EIE-06-256 REEPRO

Intelligent Energy Europe

Promotion of the Efficient Use of Renewable Energies in Developing Countries

Chapter VI
Gasification

Author

Sengratry Kythavone, NUOL

The REEPRO project receives funding from the European Commission within the COOPENER Programme.

5 References

1. Brian C Williams NICERT, “WORKSHOP PROCEEDINGS: PROFIT FROM GASIFICATION”, (Report No. COAL R197DTI/Pub URN 00/1079) University of Ulster, Coleraine , 2000.

2. Anna Ingwe; Programmes Officer, Stoves Component, GTZ – PSDA, GTZ Office Nairobi, P.O. Box 41607, Kilimani00100 Nairobi, Kenya.

3. Belonio, A. T. (1993, November 3-5). Cookstove Initiatives on Production, Promotion and Commercialization: The CPU Experience. Paper presented at the Consultation Meeting on the Formulation of a National Cookstove Program held at Silliman University. Dumaguete City, Negros Oriental

4. Beagle, E. C. 1978. Rice Husk Conversion to Energy. Food Agricultural Service Bulletin. Food Agricultural Organization of the United Nation. Rome, Italy.

5. Anderson, P. and Reed, T. 2004. Biomass Gasification: Clean Residential Stoves, Commercial Power Generation, and Global Impacts. LAMNET Project International Workshop on “Bioenergy for a Sustainable Development,” 8-10 Nov 2004, Vina del Mar, Chile

List of Content

List of Figures

List of Tables

List of Acronymes

AC	Alternating current
DC	Direct current
LHV	Low Heating Value
LPG	Liquidized Propane gas
SGR	Specific gas rate
FCR	Fuel Consumption rate
AFR	airflow rate
IGCC	Integrated Gasification Combined Cycles
STIG	Steam Injected Gas turbine
STEG	Steam and Gas turbine
HRSG	Heat Recovery Steam Generator

1 Types of Gasifiers, Basics and Definitions

1.1 Fixed bed gasifiers

1.1.1 Up-draught or counter current gasifier

The simplest type of gasifier is the fixed bed counter current gasifier, which principle is shown in figure 1. The biomass is fed at the top of the reactor and moves downwards as a result of the conversion of the biomass and the removal of ashes. The air intake is at the bottom and the gas leaves at the top. The biomass moves in counter current to the gas flow, and passes through the drying zone, the distillation zone, the reduction zone and the hearth zone.

In the drying zone the biomass is dried. In the distillation or pyrolisation zone the biomass is decomposed in volatile gases and solid char. The heat for pyrolisation and drying is mainly delivered by the upwards flowing producer gas and partly by radiation from the hearth zone. In the reduction zone many reactions occur involving char, carbon dioxide and water vapour, in which carbon is converted and carbon monoxide and hydrogen are produced as the main constituents of the producer gas. In hearth zone the remaining char is combusted providing the heat, the carbon dioxide and water vapour for the reactions involved in the reduction zone.

Figure 1: Up-draught, or counter current fixed bed gasifier

The major advantages of this type of gasifier are its simplicity, high charcoal burn-out and internal heat exchange leading to low gas exit temperatures and high gasification efficiencies. Because of the internal heat exchange the fuel is dried in the top of the gasifier and therefore fuels with a high moisture content (up to 60 % wb) can be used. Furthermore this type of gasifier can even process relatively small sized fuel particles and accepts some size variation in the fuel feedstock.

Major drawbacks are the high amounts of tar and pyrolysis products, because the pyrolysis gas is not combusted. This is of minor importance if the gas is used for direct heat applications, in which the tars are simply burnt. In case the gas is used for engines, extensive gas cleaning is required.

1.1.2 Downdraught, or co-current, fixed bed gasifier.

In a down-draught reactor biomass is fed at the top and the air intake is also at the top or from the sides. The gas leaves at the bottom of the reactor, so the fuel and the gas move in the same direction, figure 2. The same zones can be distinguished as in the up-draught gasifier, although the order is somewhat different. The biomass is dried and pyrolised in the drying and distillation zone respectively.

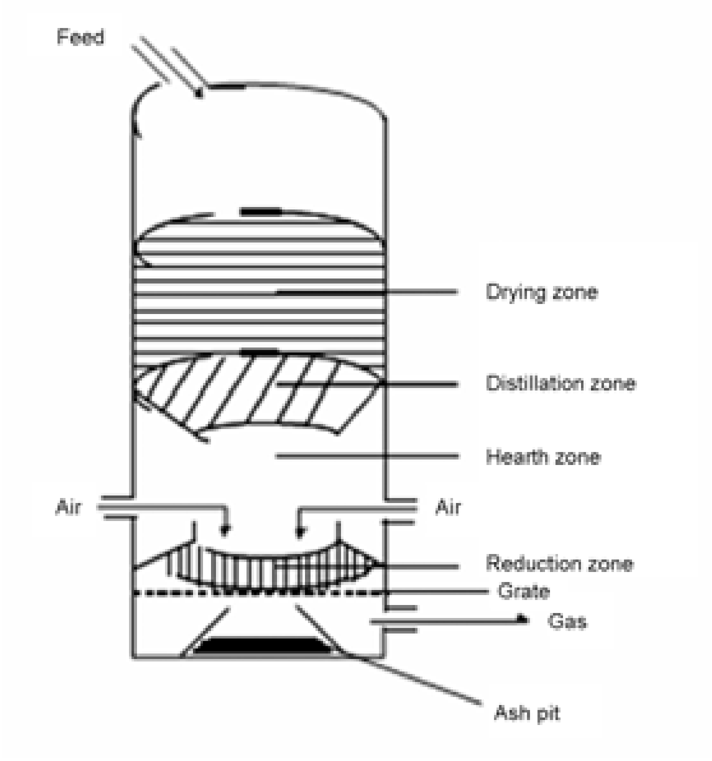


Figure 2: Downdraught, or co-current, fixed bed gasifier_Sengratry/ Anna Ingwe_2007

These zones are mainly heated by radiation (and partly convection) heat from the hearth zone, where a part of the char is burnt. The pyrolysis gases pass also through this zone to be burnt as well. The extent to which the pyrolysis gases are actually burnt depends on design, the biomass feedstock and the skills of the operator. After the oxidation zone the remaining char and the combustion products carbon dioxide and water vapour pass to the reduction zone where the reduction reactions take place forming CO and H_2.

Hence the main advantage of a down-draught gasifier is the production of a gas with a low tar content which is nearly suitable for engine applications.

In practice however, a tar-free gas is seldom if ever achieved over the whole operating range of the equipment. The main reason seems to be that not all gases pass through the hottest zones and that their residence time in the combustion zone might be too short. In each particular design other features are included to realise a high conversion rate of the pyrolysis gases.

1.1.3 Cross-draught gasifier

Cross-draught gasifiers are adapted for the use of charcoal, see figure 3. Charcoal gasification results in very high temperatures (1500°C and higher) in the hearth zone which can lead to material problems. Advantages of the system lie in the very small scale at which it can be operated. In developing countries installations for shaft power under 10 kW_{el} are used. This is possible due to the very simple gas-cleaning train (cyclone and a bed filter). A drawback is the minimal tar-converting capability, resulting in the need for high quality charcoal.

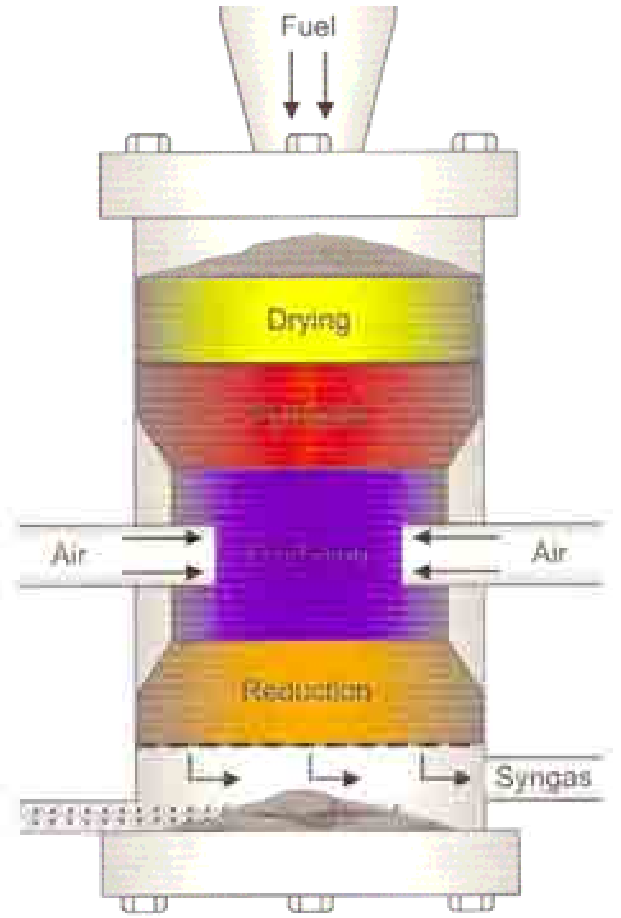


Figure 3: Cross-draught fixed bed gasifier

1.1.4 Open core gasifier

Open core gasifiers (figure 4) are especially designed to gasify fine materials with low bulk density (for example rice husks). Because of the low bulk density of the fuel no throat can be applied in order to avoid bridging of the fuel which causes hampering or even stopping of the fuel flow. Special devices, like rotating grates, may be included to stir the fuel and to remove the ash. Particularly rice husk gasifiers require continuous ash removal systems because of the high ash content of rice husks resulting in large volumes of ash (appr. 55 % of the initial fuel volume). The bottom of the gasifier is set in a basin of water by which the ash is removed.

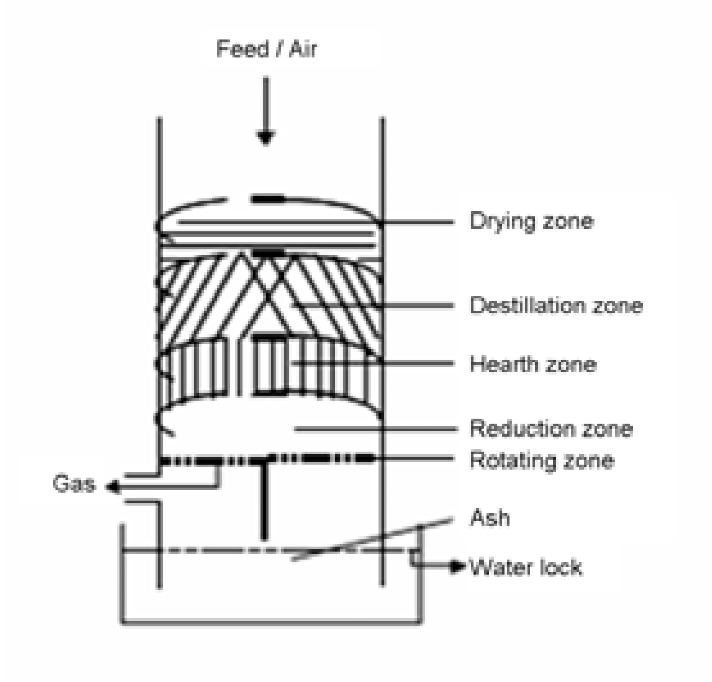


Figure 4: Open core gasifier _Sengratry/ Anna Ingwe_2007

1.1.5 Comparison of fixed bed gasifiers

For the up-draught, down-draught and open core gasifier some characteristics are presented in table 1 applying wood as feedstock. Because of the variety of gasifier designs which have been developed for each type of gasifier, the mentioned data are only rough indications which can hardly be called "typical". But least they give an indication of, in some extent, typical differences between the three basic fixed bed gasifier types.

Table 1: Characteristics of different gasifier types/ Van Swaay et al (1994), BTG (1995).

	Down draught	up draught	open core
Fuel (wood)			
-moist.cont. (%wet basis)	12 (max. 25)	43 (max. 60)	7 - 15 (max. 15)
- ash content (% dry basis)	0.5 (max. 6)	1.4 (max. 25)	1 - 2 (max. 20)
-size (mm)	20 – 100	5 – 100	1 – 5
Gas exit temp (°C)	700	200 – 400	250 – 500
Tars (g/Nm^3)	0.015 - 0.5	30 – 150	2 – 10
Sensitivity to load fluctuations	Sensitive	not sensitive	not sensitive
turn down ratio	3-4	5 – 10	5 – 10
?HG full load (%) [1)]	85-90	90 – 95	70 – 80
?CG full load (%) [2)]	65-75	40 – 60	35 – 50
Producer gas LHV (kJ/Nm^3)	4.5-5.0	5.0 - 6.0	5.5 - 6.0

[1)] ?HG Hot gas efficiency, taking into account the heat contained in the gas. To be applied for heat applications.

[2)] ?CG Cold gas efficiency. The gas will be cooled after leaving the gasifier to ambient temperature. To be applied for engine (and power) applications.

1.2 Fluidised bed gasifiers

Fluidised bed gasification (figure 5) is originally developed to overcome the operational problems with fixed bed gasification of fuels with high ash content, but is very suitable for the larger capacities (larger than 10 MWth) in general. The features of fluidised bed gasification are comparable with those of fluidised bed combustion. Compared to fixed bed gasifiers the gasification temperature is relatively low: appr. 750-900 °C. In fixed bed gasifiers the temperature in the hearth zone may be as high as 1200 °C, in charcoal gasifiers even 1500 °C. The fuel is fed into a hot (sand) bed which is in a state of suspension (bubbling fluidised bed) or circulating (circulating fluidised bed). The bed behaves more or less like a fluid and is characterized by high turbulence. Fuel particles mix very quickly with the bed material, resulting in a fast pyrolysis and a relatively large amount of pyrolysis gases. Because of the low temperatures the tar-conversion rates are not very high.

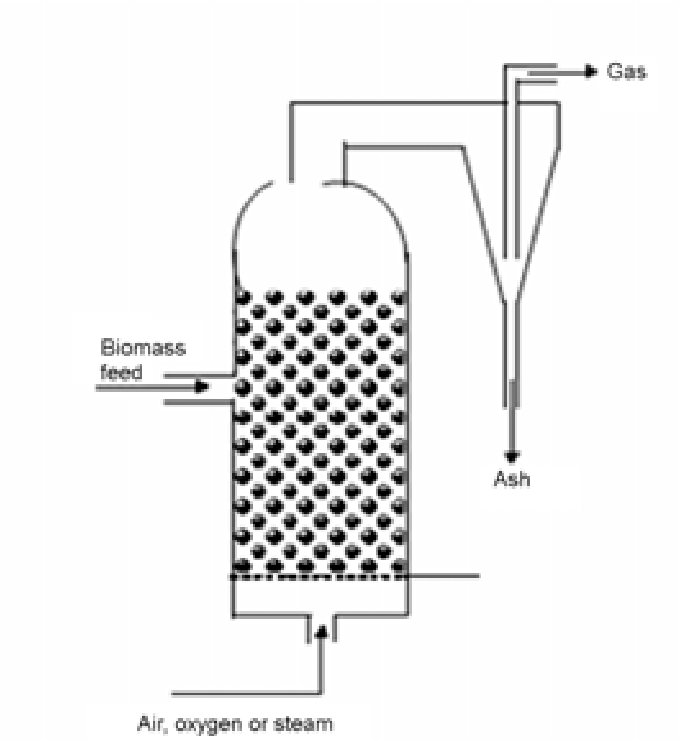


Figure 5: Fluidised bed gasifier_Sengratry/Anna Ingwe_2007

Advantages of fluidised bed reactors in comparison with fixed bed reactors are (Table 2):

- compact construction because of high heat exchange and reaction rates due to the intensive mixing in the bed;
- flexible to changes in fuel characteristics such as moisture and ash content; ability to deal with fluffy and fine grained materials with high ash contents and/or low bulk density;
- relatively low ash melting points are allowed due to the low reaction temperatures.

Table 2: Summarizes a number of important technical and operational parameter values for the different systems/http://www.fao.org/docrep/t0512e/T0512e00.htm#Contents

	Fixed bed down draught	Fluidised bed
Fuel (wood)	10-100	0-20
- ash content (% dry basis)	< 6	< 25
Operating temperature (°C)	800-1400	750-950
Control	Simple	average
Turn down ratio	4	3
Construction material	mild steel + refractory	heat resistant steel
Capacity (MW_{th})	< 2.5	1-50
Start – up time	minutes	hour
Attendance	low	average
Tars (g/Nm^3)	< 3	< 5
LHV (kJ/Nm^3)	4.5	5.1

1.3 Stove design of a down-draught gasifier

In the down-draught gasifier, schematically illustrated in (figure 2), the fuel is introduced at the top, the air is normally introduced at some intermediate level and the gas is taken out at the bottom. It is possible to distinguish four separate zones in the gasifier, each of which is characterized by one important step in the process of converting the fuel to a combustible gas. The processes in these four zones are examined below (figure 6).

1.3.1 Basic gasification process

1.3.1.1 Bunker Section (drying zone)

Solid fuel is introduced into the gasifier at the top. It is not necessary to use complex fuel-feeding equipment, because a small amount of air leakage can be tolerated at this spot. As a result of heat transfer from the lower parts of the gasifier, drying of the wood or biomass fuel occurs in the bunker section.

The water vapour will flow downwards and add to the water vapour formed in the oxidation zone. Part of it may be reduced to hydrogen and the rest will end up as moisture in the gas.

1.3.1.2 Pyrolysis Zone

At temperatures above 250°C, the biomass fuel starts pyrolysing. The details of these pyrolysis reactions are not well known, but one can surmise that large molecules (such as cellulose, hemi-cellulose and lignin) break down into medium size molecules and carbon (char) during the heating of the feedstock. The pyrolysis products flow downwards into the hotter zones of the gasifier. Some will be burned in the oxidation zone, and the rest will break down to even smaller molecules of hydrogen, methane, carbon monoxide, ethane, ethylene, etc. if they remain in the hot zone long enough. If the residence time in the hot zone is too short or the temperature too low, then medium sized molecules can escape and will condense as tars and oils, in the low temperature parts of the system.

1.3.1.3 Oxidation Zone

A burning (oxidation) zone is formed at the level where oxygen (air) is introduced. Reactions with oxygen are highly exothermic and result in a sharp rise of the temperature up to (1200 – 1500)°C.

As mentioned above, an important function of the oxidation zone, apart from heat generation, is to convert and oxidize virtually all condensable products from the pyrolysis zone. In order to avoid cold spots in the oxidation zone, air inlet velocities and the reactor geometry must be well chosen. Generally two methods are employed to obtain an even temperature distribution:

- reducing the cross-sectional area at a certain height of the reactor ("throat" concept),
- spreading the air inlet nozzles over the circumference of the reduced cross-sectional area, or alternatively using a central air inlet with a suitable spraying device.

1.3.1.4 Reduction zone

The reaction products of the oxidation zone (hot gases and glowing charcoal) move downward into the reduction zone. In this zone the sensible heat of the gases and charcoal is converted as much as possible into chemical energy of the producer gas. The end product of the chemical reactions that take place in the reduction zone is a combustible gas which can be used as fuel gas in burners and after dust removal and cooling is suitable for internal combustion engines.

The ashes which result from gasification of the biomass should occasionally be removed from the gasifier. Usually a moveable grate in the bottom of the equipment is considered necessary. This makes it possible to stir the charcoal bed in the reduction zone, and thus helps to prevent blockages which can lead to obstruction of the gas flow.

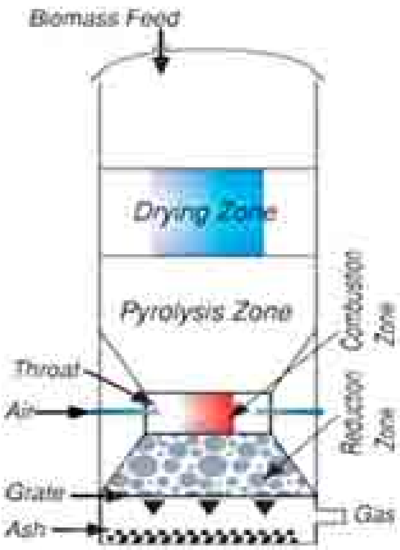


Figure 6: Basic gasification process_Sengratry/Thomas B.Reed_2004

1.3.2 Example of factor to consider in designing a rice husk gasifier stove.

There are several factors to consider in designing a rice husk gasifier stove. Proper consideration of these different factors will be of great help in order to come up with the desired design of the stove and its desired performance. As given below, the different factors that need to be considered in designing a gasifier stove using rice husks as fuel are:

Type of Reactor – The operating performance of the rice husk gas stove basically depends on the type of the reactor used. Although there are several types of combustor that can be used for rice husks, the T-LUD or IDD under the down-draft type gasifier was proven to work well with this waste material as compared with the traditional bottom-lit downdraft type, cross-draft type, or updraft-type reactors. Of the different types of reactor, the T-LUD/IDD has better operating characteristics in terms of ease of starting the fuel, least smoke emitted, and tar produced during operation. Also, it was observed that in this type of reactor, smooth operation of producing gas can be achieved. However, it has one disadvantage: it is difficult to operate in a continuous mode. A cross-draft type reactor is more fitted for a continuous operation except that smoke emission and erratic burning of gas are experienced in this type. Combining these two types in one reactor would be a new approach in the design development of a rice husk gas stove in the future.

Cross-sectional Area of the Reactor – This is the area (figure 7) in which rice husks are burned and this is where the fuel is gasified. The wider the cross-sectional area of the reactor, the stronger the power output of the stove. Uniform gasification can be achieved when the reactor is designed in circular rather than in square or in rectangular cross-section.

Figure 7: The cross-Sectional Area and the Height of the Reactor_Sengratry/ Alexis T.Belonio_2005

Height of the Reactor – The height of the reactor determines the time the gasifier can be operated continuously and the amount of gas that can be produced for a fixed column reactor. Usually, the combustion zone moves down the entire height of the gasifier reactor at a speed of 1 to 2 cm/min. The higher the reactor, however, the more pressure draft is needed to overcome the resistance exerted by the fan or by the blower.

Thickness of Fuel Bed – The thickness of the fuel bed is only considered when designing a cross-draft gasifier. It is the same as that of the height of the reactor in the down-draft gasifier. Similarly, the thicker the layer of fuel in the reactor, the greater is the resistance required for the air to pass through the fuel column. The only advantage in using a thicker column of rice husks is that it slows down the downward movement of the combustion zone in the reactor, which can help in minimizing the erratic production of flammable gas during gasification.

Fan Air flow and Pressure – The fan provides the necessary airflow that is needed for the gasification of rice husks. They are available in AC (figure 8) or DC (figure 9). The fan to be used should be capable enough to overcome the pressure exerted by the rice husks and, subsequently, by the char. A high- pressure fan is usually ideal for down-draft type gasifier reactor, while low-pressure fan isused for cross-draft type reactor. The amount of airflow per unit mass of rice husk is about 0.3 to 0.4 of the stoichiometric air requirement of the fuel. A kilogram of rice husks usually requires about 4.7 kg of air to completely burn the fuel. In case of unavailability of the fuel . A kilogram of rice husks usually requires about 4.7 kg of air to completely burn the fuel. In case of unavailability of suitable longer fan size needed, two fans can be used which are positioned either in parallel or in series which each other. Multi-staging of fan was proven to be effective in increasing the available pressure or the same airflow. Using blowers (figure 10) can overcome pressure in long reactors or those with thicker fuel column. However, the noise produced by its impeller can be destructive to the users.

Figure 8: AC 220V-16W Fan_Sengratry/ Alexis T.Belonio_2005;

Figure 9: DC 12V-3W Fan_Sengratry/ Alexis T.Belonio_2005

Figure 10: AC 220 Volt-1 Amp centrifugal blower_Sengratry/ Alexis T.Belonio_2005

Burner Type - The commonly used LPG- type burner (figure 11) can be utilized for a rice husk gasifier stove. However, there is a need to retrofit the burner design to allow proper combustion of fuel gas. Retrofitting includes enlarging of the inlet pipe of the burner and the provisions of a cone to induce secondary air, thereby making the gas properly ignited and burned. If the burner is to be designed and be fabricated for the rice husk gasifier (figure 12), burner holes of about 3/16 to 1/4 of an inch spaced at 1/8-in. apart were proven to work well with gasified rice husks. The air for combustion should be introduced at the exhaust port of the burner rather than at the inlet port.

Figure 11: Conventional LPG burner_Sengratry/ Alexis T.Belonio_2005

Figure 12: The fabricated gas burner_Sengratry/ Alexis T.Belonio_2005

Insulation for the Reactor - The gasifier reactor needs to be properly insulated for two reasons: First, this will provide better conversion of rice husk fuel into gas. Second, this will prevent burning of skin when they accidentally touch the reactor's surface. Rice husk ash (figure 13) was found to be the cheapest and the most effective insulation material for rice husk gas stove. Concrete mixed with rice husk, at a proportion of 1:1, can also be used as an insulator. However, the reactor will become heavier and freight cost would be more expensive.

Figure 13: The rice husk ash_Sengratry/ Alexis T.Belonio_2005

Location of Firing the Fuel - Rice husk fuel can be fired in the stove in different ways. For fixed bed gasifiers, like the down-draft reactor, rice husk fuel can be fired starting from the top (Top Lit) (figure 14) or from the bottom (Bottom Lit) of the reactor. So far, for an inverted down-draft type gasifier, firing the fuel on top is the best and easiest way. Firing the fuel in this manner minimizes smoke emission. However, reloading of fuel in between operation is not possible. Experience on the previous stove design revealed that reloading of fuel during operation is only possible when burning of fuel starts from the bottom of the reactor. The other advantage of firing from the bottom is that the total start-up time for the same height of the reactor can be extended, which cannot be done when firing the fuel from the top of the reactor.

Figure 14: Firing fuel on top of the reactor_Sengratry/ Alexis T.Belonio_2005

Size and Location of the Char Chamber – The size of the chamber for carbonized rice husks (figure 15) determines the frequency of unloading the char or the ash. Bigger chamber can accommodate larger amount of char and can allow longer time before the char is removed. In addition, designing a shorter chamber will give sufficient height for the stove reactor and the burn If the desired by-product of gasification is char, the size the chamber should not be too big so that it will only require a shorter time before it is discharged. The hot char discharged from the reactor undergoes further burning which will consequently convert the char into ash. To properly discharge the ash or the char from the reactor, the angle of friction at the bottom of the chamber hopper should be at 45 degrees. In the case of limited angle, scraper or scoop will be needed to properly discharge the ash or the char.

Figure 15: The char chamber_Sengratry/Alexis T.Belonio_2005

Safety Considerations - Operating the stove requires safety. Therefore, safety considerations should be part of the stove design. In this regard, a safety shield is incorporated in the design of the stove to prevent the cook or the children from getting in direct contact with the hot reactor. Pot support, such as a ring holder or protruded bars, is welded to the burner and to the pot support assembly to prevent the pot from accidentally sliding.

1.3.3 Design Calculations for an downdraught gasifier

Below are some important parameters that need to be considered in determining the appropriate size of the rice husk gas stove, taking into consideration the power output desired. The size of the stove can be easily estimated by computing these parameters.

1.3.3.1 Energy demand

Energy Demand - This refers to the amount of heat that needs to be supplied by the stove. This can be determined based on the amount of food to be cooked and/or water to be boiled and their corresponding specific heat energy as shown in Table 3 below

Table 3: Energy Requirement for Cooking Food and for Boiling Water/http://www. fao.org/docrep/t0512e/T0512e00.htm#Contents

Food	Specific heat (kcal/kg.°C)	Total energy needed (kcal/kg)*
Rice	0.42-0.44	79.3
Meat	0.48-0.93	56.5
Vegetables	0.93	74.5
Water	1.0	72

* at 72 °C temperature difference

The amount of energy needed to cook food can be calculated using the formula,

$$Q_n = \frac{M_f \ x \ E_s}{T} \quad ; \qquad (1)$$

Where:

Q_n - energy needed, kcal/hr

M_f - mass of food, kg

E_S - specific energy, kcal/kg

T - cooking time, hr

Example. A kilogram of rice has to be cooked within 15 minutes, what is the energy needed to cook the rice?

Q_n = (1 kg x 79.3 kcal/kg x 60 min/hr) / 15 minutes = 317.2 kcal/hr

1.3.3.2 Fuel demand

Energy Input – This refers to the amount of energy needed in terms of fuel to be fed into the stove. This can be computed using the formula,

$$FCR = \frac{Q_n}{HV_f \times \xi_g}; \qquad 2$$

where:

FCR - fuel consumption rate, kg/hr

Q_n - heat energy needed, Kcal/hr

HV_f - heating value of fuel, Kcal/kg

ξ_g - gasifier stove efficiency, %

Example. What is the amount of fuel needed per hour for a rice husk gas stove to be used to cook rice in the example given above? Assume a stove efficiency of 17%.

FCR = 317.2 kcal/hr / (3000 kcal/kg x 0.17) = 0.62 kg rice husk per hour

1.3.3.3 Reactor Diameter

This refers to the size of the reactor in terms of the diameter of the cross-section of the cylinder where rice husks are being burned. This is a function of the amount of the fuel consumed per unit time (FCR) to the specific gasification rate (SGR) of rice husks, which is in the range of 110 to 210 kg/m^2 -hr or 5 to 130 as revealed by the results of several test on rice husk gas stoves. As shown below, the reactor diameter can be computed using the formula,

$$D = \left(\frac{1.27x\ FCR}{SGR} \right)^{0,5}; \qquad 3$$

where:

D - diameter of reactor, m

FCR - fuel consumption rate, kg/hr

SGR - specific gasification rate of rice husk, 110-210 kg/m^2-hr

Example. For a rice husk gas stove with a required fuel consumption rate of 2 kg per hour, the computed diameter for the fuel reactor using specific gasification rate of 100 kg/m^2 -hr will be,

D = [1.27 (2 kg per hour) / 100 kg/m -hr] $^{0.5}$ = 0.15 m

1.3.3.4 Height of the Reactor

This refers to the total distance from the top and the bottom end of the reactor. This determines how long would the stove be operated in on loading of fuel. Basically, it is a function of a number of variables such as the required time to operate the gasifier (T), the specific gasification rate (SGR), and the density of rice husks (ρ). As shown below, the height the reactor an be computed using the formula,

$$H = \frac{SGRxT}{\rho}; \qquad \textbf{4}$$

where:

H - length of the reactor, m

SGR - specific gasification rate of rice husk, kg/m^2 -hr

T - time required to consume rice husk, hr

ρ - rice husk density,kg/m^3

Example. If the desired operating time for the gasifier stove above is 1 hour, assuming a rice husk density of 100 kg/m^3 for the gasifier, the height of the reactor will be,

H = [(100 kg/m^2 -hr x 1 hour) / 100 kg/m^3] = 1 m

1.3.3.5 Time to Consume Rice Husk

This refers to the total time required to completely gasify the rice husks inside the reactor. This includes the time to ignite the fuel and the time to generate gas, plus the time to completely burn all the fuel in the reactor. The density of the rice husk (ρ), the volume of the reactor (Vr), and the fuel consumption rate (FCR) are the factors used in determining the total time to consume the rice husk fuel in the reactor. As shown below, this can be computed using the formula,

$$T = \frac{\rho \times V_r}{FCR}; \qquad \textbf{5}$$

where:

T - time required to consume the rice husk, hr

V_r - volume of the reactor, m^3

ρ - rice husk density,kg/m^3

FCR - rate of consumption of rice husk, kg/hr

Example. A 20-cm diameter rice husk gas stove with a 1.2-m high reactor is to be operated at a fuel consumption rate of 2.5 kg/hr. The time required to operate the stove will be,

T = [100 kg/m x ? (0.20 m) (1.2 m) / 4] / 2.5 kg/hr = 1.5 hours

1.3.3.6 Amount of Air Needed for Gasification

This refers to the rate of flow of air needed to gasify rice husks. This is very important in determining the size of the fan or of the blower needed for the reactor in gasifying rice husks. As shown, this can be simply determined using the rate of consumption of rice husk fuel (FCR), the stoichiometric air of rice husk (SA), and the recommended equivalence ratio (ρ for gasifying rice husk of 0.3 to 0.4. As shown, this can be computed using the formula,

$$AFR = \frac{\varepsilon \times FCR \times SA}{\rho_a}; \qquad \textbf{6}$$

where:

AFR - air flow rate, m^3 /hr

ε - equivalence ratio, 0.3 to 0.4

FCR - rate of consumption of rice husk, kg/hr

SA - stoichiometric air of rice husk, 4.5 kg air per kg rice husk

ρ_a - air density, 1.25 kg/m^3

Example. The fuel consumption rate required for the husk gas stove is 2.5 kg per hour. The amount of air needed in order to gasify the fuel would be,

AFR = [0.3 (2.5 kg/hr) (4.5 kg air/ kg rice husk) /(1.25 kga/m^3)] = 2.7 m^3 /hr

1.3.3.7 Superficial Air Velocity

This refers to the speed of air flow in the fuel bed. The velocity of air in the bed rice husks will cause channel formation, which may greatly affect gasification. The diameter of the react (D) and the airflow rate (AFR) determine the superfic velocity of air in the gasifier. As shown, this can be computed using the formula,

$$VS = \frac{4xAFR}{D^2}; \qquad \textbf{7}$$

where:

Vs - superficial gas velocity, m/s

AFR - air flow rate, m^3 /hr

D - diameter of reactor, m

Example. For the stove in the example above with computed air flow rate of 2.7 m^3 per hour and a reactor diameter of 20 cm, the superficial velocity of air will be,

Vs = [4 (2.7 m^3 /hr) / 3.14 (0.2 m)^2] = 85.9 m^3/hr x 100 cm/m x hr/3600 sec = 2.38 cm/sec

1.3.3.8 Resistance to Airflow

This refers to the amount of resistance exerted by the fuel and by the char inside the reactor during gasification. This is important in determining whether a fan or a blower is needed for the reactor. The thickness of the fuel column (Tf) and the specific resistance (Sr) of rice husk, will give enough information for the total resistance needed for the fan or the blower. As shown, this can be computed using the formula,

$R_f = T_f \text{ x } R_f$; **8**

where:

R_f - resistance of fuel, cm of H_2O

T_f - thickness of fuel column, m

S_r - specific resistance, cm of water/m of fuel

Example. A 1-meter fuel column reactor with superficial air velocity of 2.38 cm/sec will have a specific pressure resistance of 0.5 cm water per m depth of fuel. Therefore, the calculated resistance needed by the fan or by the blower will be,

Rf = [1 meter x 0.5 cm water per m depth of fuel) = 0.5 cm of water

Figure 16: The rice husk gas stove_Sengratry/Alexis T.Belonio_2005

1.3.4 Wood Gas/Juntos small gasifiers With Forced Air

There are only three main components to the designs of the Wood Gas/Juntos small gasifiers with forced air. Their principal characteristics are listed below, but many variations are possible. We present the three components of the gasifier-combustion units. We do not address here the wide varieties of devices for the use of the heat, the most common of which are a “stove” structure (legs, chimney, plancha, etc.), pot, oven, drier, and room heater. The gasifier can work with a full variety of applications of heat (figure).

The “combustion unit” or “fuel unit” (made from two cylindrical “cans”)

Fuel chamber:

This cylindrical container 10 cm (4 inches) in diameter and 6 to 8 inches tall, with closed bottom and open top, has twelve primary-air holes of 7/64 inch diameter (almost 1/8 inch) evenly spaced around the can about 1 cm (half inch) above the bottom of the can. It also has thirty-two secondary-air holes of 11/64 inch diameter (almost 3/16 inch) evenly spaced around the can about 2.5 cm (1 inch) down from the top. Although tin cans will suffice, better steel helps withstand the temperatures of pyrolysis (approx. 400°C.) and of burning charcoal (over 900°C). This chamber is the most critical part of the small gasifiers because a one-to-five ratio of primary to secondary air (allowing for resistance by the fuel) is extremely important.

Outer cylinder for air control:

This cylindrical container is 15 cm (6 inches) in diameter with the same or slightly less height as the fuel chamber, with an open bottom, and a sealed top, through which the fuel chamber is inserted approximately 1.5 cm (half inch) and attached using heat-tolerant rivets, screws, spot-welds, clamps, etc. (Avoid aluminum and plastic fasteners). The attachment of a heat-tolerant handle on this outer cylinder is highly recommended but is not considered to be a separate piece.

Air base. The above described combustion unit is to be placed on top of the air base, a component that will direct the forced air upward to enter the primary and secondary air holes. Gravity holds the combustion unit on top of a flat-topped air base, preventing major leakage of the air. The air base must be sufficiently open on the top to allow the passage of the forced air upward into the combustion unit, sufficiently sealed on the sides and bottom to prevent the escape of the forced air, and with provision of access (side or bottom) for the entry of the forced air. Note that the device to provide the forced air (a fan or a blower) could be incorporated into the air base or could be external to the air base.

Fan or blower. For each kg of fuel burned, approximately six cubic meters (6 m) of air needs to be delivered with sufficient force and control. Surplus airflow is not a crucial concern because one blower could service several air bases or have controls as simple as a baffle to reduce the flow. If available, electricity (via any grid, battery, or photo-voltaic device) is the simplest power for using fans and blowers. A typical hair-dryer blower would be far too much power. Small one-watt DC electric motors can be sufficient power for a fan if properly ducted via the air base. A small battery (perhaps recharged by solar photo-voltaic cells or at a recharge shop) can provide hours of forced air, depending on the configuration of the air base. Peltier effect thermoelectric devices could be used, being powered by the heat of the stove itself. Manual power can be used but would require the person to be present continually or also require a storage mechanism. A wind-up spring mechanism is being considered. Stirling engines or steam ejectors also could be adapted. Households and societies can choose from several acceptable options to obtain the forced air.

Note that Reed's "Wood Gas CampStove" has the air base and the fan built into the lower part of the outer cylinder. This has advantages and disadvantages depending on the user's intentions. It also has four “pot supports” on top, and therefore is a totally self-contained stove.

2 Sources for gasifier power generation

2.1 Charcoal

Because good quality charocal contains almost no tars it is a feasible fuel for all types of gasifiers. Good gasifier charcoal is low in mineral matter and does not crumble or disintegrate easily (figure 17). The major disadvantages are the relatively high cost of charcoal, which reduces its competitiveness as compared to liquid fuel, and the energy losses which occur during charcoal manufacture (up to 70% of the energy originally present in the wood may be lost). This latter factor may be of special importance for those developing countries which already suffer from an insufficient biomass energy base to cater for their domestic energy requirements.

Experience has shown that most types of wood as well as some agricultural residues (e.g. coconut shell) can provide first class gasification charcoal.

Figure 17: Charcoal production from wood processing wastes (wood chips)_Source: Khamphone (own collection)

2.2 Wood sources

Wood. Most wood species have ash contents below two percent and are therefore suitable fuels fox fixed bed gasifiers (figure 18). Because of the high volatile content of wood, updraught systems produce a tar-containing gas suitable mainly for direct burning. Cleaning of the gas to make it suitable for engines is rather difficult and capital and labour intensive. Downdraught systems can be designed to deliver a virtually tar-free product gas in a certain capacity range when fuelled by wood blocks or wood chips of low moisture content. After passing through a relatively simple clean-up train the gas can be used in internal combustion engines.

Figure 18: Wood logs and chips

Sawdust. Most currently available downdraught gasifiers axe not suitable for unpelletized sawdust (figure 19). Problems encountered axe: excessive tar production, inadmissible pressure drop and lack of bunker flow. Fluidized bed gasifiers can accommodate small sawdust particles and produce burner quality gas. For use in engines, a fairly elaborate clean-up system is necessary.

Figure 19: Sawdust _Source: Khamphone (own collection)

Peat. The biggest problems in gasification of peat is encountered with its high moisture content and often also with its fairly high ash content. Up-draught gasifiers fuelled with sod peat of approximately 30 - 40% moisture content have been installed in Finland fox district heating purposes and small downdraught gasifiers fuelled with fairly dry peat-pellets have been successfully tested in gas-engine applications. During the Second World War a lot of transport vehicles were converted to wood or peat gas operation, both in Finland and Sweden.

2.3 Agricultural sources

Agricultural residues. In principle, developing countries have a wide range of agricultural residues available for gasification.

In practice, however, experience with most types of waste is extremely limited. Coconut shells and maize cobs axe the best documented and seem unlikely to create serious problems in fixed bed gasifiers. Coconut husks axe reported to present bridging problems in the bunker section, but the material can be gasified when mixed with a certain quantity of wood. Most cereal straws have ash contents above ten per cent and present slagging problems in downdraught gasifiers . Rice husks can have ash contents of 20 percent and above and this is probably the most difficult fuel available (figure 20). Research into downdraught gasifier designs fox this material is continuing while published information indicates that Italian up-draught gasifiers have been powering small rice mills for decades. The system seems to have been revived in China, where a number of up-draught gasifiers axe reported to be in operation.

Figure 20: Unused Rice husk behind the rice mill_ Source: Khamphone (own collection)

It is possible to gasify most types of agricultural waste in pre-war design up-draught gasifiers. However, the capital, maintenance and labour costs, and the environmental consequences (disposal of tarry condensates) involved in cleaning the gas, prevent engine applications under most circumstances. Downdraught equipment is cheaper to install and operate and creates fewer environmental difficulties, but at present technology is inadequate to handle agricultural residues (with the possible exception of maize cobs and coconut shells) without installing expensive (and partly unproven) additional devices.

Even for coconut shells and maize cobs, the information available is based on a limited number of operating hours and must be further verified under prolonged (say 10000 hours) tests in practical conditions. Fluidized bed gasifiers show great promise in gasifying a number of "difficult" agricultural wastes. Currently, only semi-commercial installations are available and operating experience is extremely limited. It is for this reason that no immediate application in developing countries is foreseen.

3 Fundamentals of gasification production

What is gasification?

Gasification is a process that converts carbonaceous materials, such as coal, petroleum, or biomass, into carbon monoxide and hydrogen by reacting the raw material at high temperatures with a controlled amount of oxygen (figure 21). The resulting gas mixture is called synthesis gas or syngas and is itself a fuel. Gasification is a very efficient method for extracting energy from many different types of organic materials, and also has applications as a clean waste disposal technique.

Gasification of fossil fuels is currently widely used on industrial scales to generate electricity. However, almost any type of organic material can be used as the raw material for gasification, such as wood, biomass, or even plastic waste. Thus, gasification may be an important technology for renewable energy. In particular biomass gasification is carbon neutral.

Gasification relies on chemical processes at elevated temperatures >700°C, which distinguishes it from biological processes such as anaerobic digestion that produce biogas.

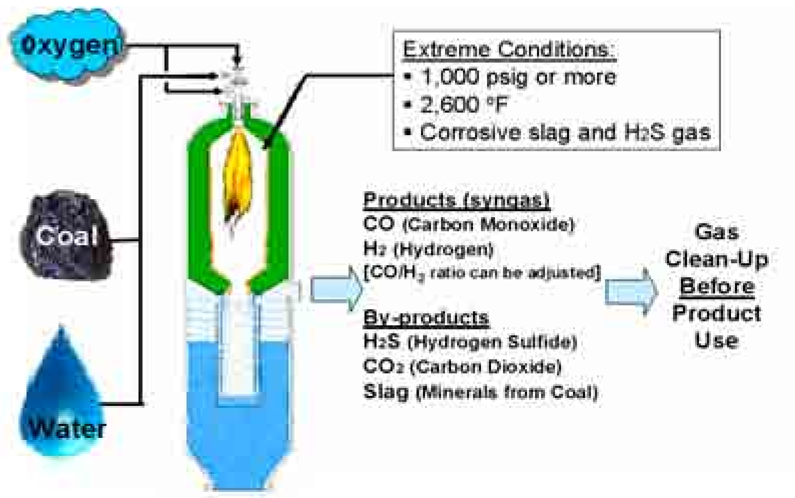


Figure 21: Gasification process_Sengratry/Gary J.Stiegel_2005

3.1 Technical basics and prerequisites

Need for selection of right gasifier for each fuel. Biomass fuels available for gasification include charcoal, wood and wood waste (branches, twigs, roots, bark, woodshavings and sawdust) as well as a multitude of agricultural residues (maize cobs, coconut shells, coconut husks, cereal straws, rice husks, etc.) and peat.

Because those fuels differ greatly in their chemical, physical and morphological properties, they make different demands on the method of gasification and consequently require different reactor designs or even gasification technologies. It is for this reason that, during a century of gasification experience, a large number of different gasifiers has been developed and marketed, all types geared towards handling the specific properties of a typical fuel or range of fuels.

Each type of gasifier will operate satisfactorily with respect to stability, gas quality, efficiency and pressure losses only within certain ranges of the fuel properties of which the most important are:

3.1.1 Energy content

The choice of a fuel for gasification will in part be decided by its heating value. The method of measurement of the fuel energy content will influence the estimate of efficiency of a given gasification system. Reporting of fuel heating values is often confusing since at least three different bases are used:

- fuel higher heating values as obtained in an adiabatic bomb calorimeter. These values include the heat of condensation of the water that is produced during combustion. Because it is very difficult to recover the heat of condensation in actual gasification operations these values present a too optimistic view of the fuel energy content;
- fuel higher heating values on a moisture-free basis, which disregard the actual moisture content of the fuel and so provide even more optimistic estimates of energy content;
- fuel higher heating values on a moisture and ash free basis, which disregard the incombustible components and consequently provide estimates of energy content too high for a given weight of fuel, especially in the case of some agricultural residues (rice husks).

The only realistic way therefore of presenting fuel heating values for gasification purposes is to give lower heating values (excluding the heat of condensation of the water produced) on an ash inclusive basis and with specific reference to the actual moisture content of the fuel. Average lower heating values of wood, charcoal and peat are given in Table 4

Table 4: Average lower heating values/http://www.fao.org/docrep/t0512e /T0512e00.htm#Contents

Fuel	Moisture content (%) 1/	Lower heating value (kJ/kg)
Wood	20 – 25	13 – 15000
Charcoal	2 – 7	29 – 30000
Peat	35 – 50	12 – 14000

1/ per cent of dry weight

3.1.2 Moisture content

The heating value of the gas produced by any type of gasifier depends at least in part on the moisture content of the feedstock.

Moisture content can be determined on a dry basis as well as on a wet basis. In this chapter the moisture content (M.C.) on a dry basis will be used.

Moisture content is defined as:

$$MC_{dry} = \frac{\text{wet weight - dry weight}}{\text{dry weight}} \times 100\% \quad \textbf{9}$$

Alternatively the moisture content on a wet basis is defined as:

$$MC_{wet} = \frac{\text{wet weight - dry weight}}{\text{wet weight}} \times 100\% \quad \textbf{10}$$

Conversions from one to another can be obtained by:

$$MC_{dry} = \frac{100 \times MC_{wet}}{100 + MC_{wet}}; \quad \textbf{11}$$

and:

$$MC_{wet} = \frac{100 \times MC_{dry}}{100 + MC_{dry}}; \quad \textbf{12}$$

High moisture contents reduce the thermal efficiency since heat is used to drive off the water and consequently this energy is not available for the reduction reactions and for converting thermal energy into chemical bound energy in the gas. Therefore high moisture contents result in low gas heating values. When the gas is used for direct combustion purposes, low heating values can be tolerated and the use of feedstocks with moisture contents (dry basis) of up to 40 - 50 percent is feasible, especially when using up-draught gasifiers.

In downdraught gasifiers high moisture contents give rise not only to low gas heating values, but also to low temperatures in the oxidation zone, and this can lead to insufficient tar converting capability if the gas is used for engine applications.

Both because of the gas heating value (engines need gas of at least 4200 kJ/m³ in order to maintain a reasonable efficiency) and of the tar entrainment problem, downdraught gasifiers need reasonably dry fuels (less than 25 percent moisture dry basis).

3.1.3 Volatile matters

The amount of volatiles in the feedstock determines the necessity of special measures (either in design of the gasifier or in the layout of the gas cleanup train) in order to remove tars from the product gas in engine applications. In practice the only biomass fuel that does not need this special attention is good-quality charcoal.

The volatile matter content in charcoal however is often underestimated and in practice may be anything from 3 to 30 percent or more. As a general rule if the fuel contains more than 10 percent volatile matter it should be used in downdraught gas producers, but even in this case the method of charcoal production should be taken into account. Charcoal produced in large scale retorts is fairly consistent in volatile matter content, but large differences can be observed in charcoal produced from small scale open pits or portable metal kilos that are common in most developing countries.

3.1.4 Ash content and ash chemical composition

Ashes can cause a variety of problems particularly in up or downdraught gasifiers. Slagging or clinker formation in the reactor, caused by melting and agglomeration of ashes, at the best will greatly add to the amount of labour required to operate the gasifier If no special measures are taken, slagging can lead to excessive tar formation and/or complete blocking of the reactor. A worst case is the possibility of air-channelling which can lead to a risk of explosion, especially in up-draught gasifiers.

Whether or not slagging occurs depends on the ash content of the fuel, the melting characteristics of the ash, and the temperature pattern in the gasifier. Local high temperatures in voids in the fuel bed in the oxidation zone, caused by bridging in the bed, may cause slagging even using fuels with a high ash melting temperature.

In general, no slagging is observed with fuels having ash contents below 5-6 percent. Severe slagging can be expected for fuels having ash contents of 12 percent and above. For fuels with ash contents between 6 and 12 percent, the slagging behaviour depends to a large extent on the ash melting temperature, which is influenced by the presence of trace elements giving rise to the formation of low melting point eutectic mixtures.

For gasification purposes the melting behaviour of the fuel ash should be determined in both oxidating and reducing atmospheres.

As far as ash content is concerned, raw wood and wood charcoals seldom present problems, the ash content being normally from 0.75 to 2.5 percent. However, in a number of tropical woods charcoal ash contents may be much higher and those charcoal types are unsuitable for gasification purposes. Table 5 lists agricultural residues which have been tested with respect to their slagging properties in a small downdraught laboratory gas producer.

Table 5: Slagging of agricultural residues in a small laboratory down draught gasifier/Jenkins.1990

Slagging fuels	Ash content percent	Degree of slagging
Barley straw mix	10.3	Severe
Bean straw	10.2	"
Corn stalks	6.4	Moderate
Cotton gin trash	17.6	Severe
Cubed cotton stalks	17.2	"
RDF pellets 1/	10.4	"
Pelleted rice hulls	14.9	"
Safflower straw	6.0	Minor
Pelleted walnut shell mix	5.8	Moderate
Wheat straw and corn stalks	7.4	Severe

1/ RDF = refuse derived fuel

Table 6: Non Slagging fuels/Jenkins.1990

Non slagging fuels	
Cubed alfalfa seed straw	6.0
Almond shell	4.8
Corn cobs	1.5
Olive pits	3.2
Peach pits	0.9
Prune pits	0.5
Walnut shell (cracked)	1.1
Douglas fir wood blocks	0.2
Municipal tree prunings	3.0
Hogged wood manufacturing residues	0.3
Whole log wood chips	0.1

3.1.5 Reactivity

The reactivity is an important factor determining the rate of reduction of carbon dioxide to carbon monoxide in a gasifier. Reactivity influences the reactor design insofar as it dictates the height needed in the reduction zone. In addition certain operational characteristics of the gasification system (load following response, restarting after temporary shutdown) are affected by the reactivity of the char produced in the gasifier. Reactivity depends in the first instance on the type of fuel. For example, it has been observed that fuels such as wood, charcoal and peat are far more reactive than coal. Undoubtedly, there is a relation between reactivity and the number of active places on the char surface, these being influenced by the morphological characteristics as well as the geological age of the fuel. The grain size and the porosity of the char produced in the reduction zone influence the surface available available for reduction and, therefore, the rate of the reduction reactions.

It is well known that the reactivity of char can be improved through various processes such as steam treatment (activated carbon) or treatment with lime and sodium carbonate.

Another interesting point is the assumed positive effect on the rate of gasification of a number of elements which act as catalysts. Small quantities of potassium, sodium and zinc can have a large effect on the reactivity of the fuel.

3.1.6 Particle size and size distribution

Up and downdraught gasifiers are limited in the range of fuel size acceptable in the feed stock. Fine grained and/or fluffy feedstock may cause flow problems in the bunker section of the gasifier as well as an inadmissible pressure drop over the reduction zone and a high proportion of dust in the gas. Large pressure drops will lead to reduction of the gas load of downdraught equipment, resulting in low temperatures and tar production.

Excessively large sizes of particles or pieces give rise to reduced reactivity of the fuel, resulting in startup problems and poor gas quality, and to transport problems through the equipment. A large range in size distribution of the feedstock will generally aggravate the above phenomena. Too large particle sizes can cause gas channelling problems, especially in updraught gasifiers.

Acceptable fuel sizes fox gasification systems depend to a certain extent on the design of the units. In general, wood gasifiers operate on wood blocks and woodchips ranging from 8 x 4 x 4 cm. to 1 x 0.5 x 0.5 cm. Charcoal gasifiers are generally fuelled by charcoal lumps ranging between 1 x 1 x 1 cm. and 3 x 3 x 3 cm. Fluidized bed gasifiers are normally able to handle fuels with particle diameters varying between 0.1 and 20 mm.

3.1.7 Bulk density

Bulk density is defined as the weight per unit volume of loosely tipped fuel. Fuels with high bulk density are advantageous because they represent a high energy-for-volume value. Consequently these fuels need less bunker space for a given refuelling time. Low bulk density fuels sometimes give rise to insufficient flow under gravity, resulting in low gas heating values and ultimately in burning of the char in the reduction zone. Average bulk densities of wood, charcoal and peat are given in Table 7. Inadequate bulk densities can be improved by briquetting or pelletizing.

Table 7: Average bulk densities/Jenkins.1990

Fuel	Bulk density (kg/m³) 1/
Wood	300 – 550
Charcoal	200 – 300
Peat	300 – 400

1/ The bulk density varies significantly with moisture content and particle size of the fuel.

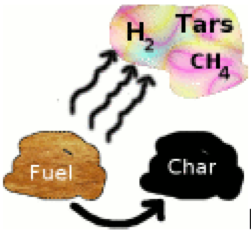
3.1.8 Charring properties

The occurrence of physical and morphological difficulties with charcoal produced in the oxidation zone has been reported. Some feedstocks (especially softwoods) produce char that shows a tendency to disintegrate. In extreme cases this may lead to inadmissible pressure drop.

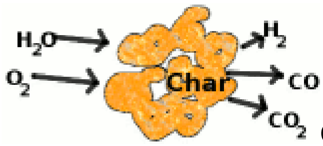
A number of tropical hardwoods (notably teak) are reported to call for long residence times in the pyrolysis zone, leading to bunker flow problems, low gas quality and tar entrainment.

3.2 Thermochemical reactions

In a gasifier, the carbonaceous material undergoes several different processes (figure 22-23):



Pyrolysis of carbonaceous fuels



Gasification of char

Figure 22: Thermo-chemical reactions_Sengratry/Steve Ienkins_2007

Pyrolysis or devolatilization process. The *pyrolysis* (or devolatilization) process occurs as the carbonaceous particle heats up. Volatiles are released and char is produced, resulting in up to 70% weight loss for coal. The process is dependent on the properties of the carbonaceous material and determines the structure and composition of the char, which will then undergo gasification reactions.

Combustion process The *combustion* process occurs as the volatile products and some of the char reacts with oxygen to form carbon dioxide and carbon monoxide, which provides heat for the subsequent gasification reactions.

Gasification process. The *gasification* process occurs as the char reacts with carbon dioxide and steam to produce carbon monoxide and hydrogen.

In addition, the reversible gas phase water gas shift reaction reaches equilibrium very fast at the temperatures in a gasifier. This balances the concentrations of carbon monoxide, steam, carbon dioxide and hydrogen.

3.3 Utilization of Producer or Wood gas

Most gasifiers in commercial operation today are used for the production of heat, rather than fuel for internal combustion engines, because of the less stringent requirements for gas heating value and tar content. The fundamental advantage of a gasifier close coupled to a burning system is its ability to produce higher temperatures than can be achieved with conventional grate, combustion, liable to slagging problems at such temperatures, and in consequence its enhancement of boiler efficiency and output.

All types of gasifiers described in Section 1 can provide producer gas for combustion purposes, but for the sake of simplicity up-draught gasifiers are preferred in small systems (below 1 MW thermal power), while fluidised bed gasifiers are appropriate in power ranges above this level.

Most conventional oil-fired installations can be converted to producer gas.

The most potential users of low-calorific fuel-gas in the future are expected to be found among the following industries: metallurgy, ceramic, cement, lime and pulp. In these industrial branches the conversion of kilns, boilers and driers from oil to fuel gas operation is in principal a quite simple operation.

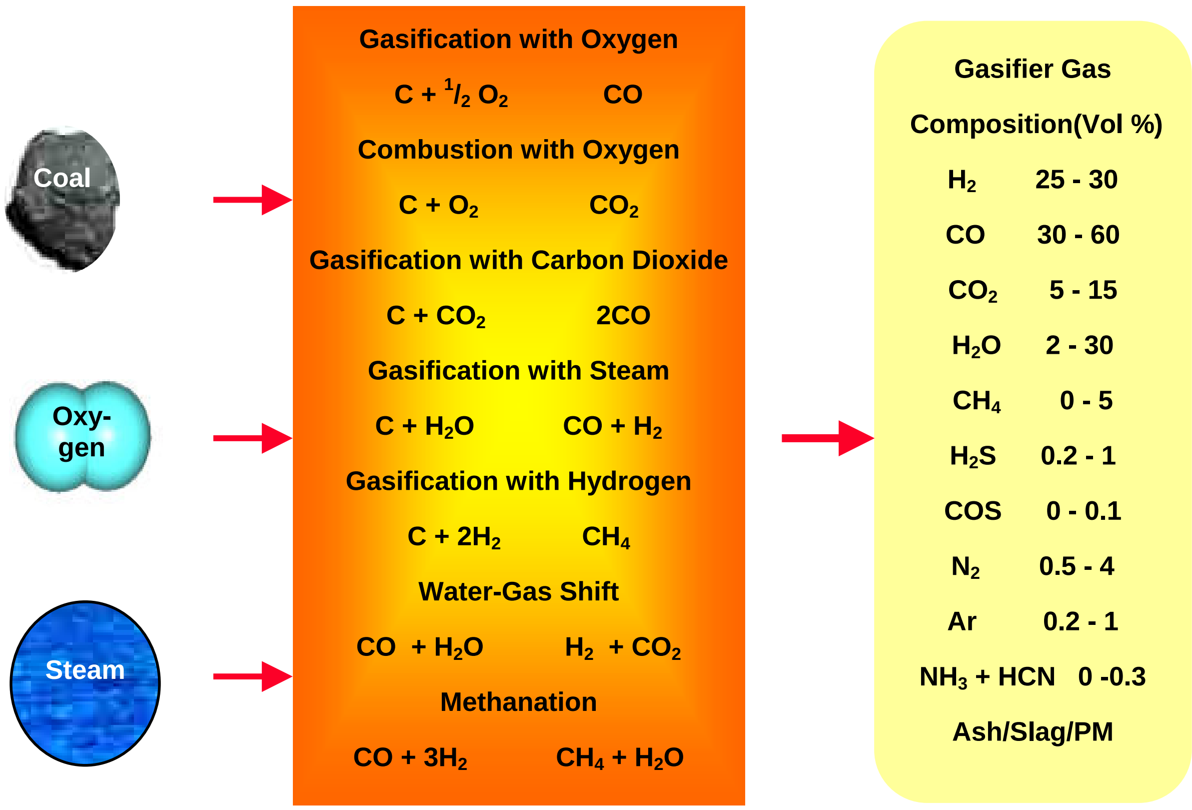


Figure 23: Gasification reaction_Sengratry/Steve Jenkins_2007

3.4 Rocket stoves

The rocket stove (figures 24-25) is a variety of wood-burning cooking stove. It is easy to construct, and it uses low-cost materials. The rocket stove's main components are:

- Chimney: a metal box (such as a 5-gallon tin can) or pipe standing vertically and supporting the cooking vessel
- Fuel magazine: a short length of steel or ceramic pipe fitted horizontally into the base of a chimney
- Fuel shelf: a flat plate to hold the fuel clear of the bottom of the magazine to allow air to flow underneath
- Heat exchanger: a tubular metal shield that forces hot gases from the chimney to pass over the sides of the cooking vessel

Overview

It operates roughly twice as efficiently, and substantially more cleanly, than the open fire cooking methods still used in many areas of the world. Furthermore, the design of the stove requires small diameter lengths of wood, which can generally be satisfied with small branches. As such, sufficient fuel for cooking tasks can be gathered in less time, without the benefit of tools, and ideally without the destruction of forested areas.

Because these qualities improve local air quality, and discourage deforestation, the rocket stove has attracted the attention of a number of Appropriate Technology concerns, which have deployed it in numerous third-world locales (notably, the Rwandan refugee camps). This attention has resulted in a number of adaptations intended to improve convenience and safety, and thus the size of the target audience. The Junta Stove, for example, is a cousin of the rocket stove adapted for indoor use and family cooking needs.

Traditional cooking method

A rocket stove addresses the environmental problems of using an open pit fire for cooking and home heating, the most important concern being indoor air quality. Biomass fuels release large amounts of air pollutants when burned on traditional open pit fire, and these pollutants become concentrated in inadequately ventilated homes and dwellings.

Another concern with traditional wood fires is the inefficiency of fuel consumption. Traditional open pit wood fires are very efficient at turning wood into energy, but inefficient at transferring the released energy into the cooking vessel. Most of the released energy in the wood is wasted heating the surrounding air rather than heating the cooking vessel. The inefficient transfer of energy requires the use of more wood, which has to be harvested from the surrounding environment, causing environmental stress.

The third drawback of traditional wood fires is the danger to children. Because open fires are located on the floor of the dwelling, children can easily fall into the fire.

Benefits

The main justifications for rocket stoves are economical, social, and environmental. Stove programs can produce economic benefits, saving time and money for the users. In urban areas where people purchase biomass fuel, the payback time for the cost of a rocket stove is short, thus saving on the cost of fuel.

Rocket stoves can help reduce the over-harvesting of trees. Improved indoor air quality and fuel efficiency have social and health benefits, especially for women and children. In order to reduce indoor air pollution, rocket stoves must improve combustion of the wood fuel, which means reducing the amount of smoke and harmful emissions produced during the burning process. The key to efficient combustion is to burn wood at a high temperature, and there are several ways to achieve this:

- A good air draft into the fire
- Insulation around the fire
- Metering the fuel

The most important factor, metering the fuel, requires only the burning portion of the wood to be heated. Fully burned biomass fuel produces less smoke and emissions.

The main way to improve the fuel efficiency of rocket stoves is to improve the heat transfer from the fire to the cooking vessel. Most importantly, the hot air and gas released from the fire must contact the cooking vessel over the largest possible surface area. This is accomplished through the use of a pot skirt that creates a narrow channel forcing hot air and gas to flow along the bottom and sides of the cooking vessel. Heat transfer can also be increased by using wide pots. Increasing the speed of the hot gases that flow around the pot can also improve heat transfer.

Rocket stoves are insulated and lifted off of the floor. This reduces the danger of children burning themselves, which is an important improvement over traditional open pit fires.

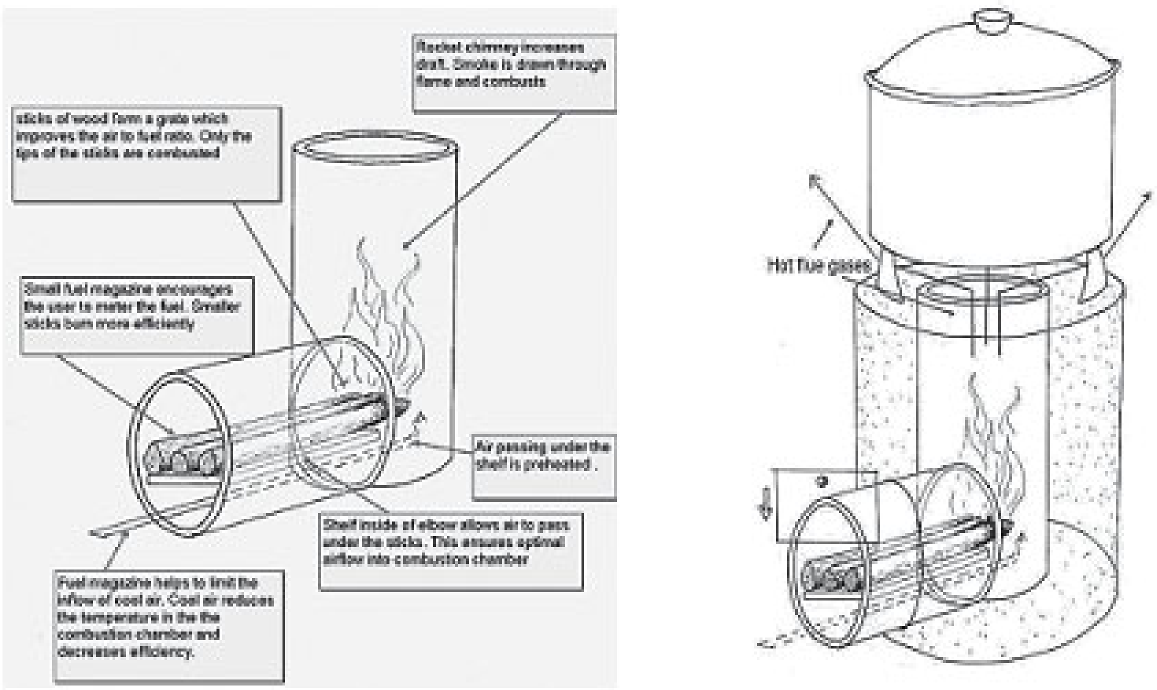


Figure 24: Diagrams showing the principles behind the fuel efficiency in rocket stoves_Sengratry/ Winiarski Buekens_1990

Figure 25: Rocket stove in Tanzania_Sengratry/Winiarski Buekens_1990

4 Electrical power generation

Industrial-scale gasification is currently mostly used to produce electricity from fossil fuels such as coal, where the syngas is burned in a gas turbine.

Gasification is also used industrially in the production of electricity, ammonia and liquid fuels (oil) using Integrated Gasification Combined Cycles (IGCC), with the possibility of producing methane and hydrogen for fuel cells. IGCC is also a more efficient method of CO_2 capture as compared to conventional technologies. IGCC demonstration plants have been operating since the early 1970s and some of the plants constructed in the 1990s are now entering commercial service.

For electrical power generation divided for three scale applications:

4.1 Large scale applications (500 kW and above)

This is the domain of the specialized fluidised bed or fixed bed installations.

The equipment is custom built and fully automized. Design and manufacture should be handled by specialized engineering and construction firms.

Equipment costs are likely to be in the range of US$ 1000 per installed kW and upwards.

4.2 Medium scale applications (30 -500 kW)

Fixed bed equipment fuelled by wood, charcoal and some types of agricultural wastes (maize cobs, coconut shells) is offered by a number of European and US manufacturers.

Adequate and continuing demand for this type of equipment could lead to standardization of parts and designs thus lowering production costs. For the moment quoted costs are in the range of 300 - 800 US$/kW (gasifier only) depending on type and capacity, level of automation and auxiliary equipment.

Full local manufacture is considered possible in countries possessing a well developed metal manufacturing industry. Major parts of the installations could be manufactured in most countries.

Applications are foreseen in small to medium size forestry and agro-allied industries (secondary wood industries, sawmills, coconut desiccating factories, etc.) as well as in power supply to remote communities.

4.3 Small-scale applications (7 - 30 kW)

This size would be appropriate for a multitude of village applications in developing countries (e.g. village maize and cereal mills, small-scale sugar crushers, looms, etc.).

The equipment must be cheap (less than 150 US$/kW), extremely reliable and should need no special operation and maintenance skills.

Designs suitable for local manufacture are tested and produced in the Philippines , Tanzania and a number of other countries. Documented evidence of their success is for the moment limited, and it should be stressed that training programmes for users and the organization of some type of maintenance service are of paramount importance.

It seems that charcoal gasifiers tend to give less operational problems in this power bracket than gasifiers fuelled by wood or agricultural residues. It is sometimes also believed that charcoal gasifier systems can be made cheaper than wood gasifiers systems in the 7 - 30 kW power range. There is some support for this in the prices charged for vehicle gasifier systems during the Second World War. It is not clear however if the difference of about twenty percent was caused by the difference in technology or was a result of better organized production or simply a matter or different profit margins.

4.4 Micro scale applications (1 - 7 kW)

This is the range Used by small and medium farmers in developing countries for providing power for irrigation systems. Equipment must be transportable, cheap, simple and light in weight. It is quite possible that only small locally manufactured charcoal gasifiers will be able to meet the above requirements.

4.4.1 Gas turbine

Gas turbines are used by themselves in a very wide range of applications, most notably for powering aircrafts of all types but also in industrial plants for driving mechanical equipment such as compressors, pumps, and electric generators in electrical utilities and for producing electric power for peak loads as well as for intermediate and some base-load duties (figure 26-28).

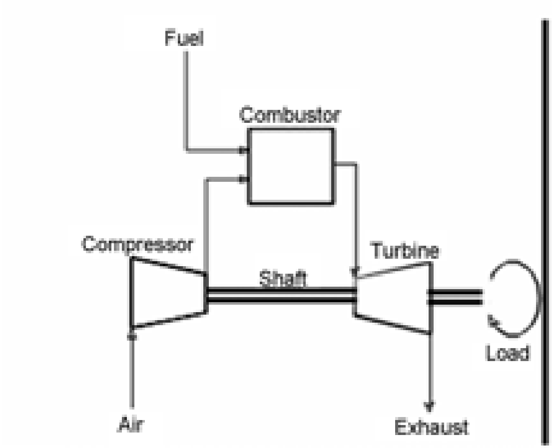


Figure 26: Basic gas turbine Sengratry/ Gary J.Stiegel 2005

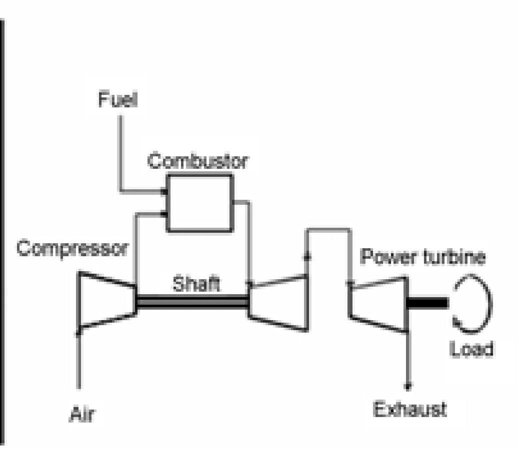


Figure 27: configuaions Sengratry/ Gary J.Stiegel 2005

The principle of a gasturbine is shown in Figure 26 where a one- and a two-shaft model are depicted. The compressor compresses the combustion air (typically 10 - 25 bar), which reacts with the fuel in the combustor. The hot pressurised flue gases expand in the turbine which drives the compressor and the additional load (generator). In the two shaft design the turbine is divided in one driving the compressor and the other (power turbine) driving the generator. The two shaft design Figure 27 provides flexibility in allowing for different compressor and generator rotational speeds.

The temperature of the hot flue gases from the combustor (up till 1250°C) entering the turbine section, is considerable higher than the steam temperature entering a steam turbine (525-560°C). Therefore, high thermodynamic efficiency may be expected. However, the exiting flue gases still have high temperatures (450 - 700°C), causing a considerable loss in a simple cycle system. Despite this loss, recently developed large scale gas turbines may reach simple cycle efficiencies which are as high as 40%.

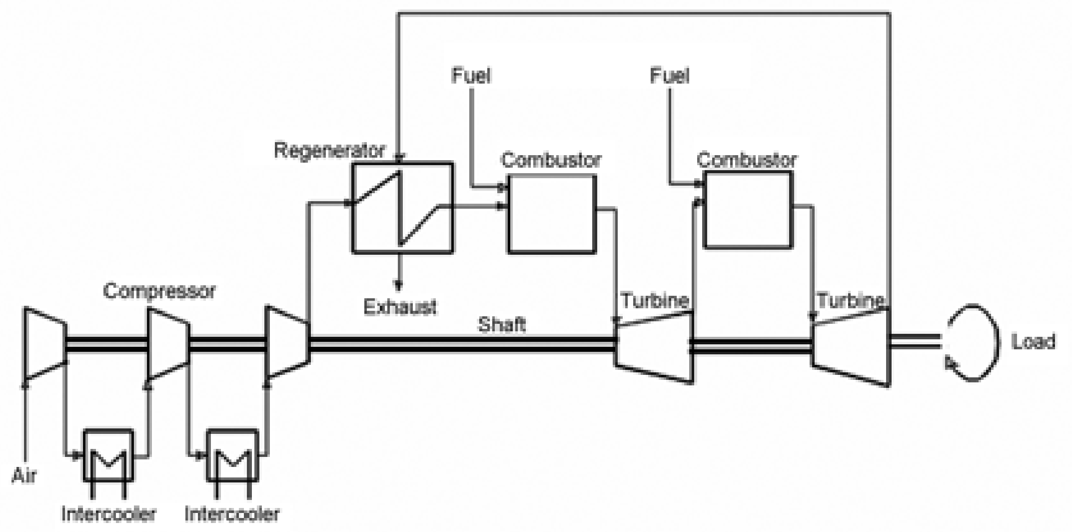


Figure 28: Gas turbine with heat recovery, intercooling and reheat_Sengratry/ Gary J.Stiegel_2005

But for medium and small scale gas turbines the simple cycle efficiency ranges from 20 - 35 %. The efficiency of the simple cycle gas turbine can be increased by recovering some heat of the exhaust gases by heating the compressed combustion air. An increase in efficiency of 30 % is possible. The power consumption of the compressor can be decreased by applying (air or water cooled) intercooling heat exchangers, which reduce the temperature and the volume of the gas and consequently the gas compression work after the intercooler. An additional option to increase simple cycle gas turbine efficiency is to reheat the flue gases after passing some turbine stages.

Heat recovery, intercooling and reheat are depicted in (figure 24), applied in one gas turbine concept. Combustion of low calorific gases in a gas turbine sets additional requirements to the design of the compressor/combustor connection and the combustor design. When pressurized gasification is applied typically 10- 20 % of the compressed air stream is used in the gasifier. The pressure of this air is raised to a slightly higher level by a booster compressor to reach the required gasifier inlet pressure. The bleed of compressed air sets additional requirements to the air off-take system, which should not have an adverse impact on the air flow to the combustion system.

The Lower Heating Value of producer gas is five to seven times lower than the LHV of natural gas. To obtain equivalent firing temperatures the flow of fuel gas has to increase substantially, which means that the incoming fuel and air streams have the same order of magnitude. Because of the high flow rates of fuel gas compared to the flow of air the aerodynamic aspects of the fuel injector design are very important.

The high level of inerts in the fuel gas tends to reduce the range of air to fuel mass ratios that burn stably. However, this effect is offset by the high concentration of hydrogen contained in the flue gas, this component burns over a much wider range of air to fuel ratios compared with the other combustible components. Furthermore the high level of inerts reduce the combustion temperature in a way analogous to steam injection or flue gas recirculation in natural gas fired turbines, thus suppressing thermal NO_x formation. Unfortunately this effect is offset by the formation of NO_x from the combustion of NH_3 contained in the producer gas, which is formed in the gasifier from the fuel Nitrogen.

Especially when pressurised gasifiers are used the fuel temperature delivered to the gas turbine is higher than in conventional gas turbine applications: typically 400 - 600 °C. These high temperatures have their impact on the selection of fuel control valves, pipe-work materials and instrumentation.

Currently only a few gas turbine manufacturers offer gas turbines suitable for combustion of low calorific gases obtained from biomass gasification (see table 8).

Table 8: Gas turbines suitable for low calorific gases/ Gary J.Stiegel_2005

Gas turbine	GT power, MW_{el}	GT simple cycle efficiency, %
Allisson, Ruston	5	28
Mitsubishi MW151	21	24
GE, Frame 6	43	33
Westinghouse	50	33
GE, Frame 6A	70	31

Because of the little experience with biomass producer gas fuelled gas turbines, the gas quality requirements are still not quite clear. An indication of current requirements set by gas turbine manufacturers is given in table 9.

Table 9 Quality requirements on gas turbine fuel gas/ Gary J.Stiegel_2005

Min. LHV	MJ/nm^3	3-11
Particles	Ppm	< 2 – 30
Alkali metals	Ppm	< 0.2 – 1

Application of pressurised gasifiers for gas turbine is advantageous, because there is no need for a large producer gas compressor after the gasifier. The gasification air can just be extracted from the combustion air compressed by the gas turbine compressor. However, full advantage of such a system is only obtained when high temperature gas treatment systems, for example ceramic filters, are applied. These systems are still in a development phase and a reliable system is currently not commercial available. The absence of effective hot gas treatment systems is one of the major bottle necks in the development of pressurised gasifier/ gas turbine systems.

4.4.2 Combined cycle: STEG and STIG

The heat contained in the exiting flue gases from a gas turbine without heat recovery can be used to produce steam. This steam can either be injected in the turbine of the gas turbine, the so-called STIG (Steam Injected Gas turbine) concept, or in a separate steam turbine in a so-called STEG (Steam and Gas turbine) concept. The STIG concept implies continuous supply of steam make-up water, as the steam is released to the environment. The advantage is however its relative simplicity compared to the STEG concept.

In the STEG concept the steam is used in a closed steam cycle. The overall electrical efficiency of this concept is higher than in the STIG concept, because:

- high steam pressures can be applied;
- the steam can be expanded to vacuum conditions;
- the efficiency of a steam turbine is higher than that of a gas turbine.

For these reasons and the fact that the water and steam are kept in a closed cycle, despite of the higher specific investment costs, the STEG cycle is preferred over the STIG cycle.

The overall efficiency of a STEG may be over 55 % in modern natural gas fired power plants and 60% will be in reach within a few years. These steps forwards are made possible by rising the turbine inlet temperature of the gasturbine by applying dedicated materials and advanced cooling systems of the turbine blades. The heat exchanger to produce steam from the gasturbine fluegases is called the Heat Recovery Steam Generator. Because the relative low fluegas entrance temperatures the design of a HRSG is quite different from a direct fired steam boiler. Typically the HRSG exists of a fluegas path filled up with (finned) pipe modules for respectively:

- the steam superheater sections;
- the evaporator section;
- the economiser section (feed water preheating).

The HRSG should be tailor made for a specific gas turbine and combined cycle concept. For a combined heat and power application a back pressure steam turbine can be used which delivers the process steam at the required conditions. A condensing/extraction turbine may provide flexibility in a CHP concept, as the steam can both be extracted to be used as process steam, or be expanded completely to the condenser and fully utilised for power production.

Currently integrated designs for biomass gasification and combined cycle (IGCC) have been prepared. This concepts offers the highest electrical efficiencies in thermo-chemical conversion of biomass. Estimated efficiencies range from 44 - 50 %, the upper values to be reached with future gas turbine designs (to be expected within five years).

However, thus far not many IGCC cycles have been realised. Just one concept, based on a pressurised circulating fluidised bed gasifier and a 4 MWe gas turbine, is currently (1995) in the demonstration phase in a plant in Varnamo, Denmark. The total electricity production capacity will be 6 MWe. Although the plant construction is finished yet, it is still not operational because of technical problems.

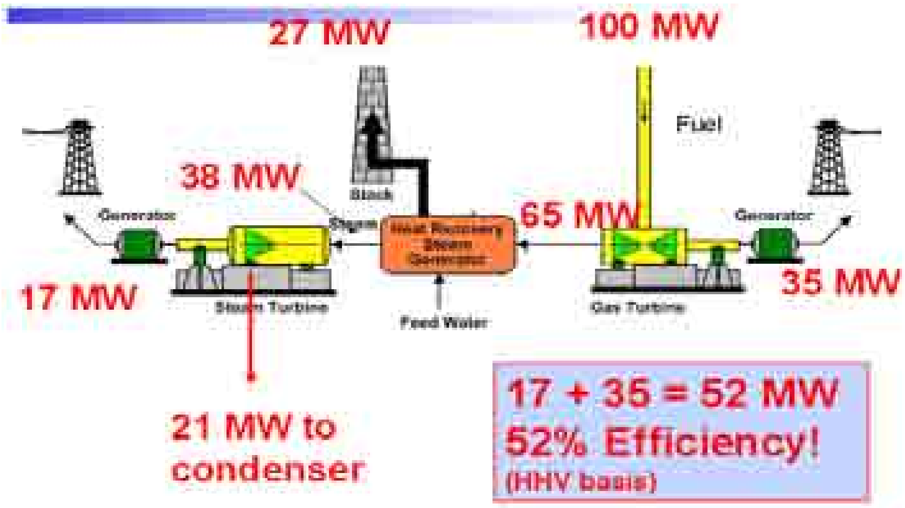


Figure 29 Gasification for power generation_Sengratry/Steve Jenkins_2005

Figure 30 The existing IGCCs_Sengratry/ Ross Fava_2004

4.5 Vehicle propulsion

Producer gas can be used both in spark ignition ("Otto" type) engines as well as in injection ignition ("Diesel" type) engines. Engine quality producer gas must have sufficient heating value for technical and economic reasons and be almost free of dust and tars in order to minimize engine wear and maintenance. Tars can condense and clog up the gas supply lines, the gas-air mixer and finally accumulate on the engine intake valves.

The latter leads especially to problems once an engine is restarted after cooling down. Any tar which has accumulated on valves and valve stem will have hardened during cooling preventing the valves to reach the closed position (see figure 31). Gas specifications to some extent may vary with engine type. Table 10 presents general gas specifications applicable to the use of producer gas in modern engines. Acids may cause severe corrosion and affect the lubricating properties of the oil.

Spark ignition engines can be run entirely on gas. Good mixing with combustion air should be assured; a T-shaped mixer is often used (figure 32). The control system should a constant gas/air ratio at all loads.

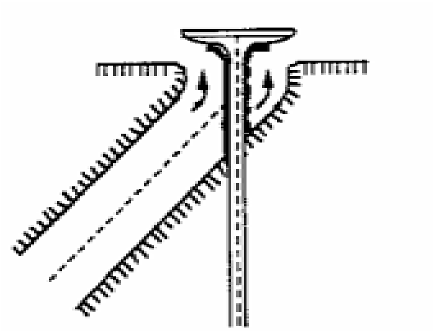


Figure 31 Tar accumulation on 26 valve and valve stem_Sengratry/Gary J.Stiegel_2005

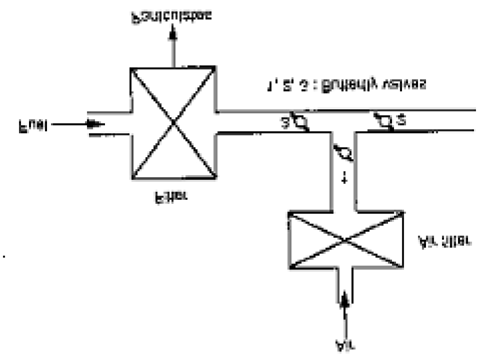


Figure 32 T-type mixing system for mixing producer gas with combustion air_Sengratry/ Gary J.Stiegel_2005

The maximum power output of an Otto engine on producer gas depends on the gas heating value, the setting of ignition timing and specific engine characteristics and is normally considerably less than its maximum power using petrol or natural gas. Because of the high compression ratio of Diesel engines, the gas engine is often obtained by converting a Diesel engine by replacement of the diesel fuel injection device by a spark ignition device. The efficiency after conversion is lower (up to 45 % lower) than the efficiency of a Diesel engine.

Diesel engines (not converted to spark ignition) can only be partly operated on producer gas (dual fuel operation) and therefore always consume a certain amount of diesel fuel (10-25 % off full load consumption [van swaay] (Table 10). The maximum power output of such an engine depends on the gas heating value, the injected diesel fuel amounts and the specific engine characteristics. The efficiency of a diesel engine operating in dual fuel mode is less (up to 25 % less) than the efficiency in single (diesel) fuel mode.

Table 10 Engine quality producer gas specifications/ Gary J.Stiegel_2005

Gas heating value	**kJ/Nm^3**	**> 4200**
Gas dust content	mg/ Nm^3	<50 (acceptable)
Dust size	µm	<5 (preferable) <10
Gas tar content	mg/ Nm^3	<500 (acceptable) <100 (acceptable)
Hydrochloric acid	Ppm	<50
Acetic acid	Ppm	<500

Engine knocking may occur when the combustion of the gas in the cylinder is continued after the ignition stroke. Knocking may cause pressure oscillations and damages the engine. Low flame propagation speeds or incorrect ignition timing (too late) may cause knocking. In producer gas the relatively high flame propagation speed of H_2 compensates for the low flame propagation speed of CO_2, so particular knocking problems have not to be expected once ignition timing is set properly.

The use of down-draught gasifiers fuelled by wood or charcoal to power cars, lorries, buses, trains, boats and ships has proved its value and at least one European country (Sweden) maintains plans for large-scale production in case of an emergency. This technique is currently being studied for powering of tractors (Switzerland, France, Finland, Netherlands) as well as small vans and boats (Philippines) and lorries (Sri Lanka) (figures 33-34).

Figure 33 Tom Reed with friend's gasifier truck (Thomas B.Reed, 2004)

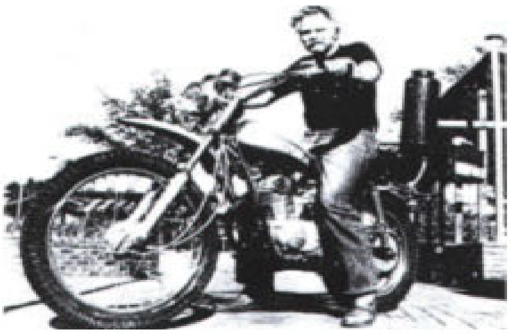


Figure 34 Motor cycle with gasifier Thomas B.Reed_2004