

# Gas cleaning strategies for biomass gasification product gas

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## Abstract

In general, the raw product gas of biomass gasification contains a range of minor species and contaminants, including particles, tar, alkali metals, chlorine, nitrogen compounds and sulphur compounds. This study reviews the recent developments in product gas cleaning technologies for these species and summarizes the findings of the research project 'Mop fan and electrofilter: an innovative approach for cleaning product gases from biomass gasification' which was recently carried out by the authors. The results of the project showed that combination of mop fan and electrofilter (ESP) has great potential in removing fine particles, tars and chemical contaminants in the product gas.

**Keywords:** biomass gasification; product gas cleaning; mop fan; ESP

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## 1 INTRODUCTION

Biomass represents one of the largest sustainable energy resources in the world and has been perceived as an attractive source of power, fuels and other chemical products. However, the bulky and inconvenient form of biomass is a major barrier to its wide applications, and this provides a motivation for the conversion of solid biomass into liquid and gaseous fuels via the two major paths: biological and thermo-chemical conversions. Gasification, one of the thermo-chemical conversions, can be a highly efficient conversion process that offers the possibility to convert various feedstocks to a wide variety of products. Although gasification technologies have been developed for over a century, their commercial successes on a large scale are still limited. The economic and technological successes of a biomass gasification plant depend on the trouble-free operation of all system components over long periods of time. Besides fuel properties, gasifier design and operation, gas cleaning is a key issue in the process chain. The product gas has to meet individual requirements of different end-users or applications, such as combustion in internal combustion engines (ICEs), (micro-) gas turbines (GTs), fuel cells (FCs) or as a resource to produce SNG, FT-hydrocarbons or methanol (Table 1 [1]).

To remove the unwanted byproducts and contaminants in the product gas, primary treatments, such as optimization of the properties of biomass feedstock, design and operation of the gasifier [2, 3], are first implemented. Secondary treatments, such as a downstream cleaning system based on physical (scrubbers, filters) or catalytic strategies, have to be incorporated for the hot gas cleaning to achieve a more satisfactory reduction for end-applications and for environmental regulations as well. In this study, recent developments in secondary treatments for product gas cleaning are reviewed, including a new concept of cleaning technology proposed and tested by the authors.

## 2 PRODUCT GAS CLEANING TECHNOLOGIES

In general, the raw product gas of biomass gasification contains a range of minor species and contaminants, including particles, tar, alkali metals, chlorine compounds such as HCl, nitrogen compounds such as ammonia and HCN, sulphur compounds such as H<sub>2</sub>S and COS, as well other species. The original chemical composition of the biomass feedstock and the operating conditions determine the amounts of these

**Table 1.** Contaminants species and tolerated levels in some end-users.

Process	Contaminant	Level	Reference
Internal combustion systems	Tars	<10 mg/Nm <sup>3</sup>	20
PEM fuel cells	H <sub>2</sub> S	<1 ppm	21
Methanol synthesis	Tars	<0.1 mg/Nm <sup>3</sup>	22
	NH <sub>3</sub>	10 ppm	23
	HCN	0.01 ppm	23
	Total sulphur	0.5 ppm	23
	Halides	0.001 ppm	23

contaminants with a typical concentration range of 1–150 g/Nm<sup>3</sup> for tars, 500–30 000 ppm for NH<sub>3</sub> and 20–200 ppm for H<sub>2</sub>S according to different publications [1].

## 2.1 Tar

Tar is a highly viscous liquid that condenses in the low-temperature zones of a gasifier, clogging the gas passage and leading to system disruption. It is the most undesirable component in both ICEs and chemical synthesis reactions. Methods for reduction or elimination of tar can be divided into two broad groups: *in situ* (or primary) tar reduction, which aims at avoiding tar formation in the reactor; and post-gasification (or secondary) reduction, which strips the product gas of the tar already produced. A combination of *in situ* and post-gasification tar reductions can prove to be more effective. The importance of tar removal has been widely recognized and recent advances can be found in many references [4–7]. The two basic post-gasification methods are physical removal and cracking (catalytic or thermal).

### 2.1.1 Physical tar removal

Physical removal approaches treat tar as dust particles or mist from the product gas which require the tar to be condensed before separation. The energy content of the tar is often lost in this process and the post-disposal of collected tar can also be a problem. Physical tar removal can be accomplished by cyclones, barrier filters, wet electrostatic precipitators (ESPs) or wet scrubbers. The application depends on the load concentrations of particulates and tar, particle size distribution and particulate tolerance of downstream users. Cyclones are not very efficient when removing small tar droplets. Barrier filters are basically porous material which can capture certain amount of tar when the product gas goes through the filters. Catalyst grains can be integrated as a fixed bed inside the filter to promote the simultaneous removal of particulate matters (PMs) and tar [8]. However, serious condensation and the growing pressure drop across the filter can be annoying problems. Wet ESPs have very high (>90%) collection efficiency over the entire range of particle size down to 0.5 μm, with a very low-pressure drop, despite the high capital and running cost. Wet scrubbers, with a much lower capital cost, can achieve a high collection efficiency up to 90% as well. However, the efficiency drops sharply with particles <1 μm.

They also consume a large amount of spray liquid and fan power, which makes the running cost relatively high.

### 2.1.2 Cracking

Cracking approaches are more advantageous in terms of recovering the energy content in the tar by converting the large tar molecules into permanent gaseous molecules such as H<sub>2</sub> or CO by high temperature (~1200°C) or catalytic reactions (~800°C). Catalytic cracking is commercially used in many plants and has been demonstrated to be one of the most effective processes and extensively reported in the literature [1, 2]. Non-metallic catalysts such as less-expensive dolomite, zeolite and calcite and metallic catalysts such as Ni, Ni/Mo, Ni/Co/Mo, NiO, Pt and Ru have been applied to various gasification processes with different product gas purity requirements.

## 2.2 Ammonia

Ammonia (NH<sub>3</sub>) and HCN are the most significant species from fuel nitrogen conversion in biomass gasification and are the main precursors to NO<sub>x</sub> emissions in downstream burners, gas engines or GTs. Biomass with relatively high N contents generates a product gas with NH<sub>3</sub> contents within the range of 500–30 000 ppm [9] and the level of conversion from NH<sub>3</sub> to NO<sub>x</sub> can be as high as 50% when the gasification gas stream is burned for electricity generation. Legal environmental regulations have given stricter limitations for NO<sub>x</sub> emissions and thus put ammonia removal onto a higher priority. The formation of NH<sub>3</sub> and HCN has been widely studied in biomass gasification [9–11]. The concentration of ammonia in the product gas depends not only on the nature of the biomass feedstock used but also on the gasifier design parameters and operating conditions. Ammonia can be removed by wet scrubbing technology which has been widely adopted in the existing biomass gasification processes. While tar separation by wet scrubbing is very efficient, the NH<sub>3</sub> separation efficiencies in the possible operation range of the scrubber are limited to ~50% [12]. Compared with wet scrubbing technology, hot-gas cleanup technology, preferably employing catalysts, is more advantageous with respect to energy efficiencies as it eliminates the needs of cooling the product gas and re-heating again for the syngas applications. Catalytic processes effectively remove NH<sub>3</sub> by converting it to N<sub>2</sub>, H<sub>2</sub> and H<sub>2</sub>O. The removal efficiencies of 10 catalysts for NH<sub>3</sub> conversion are summarized in Table 2 [13].

It is obvious that Ni-based catalysts have higher activity, while other catalysts do not have good potentials for NH<sub>3</sub> removal. Ni-based catalysts that have also been proved to be very effective in tar removal have been commercialized for decades and widely used for tar and NH<sub>3</sub> removals.

## 2.3 Sulphur compounds

Sulphur compounds, considered as another nuisance, are converted from sulphur content present in the feedstock under biomass gasification conditions. Hydrogen sulphide (H<sub>2</sub>S) and

**Table 2.** Removal efficiencies of  $\text{NH}_3$  with different catalysts at  $650^\circ\text{C}$  [13].

Type of catalyst	Main components	Removal efficiency (%)
Cu–Mn-based	CuO	7.68
	Cu:Mn = 9:1	2.68
	Cu:Mn = 4:1	0.00
Zn–Ti-based	Zn–Ti–Ni	7.00
	Zn–Ti–Cu	2.51
	Zn–Ti–Mo	8.70
Fe-based	Fe–Cr	35.00
Ni-based	NiO and calcium aluminate	88.20
	NiO and $\text{Al}_2\text{O}_3$	90.60
	NiO, $\text{MoO}_3$ and $\text{Al}_2\text{O}_3$	92.29

carbonyl sulphide (COS) are two main compounds that need to be taken into account. Generally, the  $\text{H}_2\text{S}$  concentration produced by gasification is of the order of 100 ppm [1]. Even though it is quite low, for certain applications, an efficient removal is still required to meet stringent standards. For instance, the sulphur level in product gas should be reduced to 8 ppm at the inlet of the GT to protect downstream process equipments and avoid troublesome operation problems. Furthermore, the gaseous sulphur compounds can also deactivate most catalysts used in downstream units for tar cracking and the water–gas shift reaction. Sulphur compounds can be removed by various methods depending on the required quality of the final product gas. Besides the *in situ* capture in the gasification process where mostly calcium-based sorbents such as limestone or dolomite are used, downstream capture approaches have been developed [14] using different metal oxide-based sorbents. Thermodynamic calculations performed by Westmoreland and Harrison [15] showed that the metal oxides of Fe, Zn, Mn, Mo, V, Ca, Sr, Ba, Co, Cu and W are feasible for sulphur removal. However, each has its own limitations and advantages at the same time. Among them, zinc oxide ( $\text{ZnO}$ ) is the most commonly used sorbent for  $\text{H}_2\text{S}$  removal because of its favourable sulphidation thermodynamics. However, due to vaporization, zinc migration and agglomeration problem may happen at high temperatures. Based on the criteria of sulphur sorption capacity and reaction temperature, mixed oxides combining the properties of various metals are believed to be the most promising method of sulphur capture. Long life and attrition resistance are the two difficulties in designing the sorbents. More efforts are still needed for the development of a low cost, environmentally friendly, highly efficient, rapidly reacting and regenerable sorbent with high sulphur capture capacity and durability.

## 2.4 Particulate matters

PMs that are present in the product gas can also be a serious problem for some end-users. Catalysts used for cleaning product gases have been demonstrated to be negatively affected by PMs. The gas quality for successful ICE operation has been postulated as being below  $50 \text{ mg/Nm}^3$  for the PM [16]. PM can be physically removed using ceramic candle filters at high temperatures. The

filtration efficiency and the operation and dimensioning of the filter depend upon the particle mass concentration and size distribution, as well as upon the composition of the PM. Therefore, it is crucial to characterize the PM present in the product gas [17]. The presence of alkali is of particular importance, because alkali can form silicates with low melting temperatures that may negatively affect the filter operation.

## 2.5 Alkali metal salts

Compared with fossil fuels, biomass is rich in alkali salts that typically vaporize at high gasifier temperatures but condense downstream below  $600^\circ\text{C}$ . Efforts have been made to strip the alkali contents since condensation of alkali salts can cause serious corrosion problems. The alkali will condense onto fine solid particles and can be subsequently captured in a cyclone, ESPs or filters when the gas temperature is below  $600^\circ\text{C}$ . The hot gas can also be passed through a bed of active bauxite to remove alkali when cooling of gas is not permitted.

## 3 A NOVEL STRATEGY OF PRODUCT GAS CLEANING

The research project ‘Mop fan and electrofilter: an innovative approach for cleaning product gases from biomass gasification’, funded by the UK EPSRC and the Germany FNR via ERA-NET Bioenergy, was recently carried out to evaluate a novel and flexible concept of product gas cleaning strategy from biomass gasification. The project consortium consisted of two academic partners of the University of Nottingham, UK (UoN), and Berlin Institute of Technology, Germany (TUB), one industrial partner of BETH Filtration GmbH, Germany, and one subcontractor ERK Eckrohrkessel GmbH, Germany.

### 3.1 Mop fan tests in UoN

The UoN research group investigated product gas cleaning by using a mop fan unit at the exit of a laboratory-scale bubbling fluidized bed gasifier. The mop fan (shown in Figure 1) utilizes a brush disk, instead of traditional bladed impellers within a centrifugal fan casing and operates as a gas moving device as well as a filter. The PMs, tar and chemical compounds in the dirty product gas enter the fan case, make contact with the rotating mop fibres and are captured by the fibres within the case. A small amount of water can be sprayed on the surface of mop fibre to facilitate the cleaning process. The performance of a mop fan cleaning unit depends on many factors such as the fibre number, fibre diameter, fibre arrangement on the shaft and the quantity and quality of the liquid spray. The mop fan has been successfully applied to building ventilations by other researchers [18] and the particulate removal efficiency has been proved as high as 97%. The application of mop fan cleaning unit to the gasification product gas cleaning is the first attempt by the authors.

The performance of the mop fan cleaning unit in particle removal is evaluated by measuring particle loadings at both the

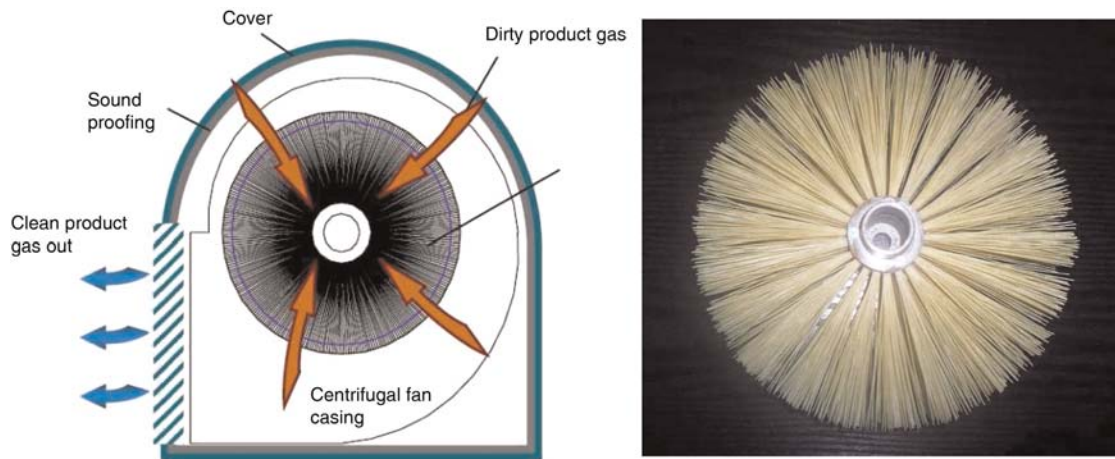


Figure 1. Schematic of a mop fan cleaning unit and an image of an example mop.

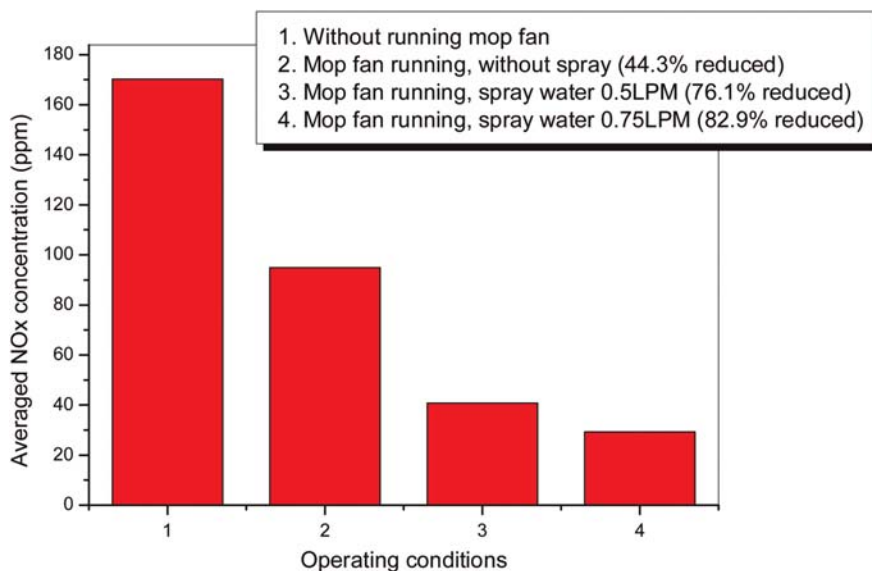


Figure 2. Removal efficiency of N-species by a mop fan with different amount of spray water.

inlet and the outlet. The main results are summarized here, and more details can be found in the previous paper [19]. When the mop fan ran without spraying water, the particle removal efficiency was in the range of 50–60%. When a small amount of spray water 0.5 l/min is used, the particle removal efficiency can be improved up to 90%.

The average NO<sub>x</sub> emission was also measured at the exit of the combustor where the product gas is burned at different operating conditions. Figure 2 indicates that the use of the mop fan cleaning unit with or without spray water resulted in a reduction in NO<sub>x</sub>, which is believed to be largely due to N-compounds (NH<sub>3</sub> etc.) of the product gas being trapped by the mop fan unit. By using the mop fan but without the spray water, an efficiency of 44.3% in removing N-species in the product gas was observed. With a small amount of spray water, the efficiency of more than 80% in removing N-species was achieved by the mop fan cleaning unit.

### 3.2 Combination of mop fan and ESP in TUB

The mop fan cleaning unit has also been installed and combined with the electrofilter system (ESP) on the gasification rig in TU Berlin. Figure 3 shows the location and integration of this unit in the whole gasification and cleaning system. The TUB research group carried out the detailed gas and tar analyses after integrating the gas cooler with the structured tube heat exchanger, the quench and ESP system and the mop fan cleaning unit with its laboratory-scale fluidized bed gasifier (FBG). BETH Filtration GmbH designed, built and set up the quench and ESP, which was used to investigate the sensitivity of separation of different tar components from the product gas and to improve the design and possibly to reduce investment costs of ESP. ERK designed and manufactured the gas cooler using the structured tube heat exchanger technology. A hot-gas filter (HGF) with three ceramic filter candles was also installed at the exit of TUB FBG and used to separate

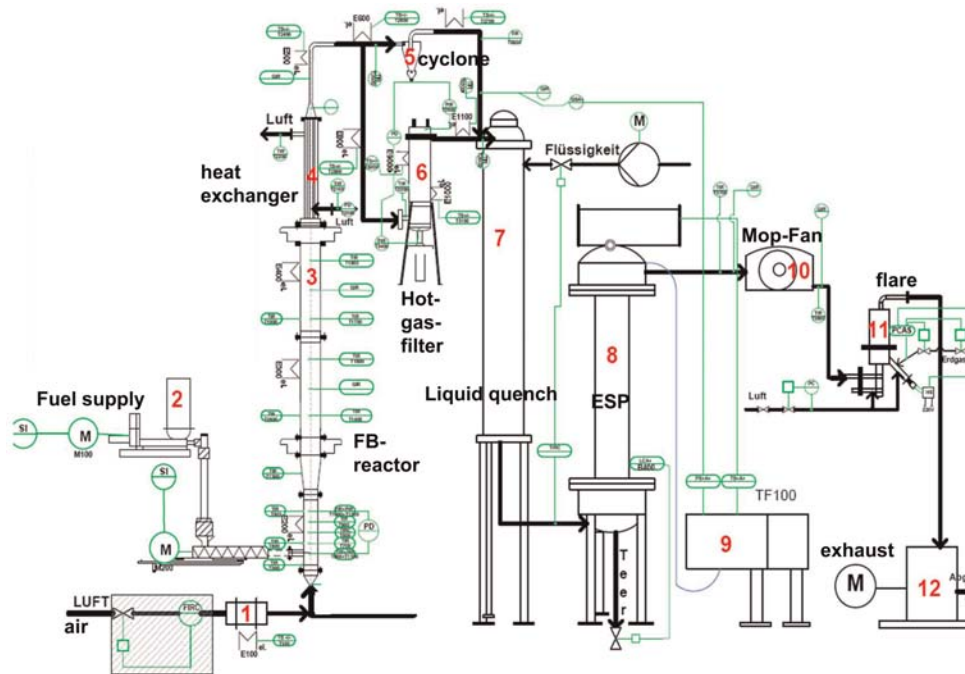


Figure 3. Combination of a mop fan cleaning unit with ESP in TUB gasification rig.

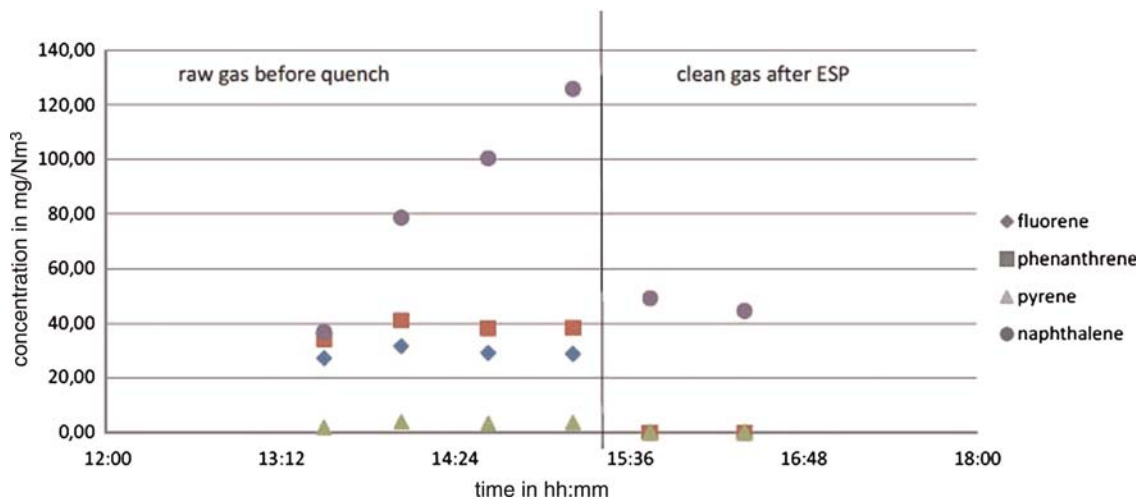


Figure 4. Online GC/MS measurement results for selected tar species in the product gas (last two measurements were taken after the quench and ESP).

particles of ash and char from the product gas to get a nearly dust free gas.

The GC/MS was connected online with the system. Sample points were installed after the HGF and before entering the quench and at the outlet of the ESP. In Figure 4, the concentrations of selected tar species are shown. The value for naphthalene changed during the run whereas the other compounds showed less change. The first four measurements were done with the raw gas and then the sampling was switched to the point after the ESP. The last two values are measured downstream of the ESP. It

is obvious that the heavier tar compounds such as phenanthrene, pyrene but also fluorene are removed completely whereas naphthalene is reduced compared with the last three raw gas measurements. The combination of different components, such as HGF, quench, ESP and mop fan, has been proved to be an effective and flexible strategy for gas cleaning and conditioning. All of these components were functioning and operated successfully. Further research to evaluate the mop fan, ESP and their combination in removing PM, tars and chemicals will be carried out at both UoN and TU Berlin in the future.

## 4 CONCLUSIONS

Gasification has been considered as a promising approach to convert biomass into useful gaseous products. However, the raw product gas contains both gaseous and particulate impurities and has to be cleaned to meet the requirements for different end-applications. The removals of the following contaminants have been discussed by the study: tar, nitrogen compounds such as ammonia, sulphur compounds such as H<sub>2</sub>S, PMs and alkali metal salts. Physical removal devices such as filters and wet scrubbers do prove their function in removing some species such as tar, PM and alkali, yet hot gas cleaning by using catalysts and sorbents is more energy efficient. Ni-based catalysts have high activity in decomposing both tar and ammonia and have been commercially applied to gasification plants. Metal oxides sorbents are found to be effective in removing sulphur compounds. The strategy of product gas cleaning depends on the requirements of end-users. Multifunctional devices, catalysts or sorbents need to be developed for simultaneous removal of different contaminants. The mop fan cleaning unit investigated by the authors is an all-in-one and multifunctional device which can be used for gas circulation, de-dusting of gas stream and efficient removal of gaseous contaminants. Product gas cleaning by the use of the mop fan gas cleaning unit has a significant potential advantage in terms of waste water treatment cost over conventional liquid scrubbers. The large surface areas provided by the mop fibres ensure high removal efficiencies of particulates, tars and chemicals, while the use of smaller amount of water compared with liquid scrubbers results in a much smaller amount of wastewater which needs to be treated before disposal. Although further research is needed, the combination of a mop fan cleaning unit with ESP has been shown to have great potential in removing fine particles, tars and chemical contaminants.

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## REFERENCES

- [1] Torres W, Pansare SS, Goodwin JG. Hot gas removal of tars, ammonia, and hydrogen sulphide from biomass gasification gas. *Catal Rev* 2007;49:407–56.
- [2] Devi L, Ptasiniski KJ, Janssen FJJG. A review of the primary measures for tar elimination in biomass gasification processes. *Biomass Bioenergy* 2003;24:125–40.
- [3] Corella J, Toledo JM, Molina G. Calculation of the conditions to get less than 2 g tar/Nm<sup>3</sup> in a fluidized bed biomass gasifier. *Fuel Process Technol* 2006;87:841–6.
- [4] Xu C, Donald J, Byambajav E, *et al.* Recent advances in catalysts for hot-gas removal of tar and NH<sub>3</sub> from biomass gasification. *Fuel* 2010;89:1784–95.
- [5] Huang J, Schmidt KG, Bian Z. Removal and conversion of tar in syngas from woody biomass gasification for power utilization using catalytic hydrocracking. *Energies* 2011;4:1163–77.
- [6] Anis S, Zainal ZA. Tar reduction in biomass producer gas via mechanical, catalytic and thermal methods: a review. *Renew Sustain Energy Rev* 2011;15:2355–77.
- [7] Neubauer Y. Strategies for tar reduction in fuel-gases and synthesis-gases from biomass gasification. *J Sustain Energy Environ* 2011;special issue:67–71.
- [8] Rapagna S, Gallucci K, Marcello MD, *et al.* Gas cleaning, gas conditioning and tar abatement by means of a catalytic filter candle in a biomass fluidized-bed gasifier. *Bioresour Technol* 2010;101:7123–30.
- [9] Zhou J, Masutani SM, Ishimura DM, *et al.* Release of fuel-bound nitrogen during biomass gasification. *Ind Eng Chem Res* 2000;39:626–34.
- [10] Leppalahti J, Kurkela E, Simell P, *et al.* Formation and removal of nitrogen compounds in gasification processes. *Fuel Process Technol* 1991;29:43–56.
- [11] Yuan S, Zhou Z, Li J, *et al.* HCN and NH<sub>3</sub> released from biomass and soybean cake under rapid pyrolysis. *Energy Fuels* 2010;24:6166–71.
- [12] Proell T, Siefert IG, Friedl A, *et al.* Removal of NH<sub>3</sub> from biomass gasification producer gas by water condensing in an organic solvent scrubber. *Ind Eng Chem Res* 2005;44:1576–84.
- [13] Dou B, Zhang M, Gao J, *et al.* High-temperature removal of NH<sub>3</sub>, organic sulphur, HCl, and tar component from coal-derived gas. *Ind Eng Chem Res* 2002;41:4195–200.
- [14] Meng X, De Jong W, Pal R, *et al.* In bed and downstream hot gas desulphurization during solid fuel gasification: a review. *Fuel Process Technol* 2010;91:964–81.
- [15] Westmoreland PR, Harrison DP. Evaluation of candidate solids for high-temperature desulfurization of low-Btu gases. *Environ Sci Technol* 1976;10:659–61.
- [16] Stassen HEM. Strategies for upgrading producer gas from fixed bed gasifier systems to internal combustion engine quality. In Graham RG, Bain R (eds). *Biomass Gasification. Hot-Gas Clean-Up*, 1993, 33–44.
- [17] Gustafsson E, Lin L, Seemann M, *et al.* Characterization of particulate matter in the hot product gas from indirect steam bubbling fluidized bed gasification of wood pellets. *Energy Fuels* 2011;25:1781–9.
- [18] Riffat SB, Zhao X. Preliminary study of the performance and operating characteristics of a mop-fan air cleaning system for buildings. *Build Environ* 2007;42:3241–52.
- [19] Zhang W, Liu H, Hai IU, *et al.* Biomass gasification in a bubbling fluidized bed and efficiency of a mop fan cleaning unit. In: *SET 2010 Proceedings of the 9th International Conference on Sustainable Energy Technologies*. Shanghai, China, August 2010.
- [20] Bui T, Loof R, Bhattacharya SC. Multi-stage reactor for thermal gasification of wood. *Energy* 1994;19:397–404.
- [21] Sardesai P, Seames W, Dronen L, *et al.* Exploring the gas-phase anaerobic bioremoval of H<sub>2</sub>S for coal gasification fuel cell feed streams. *Fuel Process Technol* 2006;87:319–24.
- [22] Mudge LK, Baker EG, Mitchell DH, *et al.* Catalytic steam gasification of biomass for methanol and methane production. *J Solar Energy Eng* 1985;107:88–92.
- [23] Spath PL, Dayton DC. *Preliminary Screening—Technical and Economic Assessment of Synthesis Gas to Fuels and Chemicals with Emphasis on the Potential for Biomass-derived Syngas*. National Renewable Energy Laboratory, 2003.