LAPPEENRANTA UNIVERSITY OF TECHNOLOGY
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Master's degree programme in Bioenergy technology

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USE OF BIOMASS GASIFICATION FOR TRANSPORT

Examiners and supervisors: Professor D. Sc. Esa Vakkilainen
Professor D.Sc. Timo Hyppanen

ABSTRACT

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This thesis represents an overview of biomass gasification technology together with some practical aspects of this technology application for transport in Finland.

The main aim of this work is an assessment whether this technology is perspective in the nearest future for the wide use on transport or not.

The first part of the thesis is a kind of survey of the previous works and materials concerning the usage of biomass gasification for transport. The second part concentrates more on the practical moments of its use for mobile applications in Finland (taxation, emissions, etc.).

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1. INTRODUCTION

The global warming, climate change threat and green house gas (GHG) emissions as a major source of this problem are the subjects of great and strong concern of the world community.

The EU is working to reduce GHG emissions in order to mitigate global warming, improve air quality and establish a common energy policy. As part of this policy, European Heads of State or Government agreed in March 2007 on binding targets to increase the share of renewable energy. By 2020 renewable energy should account for 20% of the EU's final energy consumption (Finnish target is 38%). To meet this common target, each Member State needs to increase its production and use of renewable energy in electricity, heating and cooling and transport. (Finland – Renewable Energy Fact Sheet. 2008)

Finland has commitment to maintain its greenhouse gas emissions at the 1990 level, at the highest, during the period 2008–2012. The Finnish energy policy aims to achieve the target, and a variety of measures are taken to promote the use of renewable energy sources and especially wood fuels. In 2007, the government started to prepare a new long-term (up to the year 2050) climate and energy strategy that will meet EU's new targets for the reduction of green house gas emissions and the promotion of renewable energy sources. (Heinimö 2008)

At the present moment, biomass is the most important renewable energy source in Finland, representing 21% of the total energy consumption in 2006. A new law on the promotion of biofuels entered into force on 1 January 2008. The aim of this law is to promote an increase in share of renewables on the transport market (at least 5.75% by the year 2010).

But still, the share of renewable energy sources (RES) in the Finnish transport sector is negligible, accounting for only 1.3% owing to gas and electricity use. (Finland – Renewable Energy Fact Sheet. 2008)

And at present, transport is still a major source of air pollution. In Finland, inland transport generates about 20% of the total CO_2 emissions, of which road traffic alone accounts for 85%. (Energy Visions 2030 for Finland. 2003)

A number of alternative solutions for reducing CO_2 emissions in the transportation sector, based on renewable energy sources utilization are being employed all over the world, e.g. use of natural gas and biofuels (methanol, ethanol) for petrol substitution.

But there can be another route for reducing the net carbon emissions and providing renewable energy supply in the transportation sector – use of biomass gasification.

Coal, wood and charcoal gasifiers have been used for operation of internal combustion engines in various applications since the beginning of this century. The utilization peak was during the Second World War, when almost a million gasifiers were used all over the world, mainly vehicles operating on domestic solid fuels instead of gasoline. But then these vehicles fell into disuse, because of their economic and technical disadvantages comparing with relatively inexpensive imported fuels. (Wood Gas as Engine Fuel 86, 1)

At the present moment, biomass gasification technology is used for the power generation, but its application for transport is not widely spread. Although, this technology can provide use of renewable energy sources and is carbon neutral, thus decreasing the CO_2 emissions level.

Moreover, an important motivation for supporting the development and increasing the consumption of bioenergy is the improvement of energy supply security, which is definitely under threat – Finland is highly reliant on imported fossil fuels and particularly on oil, which is the most important source of primary energy and most of it is used in the road transport. (Energy Visions 2030 for Finland. 2003)

Thus, biomass gasification technology application for transport can contribute not only to the CO_2 emissions level reduction, but can also help to increase energy security and self-sufficiency.

In this work is presented an overview of biomass gasification technology together with some practical aspects of this technology application for transport and an attempt to assess the real possibility of its use in the nearest future in Finland.

The theory of biomass gasification (gasifiers and fuel types, gas composition, etc.) is described in the Chapter 2. The downdraught gasifier design and gas cleaning and cooling equipment are examined in a more detailed way in Chapters 3 and 4. Health and environmental hazards associated with the use of producer gas are outlined in Chapter 6. Some practical moment concerning the vehicles running on the producer gas (taxation, emissions) are discussed in Chapter 7.

And finally, in Chapter 8 the problem of the security of supply is discussed, specifically – if there is enough biomass for producing wood gas for transport and what percentage of Finnish road vehicle fleet can be converted for running on wood gas.

The main aim of this work is an assessment whether biomass gasification technology is perspective in the nearest future for the wide use on transport or not.

2. BIOMASS GASIFICATION – WHAT IS IT?

2.1. Principles of biomass gasification

Gasification is a chemical process during which biomass converts into carbon monoxide and hydrogen by reacting the raw material with a controlled amount of oxygen and/or hot steam. The substance of a solid fuel is usually composed of the elements carbon, hydrogen and oxygen. In addition there may be nitrogen and sulfur. The occurring gasification reactions need high operating temperatures (800 – 1300 ^{0}C) and pressures. The reactor is called a gasifier and the resulting gas mixture is called syngas or producer gas and is itself a fuel. (Boyle (ed.) 2004, 131; Niessen 2002, 479; Yogi Goswami 86, 83–102)

When the complete combustion takes place, carbon dioxide is obtained from the carbon and water from the hydrogen. Oxygen from the fuel is also incorporated in the combustion products and decreases the amount of combustion air needed. (Wood Gas as Engine Fuel 86, 16) Combustion is described by the following chemical reaction formulae:

$C + O_2 \Rightarrow CO_2 - 401.9$ kJ/mol
$H_2 + 1/2O_2 \Rightarrow H_2O - 241.1$ kJ/mol

This means that burning 1 gram atom, i.e. 12.00 g of carbon, to dioxide, a heat quantity of 401.9 kJ is released, and that a heat quantity of 241.1 kJ is released during the oxidation of 1 gram molecule, i.e. 2.016 g of hydrogen to water vapour.

In all types of gasifiers, the carbon dioxide (CO_2) and water vapour (H_2O) are reduced (as much as possible) to carbon monoxide (CO), hydrogen (H_2) and methane (CH_4), which are the main combustible components of producer gas. (Wood Gas as Engine Fuel 86, 16)

The most important reactions of the gasification process (they are taking place in the reduction zone of a gasifier between the gaseous and solid reactants) are given below:

a. $C + CO_2 \Rightarrow 2CO$
b. $C + H_2O \Rightarrow CO + H_2$
c. $CO_2 + H_2 \Rightarrow CO + H_2O$ (known as water-gas equilibrium)
d. $C + 2H_2 \Rightarrow CH_4$

e. $CO + 3H_2 => CH_4 + H_2O$

So, the steps of the gasification process are the following:

1. Biomass heating and converting volatile compounds to gas (when heated, biomass releases volatile matter leaving fixed carbon – app. 20 – 25 %);
2. Combustion of the volatile compounds with air (volatile compounds react with air, provide energy for the heating of biomass and rise the temperature of gases to 1200 – 1300 ^{0} C);
3. Reduction of combustion products CO_2 and H_2O to CO, H_2 and CH_4 (the hot gases, contained carbon dioxide and water vapour, react with the fixed carbon) – these reactions are endothermic – the reduction requires heat and so, the gas temperature decreases (app. 600 – 700 ^{0} C);
4. The rate of reactions decreases with falling temperature. In the case of the water-gas equilibrium, the reaction rate becomes very low below 700°C (reaches equilibrium very fast). The gas composition (the concentrations of carbon monoxide, steam, carbon dioxide and hydrogen are now balanced) then remains unchanged. (Wood Gas as Engine Fuel 86, 17; Anon. Principles of Biomass Gasification, conference paper)

So, the essence of the gasification process is a sub-stoichiometric combustion of the fuel: limited amount of oxygen or air is supplied to the gasifier to allow some of the organic material to be "burned", thus producing carbon monoxide and energy, which drives the next reaction that further converts organic material to hydrogen (H_2) and additional carbon dioxide (CO_2).

2.2 Fuel

There is a vast amount of biomass fuels available for the gasification process (“almost any biomass fuel can be gasified under experimental and laboratory conditions”) (Yogi Goswami 86, 83–102):

- charcoal
- wood
- wood waste (roots, branches, twigs, bark, sawdust, wood shavings)
- agricultural residues (coconut shells and husks, rice husks, straw, etc.)
- peat

Those kinds of fuel differ greatly in their properties (physical, chemical, morphological) and, as a consequence, demand different gasification methods, technologies and gasifier constructions. (Wood Gas as Engine Fuel 86, 26)

So, although, some gasifier manufacturers claim that there exist gasifier which can gasify almost any fuel or fuel type – "universal" gasifier, this can't be possible and realized in practice. Gasifier is very fuel specific and is closely connected with the certain fuel or range of fuels.

Thus a gasifier fuel can be classified according to the following parameters:

- energy content
- moisture content
- volatile matter
- ash content and chemical composition
- bulk density
- reactivity

"Before choosing a gasifier for any individual fuel it is important to ensure that the fuel meets the requirements of the gasifier or that it can be treated to meet these requirements. Practical tests are needed if the fuel has not previously been successfully gasified."(Wood Gas as Engine Fuel 86, 27)

Energy content

The choice of a fuel for gasification will be partly based on its heating value – the higher is the heating value (energy content) of the fuel, the higher is the efficiency of the gasifier – "for one charge one can get power for longer time". (Yogi Goswami 86, 83–102)

The method of determination of the fuel energy content will influence greatly on the efficiency estimation of the gasification system:

- fuel higher heating value determined experimentally using an adiabatic bomb calorimeter (overrated);
- fuel higher heating value on a moisture-free basis (overrated);
- fuel higher heating value on a moisture and ash free basis (overrated).

Thus, the only realistic and most reliable way of presenting fuel heating value for gasification purposes is to adduce lower heating value (excluding the latent heat of water evaporation). (Wood Gas as Engine Fuel 86, 27) Average lower heating values are given in Table 2.2.1.

Table 2.2.1 Average lower heating values (Wood Gas as Engine Fuel 86, 27; Yogi Goswami 86; Nemestothy; Trossero et al. 2001]

Fuel	Moisture content, %-dry basis	Lower heating value, MJ/kg
Wood	20–25	13–15
Charcoal	2–7	29–30
Peat	35–50	12–14
Coconut husks	5–10	16–17
Rice hulls	9–11	13–15
Wheat straw	15	18–19

Moisture content

The moisture content of the fuel affects greatly the energy available from it – the heating value of the produced gas is highly dependent on the amount of water in the feedstock.

It is desirable to use fuel with low moisture content for several reasons: first of all, high moisture content reduces the thermal efficiency of the process, because the heat is wasted for the water evaporation and thus is not available for the reduction reactions and conversion of the energy. As a result we will have low gas heating values. (Wood Gas as Engine Fuel 86, 28)

Secondly, in the case with downdraught gasifiers (the most suitable type for the wood gas producing for engine applications – see below) high moisture content result in not only low gas heating values, but also low temperatures in the gasifier oxidation zone. The latter can lead to the tar entrainment problems.

And the last reason is that high moisture content also creates difficulties during cooling and filtering gas processes: increasing the pressure drop across the equipment as a result of condensing liquid. (Yogi Goswami 86, 83–102)

So, desirable moisture content for fuel should be less than 20 – 25%-dry basis.

Volatile matter

The volatile matter content of the fuel result in the tar formation (the higher the volatile matter content the higher amount of tar produced), which in turn causes the problems to the internal combustion engine operation.

Thus, the amount of volatiles in the biomass fuel determines the design of the gasifier and gas cleaning equipment.

In practice the only biomass fuel that does not need this special attention is good-quality charcoal. The volatile matter content in charcoal varies from 3 up to the 30% and even more. For the comparison, volatile matter content for other biomass materials is for crop residue – 63–80%, for wood – 72–78% and for peat – up to 70%. (Wood Gas as Engine Fuel 86, 28; Turare, conference paper 2002)

Ash content and chemical composition

Ash is the mineral content of the fuel that remains in oxidized form after complete combustion. The ash content and chemical composition affects greatly the gasifier operation process:

- ash melting and agglomeration result in slagging and clinker formation, which, if no measures are taken, can cause excessive tar formation and complete blocking of the reactor;
- possibility of “air-channeling”, which can lead to the explosion. (Yogi Goswami 86, 83–102; Wood Gas as Engine Fuel 86, 29)

The slagging formation depends on the ash content of the fuel, the melting characteristics of the ash, and the temperature mode of the gasifier.

Charcoal and raw wood have the lowest ash content – approximately 0.75–2.5%. “In general, no slagging is observed with fuels having ash contents below 5–6%. Severe slagging can be expected for fuels having ash contents of 12% and above. For fuels with ash contents between 6 and 12%, the slagging behaviour depends to a large extent on the ash melting temperature". (Wood Gas as Engine Fuel 86, 29) The ash content of the different biomass fuels is given in Table 2.2.2.

Table 2.2.2 Fuels ash content (Wood Gas as Engine Fuel 86, 29; Turare, conference paper 2002)

Fuel	Ash content, % - weight
Barley straw	10.3
Charcoal	2–5
Coffee hulls	1.3
Peanut husks	0.9
Rice hulls	16–23
Wood chips	0.1
RDF[1] pellets	10.4

[1]RDF – refuse derived fuel

Bulk density

Bulk density is the weight per unit volume of loosely tipped fuel. Fuels with high bulk density are more preferable as they represent a high "energy-for-volume value". As a consequence these fuels need less storage space. (Wood Gas as Engine Fuel 86, 31)

Average bulk densities are given in Table 2.2.3. Insufficient bulk densities can be improved by briquetting and pelletizing.

Table 2.2.3 Average bulk densities (Wood Gas as Engine Fuel 86, 31; Turare, conference paper 2002)

Fuel	Bulk density, kg/m^3
Wood	110
Charcoal	223
Peat	197
Saw dust loose	134
Corn-cobs	202

Reactivity

Reactivity of the fuel is a very important factor as it determines the rate of reduction reactions in the gasifier (from carbon dioxide to carbon monoxide). Reactivity depends on the type of the fuel (morphological characteristics, geological age) and can be improved through the stream treatment with activated carbon or with lime and sodium carbonate. Also the small quantities of potassium, sodium and zinc can act as catalysts and affect the rate of gasification. (Wood Gas as Engine Fuel 86, 30)

Suitability of several types of biomass as a fuel for gasifier

Charcoal

Good-quality charcoal has low moisture, volatile matter and ash contents that is why it is suitable and feasible for almost all gasifier types.

But there are two main disadvantages of charcoal:

- relatively high cost, which reduces competitiveness of charcoal comparing with liquid fuels;
- energy losses, which occur during conversion of wood to charcoal (up to 70% of the original energy presented in wood may be lost). (Wood Gas as Engine Fuel 86, 31)

Wood

Wood has low ash content, but relatively high moisture and volatile matter contents. The latter result in high tar content in gas produced by the updraught gasifier system. Cleaning of the gas before using in internal combustion engines is very expensive and labour consuming process. But the downdraught systems can be designed to produce relatively tar-free gas ("in a certain capacity range when fuelled by wood blocks or wood chips of low moisture content"). And after passing through the quiet simple cleaning system this gas can be used in internal combustion engines. (Wood Gas as Engine Fuel 86, 32; Turare, conference paper 2002)

Sawdust

The downdraught gasifier systems are not suitable for unpelletized sawdust. The arisen problems in this case are:

- excessive tar production;
- inadmissible pressure drop;
- lack of the bunker flow.

All these problems can be alleviated by using of pelletized sawdust. For the application of produced gas in internal combustion engines gas cleaning system is necessary.

Peat

The main problems in peat gasification are its high moisture and ash content. So, it can't be utilized unless dried (reducing moisture content to 30% or even less).

"During the Second World War a lot of transport vehicles were converted to wood or peat gas operation, both in Finland and Sweden". (Wood Gas as Engine Fuel 86, 32)

Agricultural residues

It is possible to gasify most types of agricultural residues in pre-war design updraught gasifiers. But the capital, maintenance and labour costs, and the environmental consequences of the gas cleaning process in this case prevent engine applications. Downdraught equipment is cheaper in installation and operation. It also creates less environmental difficulties, but at the present level technology is not appropriate for the agricultural residues handling without expensive additional equipment installation. (Wood Gas as Engine Fuel 86, 33)

2.3 Gas composition

The producer gas composition is highly dependent on the fuel properties, gasifier design and the mode of gasification process itself. Thus the same fuel may give different gas composition and calorific values if used in different gasifier types. The producer gas composition from different biomass fuels is given in Table 2.3.1.

Table 2.3.1 Composition of producer gas from different biomass fuels (Wood Gas as Engine Fuel 86, 17; Yogi Goswami 86, 83–102)

Fuel	Gasification method	Components, %-vol.					Calorific value, MJ/m^3
		CO	H_2	CH_4	CO_2	N_2	
Charcoal (7% moisture content)	downdraught	28–31	5–10	1–2	1–2	55–60	4.60–5.65
Wood (12–20% moisture content)	downdraught	17–22	16–20	2–3	10–15	50–55	5.00–5.86
Wheat straw pellets	downdraught	14–17	17–19	-	11–14	-	4.50
Corn-cobs	downdraught	18.6	16.5	6.4	-	-	6.29
Charcoal	updraught	30	19.7	-	3.6	46	5.98

Also the producer gas contains certain amounts of impurities – tar and dust, which cause the necessity of gas cleaning for the trouble free engine operation.

Tar content

Tar is an unconverted volatile matter and one of the most unpleasant components of the producer gas as it tends to condense and deposit in the various engine passages causing sticking and operational problems. The process resulting in tar formation takes place in the pyrolysis zone of the gasifier. (Yogi Goswami 86, 83–102)

So far, very little research work has been done in the area of removing or burning tar in the gasifier for the relatively tar-free gas to come out – the major effort has been devoted to cleaning the tar by filters and coolers. A well-designed gasifier should put out less than 1 g/m^3 of tar. Usually it is assumed that a downdraught gasifier produces less tar than other gasifier types. (Remulla, 82)

Dust content

All types of the gasifier fuels produce dust. The dust has to be removed from the producer gas as it can clog the internal combustion engine. The concentration of dust in the gas depends on the fuel and gasifier type, and intensity of load (with the load increase, dust concentration in producer gas also increases). "The gasifier design should be such that it should not produce more than 2–6 g/m^3 of dust". (Kaupp, 82)

On the average the temperature of gas leaving the gasifier is about 300–400 ^{0} C. If the temperature is higher than these values it means that partial combustion of gas is taking place - this might happens when the air flow rate through the gasifier is higher than the design value. (Yogi Goswami 86, 83–102)

2.4 Types of gasifiers

The choice of the one particular gasifier depends on type of fuel used (its final available form, size, moisture and ash content) and on the application – portable or stationary.

Gasifiers are classified according to the way in which air is introduced in the fuel column. Thus, there exist three main gasifier types:

- updraught;

- downdraught;

- crossdraught.

Updraught or counter-current gasifier

The counter current or updraught gasifier is the oldest and the most simple gasifier type. Figure 2.1 shows the scheme of this gasifier.

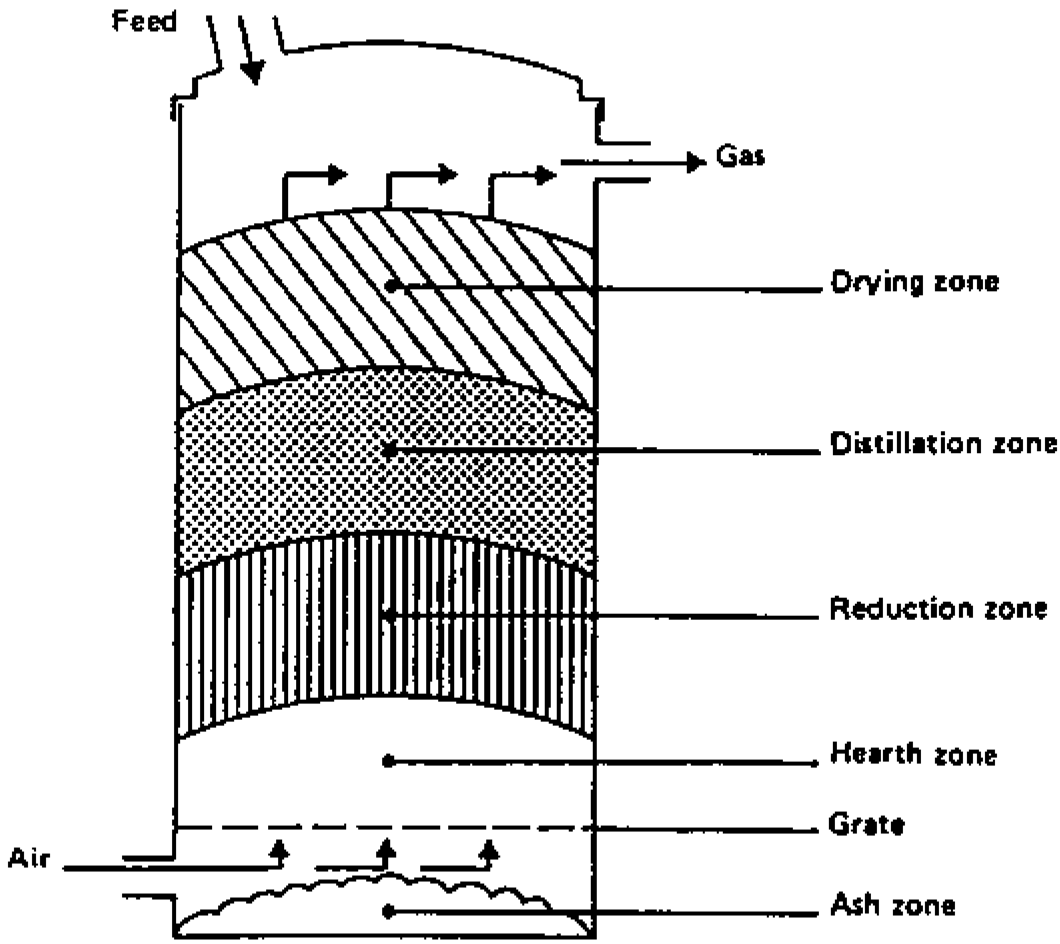

Figure 2.1 Updraught or counter-current gasifier (Skov and Papworth 74)

An updraft gasifier has clearly defined partial combustion, reduction, and pyrolysis zones. The air intake takes place at the bottom and the gas leaves from the top of the gasifier (so, the air flow is countercurrent to the fuel flow). The combustion reactions occur near the grate at the bottom. Then the reduction reactions take place a little bit higher up in the gasifier, followed by heating and pyrolysis of the fuel in the upper part (as a result of "heat transfer by forced convection and radiation from the lower zones").

The updraft gasifier allows achieving the highest efficiency level as the hot gas passes through the fuel bed and leaves the gasifier at low temperature. But in this case the tar, produced during the gasification process is carried out with the gas stream (ash is removed from the bottom of the gasifier). (Wood Gas as Engine Fuel 86, 22)

Advantages of updraught gasifier:

- simplicity;
- high charcoal burn-out;
- internal heat exchange, which leads to low gas exit temperatures and high equipment efficiency;
- possibility of operation with many biomass fuel properties (contaminated, unsized, various shapes) and types (sawdust, cereal hulls, etc.) – in this case the applications can be only thermal.

Drawbacks of updraught gasifier:

- possibility of the equipment "channeling", which in turn can lead to oxygen break-through and risk of explosions;
- problems connected with disposal of the tarry condensates (result from the gas cleaning operations). (Wood Gas as Engine Fuel 86, 22)

Downdraught or co-current gasifiers

In the case with the updraft gasifier producer gas has very high tar content which can cause serious problems during the internal combustion engine operation.

The tar entrainment problem in the gas stream is minimized in co-current or downdraught gasifiers, in which primary gasification air is introduced at or above the gasifier oxidation zone and the producer gas leaves from the bottom of the gasifier (so, the air and fuel flow move in the same direction – co-current). (Wood Gas as Engine Fuel 86, 23)

Figure 2.2 shows the scheme of the downdraught gasifier.

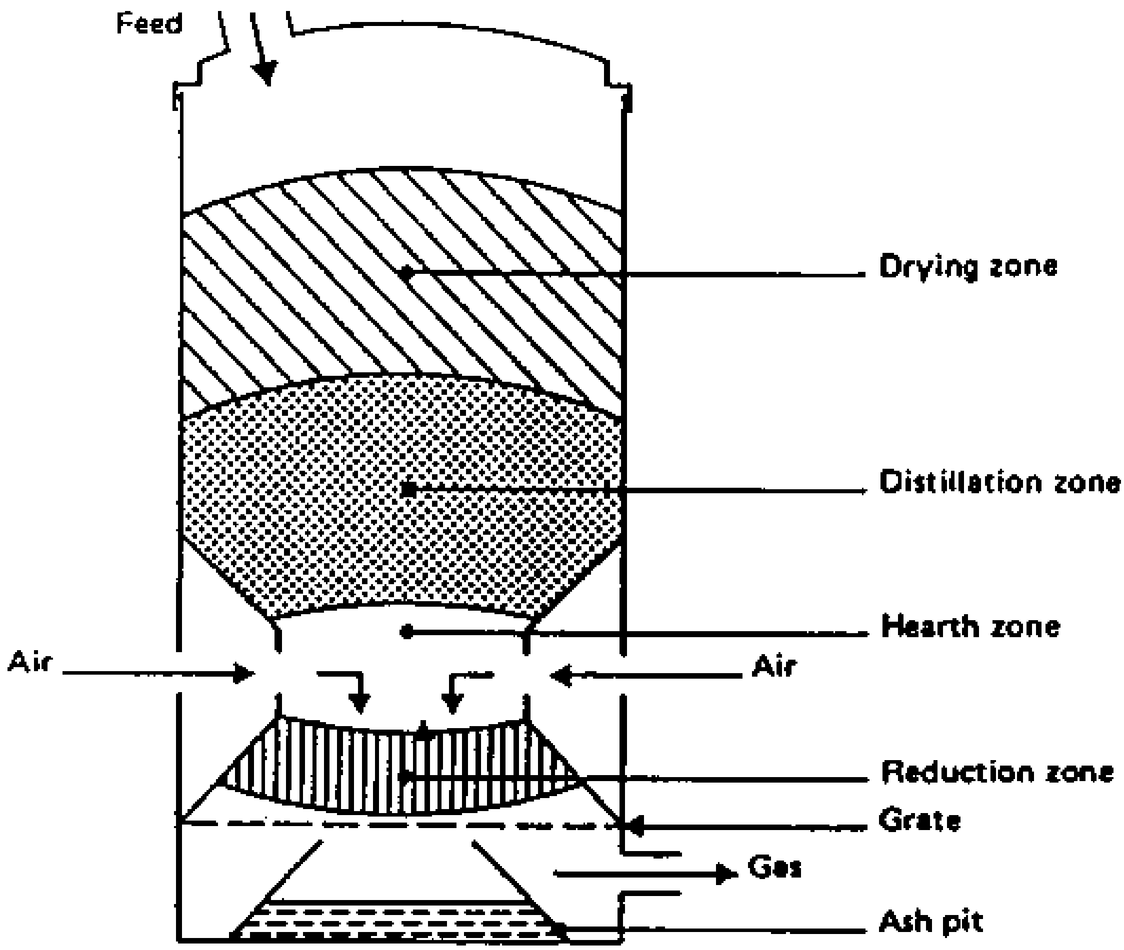

Figure 2.2 Downdraught or co-current gasifier (Skov and Papworth74)

Tarry distillation products from the fuel in this gasifier type have to pass through the burning bed of charcoal and by means of this they are converted into gases: hydrogen, carbon dioxide, carbon monoxide and methane. (Wood Gas as Engine Fuel 86, 23)

The tar decomposition degree depends on the gasifier hot zone temperature and on the residence time of tarry vapours there.

Advantages of downdraught gasifier:

- possibility of producing the relatively tar-free gas suitable for engine applications ("in practice, however, a tar-free gas is seldom if ever achieved over the whole operating range of the equipment");
- downdraught gasifiers are more environmentally safe, because of the lower level of organic components in the condensate (comparing with the updraught gasifier).

Drawbacks of downdraught gasifier:

- the lower overall efficiency (comparing with the updraught gasifier);
- the lower heating value of the gas;
- inability to operate on a number of unprocessed fuels – fluffy, low density materials result in flow problems and excessive pressure drop, and the solid fuel must be pelletized before use;
- downdraught gasifiers also has difficulties in handling high ash and moisture content fuels (slagging). (Wood Gas as Engine Fuel 86, 24)

<u>Cross-draught gasifier</u>

Cross-draught gas producers were adapted for the use of charcoal as a fuel. They have certain advantages over the updraught and downdraught gasifiers and unlike these types, the ash bin, fire and reduction zone in cross-draught gasifiers are separated. (Turare, conference paper 2002) Figure 2.3 shows the scheme of the cross-draught gasifier.

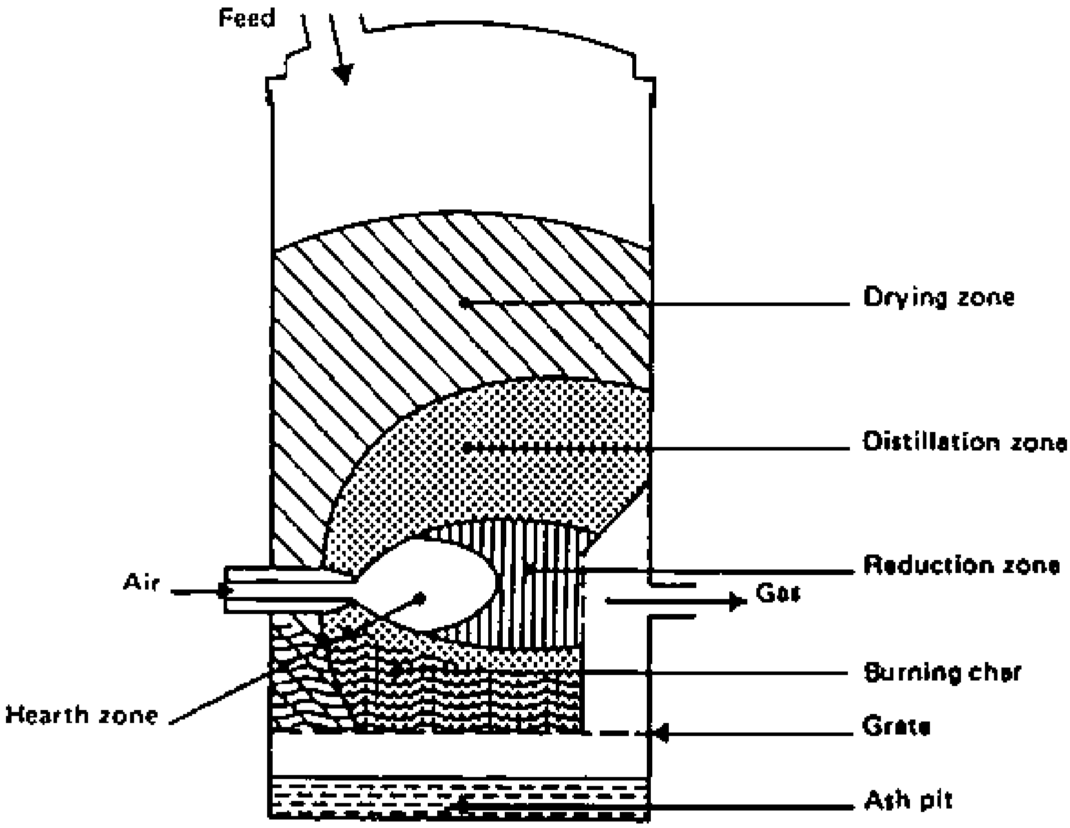

Figure 2.3 Cross-draught gasifier (Skov and Papworth 74)

Charcoal gasification results in very high temperatures (1500 ^{0} C and even higher) in the oxidation zone which can lead to material problems and affect the producer gas composition – high carbon monoxide content, and low hydrogen and methane content. (Wood Gas as Engine Fuel 86, 24; Turare, conference paper 2002)

Advantages of cross-draught gasifier:

- it takes less time to start the gasifier up (comparing with the downdraught and updraught gasifiers);
- very small operational scale can be possible - installations below 10 kW (shaft power) can, under certain conditions, be economically feasible (the reason is very simple gas-cleaning equipment – cyclone and hot filter – which can be employed when using cross-draught gasifier in combination with small engines).

Drawbacks of cross-draught gasifier:

- high exit gas temperature;
- poor CO_2 reduction;
- high gas velocity;
- minimal tar-converting capability and, as a consequence, limiting of the fuel type for operation – the high quality (low volatile matter content) charcoal;
- operates well only with dry air and fuel flows. (Wood Gas as Engine Fuel 86, 24; Turare, conference paper 2002)

Other gasifier types

There exist various other biomass gasifier types (twin-fired, fluidized bed, etc.), which are partly spin-outs of the coal gasification technology. Some of these types are built to combine the advantages of cross-draught with downdraught or updraught gasifiers, but in most cases these systems have unnecessary complications or their equipment is too large and sophisticated for the near-term application.

Thus, we can conclude, that if we need the internal combustion engine conjunction with gasifier (for transportation) – the downdraught will be the most suitable gasifier type for this kind of application.

2.5 Benefits and drawbacks of using the producer gas for transport

Compared to the conventional internal combustion engine systems biomass gasification technology for mobile applications is not so convenient. Operation of diesel or gasoline engine is quite simple – engine starts immediately, has no trouble within the running process, handling of the traditional fuel (diesel or gasoline) is also very easy.

And in the case with the biomass gasification system the start-up time takes at least half an hour, fuel is bulky and for the continuous system running frequent refueling is needed. Moreover, handling residues (ash, soot and tarry condensates) is time consuming and dirty work. (Wood Gas as Engine Fuel 86, 5)

Although, wood gas producing process is not difficult itself, the quality of the obtained gas varies a lot (physical and chemical properties, such as energy content, gas composition and impurities) – and gasoline/diesel have quite homogenous properties.

It is a widespread delusion to assume that any biomass fuel type can be used to produce wood gas in an any gasifier. As it was already mentioned above, different gasifier types have quite strict requirements for the fuel properties – sizing, moisture, volatile matter and ash content. Use of unsuitable fuel or improper fuel preparation can cause various technical problems and operational difficulties during the biomass gasification and vehicle running processes:

- bridging in the fuel bunker;
- reduced power output because of large pressure losses;
- "weak" gas;
- slag cakes;
- tar in the engine;
- damage to the gasifier caused by overheating.

In order to avoid all these problems it is necessary to choose very carefully fuel type with certain properties for each particular gasifier type and kind of application. But these limitations are not more serious than “the need to use gasoline of super grade for high compression spark ignition engines rather than regular gasoline or diesel fuel”. The main difference in this latter case between biomass and gasoline/diesel fuel is that biomass fuel quality control is the responsibility of the operator.

Operation of wood gas engines can also be dangerous if the operator neglects the safety rules or maintenance of the system (poisoning accidents, explosions and fires, caused by unsafe design or careless handling of the equipment). Although, the modern systems are designed according to the all safety standards, it is still necessary to handle the equipment in a responsible manner. (Wood Gas as Engine Fuel 86, 5)

Use of producer gas in internal combustion engines also affects their performance. Cold gas efficiency of producer gas in favorable condition can be as high as 70%. The actual efficiency of engine varies with design, size and running condition (the geographical situation – flat or hilly terrain, the skills of the driver, etc.).

Theoretically, gasoline and diesel engine operated on producer gas undergo a power loss of 30 (for gasoline engine) and 20 (for diesel engine) per cents. (Turare, conference paper 2002) Figure 2.4 illustrates theoretical efficiency and power losses in different units of the gasifier-engine system.

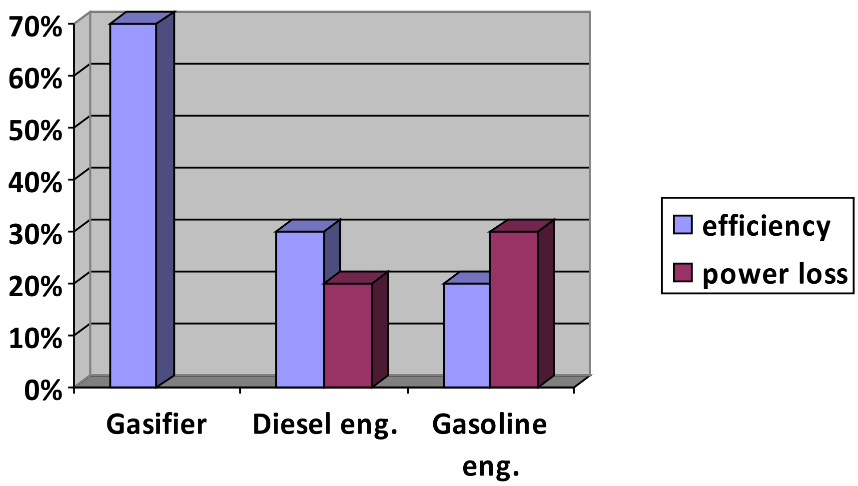

Figure 2.4 Theoretical efficiency and power loss in different units of gasifier-engine system (Turare, conference paper 2002)

Benefits of using the producer gas for transport:

- economic advantages (if biomass is already available at reasonable low prices);
- biomass gasification technology is environmentally friendly (reduction in CO_2 emissions);
- provides energy security;

- independence of fossil fuel prices and supply.

Drawbacks of using the producer gas for transport:

- biomass gasification is very sensitive process (fuel type and properties);
- not very simple operation process;
- risk of toxic gaseous emissions (i.e., carbon monoxide), fire and explosion hazards.

Whether these drawbacks will be balanced by the better economy of producer gas fuelled transport vehicles depends entirely on the local situation, especially on the cost and availability of petrol and diesel oil.

Additional difficulties as compared with stationary units:

- mobile gasifier system must be compact and lightweight (fuelled manually, compact ash pits and filters design result in frequent cleaning necessity);
- minimum use of material, which enables the lightweight construction leads to the shorter lifetime for parts exposed to corrosion;
- mobile applications are operated within the wide range of engine and gasifier loads, this circumstance can lead to tar formation and clogging of cooling and cleaning equipment and engines.

Nevertheless, these latter difficulties can be minimized if the gasifier-engine system is used on trains or boats, as in these cases the weight and load constraints are not so strict, and system gives better results. (Wood Gas as Engine Fuel 86, 44)

Thus, we can conclude that driving the producer gas fueled vehicles requires more attention than gasoline or diesel fueled ones, but is more environmentally safe and gives the possibility of traditional fuel supply and prices independence.

2.6 Several present examples

Here in this section I would like to give some present examples of vehicles running on the wood (producer) gas.

Picture 1. Yugo 45 runs on wood gas (Zastava Yugo Page)

Mr. Anton Peterka from Belgrade, Serbia along with his team, made his '85 Yugo 45, using wood and coal as a fuel (see Picture 1). The whole mechanism is made of steel plate and it weighs 60 kg. The highest speed that can be achieved with this engine type is about 85 km/h, because of the power losses and increased weight and air resistance (the aerodynamic properties of the vehicle is worse because of the external firebox). Capacity of the firebox is 35 kg of wood or coal, which is enough to run approximately 150 km. On the roof you can see filters for gas cleaning and cooling.

Picture 2. Lincoln Continental runs on wood gas (Renewable Energy for Housing and Transportation 2008)

Mr. Vesa Mikkonen from Finland has converted his Lincoln Mark V 1979 to run on wood gas (see Picture 2).

Technical characteristics:

- engine 6.6 litres;
- top speed 110 km/h;
- fuel demand 50 kg/100 km;
- operation distance 250 km (peat);
- possibility to use both peat and wood as a fuel;
- fuel expense 4€/100 km (peat);
- service: cleaning of the filter every 1000 km;
- carbon dioxide emissions 0 g/km.

Picture 3. Ford F-250 powered by wood gas (Woodgas.net 2009)

Mr. Jonathan Spreadborough from the USA has built wood gas generator to power his 1990 Ford F-250 (fuel injected, 5.0 litres) (see Picture 3). This generator was constructed from the scrap parts, including metal barrels of various sizes and lots of pipes. Filtration equipment to remove soot was mounted on the front bumper. The fuel injected truck was modified so it can burn either gasoline or wood gas (dual fuel), but it needs gas when the engine is started. Driving solely on wood gas costs a vehicle 30% of its acceleration. Mr. Spreadborough said that "he doesn't have to pay tax on his fuel because there's no tax on wood". (Woodgas. net 2009)

Picture 4. Volvo 142 powered by wood gas (Wood car - A car that runs on wood 2008)

Mr. Johan Linell from Sweden along with his friends made '68 Volvo 142, using wood as a fuel (see Picture 4). The gasifier is double hulled and it was manufactured in 1942 by Bolinder's AB for Ford Motorcompany AB. The gas cleaning system consists of a cyclone and a fibreglass filter made from stainless steel. The fuel mixing system allows switching between producer gas and gasoline with a throttle switch while the car is running.

Technical characteristics:

- top speed 90 km/h;
- wood consumption $1 m^3$/ 1000 km;
- operation distance on one load 70 km;

- producer-gas systems weight 260 kg.

3. THE DOWNDRAUGHT GASIFIER DESIGN

As it was already discussed in the previous part, the downdraught gasifier makes it possible (using biomass as a fuel) to produce wood gas with relatively low tar content which can be applied for the internal combustion engine operation.

Moreover, the down-draught gasifier is comparatively easy in construction, operation and maintenance processes, so it is the most appropriate gas producer type for the mobile applications.

It is for this reason the process of conversion of solid fuel into gas in a downdraught gasifier and the design basis for such gasifier type will be examined here more detailed.

3.1 Processes occurring in the downdraught gasifier

It is possible to distinguish four separate zones in the gasifier:

- drying zone;
- pyrolysis zone;
- oxidation (combustion) zone;
- redaction zone.

Each zone is characterized by one certain process of the biomass fuel convertion into the producer gas. Although these processes are, to the some extent, overlapped, each can be assumed to occupy a separate gasifier zone where fundamentally different chemical and thermal reactions take place. (Yogi Goswami 86, 83–102) These zones and processes are described below.

<u>Drying zone</u>

Solid fuel is introduced into the gasifier at the top. There is no need in using of the complicated fuel-feeding equipment as a small amount of air leakage is tolerable at this spot. Biomass fuel entering the gasifier has variable moisture content – of about 5–30% (depending on the fuel type) and in this gasifier zone drying of the fuel takes place (as a result of heat transfer from the lower parts of the gasifier).

Then the water vapour flows downwards and is added to the water vapour formed in the oxidation (combustion) zone. Part of this vapour may be reduced to hydrogen while the rest will end up as a moisture content of the producer gas. (Wood Gas as Engine Fuel 86, 33)

Some organic acids that can result in gasifier corrosion are also released during the drying process.

Pyrolysis Zone

At the temperature range between 280 and 500 ^{0} C pyrolysis of the biomass fuel occurs. The details of the pyrolysis reactions are not yet well known, but it can be assumed that the large molecules (e.g., cellulose, hemi-cellulose and lignin) break down into the medium size molecules and carbon (char) during the fuel heating. Then the products of the pyrolysis process flow downwards into the hotter zones of the gasifier. Some of them will be burned in the combustion zone, and the rest (depending on the residence time in the hot gasifier zone) will break down to even smaller molecules of hydrogen, methane, carbon monoxide, ethane, ethylene, etc. If the residence time will be too short or the temperature too low, then medium sized molecules can escape and condense as tars and oils, in the low temperature parts of the system. (Wood Gas as Engine Fuel 86, 34; Yogi Goswami 86, 83–102)

Oxidation (Combustion) Zone

The oxidation zone is formed at the air intake level of the gasifier. Reactions that take place in this zone (reactions with oxygen) are highly exothermic and raise the temperature up to 1200–1500 ^{0} C.

Oxidation zone has two important functions:

- heat generation;
- convertion and oxidation of condensable products from the pyrolysis zone.

To help gasifier establish its functions well, cold spots in the oxidation zone must be avoided. It is for this reason, two parameters – air inlet velocities and the reactor geometry – must be carefully chosen.

There are two widely used methods 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 using a central air inlet with a suitable spraying device. (Wood Gas as Engine Fuel 86, 34)

Reduction zone

The products of partial combustion move downwards through the red-hot charcoal bed, where reduction reactions take place. These reactions are endothermic – the reduction requires heat and so, the gas temperature decreases (app. 600 – 700 ^{0} C). "In this zone the sensible heat of the gases and charcoal is converted as much as possible into the chemical energy of the producer gas".

The end product of the chemical reactions that take place in the gasifier reduction zone is a producer (wood) gas which can be used (after dust and tar removal and cooling) as a fuel for internal combustion engines.

The moveable grate at the bottom of the gasifier is necessary for the ash removal – it makes possible the stirring of the charcoal bed in the reduction zone and, thus, helps to prevent blockages, which may result in the gas flow obstruction. (Wood Gas as Engine Fuel 86, 34; Yogi Goswami 86, 83–102)

3.2 Design guidelines for the downdraught gasifier

The downdraught (co-current) gasifiers can be of two types (see Figure 3.1):

- throat type design (including "single" and "double" throat designs);
- open core design.

Throat type gasifiers are usually used for biomass fuels with low ash content and uniform size – "single" throat gasifiers are mainly used for stationary applications while "double" throat are more suitable for varying loads and for the transport applications. The small throat diameter gives rise to the higher gas velocities at the oxidation (combustion) and reduction zones. This result in tar formation reduction, but increases dust loading. Large throat diameter causes an increase of tar in the gas stream because of the hot zone by-passing. (Sivakumar et al.)

Open core gasifiers are more tolerant to the various fuel properties (moisture and ash content, size). Fuels with high ash content create problems by ash clogging and slogging at the combustion zone in downdraught gasifiers. The open core and throat type combustion regions used in downdraught gasifiers "work well with lower coking tendency fuels (e.g. wood), but when high coking fuels (e.g. cotton stalk) are used they cause bridging in and above the pyrolysis zone". (Reed and Markson 83; Dasappa et al. 2000)

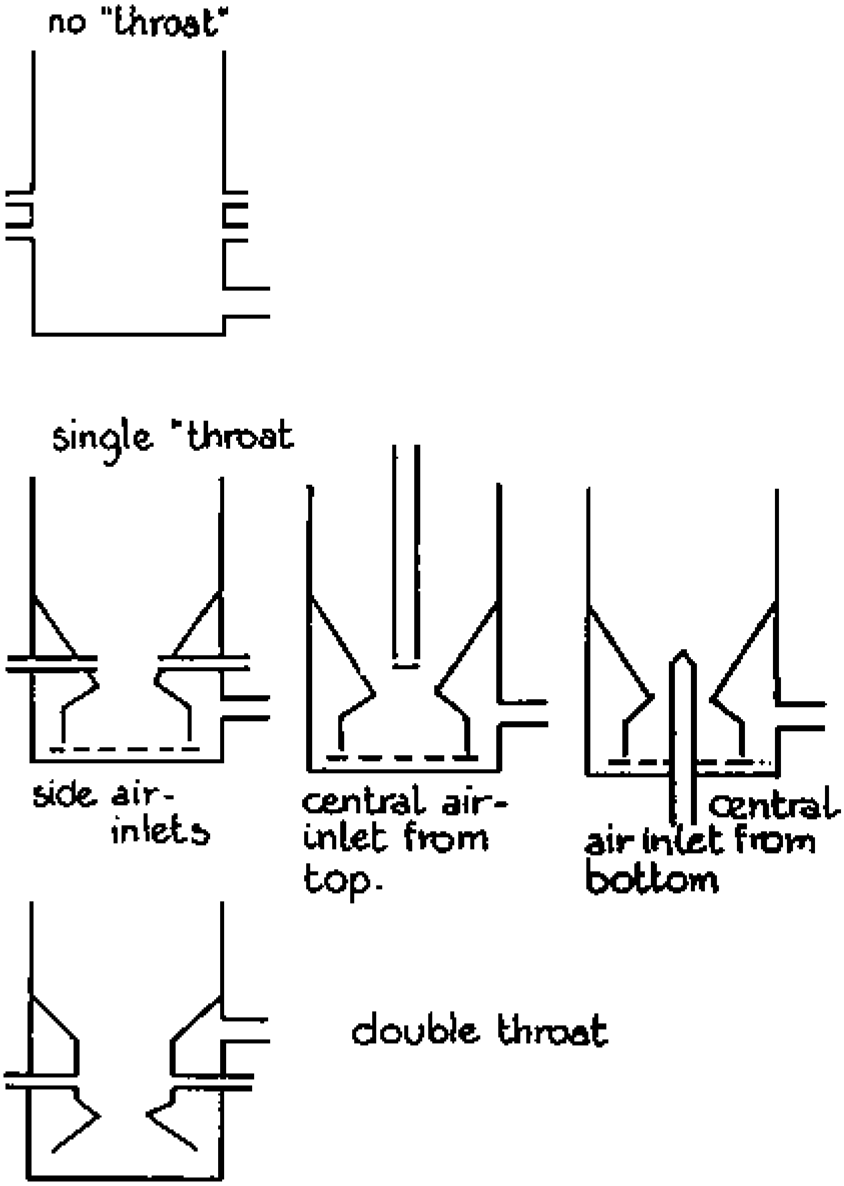

Figure 3.1 The downdraught gasifier classification (Wood Gas as Engine Fuel 86, 39)

Design of the gasifier implies obtaining the dimensions of the various gasifier components. This process is, to the certain extent, empirical – it is carried out through computations and using empirical relations and some experimental data. (Sivakumar et al.)

The principal design parameters are the following:

- specific gasification rate (SGR);
- gas reduction time (GRT);
- area of air nozzles.

The derived parameters are:

- diameter of hearth and throat;
- total length of combustion and reduction zone;
- air velocity;
- diameter of nozzles;
- number of nozzles.

Equivalence ratio (ER)

ER fixes the amount of air supplied for gasification and is defined as the ratio of oxygen supplied per kilogram of wood to the stoichiometric requirement. A value of 0.3 ER is the theoretical optimum. (Zainal et al. 2002)

Specific gasification rate (SGR)

SGR is the volumetric flow rate of gas per unit area based on throat diameter (the gas volume is measured at the standard conditions). The recommended SGR is in the range between 0.3 and 1.0.

Specific solid flow rate (SSR)

SSR is the fuel mass flow measured at the throat and it is a derived parameter which can be obtained from SGR. As one kilogram of wood gives approximately 2.5 m^3 of the producer gas, SSR can be related to SGR as SGR/2.5.

Gas reduction time (GRT)

GRT is defined as the average time spent by the gas phase in the reduction zone.

$$GRT = (V\varepsilon/G) * (273/T) * 360 \text{ sec} \quad (3.1)$$

V = total volume of reactor

ε = void fraction (volume of voids in the bed/total volume of reactor)

G = gas flow rate

T = average temperature inside the reactor

Recommended value of GRT is 0.5 sec. (Reed and Das, 88)

Air blast velocity (V_b)

This is the linear velocity of air in the nozzle at the standard conditions. The recommended V_b range is 15–30 m/s. There is an opinion that the high air blast velocity helps in higher air penetration into the bed and also helps to prevent hot spots formation. (Sivakumar et al.)

Design of hearth and nozzle

In this case the controlling parameters are air inlet velocity and number of nozzles. Both, high and low air inlet velocities are not suitable – the former will produce narrow jets and the latter will not allow the air to reach the central area. These, in turn, lead to the central cold (dark) zone formation which means poor non-uniform combustion zone and inefficient tar-cracking process. (Reed and Das, 88; Bridgwater 95)

Thus, the general range for air inlet velocity is 6 m/s up to 10 m/s, and the number of nozzles used – from 1 up to 10. The aim of the nozzle design is avoiding of cold (dark) zones in the oxidation (combustion) zone. (Sivakumar et al.)

Sizing of the hopper

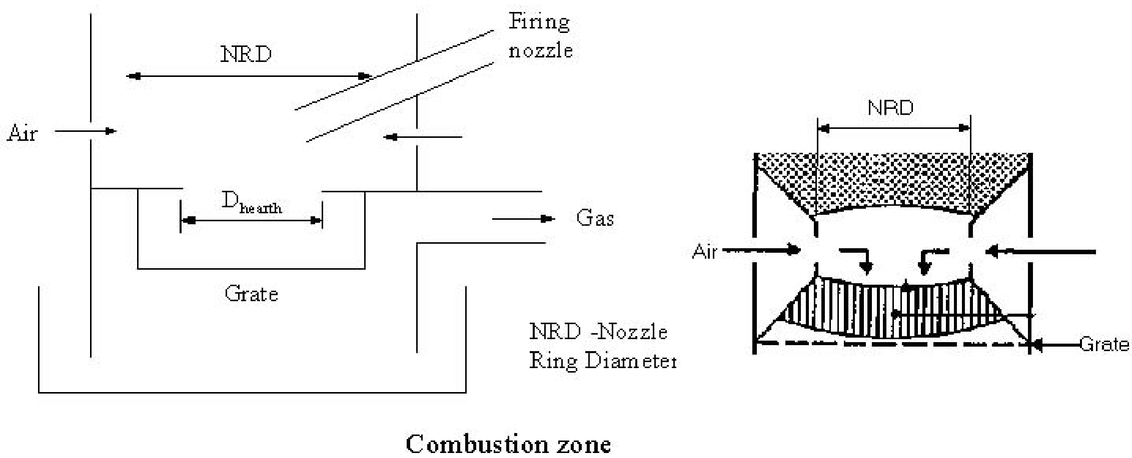

Figure 3.2 Close up view of the combustion and reduction zones (Sivakumar et al.)

Main parameters here are the diameter and the height of the hopper. The main considerations that have to be taken into account when designing the hopper diameter are the following:

- storage requirements;
- the hearth size (D_{hearth});
- size of the biomass particle.

Figure 3.2 illustrates the close up view of the combustion and reduction gasifier zones. (Sivakumar et al.)

4. GAS CLEANING AND COOLING

For the trouble-free operation internal combustion engine must be supplied with fairly clean producer gas – sufficiently free from tars, dust and acids. If these contaminants are not removed properly they can cause engine wear and tear, which in turn may result in maintenance, repair and reliability problems. "In fact, it is likely that more gasifier engine systems have failed because of improper cleanup systems than for any other cause." (Wood Gas as Engine Fuel 86, 40; Reed and Das 88; Turare, conference paper 2002)

The first step in the clean gas producing is to choose such a gasifier design, which allows minimizing tar formation – for example, downdraught gasifier type and to make sure, that it is operated properly. The next step is to remove tars, dust and water in the proper order and at the right temperature – this will simplify the handling of the captured contaminants. For example, if the producer gas is immediately cooled and quenched in one operation, then dust, tars and water will be removed altogether and form sticky, tarry mess, which is difficult to handle.

Thus, the optimal sequence of the contaminants removal is the following:

- dust removal at the temperature above the tar dew point (app. 300 ^{0} C);
- tars removal at the intermediate temperatures (above 100 ^{0} C);
- water removal (30–60 ^{0} C).

This order makes the handling of each separated contaminant easier. (Reed and Das 88)

As it was already mentioned above, well designed downdraught gasifier makes it possible to produce the relatively tar-free gas suitable for engine applications ("in practice, however, a tar-free gas is seldom if ever achieved over the whole operating range of the equipment"). Updraught gasifier, in case of the conjunction with internal combustion engine, has to be equipped with bulky and expensive tar separating equipment.

Thus, we can conclude, that when the gasifier and the cleaning system are carefully chosen, well designed and properly operated (with the suitable fuel type used), tar contamination of the producer gas does not present a major problem. (Wood Gas as Engine Fuel 86, 40)

4.1 Gas cleaning

The main problem in producing wood gas for the engine applications is the removal of dust. The amount of dust contained in the producer gas at the gasifier outlet depends on several factors:

1. Equipment design – “in most gasifiers the direction of the gas stream is already reversed over 180^0 inside the apparatus, and this simple measure removes the coarse dust”. (Wood Gas as Engine Fuel 86, 40)

2. The load of the gasifier – the amount of dust per m^3 of the producer gas generally increases with the gasifier load: high loads result in higher gas velocities and dust entrainment.

3. The type of fuel used – smaller fuel particles generally cause higher dust concentrations in the gas than the larger fuel blocks. Moreover, hardwoods usually generate less dust than softwoods.

Table 4.1 shows the results of the producer gas dust size and size distribution investigations carried out by the Nordstrom. It is possible to separate approximately 60–70% of this dust from the gas by means of a well designed cyclone. (Wood Gas as Engine Fuel 86, 40)

Table 4.1 Size distribution of producer gas dust (Nordstrom 63)

Particle size of dust, $m.10^{-6}$	Percentage in the gas, %
over 1000	1.7
1000–250	24.7
250–102	23.7
102–75	7.1
75–60	8.3
under 60	30.3
Losses	4.2

So, after passing through cyclone the producer gas still contains fine dust, particles and tar. These contaminants have to be removed by other means.

The best cleaning effect can be obtained by employing cloth filters. But they are normally very sensitive to the gas temperature. In the case of wood or agricultural waste gasification, the dew point of the gas will be around 70 ^{0} C. Below this temperature water will condense in the filters and this condensation will stop the gas flow, because of the increased pressure drop over the filter section of the gas cleaning system.

That is why, in almost all gasification systems the hot gas first passes through the cloth filter and only after this it is headed to the cooler. (BECE 82) In this latter case, as the gas is still above the dew point, no condensation takes place in the filter. (Yogi Goswami 86, 83–102)

The gas cleaning system for the typical wood gasifier used during the Second World War consisted of the cyclone, the gas cooler with some scrubbing action and the packed bed filter. Figure 4.1 illustrates such kind of a system.

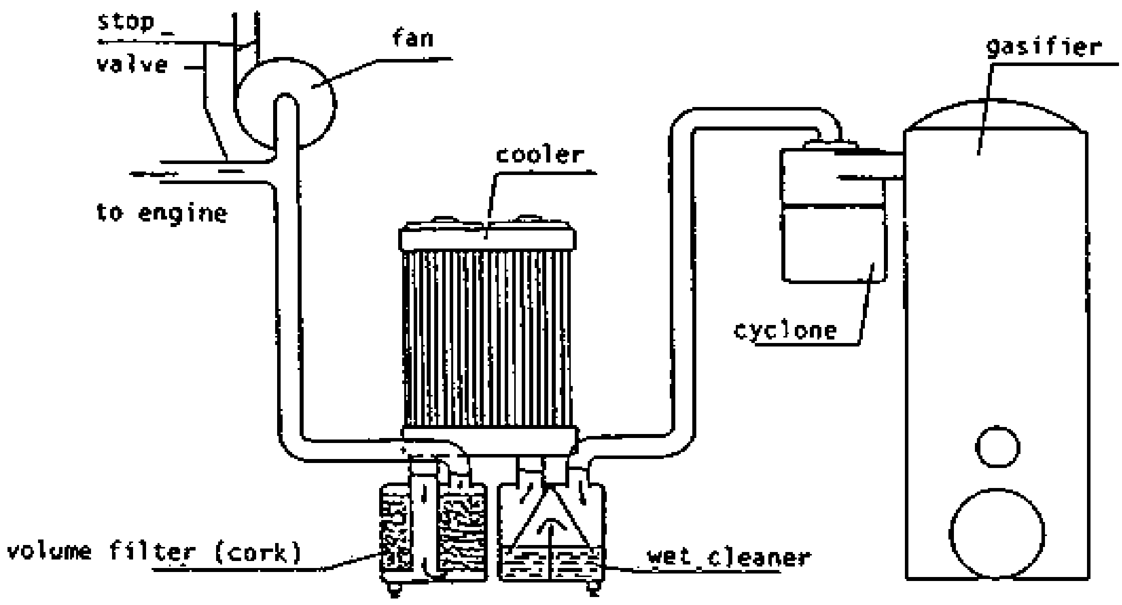

Figure 4.1 Gas cleaning system for vehicles – traditional wet cleaning system (Nordstrom 63)

Systematic tests with this type of gas cleaning system have been conducted by Nordstrom. According to these tests such kind of a system is not very efficient and may cause different operational problems. “The engine wear and the contamination of the lubrication oil in this case exceeded considerably those observed on diesel fuel operation”. (Nordstrom 63)

After considering several possibilities for gas cleaning system improving such as fabric filters, electrostatic filters (although they have very good particle separating properties, they are very expensive, and their use is not feasible for the mobile applications) and wet scrubbers, fabric filters using a glassfibre cloth as filtering material were selected as most suitable for vehicle applications. (Wood Gas as Engine Fuel 86, 60; Nordstrom 63) Figure 4.2 illustrates improved gas cleaning system.

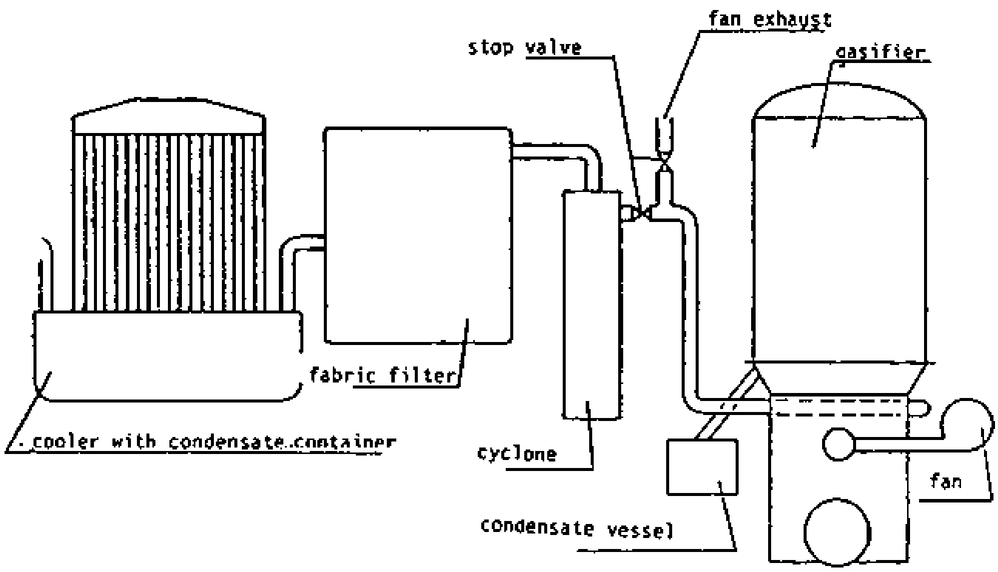

Figure 4.2 Gas cleaning system for vehicles – fabric filter cleaning system with cyclone (Nordstrom 63)

Hot gas cyclone separator, fitted into this system, is simple, inexpensive, and is widely used as a prefilter for the solid particles elimination before the fine particles removal and gas cooling. “A cyclone separator is essentially a gravitational separator that has been enhanced by a centrifugal force component.” The cyclone performance is usually evaluated in the terms of particle cut diameter or cut size (d_{p50}) – particle size, which is captured with the 50% efficiency. (Reed and Das 88) Figures 4.3 and 4.4 show schemes of the cyclone separator.

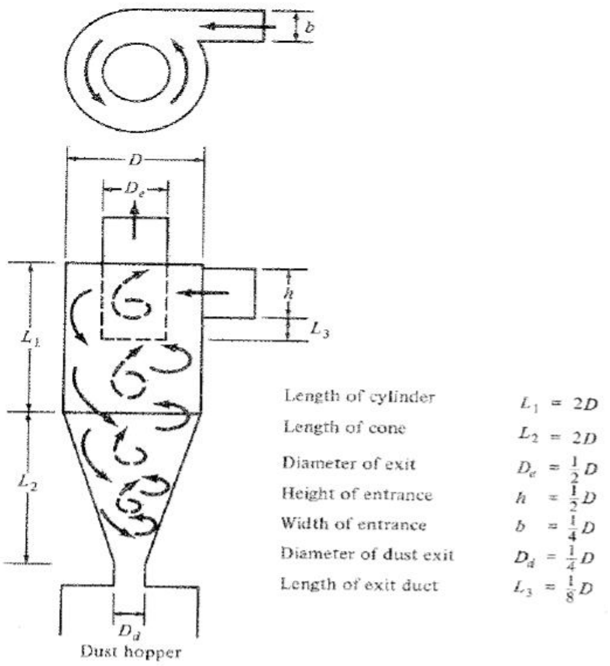

Figure 4.3 Cyclone proportions (Perry and Chilton 73)

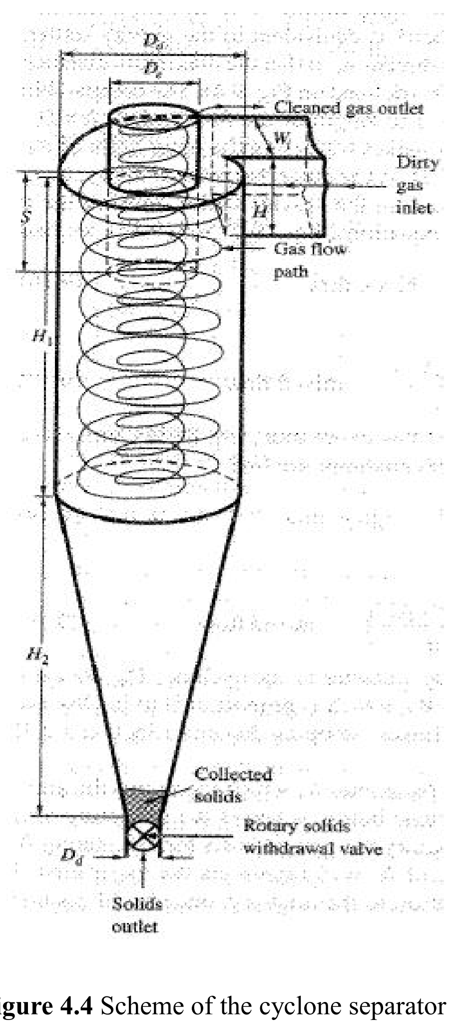

Figure 4.4 Scheme of the cyclone separator (de Nevers 2000, 257)

Glassfibre cloth, which is used as a filtering material in the fabric filters can be used at a maximum temperature of about 300 ^{0} C, which means that “it is possible to operate the filter at a temperature giving a large margin over the dew point of the gas”.

To study engine wear and contamination of the lubricant oil Nordstrom has carried out a number of comparative tests between the wood gas operation system with a fabric filter cleaning train and diesel fuel operation system (Nordstrom 63). It was found, that the cylinder wear is considerably less comparing with the old type of cleaning system and, in some cases, even less than during the operation on diesel fuel. The similar results were found for the lubricant oil contamination. Dust concentration after cleaning was 0.3 mg/m^3 with the fabric filter system and 200–400 mg/m^3 with the old type wet cleaning system. According to the Tiedema et al. (83) dust concentration less than 50 mg/m^3 is acceptable, and less than 5 mg/m^3 is preferred.

After a series of tests for the filter configuration determination, a standard filter box with eight filter bags giving a total filter surface of 3.0 m has been designed. The box is insulated with 10 mm thick layer of mineral wool and its complete weight is 65.5 kg. (Wood Gas as Engine Fuel 86, 61) Figure 4.5 illustrates the standard fabric filter type.

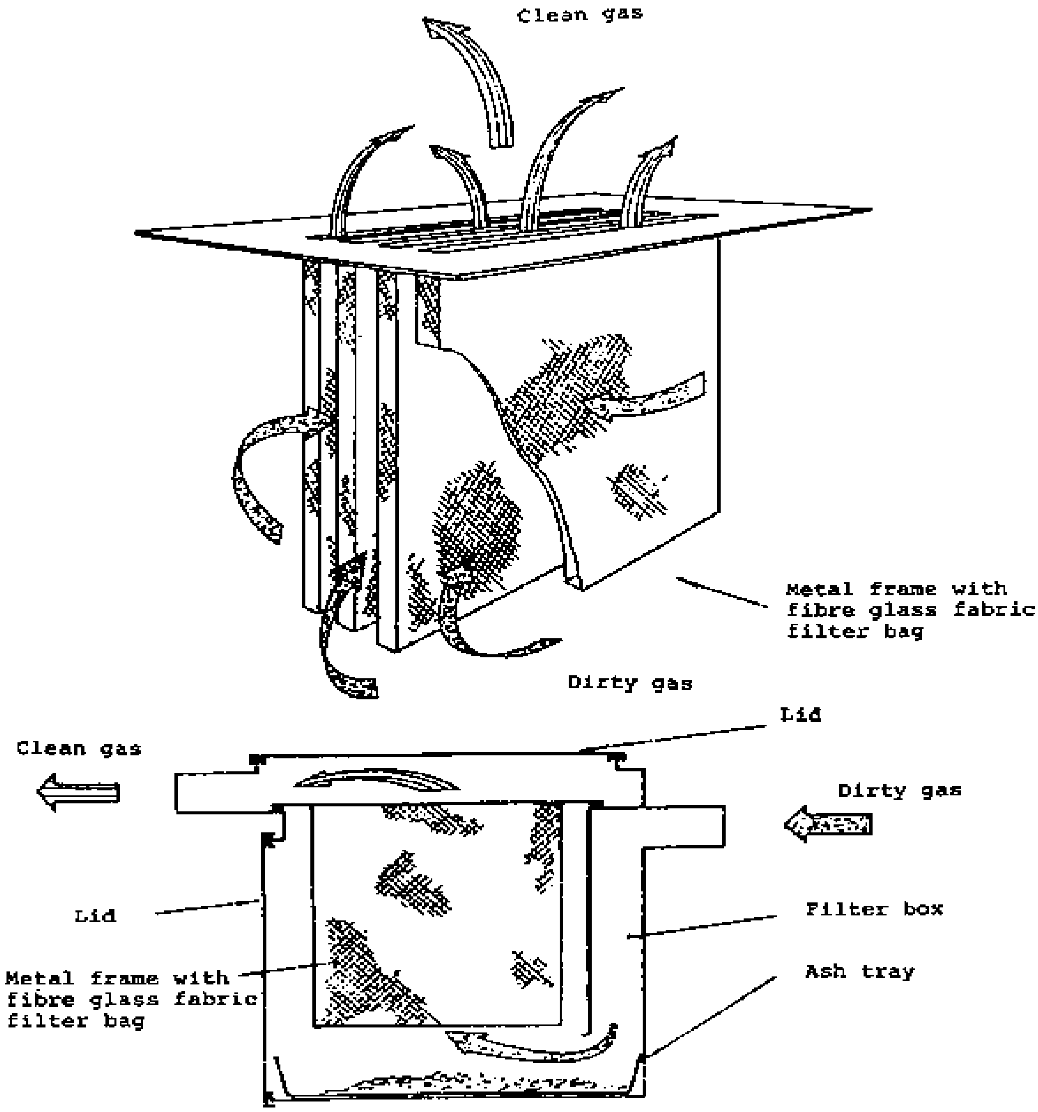

Figure 4.5 Sketches of the standard type fabric filter (Wood Gas as Engine Fuel 86, 64)

The maximum recommended gas flow through the one filter box shall be less than 65 m/h, “giving an equivalent velocity through the filter fabric of 0.01 m/s at the operating temperature of 200 ^{0} C”.

“The pressure loss over the filter depends on the load and the amount of dust in the filter. If condensation occurs in the filter, and the fabric gets wet, the pressure loss will increase considerably”.

The filter cleaning interval on practice depends on the power loss, resulting from the filter pressure drop, which the driver can accept. Normal cleaning intervals vary between 1500 and 3000 km. (Wood Gas as Engine Fuel 86, 61)

4.2 Gas cooling

The producer gas has to be cooled to increase its energy density. The latter will allow maximizing the amount of the combustible gas entering the engine cylinder at each stroke: the reduction of the gas temperature on 10% increases the maximum output of the engine by almost 2%. The cooling also contributes to gas cleaning process, making it possible to avoid the moisture condensation of producer gas after it is mixed with air before the engine intake. (Wood Gas as Engine Fuel 86, 40)

According to the Swedish Academy of Engineering Sciences (79), major factors that have to be taken into the consideration in the gas cooling process are the following:

- the sensible heat of the gas;
- the water vapour content of the gas and its heat of condensation;
- the effects of cooler fouling.

Various types of the equipment are used to achieve the gas cooling purpose. Producer gas coolers can be divided into three following categories:

- natural convection coolers;
- forced convection coolers;
- water coolers.

Natural convection coolers are represented as a simple combination of pipes. They are easy to use and clean and require no additional energy input. Although the construction can be rather cumbersome, this problem can be partly neutralized by using fined pipes to increase the conductive surface.

"Forced convection coolers are equipped with a fan which forces the cooling air to flow around the gas pipes". This cooler type is usually smaller than the natural convection coolers, but they require the extra energy input for the fan. Another disadvantage of the forced convection coolers is the necessity to use gas cooling pipes of small diameters, which can result in fouling problems.

Water coolers can be of two types: the scrubber and the heat exchanger. When the scrubber is used, the objective is usually to clean and to cool the gas simultaneously during the one operation process.

There are many different scrubber types, but the principle is always the same: the gas is brought in direct contact with a liquid medium (e.g., water) which is sprayed into the gas stream through the nozzles. The main advantage of this system is its small size. But there are too many disadvantages: the fresh water need, increased complexity of maintenance, increased power consumption, as a result of the water pump usage and the waste water treatment necessity. (Wood Gas as Engine Fuel 86, 42)

5. FUELLING OF ENGINES BY PRODUCER GAS

5.1 Engine modifications for the producer gas operation

The producer gas has relatively low energy content and the certain combustion characteristics that differ greatly from these of the gasoline and diesel fuel. (Yogi Goswami 86, 83–102)

Moreover, there is a significant difference between diesel and spark ignition (gasoline) engine systems in their suitability for running on producer gas. In the diesel engine, diesel fuel is injected at the end of the compression stroke and gets ignited without any spark ignition. But this will not work with the producer gas – it cannot be ignited under the prevailing pressure. Thus, a certain amount of diesel fuel has to be injected into the engine combustion chamber. (Turare, conference paper 2002; Yogi Goswami 86, 83–102)

In the gasoline engine, air-fuel mixture is sucked during the suction stroke and mixture is ignited with a spark at the end of the compression stroke. Thus, gasoline engine can operate on producer gas alone without any gasoline injection, which is certainly very convenient and economically beneficial. But this will work only in the case with the constant engine loads. This approach is not practically workable for any automobile application, as in this latter case the engine has to work under different loading conditions.

Thus, for the transport application we have only one possibility left – diesel engine. As it was already mentioned above, diesel engines are compression ignition engines (compression ratio of about 16–24, depending on whether they are direct combustion chamber, pre-combustion chamber, four strokes or two strokes), where fuel is ignited by high air temperature. And so, diesel engine cannot be operated on producer gas alone. (Turare, conference paper 2002)

For the using producer gas as a fuel, diesel engines can be either converted completely into the spark ignition systems (full producer gas operation mode) or the normal unconverted diesel engine can be operated in the "dual-fuel" mode, where the diesel fuel is necessary for the combustible gas-air mixture ignition. (Turare, conference paper 2002, Wood Gas as Engine Fuel 86, Yogi Goswami 86, 83–102)

However, not all the types of diesel engines can be converted to the "dual-fuel" operation mode. Compression ratios of ante-chamber and turbulence chamber diesel engines are too high for satisfactory "dual-fuel" operation and use of the producer gas in those engines leads to knocking, as a result of too high pressures combined with delayed ignition. (Kaupp and Goss 81) Direct injection diesel engines have lower compression ratios and can generally be successfully converted. (Wood Gas as Engine Fuel 86, 9)

Diesel engine conversion to spark ignition system

Nordstrom in 1957–1963 has conducted detailed studies of conversion of two diesel engines, produced by Swedish manufacturers – Volvo and Bolinder-Munktell, to spark ignition system for operation on straight producer gas. (Nordstrom 63)

The conversion included the following modifications:

- replacement of the cylinder head for the spark plugs fitting;
- replacement of the injection pump by a distributor;
- use of special producer gas pistons giving a lower compression ratio.

Moreover, different shapes of the combustion chamber were tested on one of the engines. (Wood Gas as Engine Fuel 86, 62)

Although, the power loss in diesel engine converted to spark ignition system is not as severe as in gasoline engine running on producer gas, conversion of the diesel engine to the spark ignition system is complicated, expensive and time consuming affair, the advantages of which are nullified by the cost. (Yogi Goswami 86, 83–102; Turare, conference paper 2002)

Thus, most of the diesel engines running on producer gas are of the "dual-fuel" type. As a rule, the diesel engine can run on 15–20% (of the original consumption) of the diesel fuel and rest on the producer gas. Generally, "the engine is started on diesel fuel and as the gas generation builds up the diesel consumption is then kept at the idling level". (Yogi Goswami 86, 83–102) In this case the engine efficiency is about 25%. So, one can conclude, that running in the "dual-fuel" engine mode for producing 1 kWh requires 1 kg of biomass and consumes 0.07 liters of diesel fuel. (Johansson 80)

Dual fuelling of ante-chamber and turbulence chamber diesel engines

Nordstrom has carried out a number of tests with "dual-fuel" operation of ante-chamber and turbulence chamber diesel engines. (Nordstrom 63) During the tests it was found that these engines are not suitable for the "dual-fuel" operation mode, as too early ignition of the gas-air mixture, result in engine knocking, will occur if the load is fairly high or the gas-air mixture is dirty. This will lead to the poor diesel oil substitution.

Dual fuelling of direct injection engines

According to the studies of the performance of direct injection diesel engines operated in a "dual-fuel" mode with a minimum diesel fuel injection, which have been carried out at the National Swedish Testing Institute for Agricultural Machinery, the required modifications are generally simple and limited to:

"- installation of a control lever for obtaining low injection quantities and maintaining the possibility for normal injection by straight diesel operation;

- modification of the injection pump to provide suitable injection characteristics (constant injection per stroke at varying engine speed);

- advancing the injection timing".

The injection timing is not very important for engine speeds below 1200 rpm, but its advancing becomes more important as the engine speed increases. The injection timing setting for the "dual-fuel" operation mode should be determined through the bench tests for each engine type.

In the case with the direct injection engines operated in the "dual-fuel" mode, the full power efficiency is about 35%, the diesel fuel substitution is between 80 and 90%, and the power loss is about 10–38%.

The main advantage of this latter system (direct injection diesel engine operated in a "dual-fuel" mode) lies in its flexibility: in case of malfunctioning of the gasifier or lack of biomass fuel, an immediate change to full diesel fuel operation is generally possible. (Wood Gas as Engine Fuel 86, 8)

Apart from the above mentioned required engine modifications, there is one more necessary condition for the successful engine operation on the producer gas – it is airtightness of the gasifier unit-engine connection. The producer gas is unable to burn without being mixed with certain amount of oxygen. If an air leakage occurs below the grate area, the hot gas will burn, consuming the available oxygen and creating heat. This latter process will almost certainly destroy the gasifier unit (if it is not detected). If an air leakage occurs in the filter unit or in the connecting pipes, the producer gas will become saturated with improper amounts of oxygen and, thus, will become unsuitable for the engine running. Therefore airtightness of the gasifier unit-engine connection is very essential. (La Fontaine and Zimmerman 89)

5.2 Engine power output and its maximizing in the producer gas operation

The power output of the engine operating on the producer gas is determined by the same factors as of the engine operating on traditional liquid fuel:

"- the heating value of the combustible mixture of fuel and air which enters the engine during each combustion stroke;

- the amount of combustible mixture which enters the engine during each combustion stroke;

- the efficiency with which the engine converts the thermal energy of the combustible mixture into mechanical energy (shaft power);

- the number of combustion strokes in a given time (number of revolutions per minute – rpm)." (Wood Gas as Engine Fuel 86, 9)

The engine conversion to the "dual-fuel" operation mode will, in most cases, lead to the reduced power output. The reasons for the power losses and the possibilities to minimize them are the following:

<u>Heating value of the combustible mixture</u>

The producer gas heating value depends on its content, to be more precise, on the relative amounts of the main combustible components – carbon monoxide, hydrogen and methane.

As it was already mentioned above, for the combustion, the producer gas has to be mixed with a suitable amount of air. And the combustible mixture will have a lower heating value per unit of volume than the producer gas alone.

It is, thus, evident that the highest heating value for the combustible mixture is achieved at the highest heating value of the producer gas itself. And the latter one depends on the design of the gasifier and on the gasifying fuel characteristics. In the case with the gasifier design, it is very important to minimize heat losses, and for the fuel, it is very important to consider carefully such characteristics as the moisture content and the size distribution.

During the practical tests with wood chips gasifiers, developed at the National Swedish Testing Institute for Agricultural Machinery, it was found that the upper limit for the fuel moisture content for acceptable gas quality is 30% (wet basis). If the moisture content of the fuel exceeds 40%, the gas will not be combustible.

Concerning the size distribution characteristic, it is recommended that, e.g., the wood chips be screened to remove fines and coarse pieces. (Wood Gas as Engine Fuel 86, 66) Table 5.1 presents the typical size distribution of the suitable for vehicle gasifiers wood chips.

Table 5.1 Typical size distribution for wood chips suitable for the vehicle gasifiers (Wood Gas as Engine Fuel 86, 68)

Size range	% -weight
below 5 x 5 mm	2–3
5 x 5–10 x 10	6–11
10 x 10–15 x 15	12–19
15 x 15–20 x 20	20–24
20 x 20–25 x 25	25–30
25 x 25–30 x 30	9–20
30 x 30–35 x 35	about 5
35 x 35 and above	about 3

To study the effect of the size distribution on the engine maximum power output the number of tests was carried out with the mounted on the tractor gasifier type F5. Table 5.2 shows the results of these tests.

Table 5.2 Improvement of the maximum power output by wood chips screening (Wood Gas as Engine Fuel 86, 68)

Size range	Unsieved chips	5–10 mm	10–15 mm	15–40 mm
Sieving loss, %	-	3	14	34
Pressure drop across gasifier, bar	0.18	0.13	0.09	0.08
Power output at 1800 rpm, kW	16.8	18.1	21.1	21.0
Power increase by sieving, %	0	7.7	25.5	25.5

The power increase can be explained both, by reduced pressure losses in the gasifier and the producer gas quality improvement after fines removing (since less than 50% of the power increase can be explained by reduced pressure losses).

Also, according to these tests, "removal of the fines gives a substantial power increase at a fairly small expense, i.e. about 3% increase of the feedstock cost. Screening for removal of material in the range of 10–15 mm may also be considered worthwhile, whereas further screening does not appear to give any power increase".

Moreover, the engine power output can be improved by at least 10%, if instead of the wood chips, wood blocks are used. And this will also be the result of the gasifier pressure losses reduction.

As it was already mentioned above, another reason for the power loss is in the mixing the producer gas with the combustion air, which result in the gas composition changes and in variations in pressure drop across the gasifier.

Both, excess and deficiency of air will lead to the power output decrease, as both of them result in the decrease of the heating value of the combustible mixture (per unit of volume). In practice, however, it is normally better to operate the engine with a slight air excess – to prevent backfiring in the engine exhaust gas system. (Wood Gas as Engine Fuel 86, 13)

<u>Engine speed and ignition advance</u>

As the engine power output is defined per unit of time, the engine power output depends on the engine speed. For diesel engines the power output is nearly linear with the rpm. (Wood Gas as Engine Fuel 86, 14)

If a diesel engine is operated in the "dual-fuel" mode, it is also necessary to advance the timing of the diesel fuel injection. And this advance depends on the engine speed, as it was shown by Nordstrom. (Nordstrom 63)

Moreover, in the process of "dual-fuelled" engine operation, one can sometimes encounter with the problem of detonation. "Apart from the engines with too high compression ratios (above 1:16), this phenomenon mostly occurs when an attempt is made to remedy low power output of the engine by introducing increased amounts of diesel fuel". Depending on the producer gas composition, an excess of pilot fuel can lead to the detonation. That is why, the amount of pilot diesel fuel in "dual-fuel" operation mode must be limited – in most cases "a limitation at around 30% of the maximum engine power output will prevent detonation". (Wood Gas as Engine Fuel 86, 15)

The certain minimum amount of diesel fuel, injected per cycle to ensure the ignition, also depends on the engine speed. According to the Middleton and Bruce (46) this minimum amount varies from 3 up to 5 mm^3 per cycle.

In practical operation, however, a somewhat higher amount of diesel fuel has to be injected per cycle "to stay on the safe side". Diesel fuel injection of 8–9 mm^3 per cycle and cylinder is recommended. (Wood Gas as Engine Fuel 86, 15)

6. HEALTH AND ENVIRONMENTAL HAZARDS ASSOSIATED WITH THE USE OF PRODUCER GAS

During the gasifier operation process one can encounter with various dangers, namely toxic, fire and explosion hazards. Moreover, this process and men's activities connected with it can affect the environment. Thus, we also should consider the environmental hazards of the gasifier operation. A review of the different types of hazards and environmental impacts of producer gas operation was published by Kjellstrom (84).

6.1 Toxic hazards

An important component of the producer gas is carbon monoxide (CO) – an extremely toxic and dangerous gas as it tends to combine with the hemoglobin of the blood and, thus, prevents oxygen absorption and distribution. The carbon monoxide is also extremely dangerous, because it is odorless and tasteless. Table 6.1 shows the effects caused by different concentrations of carbon monoxide in the air.

Table 6.1 Toxic effects caused by different concentrations of carbon monoxide in the air (Wood Gas as Engine Fuel 86, 45)

CO concentration in the air, %	ppm	effects
0.005	50	no significant effects
0.02	200	possible mild frontal headache after two to three hours
0.04	400	frontal headache and nausea after one to two hours; occipital head-ache after 2.5 to 3.5 hours
0.08	800	headache, dizziness, and nausea in 45 min; collapse and possibly un-consciousness in two hours
0.16	1600	headache, dizziness, and nausea in 20 min; collapse and possibly death in two hours
0.32	3200	headache and dizziness in 5 to 10 min; unconsciousness and danger of death in 30 min
0.64	6400	headache and dizziness in 1 to 2 min; unconsciousness and danger of death in 10 to 15 min
1.28	12800	immediate effect; unconsciousness and danger of death in 1 to 3 min

Generally, producer gas system works under suction, so that even if a minor leakage occurs, no dangerous gases will escape from the equipment during actual operation, thus the risk of poisoning through leakage is minimal. The situation is, however, different during starting-up and shutting-down of the gasification installation. (Wood Gas as Engine Fuel 86, 45; La Fontaine and Zimmerman 89)

When the engine is shut down, formation of the producer gas still continues, resulting in pressure increasing inside the gasifier. This pressure increase lasts for approximately 20 minutes after the engine shutdown. Thus, it is not advisable to stay in the vehicle during this period. Moreover, the gasification system should be allowed to cool for at least 20 minutes before the vehicle is placed in the closed garage, especially, connected with the living premises. The gas formed during the shutdown period has a carbon monoxide content of 23 up to 27% and is, thus, very toxic. (La Fontaine and Zimmerman 89)

It is still arguing, whether chronic poisoning can occur as a result of prolonged inhalation of relatively small amounts of carbon monoxide. But, to the present moment the majority of researchers tends to opinion that no chronic symptoms can occur through carbon monoxide poisoning. (Wood Gas as Engine Fuel 86, 45)

However this does not mean that the symptoms mentioned in the literature (tiredness, irritability and touchiness, difficulty in sleeping) did not result from prolonged exposure to the producer gas. There exist a possibility that some other gas compounds can be responsible for these symptoms. (Reed and Das 88; Wood Gas as Engine Fuel 86, 46)

The latter facts again emphasizes the importance of carrying out starting-up and shutting-down processes of the gasifier unit in an open environment, as well as of taking care to avoid close contact with the gases during these phases. (Wood Gas as Engine Fuel 86, 46)

6.2 Fire hazards

Fire hazards can result from the following causes:

- high surface temperature of equipment;

- risks of sparks during refueling;

- flames through gasifier air inlet on refueling lid (may ignite nearby flammable materials).

However, fire risks can be considerably decreased by taking certain precautions. First of all, hot parts of the system must be carefully insulated. Secondly, installation of the double-sluice type filling device and back-firing valve at the gasifier inlet should be considered. (Wood Gas as Engine Fuel 86, 46)

Moreover, size of the clearance between the gasifier unit and the vehicle should be carefully chosen. Also the ash disposal should be carried out only after the unit cool down (this residue must be placed away from any combustible material). (La Fontaine and Zimmerman 89)

6.3 Explosion hazards

Risk of explosion can arise from the producer gas-air explosive mixture formation. This mixture can be formed under the following circumstances:

- air leakage into the gas system;

- air penetration during refueling process;

- air leakage into the cold gasifier still containing residual producer gas, which can ignite;

- back-firing from the fan exhaust burner when the system is filled with a combustible mixture of air and gas during the starting-up process. (Wood Gas as Engine Fuel 86, 46; Reed and Das 88)

Air leakage into the gas system does not generally give rise to explosions. If a leakage occurs in the lower part of the gasifier, this will result in partial combustion of the gas, which in turn will lead to higher gas outlet temperatures and a lower gas quality. (Wood Gas as Engine Fuel 86, 46)

Air leakage into the cold gasifier and residual producer gas-air mixture ignition will lead to an explosion. That is why, the cold system should always be carefully ventilated before igniting to ensure that it contains only fresh air. (Wood Gas as Engine Fuel 86, 46; Reed and Das 88)

6.4 Environmental hazards

During the gasification process of wood or agricultural residues, besides the producer gas itself, certain amounts of ash (from the gasifier unit and the gas cleaning system) and condensate, polluted by phenol and tar, are produced.

The ash disposal creates no problem, but with the tarry condensate the situation is quite different – disposal of this condensate from a large number of the gasifiers can have undesirable environmental effects. Thus, this problem (the tarry condensate disposal) needs careful investigation.

“The properties of exhaust emissions from engines running on the producer gas are generally considered to be acceptable, comparable to those of diesel engines”. (Wood Gas as Engine Fuel 86, 47)

There is one more question to consider, when talking about the wide use of the biomass gasification for transport – the increased demand for wood and agricultural residues fuels. The effect of this increased demand on the environment can be either positive or negative – depending on the approach to the problem. “Selective wood cutting and use of some residues can improve the forests and fields. Indiscriminate cutting and use of residues can lead to poor wood lot stands, erosion and soil depletion”. (Reed and Das 88)

“It is essential that a careful survey of available sources of biomass fuel, and analysis of alternative uses and existing competing markets of these fuels, be carried out” before the wide introduction of the biomass gasification for transport. (Kjellstrom et al. 83)

7. REQUIREMENTS FOR WOOD GAS POWERED CARS

So, one has decided to converse the car to enable wood gas fuelling. In this case, apart from the technical questions, there are certain considerations from the part of the Finnish laws and taxes that have to be taken into account before the vehicle conversion and in the process of its operation.

At the present moment, only vehicles, produced before the 1.7.1987, can be conversed for the wood gas utilization, as for the newer vehicles there exist certain Euro-norms for transport fuels – Euro Emission Standards – where for wood gas there are no defined limits. The first standard – Euro 0 – defined the acceptable limits for vehicles exhaust emissions for the 1988–1992 years.

Emission measurements and their results, submitted to the vehicle inspection authorities, cannot help in this case, even if the emissions are lower than allowed for this car type/model.

In Finland one cannot easily find fairly good old vehicles, so the car, in most cases, has to be purchased abroad.

After the car is purchased and conversed, all the changes must be approved in the corresponding authority (Vehicle Administration AKE) after the alteration inspection procedure. Only after this one can use modified vehicle on the road:

- "a power-driven vehicle and a vehicle coupled to the power-driven vehicle or to its trailer shall be approved in a modification inspection prior to entry into service, if essential modifications are made to the construction or use of the vehicle or if components or equipment are added to or removed from the vehicle, thus changing its characteristics or use considerably. A vehicle shall also be submitted to a modification inspection if the prerequisites for a tax or a fee for the vehicle change or if the data on the classification or subclassification of the vehicle is no longer valid". (Vehicles Act, 402/2005)

The special attention, when the conjunction of the gasification unit and the vehicle takes place should be paid to the dimensioning of the whole construction – the maximum weight and the main vehicle dimensions should not exceed permissible norms.

If the gasification unit is mounted on the towed device (e.g., trailer), one should remember that the maximum allowable speed in this case is 80 km/h. (Ministry of Transport and Communications Finland. Driving in Finland. 2004)

7.1 Taxes

According to the Ministry of Finance Finland, motor vehicles and fuel used for road traffic are subject to the following taxes:

- "car tax on passenger cars, delivery vans and motorcycles – Car Tax Act of 29 December 1994;
- vehicle tax on diesel driven vehicles – tax on the propelling force; Act on Vehicle Tax of 30 December 2003;
- vehicle tax on passenger cars and vans – basic tax; Act on Vehicle Tax of 30 December 2003;
- fuel fee – Act on Fuel Fee of 30 December 2003". (Ministry of Finance. Taxation in Finland 2005)

<u>Car tax</u>

"The car tax is a purchase tax, which must be paid before the first registration or use of the vehicle in Finland". (Ministry of Finance. Taxation in Finland 2005) So, this tax can be applicable only in case, when one purchases the vehicle for the modification abroad – and it is obvious, that future car conversion doesn't influence on this tax value.

<u>Vehicle tax</u>

Vehicle tax is divided into two following parts:

- basic tax ("owners of passenger cars, vans and special-purpose cars that have a maximum unladen weight 3,500 kg are liable to pay vehicle tax if the vehicle has been or should have been registered in Finland. The tax is 26 cents per day on vehicles in use before 1 January 1994, otherwise 35 cents per day. The tax is assessed for 12-month tax periods" (Ministry of Finance. Taxation in Finland 2005)).
- tax on the propelling force ("the tax on the propelling force is levied annually on all vehicles using, entirely or partly, fuel other than petrol, i.e. diesel oil, ker-

osene, liquefied petroleum gas or electricity. The tax is assessed for 12-month tax periods" (Ministry of Finance. Taxation in Finland 2005)).

The rates per day are the following – "for passenger cars and dual-purpose cars, 6.7 cents/100 kg of the total weight or a fraction thereof and for motor caravans and delivery vans 0.9 cents /100 kg." (Ministry of Finance. Taxation in Finland 2005)

Thus, the vehicle tax on the propelling force can be applicable to our case of the wood gas powered vehicle. But there are certain exceptions from the vehicle tax – vehicles using wood-based or peat-based fuels. However, if the vehicle is operated in the "dual-fuel" mode (starting on diesel and then switching to the wood gas) it cannot wholly be excised from the vehicle tax (on the propelling force).

Fuel fee

"Fuel fee is payable if certain more lightly taxed fuels are substituted for highly taxed fuels. The purpose is to prevent the use of such fuels in vehicles (e.g. heating oil in diesel-driven vehicles). The amount of the fee is 100–1.000 euros a day according to the vehicle group. Passenger cars, vans, buses and lorries using liquid gas, natural gas or biogas are exempt if they fulfill certain criteria of exhaust emissions (EURO 4)". (Ministry of Finance. Taxation in Finland 2005)

At the present moment, vehicles using wood-based or peat-based fuels are also exempted from the fuel fee. (Parkkinen 2008)

Moreover, according to the Ministry of the Environment, there exist also "the environmental tax component (i.e. carbon surtax), based on the carbon content of fuels used for heating and transportation. Its value since January 2008 is €20 per tonne of CO_2 (€75 per tonne of carbon)". (Ministry of the Environment. Environmentally Related Energy Taxation in Finland. 2008) Table 7.1 shows the excise duty and strategic stockpile fee rates in Finland (January 2008).

Table 7.1 Excise duty and strategic stockpile fee rates in Finland (January 2008) (Ministry of the Environment. Environmentally Related Energy Taxation in Finland. 2008)

Fuel	Basic tax	Surtax (*=carbon comp., €20/tonne CO_2)	Strategic stockpile fee
Diesel oil, euro cents/litre			
- sulphur free	30.67	*5.38	0.35
- other grades	33.32	*5.38	0.35
Light fuel oil, euro cents/litre	2.94	*5.41	0.35
Peat	-	-	-

The table above is not all-inclusive; substitutes for liquid fuels may face the same rate. Fuels for commercial aviation and commercial yachting exempted; also other exemptions exist. Strategic stockpile fee = precautionary stock fee.

7.2 Emissions

Against general belief, exhaust gas emission level of internal combustion engine is significantly lower on wood gas than on petrol. Especially low are HC emissions. A normal catalytic converter works well with wood gas but even without it, emission level less than 20 ppm HC and 0.2% CO can easily be achieved by most automobile engines. Combustion of wood gas generates no particulates and the gas thus renders very little carbon black amongst motor oil. (Renewable Energy for Housing and Transportation 2008)

Table 7.2 shows the emission measurements of the modified cars using only wood gas as a fuel (not “dual-fuel” mode). For the case of Chevrolet ElKamina both the emissions when running on wood gas and gasoline are presented. This allows making some kind of a comparison of the emissions level.

Table 7.2 Emission measurements (Suomen Ekoautoilijat Ry 2009)

Component	Chevrolet ElKamina, wood gas/gasoline	Saab 99, wood gas	Chevrolet Fleetside, wood gas
Lambda	1.163/1.096	1.407	1.266
CO	0.18%/2.45%	0.32%	0.23%
CO_2	16.38%/10.94%	12.66%	15.70%
HC	48 ppm/519 ppm	29 ppm	10 ppm
O_2	4.01%/4.05%	7.92%	6.20%
CO_2 calculated	0.18%/2.74%	0.36%	0.20%

As it can be perfectly seen from the table above, the emissions of CO and HC when running on wood gas are much lower than that when running on gasoline. Thus, these data confirm the given above statement.

Moreover, in the work of Sridhar et al. (2005) the overall performance and emission of reciprocating internal combustion engines in "dual-fuel" mode and gas alone mode of operation using biomass derived producer gas were considered.

The emissions in gas alone and "dual-fuel" mode were compared with existing emission standards of various countries (EU, USA, India). The data given in this work indicates that emission levels with gas alone operation are lower than emission norms of EU and USA. However, in the case of "dual-fuel" operation mode, the CO levels are higher than these norms (as a result of the combustion inefficiency) thus requiring improved gasifier construction or exhaust gas treatment. (Sridhar et. al 2005)

8. EVALUATION OF POSSIBILITY OF USING WOOD GAS FOR TRANSPORT – SECURITY OF SUPPLY

From the previous chapters one can perfectly see that using wood gas as a fuel for transport has a number of economical and environmental advantages.

Although, biomass gasification technology has also some disadvantages, its application for transportation needs, especially in the agricultural sector (driving of farm machinery like tractors, harvesters etc.), seems feasible and promising in the nearest future. (Yogi Goswami 86, 83–102)

But, if we are discussing the possibility of using this technology, we must consider one very important moment – if there is enough biomass for producing wood gas for transport and what percentage of, e.g. Finnish road vehicle fleet can be converted for running on wood gas.

At the present moment, traffic energy consumption in Finland is about 230 PJ and approximately 74% of this is the road traffic consumption, which is 170 PJ. Figure 8.1 illustrates these data.

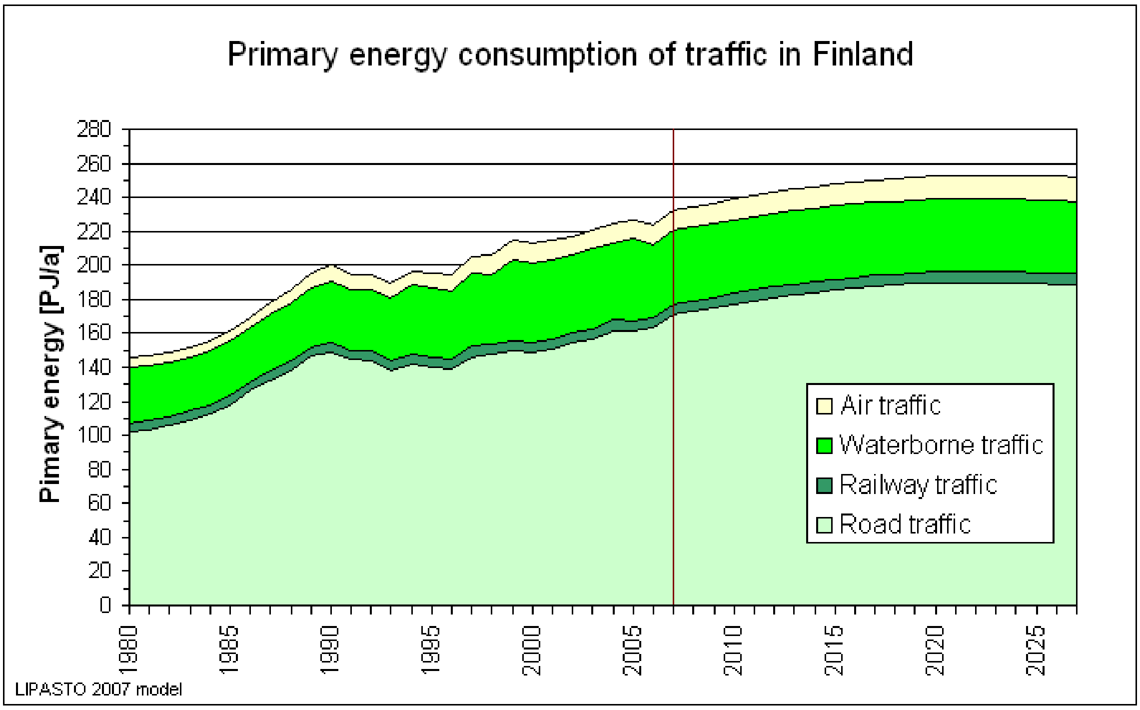

Figure 8.1 Primary energy consumption of traffic in Finland (LIPASTO. Traffic Emissions. 2007)

Thus, we have to assess the present utilization of biomass resources in various sectors (industrial and non-industrial).

Nowadays, wood and peat covers over 90% of the biofuels use in Finland. Table 8.1 summarizes the energy use of wood and peat in different sectors in Finland in the year 2006. (Heinimö 2008, 16)

Table 8.1 End use of wood and peat by end user groups in 2006, PJ (Heinimö 2008, 16)

Fuel/End use sector	Forest industry	District heating	Small-scale use(c	Other industry & users	Total
Forest fuels(a	7.8	9.0	2.8	5.0	24.6
Firewood	0	0	45.3	0	45.3
Solid wood processing industry by-products and residues(b	43.6	17.2	1.0(d	21.7	83.5
Total wood(e	**51.4**	**26.2**	**49.1**	**26.7**	**153.4**
Fuel peat	18.6	39.4	1.1	34.5	93.6

(a Excludes firewood.
(b Includes bark, sawdust, industrial chips, pellets, briquettes, recovered wood and all other wood fuels excluded from the other columns. The share of pellets and briquettes was estimated at 1.5 PJ.
(c Includes the use of forest chips by farms and detached house properties.
(d In addition includes wood pellets.
(e Excludes black liquor.

So, the total amount of biomass (wood and peat), which is currently in use is about 250 PJ.

Now, we have to estimate the production potential and future use of the biofuels in Finland:

- solid forestry industry by-products consist of pulp chips, bark, sawdust and industrial chips and they are utilized both as raw material and in energy production. Their total volume available for energy purposes would not change substantially from the current level by the year 2010 (Ranta et al. 2005);

- forest chips (forest fuels) from logging residues, stump and root wood and small-diameter energy wood constitute a large and underutilized biofuel potential, and they will consist the largest share of the future growth of biofuels production; (Heinimö 2008, 18)

- peat has a significant role in the Finnish energy system. The Geological Survey of Finland has estimated the employable energy reserve of peat at 48 EJ (Virtanen 2003).

Table 8.2 compares the current use, production potentials and estimated use of major biofuels.

Table 8.2 The current use, production potential and prospective use of the biofuels in Finland (Heinimö 2008, 19)

Fuel	Use in 2006, PJ	Production potential, PJ/a	Estimated use in 2010-2015, PJ/a
Solid wood processing industry by-products and residues	81.5	-	65–85[a]
Forest fuels (forest chips)	24.6	80–140[b]	40–73
Firewood	45.3	-	55–63
Wood pellets	1.5	9–25[c]	1–25
Peat	93.6	-	61–97
Total	**246.5**	**-**	**222–343**

(a The lower value results from the increased use of sawdust in pellet production.
(b The theoretical maximum production potential was evaluated at 45 million solid-m^3 (324 PJ).
(c This equals 0.55-1.5 Mt/a pellet production. The lower limit is a production target of the Finnish pellet energy association for the year 2010.

Analyzing these two tables, we can make a conclusion that, e.g. solid wood processing industry by-products and residues can't be utilized for wood gas production for transportation needs, because in this case forest industry is the major user of wood fuels. Almost two thirds of wood fuels use takes place in the forest industry. Wood is the most important fuel at forest industry mills, accounting for about 75% of their fuel consumption. (Peltola (ed.) 2007)

Moreover, as it was already mentioned above, the total volume of the forest industry by-products available for energy purposes would not change substantially in the nearest future (production potential is not much higher than current and estimated use).

Thus, we can conclude that only forest fuels (forest chips) and peat can be utilized as raw materials for the wood gas production, as their production potential is considerably higher than their use (both, current and estimated).

But, we also have to take into account the strategy aims to secure and promote biomass utilization in the Finnish energy sector, so use of wood and peat fuels can increase in the nearest future. This would again decrease the available amount of resources for wood gas production.

So, we can roughly estimate that if the road traffic energy consumption is at the present moment about 170 PJ and will increase in future and the production potential of forest fuels is 140 PJ/a (maximum estimated level) minus 73 PJ/a (maximum estimated demand), about 40% of Finnish vehicle road fleet can be converted for running on wood gas as a fuel. But this can be realized only if the whole 67 PJ (140 PJ/a–73 PJ/a=67 PJ) of available biomass resources would be directed to the wood gas production. The latter is very unlikely, so the number of road vehicles that can be converted for the wood gas utilization is up to 20%.

9. SUMMARY AND CONCLUSIONS

In the first part of this thesis a kind of survey of the previous works and materials concerning the usage of biomass gasification for transport was made.

First of all, the principles of biomass gasification process along with possible fuel and gasifier types, and gas composition were considered. Also the benefits and drawbacks of using the resulting producer (wood) gas for transport were outlined.

From this part, it was concluded that the most appropriate biomass fuels for gasification are wood and peat, and the most suitable gasifier type is downdraught (if we are speaking about transportation needs), as it makes possible to produce wood gas with relatively low tar content which can be applied for the internal combustion engine operation.

It is for this reason the process of conversion of solid fuel into gas in a downdraught gasifier and the design basis for such gasifier type was examined in this work in a more detailed way.

In this study, also the gas cleaning and cooling equipment was discussed, as for the trouble-free operation internal combustion engine must be supplied with fairly clean producer gas – sufficiently free from tars, dust and acids.

Then, such an essential process as fuelling of engines by producer gas was considered with respect to such moments as necessary engine modifications and engine power output and ways of its maximizing.

Moreover, different hazards (health and environmental) associated with use of the producer (wood) gas were also mentioned here.

And, finally, the last chapters concentrated more on the practical aspects of the wood gas application for vehicles fuelling, specifically on the taxation of such vehicles in Finland, their emissions and the security of biomass and, as a consequence, wood gas supply.

It was roughly estimated that with the present level of the road traffic energy consumption and the production potential of forest fuels and current level of their use, up to 20% of Finnish vehicle road fleet can be converted for running on wood gas as a fuel.

The main aim of this work was an assessment whether biomass gasification technology is perspective in the nearest future for the wide use on transport or not.

As it can be perfectly seen from the above estimation there is a possibility (from the part of the resources availability) to convert some percentage of the Finnish vehicle fleet for the running on wood gas.

Of course, driving the producer gas fueled vehicles requires more attention than gasoline or diesel fueled ones, but it is more environmentally safe and gives the possibility of traditional (fossil) fuel supply and prices independence. The latter is very important for Finland, as it is highly reliant on imported fossil fuels and particularly on oil, most of which is used in the road transport.

If we also take into account the low cost of wood gas, comparing with the costs of available green alternatives, the extra work (that is certainly needed for the biomass gasification technology development and promotion in the transport sector) seems acceptable.

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