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Gas cleaning for IC engine applications from fixed bed biomass gasification

P. Hasler*, Th. Nussbaumer

Verenum Research, Langmauerstrasse 109, CH-8006, Zurich, Switzerland

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Abstract

Gas cleaning for tar and particle removal is necessary for internal combustion (IC) engine applications of producer gas from fixed bed biomass gasifiers which are usually in the capacity range from 100 kW up to 5000 kW. In the present investigation, tar and particle collection efficiencies have been determined in a sand bed filter, a wash tower, two different fabric filters, and a rotational particle separator (RPS) in different test runs with fixed bed gasifiers. Tar adsorption on coke has been investigated in a fixed bed batch reactor. Furthermore data from literature for catalytic tar crackers, venturi scrubbers, a rotational atomizer, and a wet electrostatic precipitator (ESP) are given. Based on the presented gas cleaning efficiencies and the investment cost, an assessment of gas cleaning systems is made for IC engine applications from cocurrent gasifiers. The results show that the postulated gas quality requirements for IC engines cannot be safely achieved with state-of-the-art gas cleaning techniques and that 90% particle removal is easier to achieve than 90% tar removal. Except for the catalytic tar crackers which are considered as an option for applications above several MW and for gases with a high tar level, none of the investigated gas cleaning systems can securely meet a tar reduction exceeding 90%. Therefore one of the key issues for a successful application of biomass derived producer gas from small scale gasifiers is the tar removal, where further development is needed. © 1999 Elsevier Science Ltd. All rights reserved.

Keywords: Gas cleaning; Tar separation; Particle separation; Biomass gasification; IC engine application

1. Introduction

Producer gas from biomass gasification contains particulates and organic contaminants (tars) which, if not removed, can cause severe operational problems. For fixed bed gasifiers with IC engine applications, high concentrations of particulates and tars can damage the engine or lead to an unacceptable level of maintenance. Producer gas cleaning is therefore a fundamental step in integrated biomass gasification systems. Results from the evaluation of gas cleaning technologies for IC engines are presented in this paper.

* Corresponding author. Tel.: +41-1-364-14-12; fax: +41-1-364-14-21.

E-mail address: verenum@access.ch (P. Hasler)

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Table 1
Gas quality of raw producer gas from atmospheric, airblown biomass gasifiers [3–5]. Some tar values are indicative since definitions are not specified

		Fixed bed cocurrent gasifier	Fixed bed countercurrent gasifier	CFB gasifier
Fuel moisture	% mf	6–25	n.d.[a]	13–20
Particles	mg/Nm^3	100–8000	100–3000	8000–100,000
Tars	mg/Nm^3	10–6000	10,000–150,000	2000–30,000
LHV	MJ/Nm^3	4.0–5.6	3.7–5.1	3.6–5.9
H_2	Vol.%	15–21	10–14	15–22
CO	Vol.%	10–22	15–20	13–15
CO_2	Vol.%	11–13	8–10	13–15
CH_4	Vol.%	1–5	2–3	2–4
C_nH_m	Vol.%	0.5–2	n.d.[a]	0.1–1.2
N_2	Vol.%	rest	rest	rest

[a] n.d. = not determined.

The performance as well as the investment and operational cost of gas cleaning systems are determined by the gasifier performance and the gas quality requirements. The gasifier performance influences the operability of the gas cleaning unit (e.g. high amounts of tars can block a filter) whereas the collection efficiency is a result of the gas cleaning principle.

Small-scale atmospheric fixed bed gasifiers are selected as gas producers for IC engine power generators. Typical fixed bed gasifiers have thermal capacities in the range of 100 kW up to 5000 kW. The raw producer gases of the investigated concurrent gasifiers exhibit a particle level in the range 50 mg/Nm^3 up to 500 mg/Nm^3, whereas the concentration of the high boiling tar components ranges from 50 mg/Nm^3 to 1000 mg/Nm^3. These contaminant levels are considered as typical values for state-of-the-art biomass gasifiers operated with dry and uncontaminated wood chips.

Both wet and dry gas cleaning systems are evaluated. Since IC engines are generally fuelled with cold gas, the dew point of the producer gas is generally higher than the gas inlet temperature and hence condensates will be generated in all gas cleaning systems. In gas cleaning systems with dry filter units such as fabric filters condensates can arise, e.g. from condensing heat exchangers after the particle filter.

1.1. Gas quality requirements

For satisfactory IC engine operation, an acceptable particle content < 50 mg/Nm^3 and a tar content < 100 mg/Nm^3 is postulated [1,2]. Gas cleaning systems are expected to reduce particles and tar components from the raw producer gas to the postulated levels. Typical values of the main components as well as the particulate and tar contents in the raw producer gas from fixed and fluidized bed gasifiers are given in Table 1. The lower heating values of the gas do not vary in a wide range. However, the amount of tars is much higher in countercurrent than in cocurrent gasifiers. For IC engine applications, countercurrent gasifiers are therefore not considered as an option. State-of-the-art cocurrent gasifiers exhibit a tar level of less than 1000 mg/Nm^3. CFB gasifiers exhibit very high particle contents and moderate to high tar levels in the producer gas.

Table 2
Gas quality requirements for power generators [1,2]

		IC engine	Gas turbine
Particles	mg/Nm^3	< 50	< 30
Particle size	μm	< 10	< 5
Tar	mg/Nm^3	< 100	
Alkali metals	mg/Nm^3		0.24

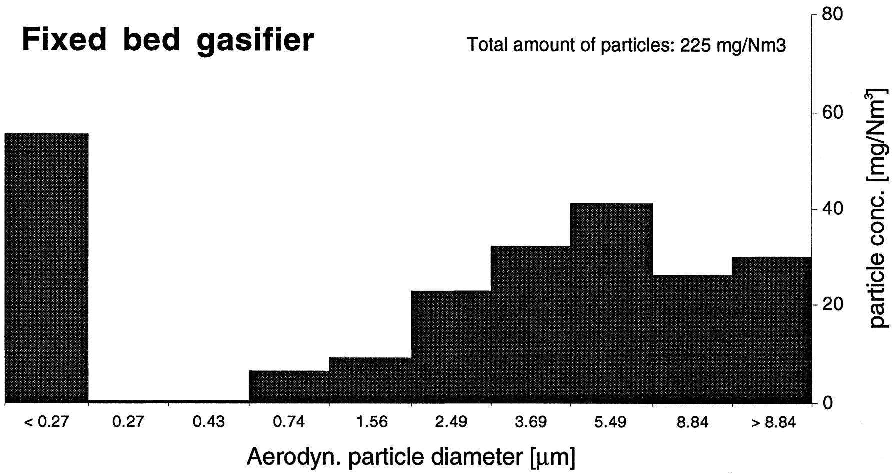

Fig. 1. Particle size distribution during gasification of native wood in the IISc open-top fixed bed gasifier [9].

Generally, cocurrent and CFB gasifiers are operated with dry fuel only, whereas in countercurrent gasifier water contents up to 50 wt% are possible.

The gas quality requirements for the power generators are very strict (Table 2). However, the postulated gas quality given in the literature should be interpretated carefully since the type of engine used can play an important role and satisfying engine operation has also been shown with higher tar levels than the postulated values [6,7]. Furthermore, numerous methods of contaminant sampling and analysis procedures are in use which may lead to results which are not strictly comparable. Large differences can be expected, especially for the sampling and analysis of tars. Within this paper, solely high boiling organic components present in the gas are considered as tar. A description of the sampling method is given in the literature [8].

For satisfactory IC engine operation and producer gases from state-of-the-art cocurrent fixed bed gasifiers, the particle collection efficiency must be higher than 90%. For the collection of high boiling tars, a 90% reduction can be estimated.

1.2. *Influence of the particle size distribution*

Measurements of the particle size distributions from two different fixed bed gasifiers showed bimodal size distributions with maxima < 1.5 μm and > 5 μm (Fig. 1). In both gasifiers, the mass of particles with an aerodynamic diameter < 1.5 μm amounts to more than 60 mg/Nm^3. The general behaviour for particle collection of conventional gas cleaning systems is shown in Fig. 2. Cyclones, wash towers and swirl scrubbers have a limited collection efficiency for particles < 1.5 μm and hence the particles from biomass

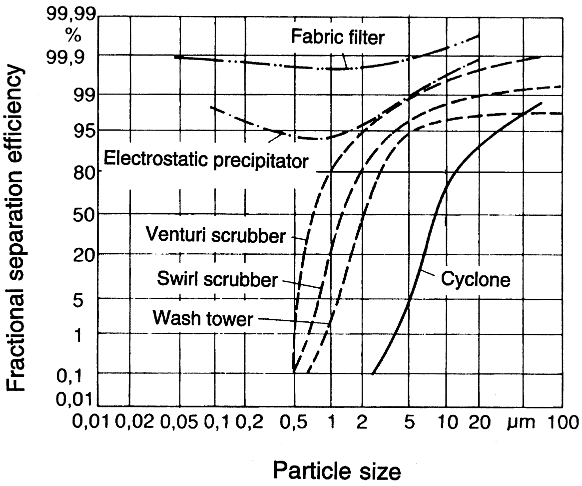

Fig. 2. Particle collection efficiencies of conventional gas cleaning systems [10].

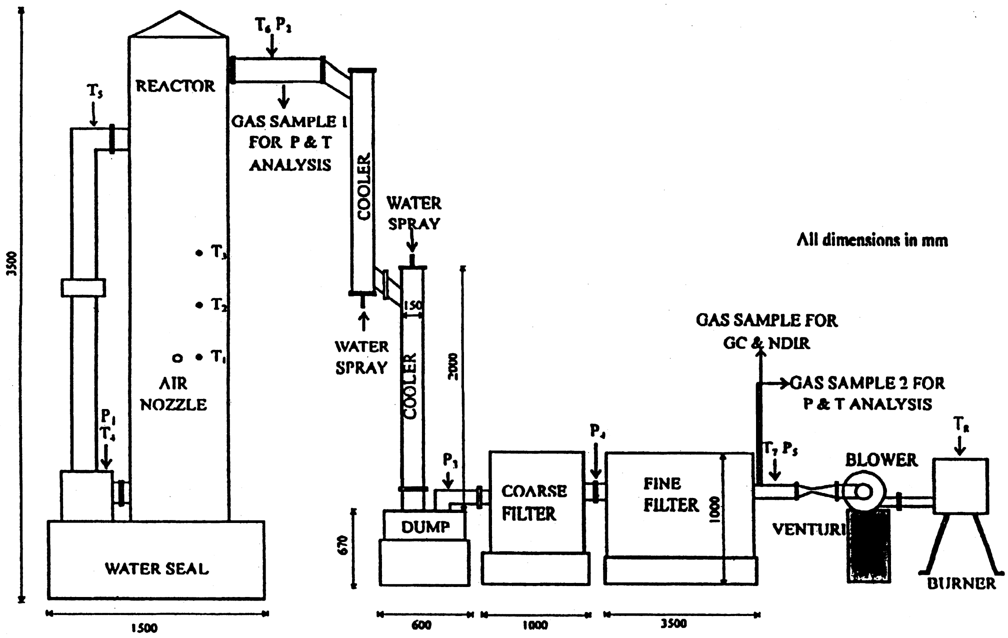

Fig. 3. Open-top gasifier of IISc/Dasag with quench and sand bed filters (coarse and fine sand filter) used for test runs in Chatel St Denis, Switzerland [7].

gasifiers will only be partially separated. The tar collection of gas cleaning systems can hardly be calculated and must be derived from experimental data.

2. Experimental

In the present investigation, tar and particle collection efficiencies have been determined in the following gas cleaning systems in different test runs with raw gas from fixed bed gasifiers:

- a system of quench and sand bed filter with a coarse and a fine filter
- a wash tower
- two different fabric filters
- a rotational particle separator (RPS)
- a fixed bed adsorber for tar removal.

Furthermore, to the proposed filter units, data from literature for catalytic tar crackers, a venturi scrubber, a rotational atomizer, and a wet electrostatic precipitator (ESP) are included for the evaluation. The detailed evaluation of the gas cleaning technologies is described in [11] and the detailed results of the performed experiments are presented in [12].

2.1. Sand bed filter

The investigated sand bed filter is used for the cleaning of the gas from a IISc/Dasag open-top gasifier. Before the sand bed filter, the hot producer gas is quenched by water injection (Fig. 3). After the quench, the gas flows through two granular beds with a coarse and a fine sand. For a gasifier with a nominal capacity of 270 kW (thermal input), the total amount of sand used is approximately 1100 kg. The clean gas leaves the sand bed filter at temperatures between 5°C and 25°C.

In practice, the cleaning procedure of the sand bed filters is a possible disadvantage in compari-

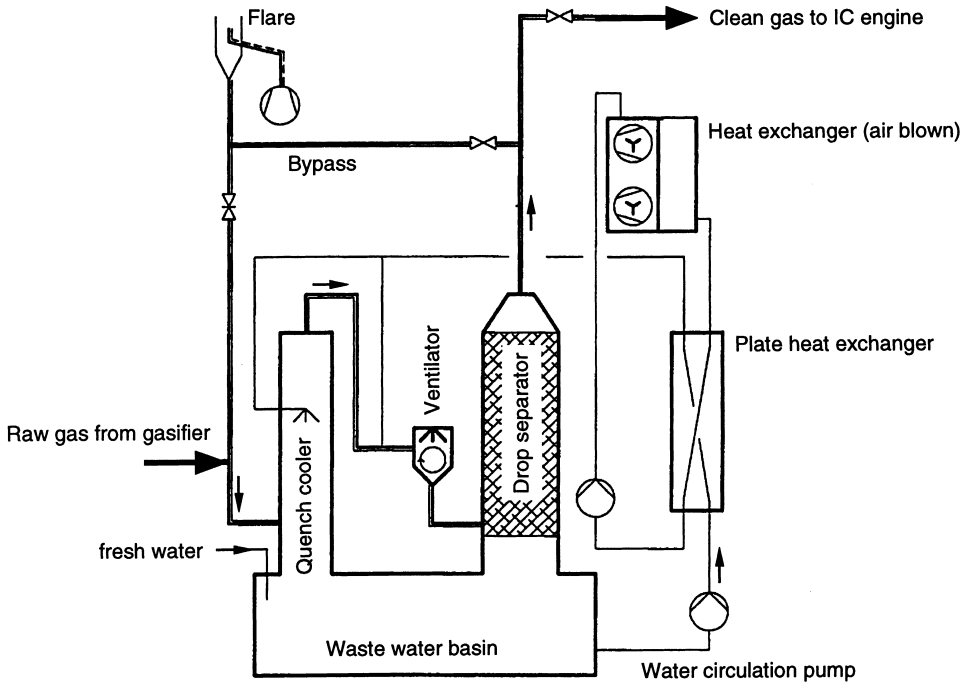

Fig. 4. Wash tower used during test runs at the hydrotest gasifier in Emmenbrücke, Switzerland [6].

son to other technologies. Experiences with a sawdust filter after a concurrent gasifier showed that cleaning intervals are in the range of 200 h of operation. The cleaning requires very rigid safety precautions since the tar-laden sawdust is extremely toxic. The sawdust must be treated as hazardous waste. Sand bed filter cleaning is regarded less critical than sawdust filter cleaning.

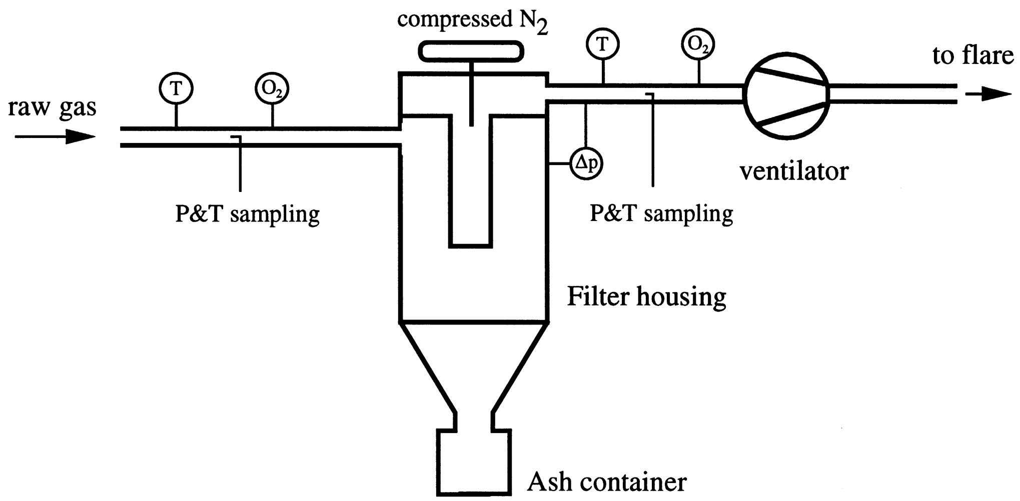

Fig. 5. Schematic of the fabric filter unit for particle and tar removal investigated at the IISc/Dasag gasifier.

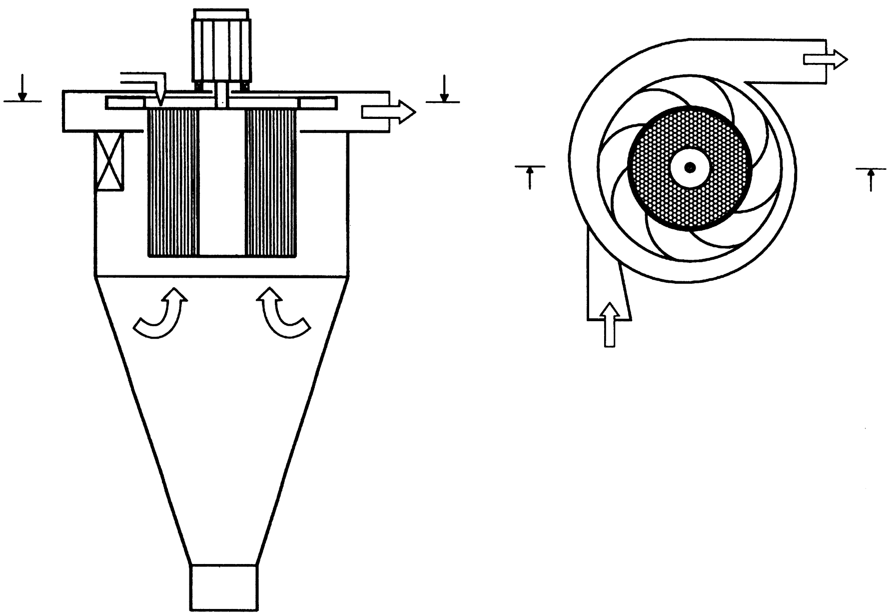

Fig. 6. Rotational particle separator (RPS) with cyclone and rotating cylinder [13].

However, few practical experience has been gathered so far with the cleaning and will be necessary for further applications.

2.2. Wash tower

The wash tower shown in Fig. 4 was used for gas cleaning at an AHT fixed bed gasifier at Hydrotest AG in Emmenbruecke, Switzerland. The hot gas leaves the gasifier at temperatures between 400°C and 600°C and enters the quench gas cooler from the bottom. The saturated gas passes a wet *fan* with additional water injection and a counter current wash column. Particles and tar components are removed in the ventilator and in the wash column which acts as a drop separator. The wash water is collected in a basin and recirculated to the quench cooler. The clean producer gas leaves the wash tower at temperatures between 45°C and 60°C. The exit temperatures are higher than desired since the plate heat exchanger in the test equipment is too small. As a result of the relatively high exit temperatures, the wash tower can be operated as a water consuming system.

2.3. Fabric filter

Fabric filters are well established for flue gas dedusting in combustion processes. However, only limited experience is available in gasification. In this investigation, two fabric filter units were tested with producer gases from a IISc/Dasag and a KARA gasifier. The filter unit tested at the IISc/Dasag gasifier is a laboratory scale test filter with one filter bag and a total filter surface of 0.31 m^2 (Fig. 5). The gas lines and the filter housing are heated electrically to the desired operating temperature. The unit can be heated up to 350°C. As filter material, Nextel® by 3 M is used. This ceramic fibre tissue can be operated at least up to a temperature of 600°C, which makes it attractive in cases where tar condensation on the filter material can be a problem. Tar condensation in filter is observed at filter temperatures below 300°C. However, the particle collection efficiency of the Nextel® filter element is expected to be lower than for Teflon (PTFE) based filter materials which have a maximum operating temperature of 230°C.

The fabric filter unit was fed with a slip stream

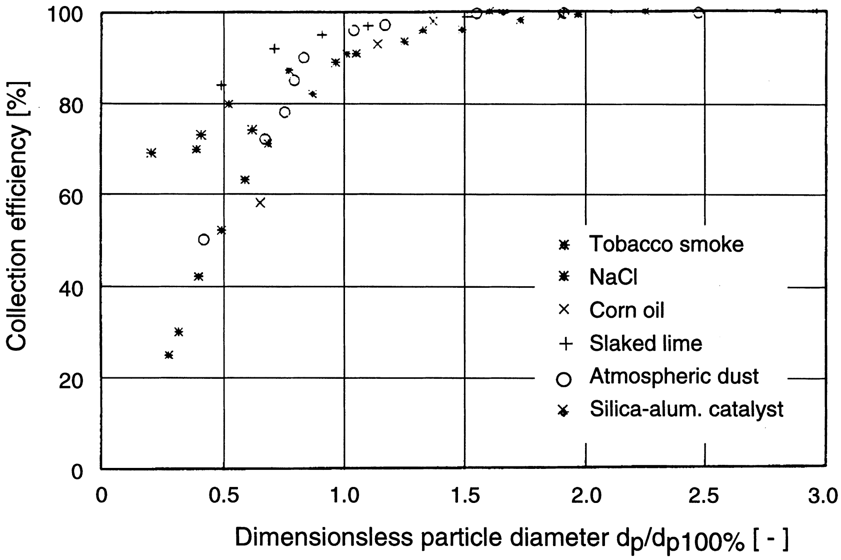

Fig. 7. Particle collection efficiency for RPS of different design [14].

of the raw gas from the IISc/Dasag gasifier. Sampling of particles and tars was made before and after the filter. The clean gas passes a ventilator and a water seal as a fire safety precaution before it is flared in a swirl burner. Dedusting of the laden filter bag is made by backflushing with a jet pulse of compressed nitrogen. The operation of the fabric filter and the data aquisition is PC controlled.

2.4. Rotational particle separator (RPS)

The concept of the rotational particle separator (RPS) uses a rotating cylinder which is centred in a single cyclone (Fig. 6). The rotating cylinder consists of a bundle of axial capillary channels with an inner diameter of 2.2 mm. The rotating cylinder is mounted on the driving shaft of the prime mover. An impeller which brings the gas to the desired pressure is mounted downstream of the filter element. The overpressure in the clean gas and an appropriate impeller design prevents unwanted leakages of nonfiltered gas into the clean gas.

The RPS can be operated with fixed or variable rotation speed. The overall particle collection behaviour of the RPS is expressed as the $d_{p100\%}$ value [13]. This value can be calculated as follows and represents the theoretically calculated particle diameter which can be completely separated:

$$d_{p100\%} = \sqrt{\frac{27\eta\Phi d_c}{\rho_p\Omega^2 L\pi(1-\varepsilon)(R_o^3 - R_i^3)}} \quad (1)$$

where η, dynamic fluid viscosity (kg/ms); Φ, volume flow (m^3/s); d_c, channel diameter (m); ρ_p, particle density (kg/m^3); Ω, angular velocity (rad/s), L, channel length (m); ε, wall thickness correction (–); R_o, outer filter element radius (m); R_i, inner filter element radius (m).

The particle collection efficiency has been experimentally verified as a function of the dimensionless particle diameter (Fig. 7). The effective $d_{p0,max}$ was found to be higher by a factor of approximately 1.5 than the calculated value $d_{p100\%}$ according to Eq. (1). The $d_{p0,max}$ value represents the experimentally verified particle diameter which is completely separated. The RPS will also separate smaller particles than the $d_{p100\%}$ but with a lower efficiency. In the case of the tangential design (see Fig. 6), the collection efficiency for particles with $d_p = 0.5\ d_{p0,max}$ is approximately

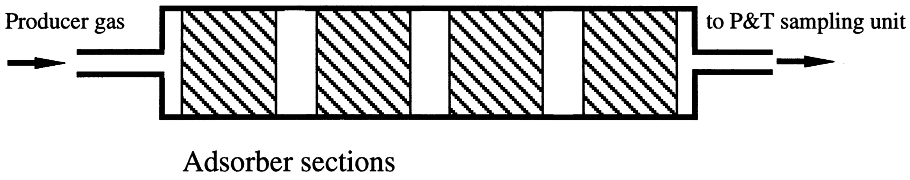

Fig. 8. Laboratory scale fixed bed adsorber for tar removal from producer gas.

80%, for $d_p = 0.2\ d_{p0,max}$ the collection efficiency is approximately 30%.

Cleaning of the particle loaden cylinder channels is done by injecting compressed nitrogen from the top of the rotating filter element through a nozzle. Dedusting can be made during filter operation.

The tested RPS is a laboratory version for hot gases with a nominal gas flow rate of 150 m^3/h. The design of the RPS is such that the $d_{p0,max}$ is 0.53 μm at nominal flow conditions. The RPS was fed with a slipstream of the raw gas from the IISc/Dasag open top gasifier. The gas lines and the RPS housing are heated electrically to the desired operating temperature. Sampling of particles and tars are done before and after the filter unit. The clean gas passes a ventilator before it is flared in a swirl burner. The operation of the RPS and the data acquisition is PC controlled.

2.5. *Activated carbon filter for tar adsorption*

Literature data and our own experiments have shown that most of the producer gas cleaning systems in use exhibit a limited capability of reducing tar. Since tar components are key elements for IC engine application of producer gases, additional tar reduction may be necessary. A possible method for improved tar reduction is the adsorption of high boiling tar components from the producer gas on carbonaceous materials such as lignite coke or activated carbon. Adsorption is a widely used purification process for the removal of gaseous impurities [15]. At room temperature, activated carbon loadings from 20 wt% up to 80 wt% are reported, e.g. for halogenated aliphatic hydrocarbons [16].

For preliminary test runs, a laboratory scale fixed bed with granular lignite coke as an adsorbent has been designed and tested (Fig. 8).

Table 3
Reduction of particles and tars in various producer gas cleaning systems (with various definitions of "tar")

	Temperature (°C)	Particle reduction (%)	Tar reduction (%)
Sand bed filter[a]	10–20°C	70–99	50–97
Wash tower[a]	50–60	60–98	10–25
Venturi scrubber			50–90
Rotational atomizer	< 100	95–99	
Wet electrostatic precipitator	40–50	> 99	0–60
Fabric filter[a]	130	70–95	0–50
Rotational particle separator[a]	130	85–90	30–70
Fixed bed tar adsorber[a]	80		50
Catalytic tar cracker	900		> 95

[a] Data based on own results from cocurrent gasifier test runs with identical sampling method (see [8] and [12]; other data from literature according to [11].

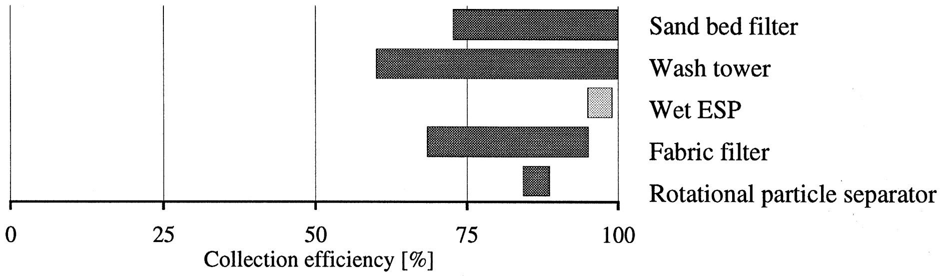

Fig. 9. Collection efficiency for particles in (%) in different gas cleaning systems. The presented results are from our own investigations [12] except for the wet ESP where data are taken from [17].

Lignite coke has been chosen due to its favourable cost and the good adsorption characteristics. The coke is supplied by Rheinbraun (Germany). Lignite coke are thermally stable up to 300°C. For the adsorption test runs, the sieved coke fraction from 0.56 mm to 1.0 mm is used. Test runs were made with clean producer gas from the IISc/Dasag gasifier and after the RPS and the sand bed filter. The tar-laden coke can potentially be used as an extra fuel in the gasifier and hence no solid waste is generated.

3. Results

The reduction of particles, tars and some trace components are given in Table 3. All values are based on experimental data from various biomass gasification test runs [12]. The sampling and analysis of the particles and tar components from the test runs in the sand bed filter, the wash tower, the RPS, the fabric filter and the tar adsorber have been made with the same method according to [8] and hence all these data are comparable.

The results show that particle collection is less critical than tar separation (Figs. 9 and 10). The highest particle separation was observed in sand bed filters, rotational atomizers and in wet electrostatic precipitators (ESP). Surprisingly, fabric filters can exhibit lower particle collection efficiencies than wet gas cleaning systems, and higher tar levels can often be found at the exit than at the inlet [12]. The low particle collection possibly resulted from an insufficient filter cake thickness whereas the higher tar level at the exit of the filter may be attributed to tar polymerization reactions on the filter cake or to desorption

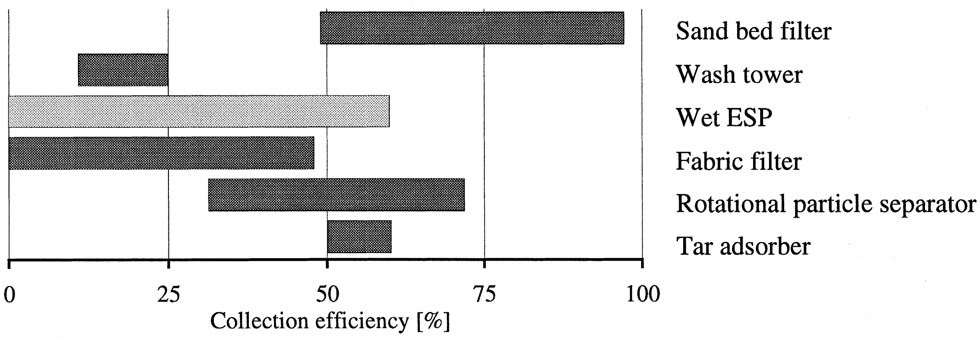

Fig. 10. Collection efficiency for heavy tars in (%) in different gas cleaning systems. The presented results are from our own investigations [12] except for the wet ESP where data are taken from [17; different tar definition].

Table 4
Expected particle and tar collection and investment cost of the gas cleaning for a 1000 kW_{th} fixed bed biomass gasifier without waste water treatment (excluding V.A.T. and installation)

Gas cleaning system	Particle separation (%)	Tar separation (%)	Cost (kECU)
Venturi scrubber	95	60	40
Sand bed filter	85	70	28
Wet electrostatic precipitator	95	50	125
RPS, tar adsorber and heat exchangers	90	70	49
Fabric filter, tar adsorber and heat exchangers	90	70	78

of tars which have been adsorbed during former operation. Both observations need further investigation.

The preliminary test runs with the tar adsorber have shown a tar collection of approximately 50%, which is much lower than expected.

The highest tar reduction so far has been found in high temperature catalytic tar crackers, in venturi scrubbers and in sand bed filters. Catalytic tar cracking is generally done in fluidized bed reactors and requires operating temperatures of 900°C. Therefore catalytic cracking is considered as an option for large-scale gasifiers and for high temperature producer gases with tar levels exceeding 10 g/Nm^3. In small-scale fixed bed gasifiers, the producer gas temperatures are in the range 500°C to 600°C and the tar concentrations are lower than 1 g/Nm^3. Hence, significant losses of chemical energy will be observed in the producer gas when the heat from the cracked gas cannot be transferred to the raw gas and therfore catalytic tar cracking is not an option for fixed bed gasifiers.

For the sand bed filter, the filter cleaning procedure needs further improvement since significant manual work is required at the present and the disposal of the residues has to be solved.

4. Investment cost for IC engine applications

The total investment cost for different gas cleaning systems have been determined for a state-of-the-art cocurrent biomass gasifier with 1000 kW thermal coupled to an IC engine (Table 4). Ceramic filters have not been considered due to their complexity and high investment cost for atmospheric producer gas. They are mainly used for particle removal from pressurized gasifiers at high temperatures. Presumably, fabric filters or the RPS will alone not be able to reduce the tar level to the same degree as wet gas cleaning systems. Hence, an activated carbon based adsorber is proposed as an additional tar removal unit. The lowest investment cost arise from the sand bed filter. The fabric filter system costs significantly more but less than a wet electrostatic precipitator based system.

5. Conclusions

The present investigation shows that a 90% particle removal is easier to achieve than a 90% tar removal. Except for the catalytic tar crackers, none of the gas cleaning systems tested so far can securely meet a tar separation exceeding 90% and hence new concepts for tar removal are required. Based on experimental data for the removal of particles and tars (Table 3), none of the investigated gas cleaning systems can safely meet the gas quality requirements for satisfactory IC engine applications (Table 2). If the postulated gas qualities are assumed as correct, some operational problems in the IC engine will occur. Hence, the tar separation is a key issue for a successful application of biomass derived producer gas.

High particle collection efficiencies are expected for dry gas cleaning systems such as high performance fabric filters and the rotational particle separator. For both, the tar reduction is smaller than in wet gas cleaning systems and hence an additional tar reduction is required. A tar collection in the range of at least 70% can be expected with additional tar adsorbers based on activated carbon. The sand bed filter and the wash tower have already been successfully tested in fixed bed biomass gasifiers coupled to IC engines. For a final cost assessment of the different gas cleaning systems, operating cost based on practical experience are needed.

Acknowledgements

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