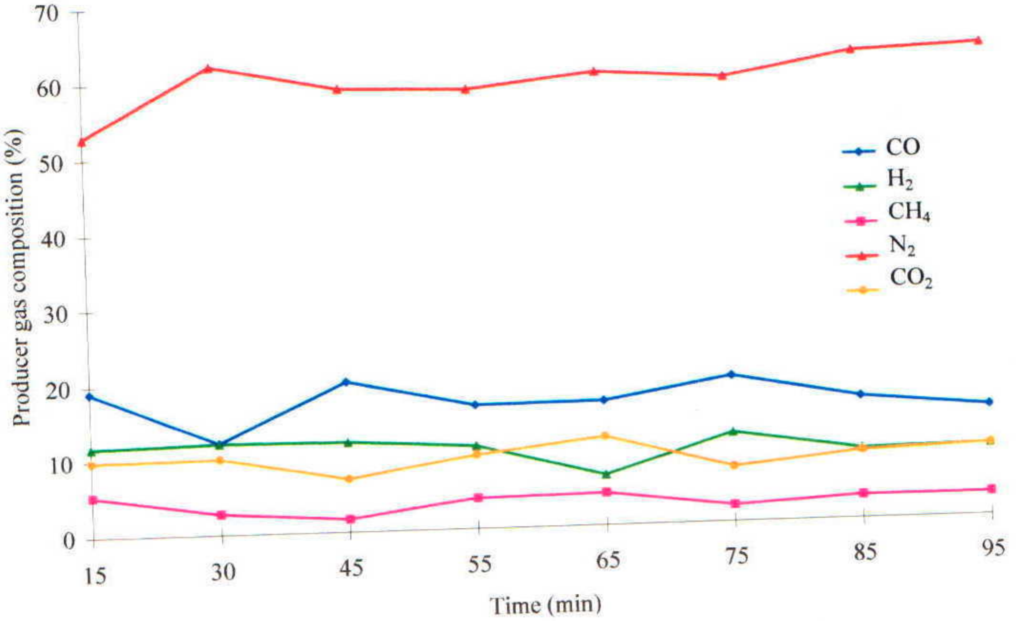


Fig. 4.10 Producer gas composition vs. run time for 22.5 cm diameter reactor at optimum SGR

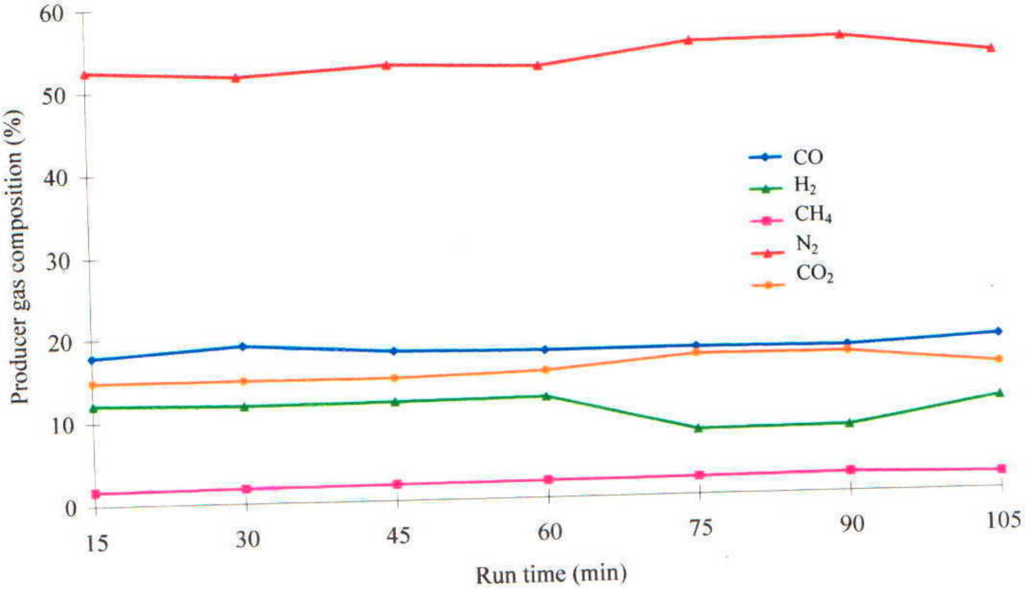


Fig. 4.11 Producer gas composition vs. run time for 30 cm diameter reactor at optimum SGR

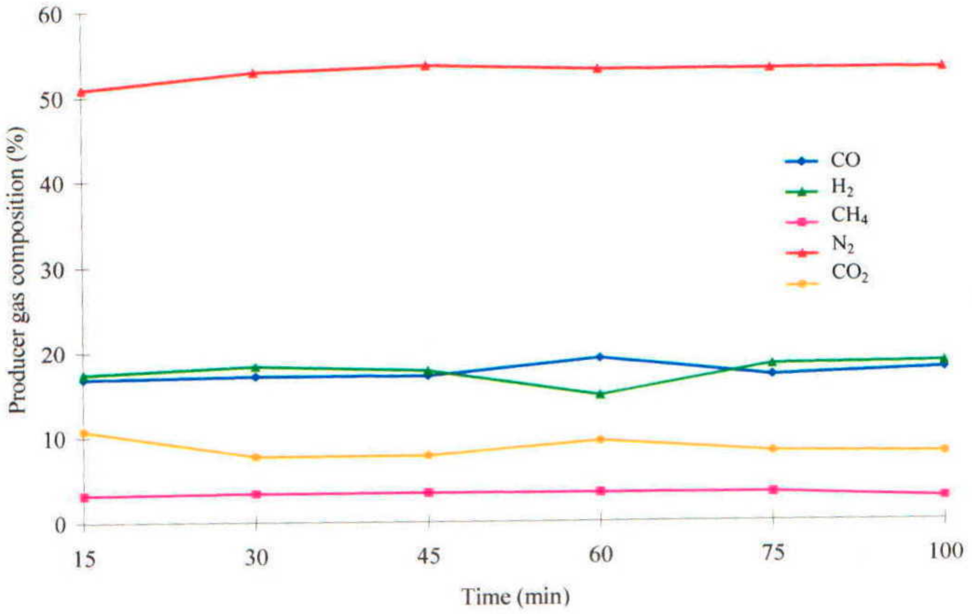


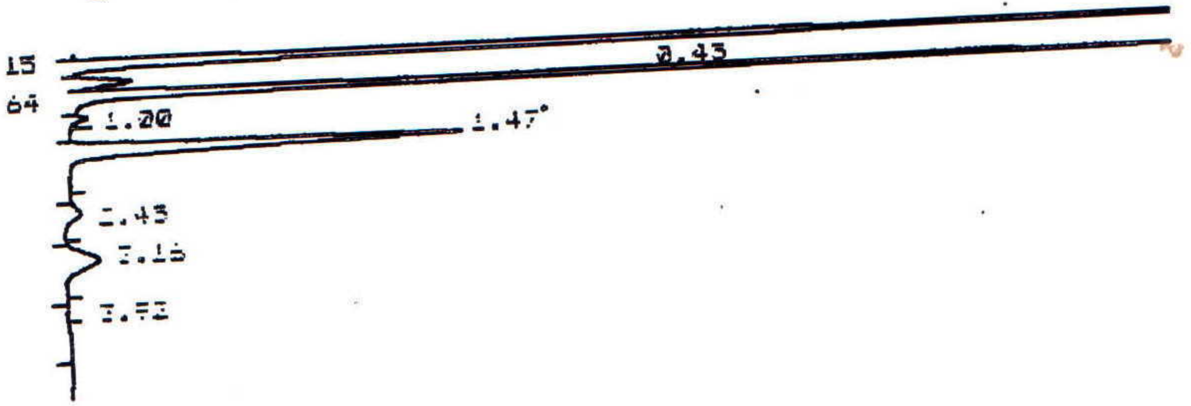
Fig. 4.12 Producer gas composition vs. run time for 36 cm diameter reactor at optimum SGR

The typical chromatograms of producer gas for the runs of optimum SGR in 15, 22.5, 30 and 36 cm diameter reactors are shown in Figures 4.13, 4.14, 4.15 and 4.16 respectively.

4.2.11 Optimum operation of gasifier

The gasification of maize cobs in throatless gasifier was observed to be optimum at specific gasification rate (SGR) in the range of 161.7-169.9 $kg{\cdot}h^{-1}{\cdot}m^{-2}$. The average value of optimum SGR was 165.2 $kg{\cdot}h^{-1}{\cdot}m^{-2}$. The optimum operating parameters such as gasification efficiency, lower heating value of producer gas, per cent combustible gases, fuel feed rate, gas flow rate, air fuel ratio and char production rate for gasification of maize cobs in throatless gasifiers are given in Table 4.14. It was possible to produce combustible producer gas from maize cobs in a throatless gasifier.

```
;  ARREJ   PKWD   ATTN   CHTSPD   ZERO   SLPSTV   BSSTV   SKMSTV
     6       4      4      1.0     10      32       16       8
```



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------------------------------------------------------------------------------
.TIME    HEIGHT        AREA          HT%          AREA%     TYPE    AR/
------------------------------------------------------------------------------
0.15     15337       1292806       61.2892       50.6814    BV      0.0
0.45       276         44440        1.1029        1.7422    TTT     0.1
0.64      7140        700266       28.5326       27.4524    VP      0.0
1.00                    9125                      0.3577    TTT     0.0
1.47      2090        417416        8.3520       16.3636    PB      0.1
2.45                   16485                      0.6463    BB      0.1
3.16       181         70307        0.7233        2.7562    BB      0.2
------------------------------------------------------------------------------

    TOTAL PEAKS =              6
    TOTAL HEIGHT=          25024
    TOTAL AREA  =    2.55085E+06
    MUL. FACTOR =         1.0000
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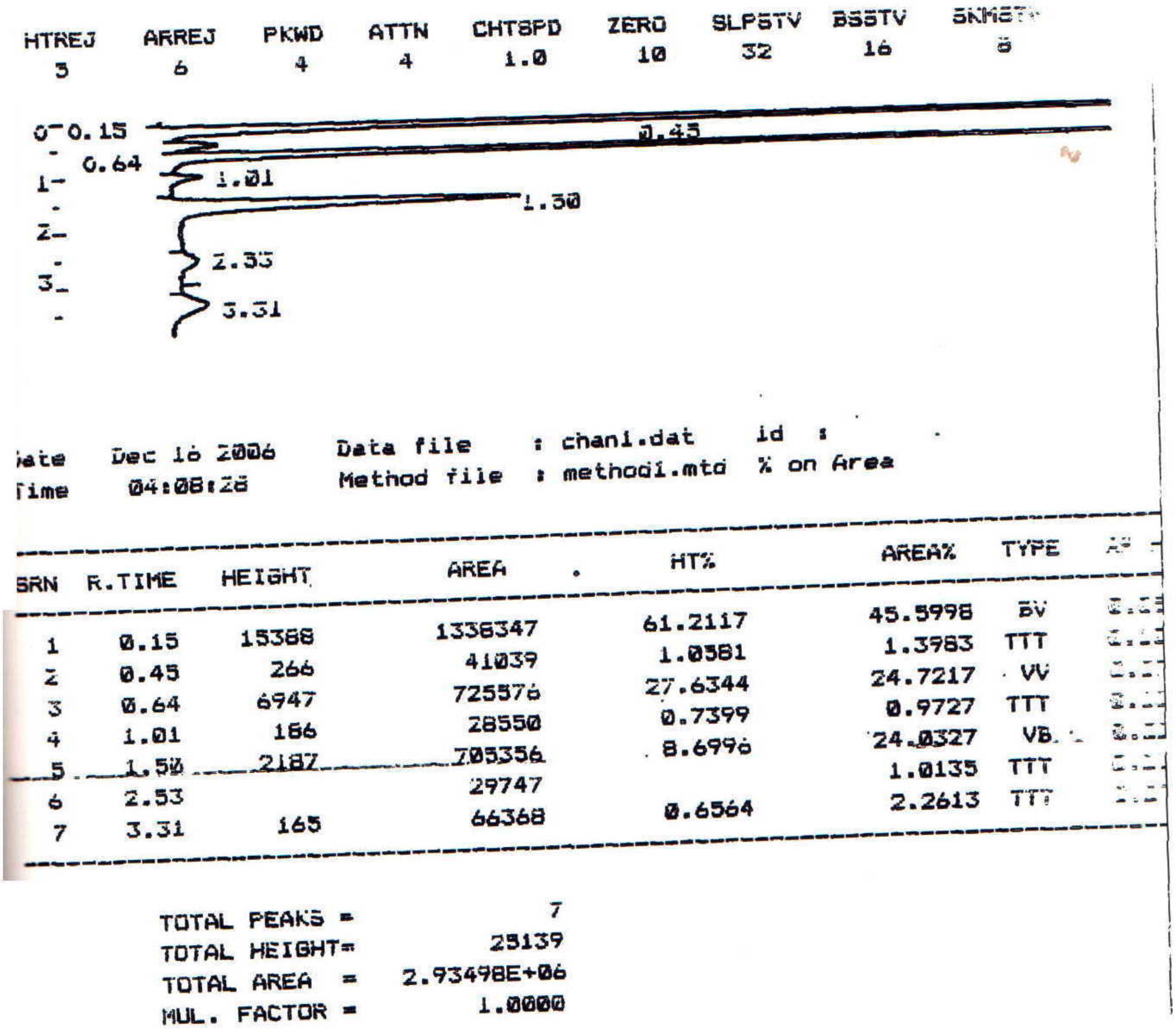
Fig. 4.13 A typical chromatogram of producer gas obtained from gasification of maize cobs in 15 cm diameter reactor



```
HTREJ   ARREJ   PKWD   ATTN   CHTSPD   ZERO   SLPSTV   BSSTV   SNMST
  3       6       4      4      1.0     10      32       16       8

0-0.15                              0.45
 - 0.64
1-     1.01
 -                      1.50
2-
 -     2.53
3-
 -     3.31

ate    Dec 16 2006     Data file    : chani.dat    id  :
Time    04:08:28       Method file  : method1.mtd  % on Area

---------------------------------------------------------------------------
SRN  R.TIME   HEIGHT        AREA     .     HT%         AREA%    TYPE
---------------------------------------------------------------------------
 1    0.15    15368       1336347        61.2117      45.5998    BV
 2    0.45      266         41039         1.0381       1.3983    TTT
 3    0.64     6947        725576        27.6344      24.7217    VV
 4    1.01      186         28550         0.7399      24.0327    VB
 5    1.50     2187        705356         8.6996       1.0135    TTT
 6    2.53                  29747                      2.2613    TTT
 7    3.31      165         66368         0.6564
---------------------------------------------------------------------------

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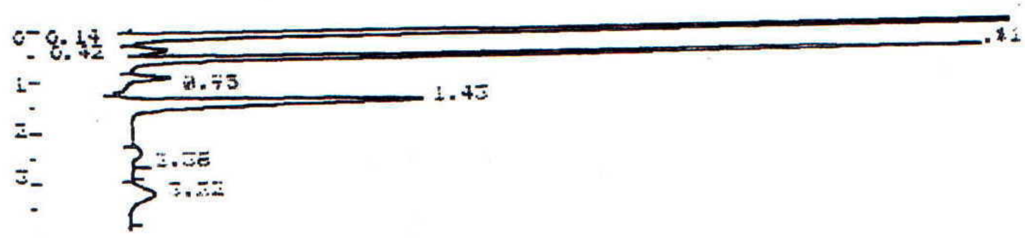
       TOTAL HEIGHT=         25139
       TOTAL AREA   =  2.93498E+06
       MUL. FACTOR  =       1.0000
```

Fig. 4.14 A typical chromatogram of producer gas obtained from gasification of maize cobs in 22.5 cm diameter reactor

```
HTREJ    ARREJ    PKWD    ATTN    CHTSPD    ZERO    SLPSTV    BSSTV    SNMSTV
  3        6        4       4       1.0      10       32        16        8
```



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Time     00:03:16        Method file  : methodi.mtd   % on Area

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SRN  R.TIME   HEIGHT        AREA           HT%
---------------------------------------------------------------------------------
                                                          46.7215   BV    0.056
 1    0.14    13614      1121962         61.6046           1.2180   TTT   0.100
 2    0.42      199        29248          0.9005          23.6815   VF    0.068
 3    0.60     5784       573487         26.1731           2.1656   TTT   0.122
 4    0.95      290        52005          1.3123          22.7801   PB    0.182
 5    1.43     2057       547038          9.3081           0.5774   TTT   0.179
 6    2.38                 13866                           2.6559   BB    0.281
 7    3.22      155        63779          0.7014
---------------------------------------------------------------------------------

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        TOTAL HEIGHT=          22099
        TOTAL AREA   =   2.40139E+06
        MUL. FACTOR  =        1.0000
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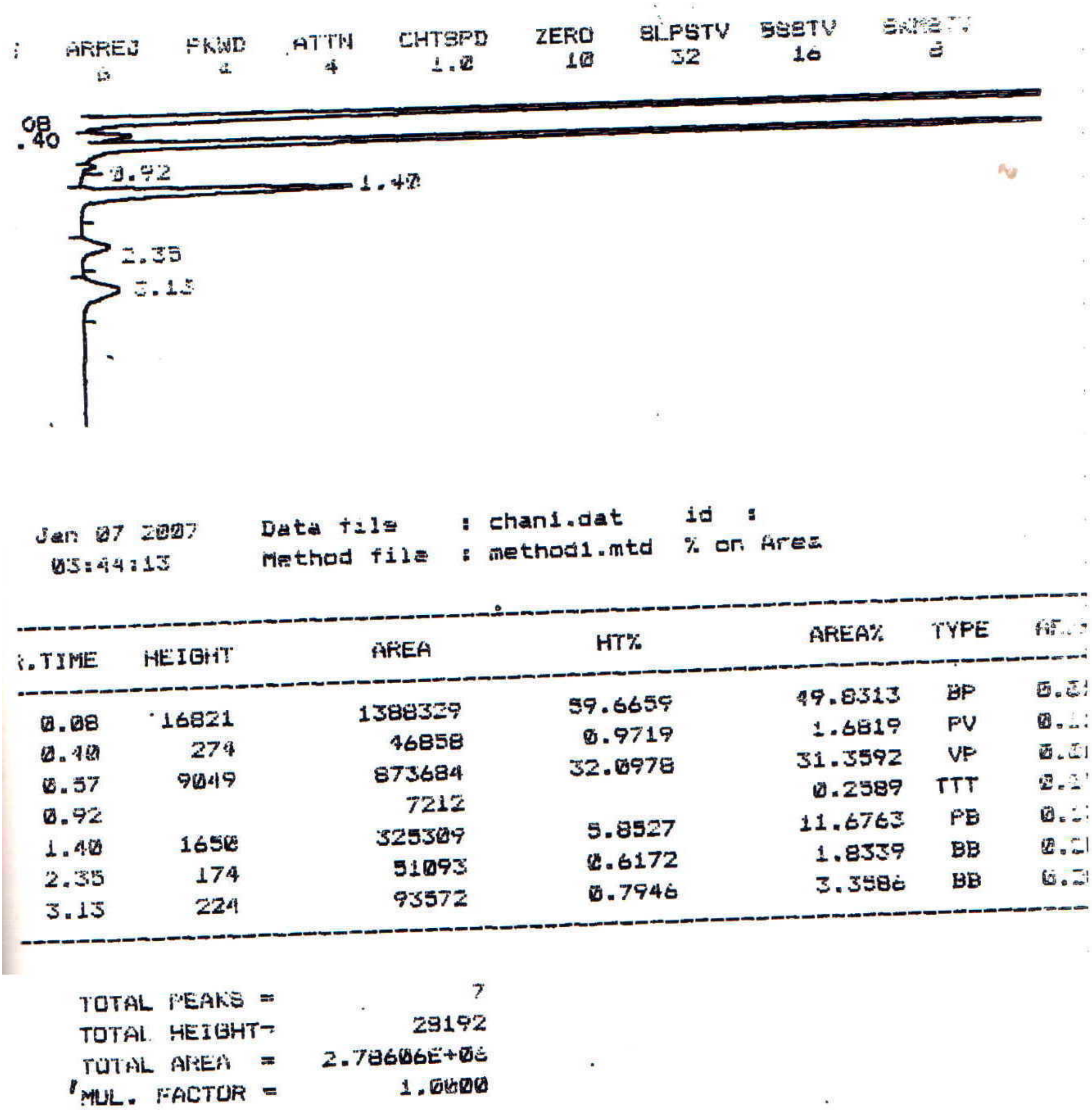
Fig. 4.15 A typical chromatogram of producer gas obtained from gasification of maize cobs in 30 cm diameter reactor



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:  ARREJ   PKWD   ATTN   CHTSPD   ZERO   SLPSTV   SSSTV   SKMSTV
     6       4      4      1.0     10      32       16       8

Jan 07 2007      Data file    : chani.dat      id  :
 03:44:13        Method file  : method1.mtd    % on Area

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 0.08    16821     1388329       59.6659      49.8313    BP     0.
 0.40      274       46858        0.9719       1.6819    PV     0.
 0.57     9049      873684       32.0978      31.3592    VP     0.
 0.92                 7212                     0.2589    TTT    0.
 1.40     1650      325309        5.8527      11.6763    PB     0.
 2.35      174       51093        0.6172       1.8339    BB     0.
 3.13      224       93572        0.7946       3.3586    BB     0.
-------------------------------------------------------------------------

 TOTAL PEAKS  =              7
 TOTAL HEIGHT=           28192
 TOTAL AREA   =    2.78606E+06
 MUL. FACTOR  =         1.0000
```

Fig. 4.16 A typical chromatogram of producer gas obtained from gasification of maize cobs in 36 cm diameter reactor

Table 4.14 Optimum operating parameters for throatless gasifiers for gasification of maize cobs

Diameter (cm)	SGR ($kg \cdot h^{-1} \cdot m^{-2}$)	Gasification efficiency (%)	Fuel feed rate ($kg \cdot h^{-1}$)	Gas flow rate ($Nm \cdot h^{-1}$)	Air flow rate ($Nm^3 \cdot h^{-1}$)	Lower heating value of gas ($MJ \cdot Nm^3$)	Air fuel ratio	Char residue obtained ($kg \cdot h^{-1}$)	Total combustible gases (%)
15	169.9	68.96	3	8.25	6.15	4.29	2.05	0.41	32.6
22.5	167.7	68.21	6.67	16.98	12.45	4.58	1.87	0.86	31.3
30	161.7	67.8	11.43	31.51	21.11	4.20	1.85	1.65	31.1
36	161.7	66.8	16.46	36.0	24.1	5.22	1.47	2.08	37.8

4.2.12 Effect of SGR on gasification efficiency

The gasification efficiency increased with increasing SGR and started decreasing after passing through a maximum for each reactor. The variation in gasification efficiency with SGR for each run on all the four reactors is shown in Fig.4.17. The figure clearly showed that for all the four reactors the maximum gasification efficiency was in a narrow range of SGR i.e. between 161.7 to 169.9 $kg{\cdot}h^{-1}{\cdot}m^{-2}$. In this range of SGR high quality producer gas (4.20-5.22 $MJ{\cdot}Nm^{-3}$) was obtained in all the reactors and the char production (12.6 - 14.4 %) was low. Thus the SGR of 165.2 $kg{\cdot}h^{-1}{\cdot}m^{-2}$ may be considered as a design parameter for throatless gasifier for gasification of maize cobs. Vyas and Singh (2007) reported a maximum gasification efficiency of 68.31 % at a gas flow rate of 5.5 $m^3{\cdot}h^{-1}$ and SGR of 270 $kg{\cdot}h^{-1}{\cdot}m^{-2}$ for gasification of Jatropha seed husk in open core gasifier. The optimum SGR for gasification of rice husk in throatless gasifiers of reactor diameters 15.1 – 34.3 cm has been reported as 192.5 $kg{\cdot}h^{-1}{\cdot}m^{-2}$ (Jain and Goss 2000) at which the gasification efficiency was maximum at around 65%. Tiangco *et al* (1996) suggested an optimal value of SGR of 200 $kg{\cdot}h^{-1}{\cdot}m^{-2}$ for gasification of rice hulls in reactor diameters ranging from 16-30 cm with gasification efficiency of 50 – 60 %. Singh *et al* (2006) observed that the gasification efficiency was maximum (70%) at SGR of 167 $kg{\cdot}h^{-1}{\cdot}m^{-2}$ for gasification of cashew nut shells in open core gasifier.

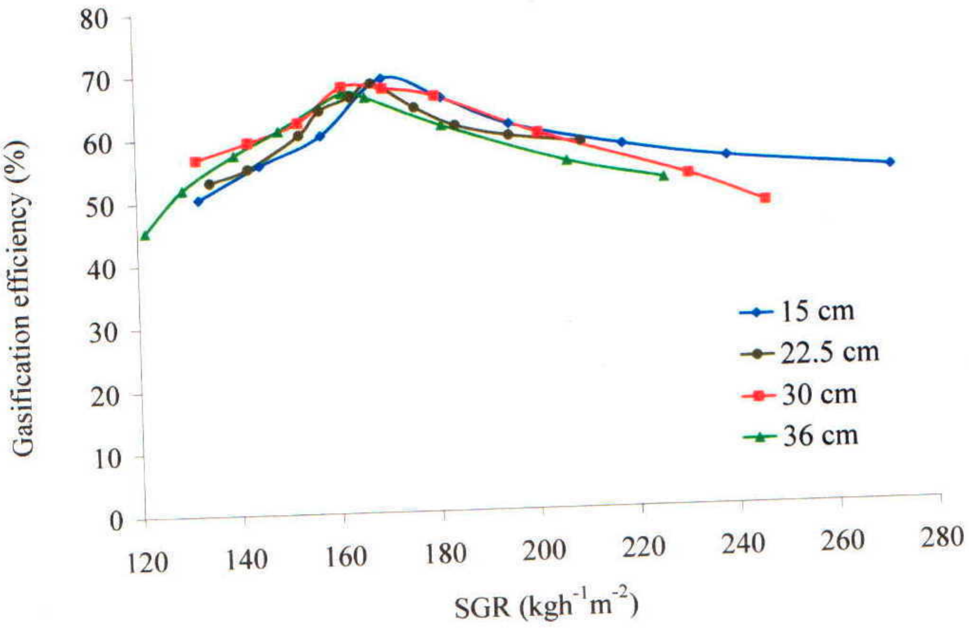

Fig. 4.17 Effect of SGR on gasification efficiency for 15, 22.5, 30 and 36 cm diameter reactors

4.3 Statistical analysis

The variation in gasification efficiency with respect to specific gasification rate (SGR) for the four reactors is shown in Fig 4.14. The variation in gasification efficiency with respect to SGR was observed to be quadratic in nature. Thus a second order polynomial equation (equation 4.1) was fitted to the observed data to measure the influence of independent variables (specific gasification rate and diameter of reactor) on dependent variable, gasification efficiency.

$$\eta_g = \beta_0 + \beta_1 (d_{rc}) + \beta_2 (SGR) + \beta_3 (d_{rc})^2 + \beta_4 (SGR)^2 + \beta_5 (d_{rc} * SGR) + e \qquad (4.1)$$

where: η_g = gasification efficiency

d_{rc} = diameter of reactor

SGR = specific gasification rate

β_0 to β_5 = regression coefficients

e = experimental error.

The multiple correlation coefficient (R) was observed to be 0.88, which indicated the closeness of the association between the observed and the predicted values of the dependent variable from the multiple regression equation 4.2. The regression coefficients ($\beta_0 - \beta_5$) were determined using the method of least squares, and are listed in Table 4.15.

Table 4.15 Regression coefficients

Coefficients	Values
β_0	-112.79
β_1	1.337
β_2	1.78
β_3	-1.13E-02
β_4	-4.60E-03
β_5	-4.38E-03

The response surface (contour plot) of gasification efficiency with respect to diameter and SGR was plotted and is presented in Fig. 4.18. It is clear from the plot that the variation in gasification efficiency was mainly due to variation in specific gasification rate and not due to the reactor diameter.

The analysis of variance (ANOVA) was conducted and the effects of the independent variables and their higher order terms on gasification efficiency, were statistically analyzed (Table 4.16). The adequacy of the regression equation was significant at 5% level ($p < 0.05$) i.e. the variation in the dependent variable gasification efficiency was due to the variations in the independent variables. The analysis of variance of the separate terms is also given in the Table 4.16.

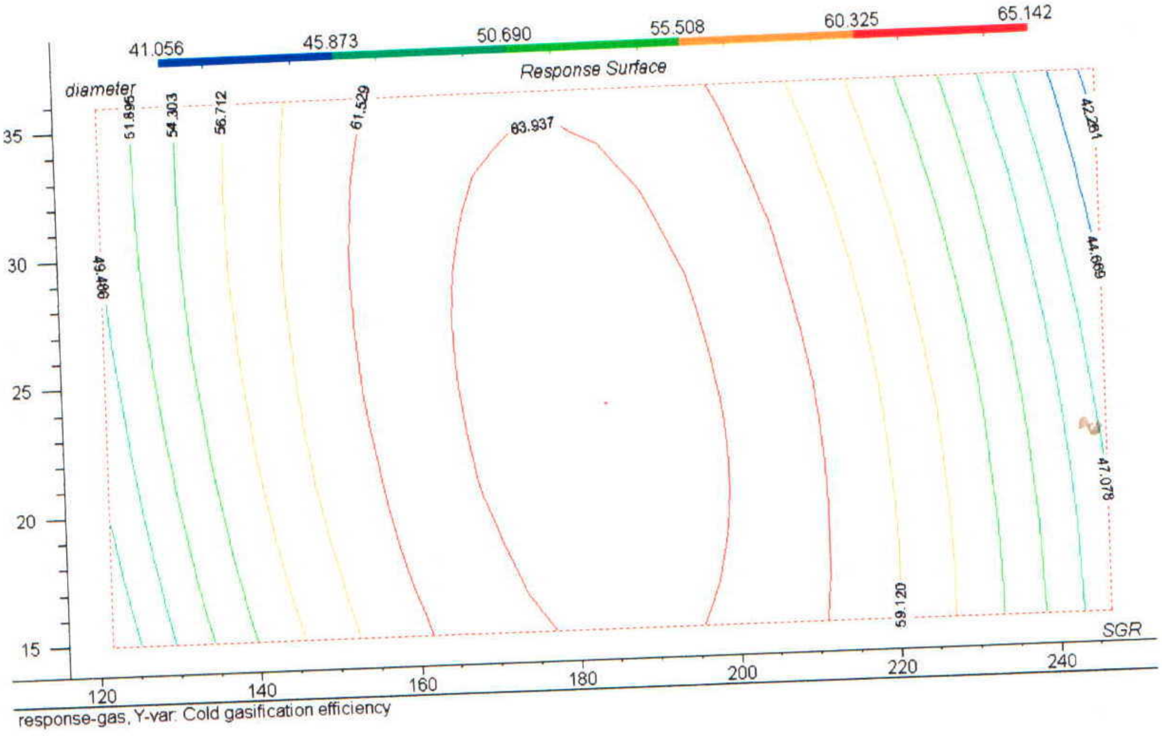

Fig. 4.18 Contour plot of SGR, diameter and gasification efficiency

Table 4.16 Analysis of effect of diameter and specific gasification rate on gasification efficiency

Summary	SS	df	MS	F-ratio	p-value	Regression coefficients
Regression	987.12	5	197.42	20.79	0.00	
Error	284.85	30	9.50			
Adjusted Total	1272.00	35	36.34			
Variables						
Intercept	292.34	1	292.34	30.79	0.00	-112.79
d_{rc}	33.21	1	33.21	3.50	0.07	1.34
$(d_{rc})^2$	10.05	1	10.05	1.06	0.31	-0.01
SGR	864.14	1	864.14	91.01	0.00	1.78
SGR^2	912.56	1	912.56	96.11	0.00	-0.005
$d_{rc}xSGR$	44.25	1	44.25	4.66	0.04	-0.004

The coefficients of SGR, SGR^2 and $(d_{rc}xSGR)$ were significant at 5% level ($p < 0.05$), whereas the terms containing d_{rc} and $(d_{rc})^2$ were not significant at 5% level ($p > 0.05$). Thus it was concluded that within the experimental range, the diameter did not significantly affect the gasification efficiency whereas SGR had a significant effect on the gasification efficiency.

The quality of the regression was also determined by plotting the predicted vs. observed values of gasification efficiency (Fig. 4.19). In Fig. 4.19, if the points lie on the line, it indicates that there is no difference between predicted and observed values. This line is also referred as target line. The distance of each point from the target line indicates the difference between the predicted and observed values of gasification efficiency. The spread of these points on both sides of the line indicate a good fit of the fitted polynomial (equation 4.2) to the observed data.

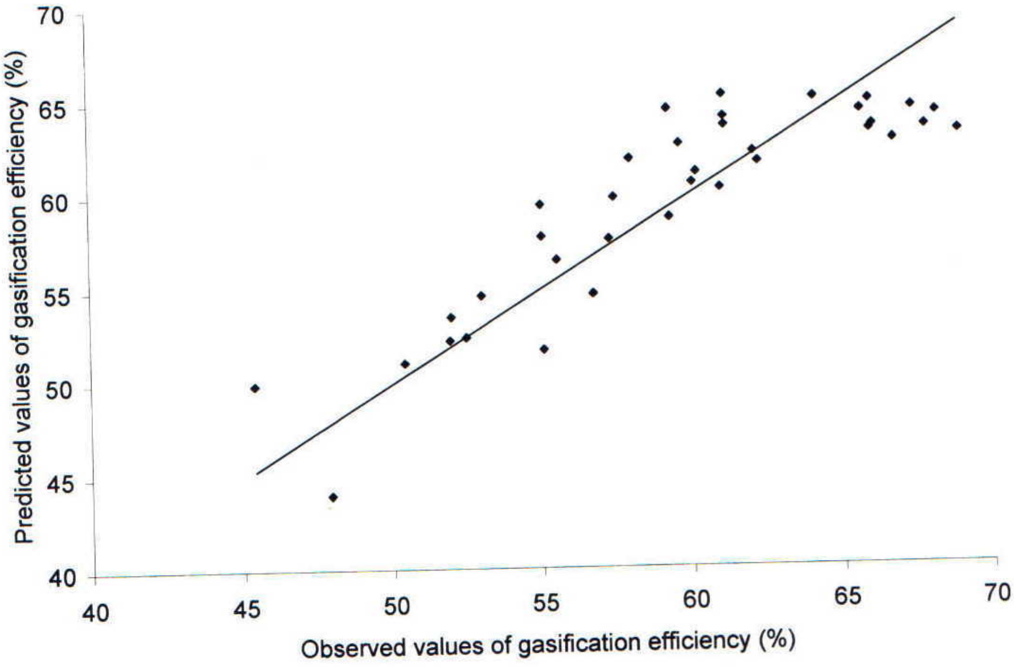

Fig.4.19 Predicted vs. observed gasification efficiency

The experimental and predicted values of gasification efficiency were plotted against specific gasification rate (SGR) and are presented in Fig. 4.20. The trend of gasification efficiency with SGR was similar for both the experimental and predicted values. The predicted and the experimental values of gasification efficiency are quite close and this indicated the adequacy of the fitted polynomial equation (4.2).

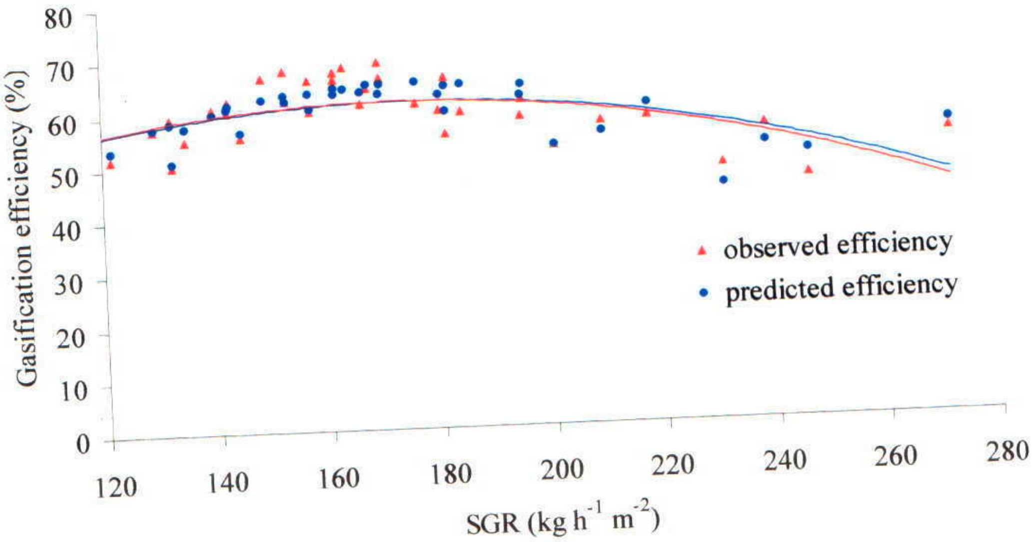

Fig. 4.20 Observed and predicted values of gasification efficiency vs. specific gasification rate

4.4 Energy analysis

The consumption of fuel and hence the total energy input was observed to increase with increase in gas flow rate for all the reactors. In order to study the energy balance of each gasifier, amount of energy input in the form of fuel was fixed and the rest of the calculations made accordingly. The energy balance data i.e. input and output energy for each run for 15, 22.5, 30 and 36 cm diameter reactors is given in Tables 4.17, 4.18, 4.19, 4.20.

The energy input to the gasifier varied in a very narrow range. The difference was primarily due to the variation in moisture content and amount of maize cobs used for the experiments. The sensible energy of maize cobs was very low (less than 1%) as the maize cobs were at ambient temperature. The chemical energy of producer gas increased with increase in SGR and was observed to be maximum at optimum value of SGR. With further increase in SGR the chemical energy of producer gas reduced. The lower heating value of producer gas was also observed to be maximum at optimum value of SGR. The sensible energy of producer gas increased with increase in gas production and temperature of producer gas. The quantity and calorific value of char residue obtained from the gasifier decreased with increase in SGR. This was due to improved utilization of maize cobs into producer gas. Both the chemical and sensible energy of char residue were observed to decrease with increase in SGR. The energy analysis revealed that at an optimum SGR of 169.8 $kgh^{-1}m^{-2}$ for 15 cm gasifier reactor, 68.82 % of energy value of maize cobs was converted to chemical energy of producer gas. The sensible energy of producer gas, which was at 225 °C, was 4.99 % of the input energy. The chemical and sensible energy of residual char was 16.27 and 0.09 % of input energy respectively. The heat losses from the gasifier were 9.82 % (Fig.4.21). Similarly, at optimum values of SGR the total energy output giving per cent chemical and sensible energy of producer gas, sensible and chemical energy of residual char and losses for the 22.5, 30 and 36 cm diameter reactors are shown in Figures 4.22, 4.23 and 4.24 respectively. The chemical energy of char varied between 15.5-17.7 % of the input energy. The losses were to the tune of 8-13 %.

Table 4.17 Energy balance data for 15 cm diameter reactor

Run No.	CE_m (MJ)	SE_a (MJ)	Total Input energy (MJ)	CE_g (MJ)	SE_g (MJ)	CE_r (MJ)	SE_r (MJ)	Output Energy (MJ)
1	47.5	0.11	47.6	24.0	1.84	9.4	0.05	35.3
2	47.5	0.10	47.6	26.4	2.03	9.1	0.05	37.7
3	47.4	0.11	47.5	28.5	2.18	8.5	0.05	39.3
4	47.5	0.09	47.6	32.8	2.38	7.7	0.04	42.9
5	47.4	0.11	47.5	31.1	2.45	7.3	0.04	40.9
6	47.3	0.10	47.4	29.0	2.54	7.0	0.04	38.5
7	47.3	0.13	47.4	27.2	2.58	6.8	0.05	36.6
8	47.5	0.10	47.7	26.2	2.61	6.8	0.05	35.6
9	47.2	0.12	47.4	25.0	2.68	6.4	0.05	34.1

CE – chemical energy, SE – sensible energy, subscripts m, a, g and r refer to maize cobs, air, producer gas and residue respectively

Table 4.18 Energy balance data for 22.5 cm diameter reactor

Run No.	CE_m (MJ)	SE_a (MJ)	Total Input energy (MJ)	CE_g (MJ)	SE_g (MJ)	CE_r (MJ)	SE_r (MJ)	Output Energy (MJ)
1	95.2	0.19	95.4	50.5	4.11	18.2	0.10	73.0
2	95.2	0.17	95.4	52.4	4.10	17.2	0.10	73.8
3	95.4	0.17	95.5	57.4	4.56	16.0	0.10	78.1
4	95.1	0.22	95.3	60.9	4.78	15.8	0.10	81.5
5	95.1	0.25	95.3	62.8	4.91	15.1	0.10	83.0
6	95.2	0.20	95.4	64.9	5.11	14.8	0.10	84.9
7	94.9	0.24	95.1	60.9	5.46	14.0	0.10	80.4
8	95.4	0.25	95.7	58.3	5.94	13.6	0.10	77.9
9	94.7	0.34	95.0	56.1	6.71	12.8	0.10	75.8
10	95.1	0.32	95.4	55.2	6.94	12.2	0.10	74.4

CE – chemical energy, SE – sensible energy, subscripts m, a, g and r refer to maize cobs, air, producer gas and residue respectively

Table 4.19 Energy balance data for 30 cm diameter reactor

Run No.	CE_m (MJ)	SE_a (MJ)	Total Input energy (MJ)	CE_g (MJ)	SE_g (MJ)	CE_r (MJ)	SE_r (MJ)	Output Energy (MJ)
1	160.5	0.50	161.0	91.1	7.75	31.9	0.18	131.0
2	159.6	0.48	160.1	94.7	8.31	31.1	0.19	134.3
3	160.2	0.48	160.7	99.8	9.27	29.1	0.19	138.3
4	159.9	0.44	160.3	108.4	9.80	28.2	0.19	146.6
5	159.5	0.44	159.9	107.5	10.48	26.9	0.19	145.0
6	159.6	0.47	160.1	105.3	11.53	25.3	0.19	142.3
7	160.6	0.39	161.0	95.8	11.99	22.6	0.17	130.6
8	159.3	0.30	159.6	83.6	11.49	20.0	0.17	115.3
9	160.2	0.49	160.7	76.8	11.45	20.1	0.17	108.5

CE – chemical energy, SE – sensible energy, subscripts m, a, g and r refer to maize cobs, air, producer gas and residue respectively

Table 4.20 Energy balance data for 36 cm diameter reactor

Run No.	CE_m (MJ)	SE_a (MJ)	Total Input energy (MJ)	CE_g (MJ)	SE_g (MJ)	CE_r (MJ)	SE_r (MJ)	Output Energy (MJ)
1	157.9	0.53	158.5	71.7	6.41	29.1	0.18	107.4
2	157.4	0.55	157.9	81.9	6.95	28.0	0.18	117.0
3	157.1	0.58	157.7	90.1	7.47	26.1	0.18	123.9
4	157.7	0.59	158.3	96.2	8.20	24.9	0.18	129.5
5	158.0	0.59	158.6	105.5	7.96	23.9	0.17	137.5
6	157.8	0.59	158.4	104.1	8.71	23.5	0.17	136.5
7	157.5	0.61	158.1	96.4	8.95	22.2	0.17	127.7
8	157.1	0.67	157.8	86.5	9.80	20.6	0.18	117.1
9	157.5	0.60	158.1	81.8	9.76	20.7	0.18	112.5

CE – chemical energy, SE – sensible energy, subscripts m, a, g and r refer to maize cobs, air, producer gas and residue respectively

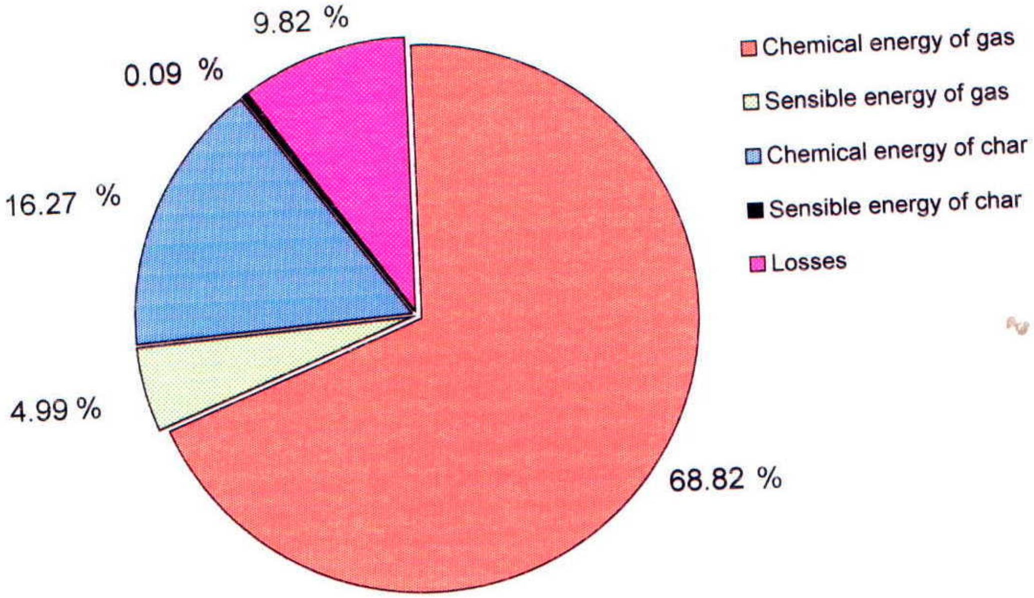

Fig. 4.21 Distribution of energy output from 15 cm diameter reactor at run of maximum efficiency

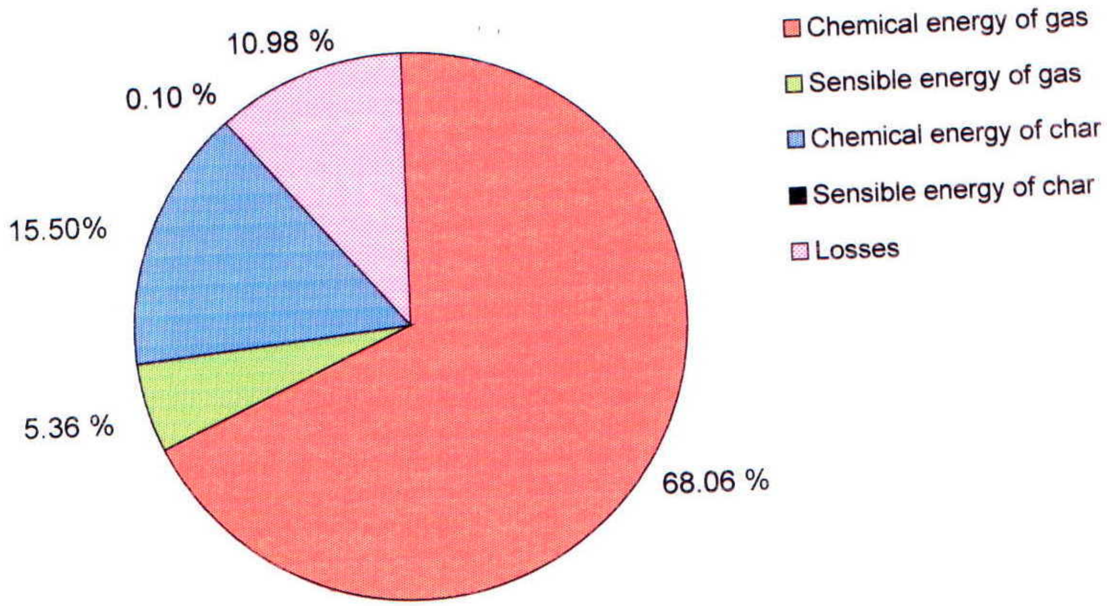

Fig. 4.22 Distribution of energy output from 22.5 cm diameter reactor at run of maximum efficiency

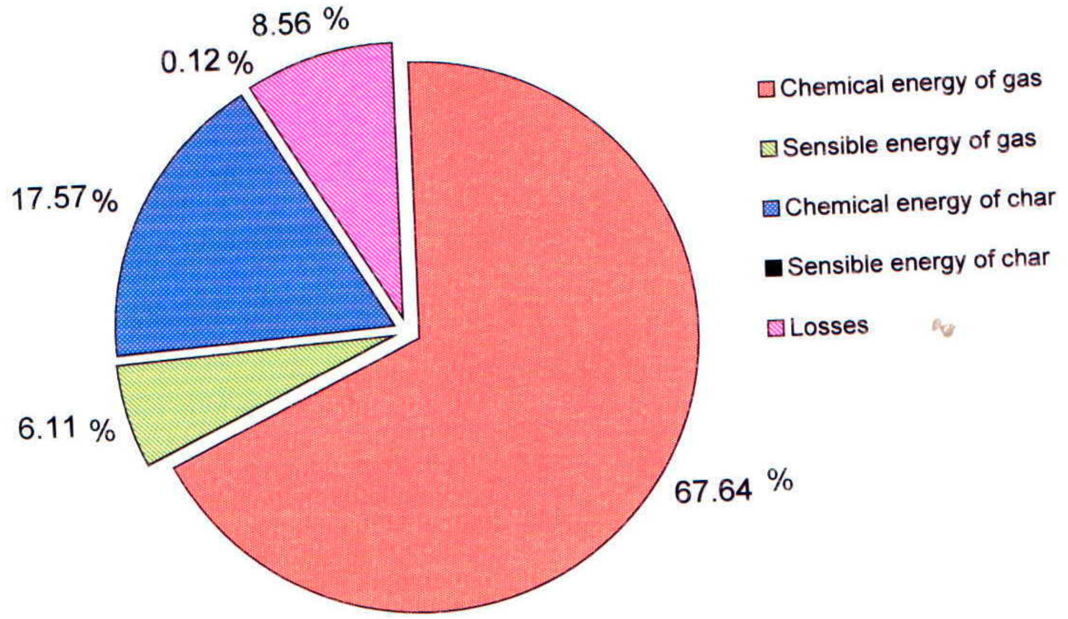

Fig. 4.23 Distribution of energy output from 30 cm diameter reactor at run of maximum efficiency

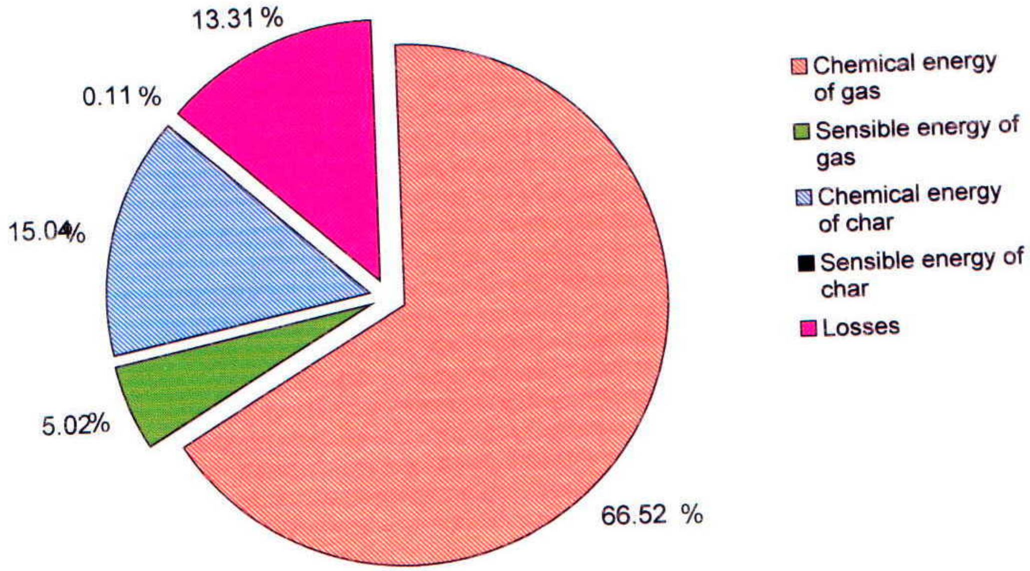

Fig. 4.24 Distribution of energy output from 36 cm diameter reactor at run of maximum efficiency

4.5 Economic analysis

The economic analysis of throatless gasifier system (gasifier of reactor diameter 30 cm, gas cleaning unit and blower etc.) for gasification of maize cobs was done on the basis of following experimental results:

Capacity of gasifier : $10\ \mathrm{kg{\cdot}h^{-1}}$
Gas production : $25.5\ \mathrm{Nm^{3}{\cdot}h^{-1}}$
Heating value of gas : $4.2\ \mathrm{MJ{\cdot}Nm^{-3}}$

The following assumptions were made for the economic analysis:

Life of gasifier system : 10 years
Operating hours per day : 8 h
Working hours per annum: 2400 h

The calculations of the financial analysis are as follows:

Fixed cost		
Cost of gasifier system	:	Rs. 40,000
Operating cost		
Annual wages	:	30,000
Cost of fuel (@ Re. 0.4 / kg)	:	9,600
Cost of electricity (Rs. 5 / kWH)	:	12,000
Repair and maintenance (10 % of fixed cost)	:	4,000
Total	:	**Rs. 55,600**
Annual cost		
Operating cost	:	55,600
Depreciation (10 % of fixed cost)	:	4,000
Interest (11 % on capital investment)	:	5,929
Total		**Rs. 65,529**
Producer gas output (annual)		
Gas produced per annum	:	$61200\ \mathrm{m^{3}}$
Energy produced per annum	:	257040 MJ
Cost of energy from producer gas (Annual cost / energy produced per annum)	:	**25.49 paisa $\mathrm{MJ^{-1}}$**

The comparison of cost of energy from producer gas with other commercial sources of energy is presented in Table 4.21. The energy cost of producer gas is lower than that of commercially available fuels.

Table 4.21 Comparison of energy cost of producer gas with commercial fuels

Fuel	Heating value	Cost/ unit	Energy cost (p MJ^{-1})
Producer gas	4.20 $MJ \cdot Nm^{-3}$	-	25.50
LPG	45 $MJ \cdot kg^{-1}$	Rs. 21 / kg	46.60
Natural gas	53 $MJ \cdot kg^{-1}$	Rs. 20 / kg	37.70
Diesel	37 $MJ \cdot l^{-1}$	Rs. 32 / l	86.00

CHAPTER 5

SUMMARY AND CONCLUSIONS

The properties of shelled maize cobs were measured to evaluate their suitability as fuel for gasification. The average length, diameter, angle of repose, bulk density and true density of maize cobs were 5.85 cm, 1.92 cm, 29.2^0, 160 $kg\cdot m^{-3}$ and 300 $kg\cdot m^{-3}$ respectively. The carbon, hydrogen, oxygen, nitrogen and sulphur content of maize cobs were 46.18, 4.93, 46.43, 0.6 and 0.03 % respectively. The volatile matter, fixed carbon and ash content of maize cobs were 83.01, 15.16 and 1.83 % respectively. The moisture content of maize cobs obtained from fields was in the range of 6-8 % (w.b.). The higher and lower heating value of maize cobs was observed to be 18.2 and 17.09 $MJ\cdot kg^{-1}$ respectively. The low ash, high-energy content, size, shape, ultimate and proximate analysis of maize cobs indicated that it can be used as a fuel for gasification.

The gasification of shelled maize cobs was conducted in throatless gasifiers having 15, 22.5, 30 and 36 cm diameter reactors. The experiments were conducted over a range of gas flow rates in each reactor resulting in specific gasification rate (SGR) in the range of 120-272 $kg\cdot h^{-1}\cdot m^{-2}$. The optimum SGR was observed to be 165 $kg\cdot h^{-1}\cdot m^{-2}$. The combustible gases were observed to be 31-38 % of the producer gas at optimum SGR. Average amount of CO, CH_4 and H_2 in producer gas were observed to be around 18, 12.5 and 3 % respectively. The lower heating value of producer gas was 4.2-5.2 $MJ\cdot Nm^{-3}$. The maximum gasification efficiency was attained in the range of 66.8-68.9 % at optimum SGR. The char produced was 12.6-14.4 % of the fuel and its average calorific value was 20.5 $MJ\cdot kg^{-1}$. The average equivalence ratio was 0.47. The effect of diameter on efficiency of gasification was not significant whereas the specific gasification rate had a significant effect on gasification efficiency. The energy analysis revealed that at optimum SGR, 66.5-68.8 % of the energy of maize cobs was converted into chemical energy of producer gas and the unaccounted losses were 8.6-13.3 %. The cost of energy obtained from producer gas worked out to be 25.5 paisa·MJ^{-1} and was lower than that of commercial fuels.

The following conclusions were drawn from the study:

- The fuel related properties of maize cobs indicate that it is a suitable fuel source for gasification.
- Maize cobs may be gasified in throatless gasifiers at an optimum specific gasification rate (SGR) of 165 kg·h^{-1}·m^{-2} with gasification efficiency of 66.8-68.9 %.
- The effect of diameter on gasification efficiency was not significant. Similar efficiencies were obtained in all the reactors having diameters 15, 22.5, 30 and 36 cm.
- The effect of specific gasification rate (SGR) on gasification efficiency was significant.
- Maize cobs can be gasified in throatless gasifiers. There were no problems with the operation of the gasifier and there was no buildup of slag. Thus, it can be concluded that maize cobs are a good fuel source for gasification.
- The SGR value of 165 kg·h^{-1}·m^{-2} may be used as design parameter for gasification of maize cobs in throatless gasifier.

CHAPTER 6

SUGGESTIONS FOR FUTURE WORK

The design parameters were established for gasification of maize cobs in throatless gasifiers in this study. Further work can be done to make the study more comprehensive. Some of the suggestions in this regard are listed below:

- There was loss of energy from the gasifier in form of heat. The effect of insulating the gasifier reactor may be studied.
- The chemical energy of char residue was quite high. Possibility of conversion of this energy into chemical energy of producer gas may be studied.
- The tar content of producer gas obtained from maize cobs may be studied.
- The utilisation of producer gas obtained from maize cobs for running diesel engines may be studied.
- The size reduction of maize cobs was done manually. The development of mechanical methods for size reduction of maize cobs may be taken up.

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