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"OLGA" TAR REMOVAL TECHNOLOGY

Proof-of-Concept (PoC)
for application in integrated biomass gasification combined heat and power (CHP) systems

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PREFACE

The major part of the work described in this report was carried out within the framework of the project *"Oliewasser voor teerverwijdering uit biomassaproductgas. Fase 3: Proof-of-Concept"* and was co-financed by the SenterNovem (formerly: Netherlands Agency for Energy and the Environment, Novem) within the framework of the DEN programme under project number 2020-02-11-14-004. Account manager for SenterNovem was Ir. K. Kwant. Partners in the project were the unit ECN Biomass of the Energy research Centre of the Netherlands (ECN) and Dahlman Industrial Group (Maassluis, the Netherlands). Applicable ECN project number was 7.2296.

In addition, the report contains some (preliminary) results from other OLGA-related projects:

- *"Application of oil washer for tar removal from biomass product gas"*. This project was carried out in 2001-2002 by ECN and Dahlman Industrial Group and was co-financed by Novem NECST under project number 0249-01-04-12-0012. Applicable ECN project number was 7.2283.
- *"OLGA Optimum - Improvement of the economics of integrated biomass gasification plants by extension of the functionalities of the OLGA tar washer"*. This ongoing project is carried out by the partners ECN, Dahlman Industrial Group, Vienna University of Technology, and Foster Wheeler Energia, and is co-financed by SenterNovem under project number 2020-03-12-14-005). Applicable ECN project number is 7.5264.
- *"Optimisation of BIVKIN"*. This ongoing project is fully ECN project. Applicable ECN project number is 7.8232.
- *"Preparation of Bio-CHP system: 1000-hour test"*. This ongoing project is carried out by the partners ECN, Dahlman Industrial Group, HoSt Engineering, Essent, and HABO/Lek, and is co-financed by SenterNovem under project number 2020-03-11-14-005). Applicable ECN project number is 7.5252.

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ABSTRACT

Gasification (of coal) is an old technology that today is the key chemical process in almost every major method of energy generation, used in the production of electricity, in refineries, and in a variety of other commercial uses. The statement about the position of coal gasification, however, does not apply for biomass gasification. The main technical challenge in the implementation of integrated biomass gasification plants has been, and still is, the removal of tar from the product gas. "Tar" is equivalent to a major economic penalty in biomass gasification. Tar aerosols and deposits lead to more frequent maintenance and resultantly decrease of revenues or to higher investments. Furthermore, removal of tar components from the process wastewater requires considerable investments. Several measures for tar removal have been studied or are under investigation.

Early 2001 the development of the "OLGA" was initiated at ECN. The OLGA is based on applying an organic scrubbing liquid (*i.e.* "OLGA" is the Dutch acronym for oil-based gas washer). In the development of the OLGA tar removal technology, ECN has chosen an approach that concentrates on the behaviour (*i.e.* the properties) of the tar and not concentrate on the tar content. Hence, a "tar-free" product gas is synonymous to a gas "free of tar related problems". The advantages of the OLGA tar removal technology, compared to alternative conventional tar removal approaches, can be summarised as:

- Tar dewpoint of clean product gas is below temperature of application, therefore there is no condensation of tars in system;
- No fouling of the system resulting in increased system reliability and higher availability;
- Tars are removed prior to water condensation to prevent pollution of process water;
- Tars are recycled to gasifier and destructed avoiding the handling of problematic (and expensive) tar waste streams;
- Scalable technology allowing the application from lab to commercial scales.

Although the OLGA development originates from the biomass gasification research, the application of OLGA is not limited to removal of tars from biomass gasification product gases. The technology is scalable and suitable for pressurised operation. Therefore, the OLGA is applicable for removal of organic components or organic impurities (to very low levels) from all types of gases as well as for product recovery processes, *e.g.* coal gasification, cokes oven gas, process gases in chemical industry, natural gas upgrading, recovery of vaporised process oils, etc.

This report gives an overview of the status of the OLGA technology around mid 2004 and comprises the considerations that laid the basis for the OLGA development, the process design approach, and results from both the extensive lab-scale and pilot test programmes. The main focus of the report is on the performance of the pilot OLGA during a 50-hour test that was carried out in May 2004 as part of the proof-of-concept (POC) project.

Lab-scale "Proof-of-Principle"

Experiments in the lab-scale OLGA unit have proven that the OLGA process is capable of removing tars to very low levels, *i.e.* tar dewpoints below -15°C. Product gases made tar-free with the OLGA process are suitable for application in gas engines and even more demanding applications in Fischer-Tropsch and synthetic natural gas (SNG) synthesis processes.

Selecting an alternative scrubbing liquid for the OLGA holds the opportunity to increase the removal efficiency of the class 2 and 4 tar compounds in the OLGA Absorber. In this way the economics of the process can be improved either by decreasing the size of the Absorber (lower investment costs) or using a cheaper scrubbing liquid (lower operational costs).

A further optimisation of the OLGA process is the combined tar and dust removal. In this way an upstream hot gas filter becomes superfluous, which has a drastic impact on the investment costs. Preliminary experimental of short test results indicate that OLGA removes dust for 99.5% without affecting the tar removal performance. Even more important: no fouling of the OLGA column packing was observed.

Pilot scale "Proof-of-Concept"

The purpose of the pilot OLGA unit and the experimental programme was to demonstrate the OLGA tar removal principles on pilot scale (*i.e*. deliver the *"proof-of-concept"* for the OLGA process) and to identify critical issues in up scaling, equipment selection, and process design. The pilot OLGA unit is a hundred times scale-up of the lab-scale unit and the unit was designed and constructed with the equipment selected in such a way that unit would be a 'blueprint' for future commercial plants.

During the operational and 50-hour test runs the most important problems were related to the operational stability and heavy tar removal performance of the Collector. The stability problems related to the oil Pump P-200 and the process interaction of the Pump with the oil Cooler E-200. From the analysis of the results it was concluded that these problems were not encountered in the extensive lab-scale test programme, as in the lab-scale set-up other hardware was applied and other operational approaches were followed (*e.g*. use of trace heating).

The performance of the hot gas filter (HGF) is insufficient for prolonged operation due to continuous increase in pressure drop over the filter candles. Within the scope of the underlying project, this problem has not been solved, however, in research is ongoing that should result in defining the proper process conditions to allow prolonged operation of the HGF.

The tar removal results in the pilot OLGA have delivered the "proof-of-concept" that the process is in principle suitable for cleaning product gas from biomass gasification and deliver a 'tar-free' gas. However, the performance of the installations needs further optimisation to allow stable operation over prolonged periods. In the pilot test programme the critical issues in scaling-up of the unit have been identified, which is valuable information for optimisation of the design and hardware selection for future OLGA units.

Economic assessment

Compared to alternative conventional tar removal systems, the specific investment costs for relatively small OLGA unit are relatively high. However, the scale-up factor of OLGA (*i.e.* economy of scale) is relatively low, as the OLGA is based on easily scalable technology and does not become more complex upon scaling-up. At sizes above approx. 4,000 m_n^3/h (*i.e.* corresponding to ~10 MW biomass input), the specific investment costs seems to stabilise around 200 Euro/m_n^3/h and the operational cost for utilities and scrubbing liquid consumption become determining.

In relation to the penalty to be paid for the tar problem (*i.e*. losses in revenues due to standstills and costs for water and tar-waste treatment), the total specific costs for OLGA are very promising. The total specific costs are substantially lower than the quantified costs for the tar problem and can even be reduced with simple process optimisations. Considering the low total specific costs of OLGA, the elimination of the tar problem with OLGA, and the positive contribution to the reliability of the process, the economical perspective for OLGA is promising.

Conclusion and continuation

After the conclusion of the proof-of-concept phase, the generated information for optimisation of the design and hardware selection for future OLGA units, must be implemented. This will be done in the first demonstration and semi-commercial systems. However, it should be taken into consideration that the operational and long duration experience with the technology is still limited. Therefore, sufficient additional time and budget should be reserved for commissioning and start-up of the next systems. In parallel, research is ongoing to further optimise the OLGA technology and demonstrate its performance during prolonged operation.

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1. INTRODUCTION

1.1. Background

Gasification (of coal) is already an old technology that formed the basis of the town gas production in the late nineteenth and early twentieth century. With the widespread introduction of natural gas, the town gas industry declined and gasification became a specialised niche technology with limited application. Since the last decades of the twentieth century, gasification experiences a revival after substantial progress and technical development. The reasons for this include the development of new applications such as gas-to-liquids (Fischer-Tropsch) projects, the prospects of increased efficiency, and environmental performance including CO_2 capture through the use of integrated gasification combined-cycle (IGCC) in the power industry. Today, gasification of coal and gas (*viz*. partial oxidation) is the key chemical process in almost every major method of energy generation, used in the production of electricity, in refineries, and in a variety of other commercial uses [1].

The statement about the position of coal gasification, however, does not apply for biomass gasification. The first significant rise in interest to use this relatively low-value fuel for electricity generation and syngas production is related to the oil crisis in the 1970s and the subsequent search for alternative energy sources. Most of the initiatives originating from that period were cancelled upon the decrease of the oil prices. The interest revived in the last decades of the last century, similar as for coal gasification, however, for biomass motivated by environmental concerns and the search for sustainable energy generation technologies.

The wide implementation of biomass gasification is hampered by the fact that there was (and still is not in most cases) no economic incentive to use biomass, *e.g*. biomass-based energy is more expensive than energy from fossil fuels. Therefore, hardly any strong industries invested in technology development and the biomass gasification plants realised were typically small-scale and based on simple and cheap technology to reduce costs. Biomass gasification, however, is similarly challenging and complex as coal gasification, with similar technology development demands. Evidently, all the small-scale initiatives had little change to succeed, which unfortunately is illustrated by the many shutdown plants.

The few technological successful biomass gasification plants have in common that they result from a long development trajectory and that the technologies are neither simple nor cheap, *e.g*. the plants in Güssing (Austria) [2], Värnamo (Sweden) [3], Harboøre (Denmark) [4], and the Viking gasifier at the Danish Technical University [5]. The main technical challenge in the implementation of integrated biomass gasification plants has been, and still is, the removal of “tar” from the product gas. Therefore, tar can be considered as the Achilles heel of biomass gasification [6].

1.2. Issue definition

1.2.1. The tar problem

Tar comprises a wide spectrum of organic components, generally consisting of several aromatic rings (in Appendix A tar definitions and properties are discussed in more detail). At gasification temperature these compounds are gaseous but upon cooling of the gas below approx 350-400°C they start to condense. Condensing tars dramatically foul the downstream system piping and gas cooling and cleaning equipment, while liquid tar droplets (*i.e*. aerosols) that enter prime movers disturb the operation of these end-use applications of the product gas [7]. Tar also plays an important (negative) role in wastewater management, as in most conventional water-based gas cleaning systems tars and condensed water are mixed, creating a costly and difficult water treatment problem.

Regarding the presence of tar in product gas, it may be stated that "tar" is equivalent to a major economic penalty in biomass gasification. Tar aerosols and deposits lead to more frequent maintenance and repair of especially gascleaning equipment and resultantly lower plant capacity factors (see Figure 1.1 for examples of tar fouling). This leads to a decrease of revenues or to higher investments, as some equipment will be installed in duplicate to overcome standstills. Furthermore, removal of tar components from the process wastewater requires considerable investments that can even be dramatic as some tar components show poisoning behaviour in biologic wastewater treatment systems (*e.g*. phenol).

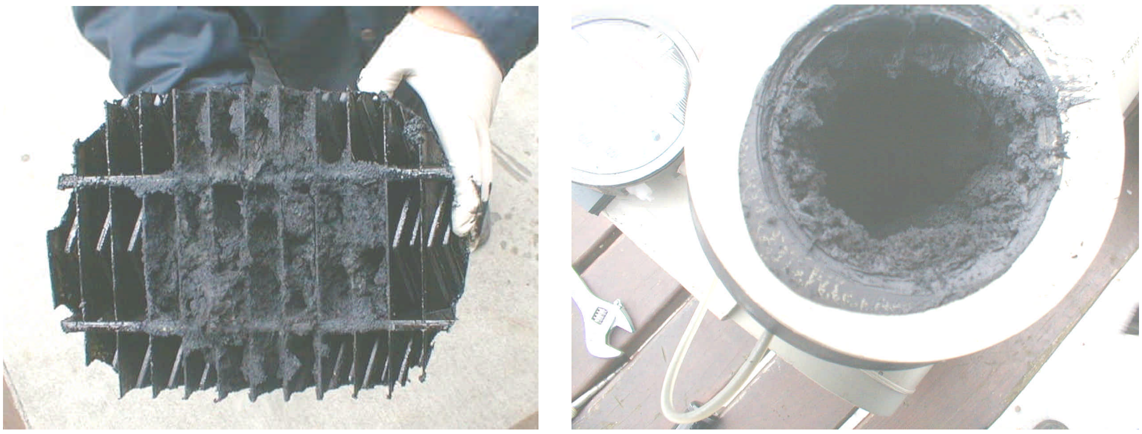


Figure 1.1. *Examples of tar-related fouling of process equipment.*

1.2.2. Tar removal

Several measures for tar removal have been studied or are under investigation. These measures can be divided into primary measures (*i.e*. measures inside the gasifier) or secondary measures (*i.e*. measures downstream of the gasifier). With the prospect of operating an integrated biomass gasification installation without struggling with tar anywhere downstream, many researcher focus on effective primary measures. This should make complex and expensive gascleaning equipment obsolete. Although measures inside the gasifier may be fundamentally more ideal, they have not yet resulted in satisfactorily solutions. Some of the primary measures do result in low tar emissions, but suffer from disadvantages related to, for instance, limits in feedstock flexibility and scale-up, the production of waste streams, a decrease in cold gas efficiency, complex gasifier constructions, and/or a narrow operating windows. Although primary measures can reduce the tar content considerably, it is foreseen that complete removal is not feasible without applying secondary measures (see Figure 1.2).

Secondary measures that have been investigated until now, exhibit similar deficiencies. The measures are either not effective enough, too expensive, or the tar problem is shifted to the treatment of wastewater. However, a secondary measure can be feasible without needing primary measures. This becomes even stronger when the problems with wastewater treatment can be eliminated as well. A secondary measure should therefore form the basis for tar removal from product gas, while primary measures could possibly be used for its optimisation [8,9].

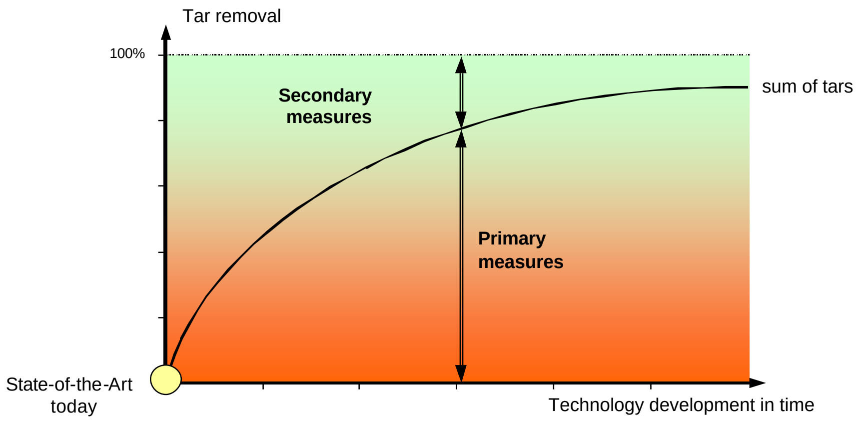


***Figure 1.2**. Illustration of the need of primary- and secondary measures versus technology development in time.*

During the 12th European Biomass Conference held in Amsterdam in 2002, some attendants expressed great disbelieve in the future prospects of biomass gasification. Tars were tagged to be the major reason for this lack of confidence. If the tar problem could not be solved in the past after trying so many alternatives for tar removal, why should one believe in future systems wherein tars would not be the major obstacle?

1.3. A new approach: "OLGA"

In the development of integrated biomass gasification systems, ECN has chosen a totally different approach. This approach does not concentrate on the tar content, but on the behaviour (*i.e.* the properties) of the tar. A feasible tar removal system is not a system that totally *removes* tars, but is a system assuring that tar related problems do not *occur* anymore. Hence, product gas free of tar is in this approach synonymous to a gas that is free of tar related problems. The (ambitious) objective of the development was to create a new process that eliminates issues involved with tar condensation and water solubility. The process to develop should be competitive with alternative technologies.

Early 2001 the development of a new technology called "OLGA" was initiated at ECN. The development of this patented technology started with a mechanistic study about the removal of tars with a scrubbing liquid that differs from water. The mechanistic study resulted in a strong belief that another scrubbing liquid than water could result in deep tar removal (*i.e.* "OLGA" is the Dutch acronym for oil-based gas washer) [8].

Since then, ECN has further developed the OLGA technology together with Dahlman Industrial Group. In 2002 the proof-of-principle (POP) of high efficient tar removal with the OLGA technology was delivered by experiments in the lab-scale OLGA unit downstream one of the ECN bubbling fluidised bed gasifiers [9]. In 2003, the proof-of-concept (POC) phase was started. For this purpose a pilot OLGA was designed, constructed, and installed downstream the ECN pilot circulating fluidised bed gasifier "BIVKIN" [10]. The experimental programme was carried out in the first half of 2004. Since mid 2004 Dahlman and ECN have started the commercialisation of the OLGA technology.

Although the OLGA development originates from the biomass gasification research, the application of OLGA is not limited to removal of tars from biomass gasification product gases. The technology is scalable and suitable for pressurised operation. Therefore, the OLGA is applicable for removal of organic components or organic impurities (to very low levels) from all types of gases as well as for product recovery processes, *e.g*.:

- Coal gasification;
- Cokes oven gas;
- Process gases in chemical industry;
- Natural gas upgrading;
- Recovery of vaporised process oils;
- etc.

1.4. This report

The purpose of this report is to give an overview of the principles, research and development activities, and the status of the OLGA technology around mid 2004. The main focus will be on the results of the pilot tests that were carried out as part of the proof-of-concept (POC) project. The results will be discussed in relation to previous and ongoing parallel studies carried out on lab-scale. Objective of the POC project was to proof the technology on pilot scale and obtain operational data based on which larger installations can be designed, this comprises scale-up correlations, process control philosophies, hardware selection, and the identification of critical process parameters. For selected system sizes budget estimates will be presented for the investment and operational costs of an OLGA unit as part of integrated biomass gasification combined heat and power (Bio-CHP) plants.

In Chapter 2 the design considerations and the fundamental principles of the OLGA technology are discussed. In Chapter 3 an overview is presented of the experimental studies carried out with the lab-scale OLGA unit. The design, construction, commissioning, and test programme of the pilot OLGA unit is discussed in Chapter 4. In Chapter 5 an economical assessment of the OLGA applied in Bio-CHP systems is presented. Chapter 6 concludes this report with conclusions and an outlook to the continuation of the development.

2. INTRODUCTION OF OLGA TECHNOLOGY

The (ambitious) objective in the design of OLGA was the development of a new process that eliminates the "tar problem", *i.e.* issues involved with tar condensation and water solubility. The process to develop should be economically competitive with alternative technologies. Reference for the development was the application of the OLGA in integrated biomass gasification systems for combined heat and power (CHP) production. A generic line-up of such a bio-CHP system is shown in Figure 2.1 [11].

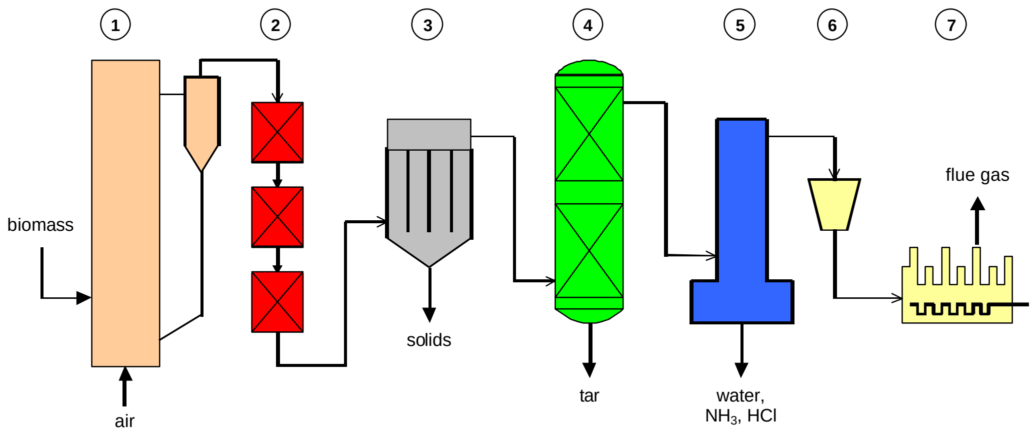


***Figure 2.1**. Generic line-up of an integrated air-blown biomass gasification system with gas engine for combined heat and power (CHP) production: (1) gasifier; (2) gas cooler; (3) solids removal; (4) tar removal; (5) water condenser and ammonia and HCl removal; (6) booster; and (7) gas engine.*

2.1. Design basis

The approach to design a process for complete and selective tar removal in a controlled way, started with a definition of the required tasks for such a process. Primary and secondary tasks are distinguished (see Table 2.1). Primary tasks deal directly with the objective. Secondary tasks are additional and need to be accomplished to obtain a system that also meets specifications from, for instance, the economic and legislation points of view. In contrast to the primary tasks, the secondary tasks are only indirectly responsible for the technical feasibility of the system and they are mainly relate to integration in the overall system. In the design of the OLGA process it is assumed that solids are completely removed upstream of the tar removal step.

2.2. Primary tasks: basic process structure

The biggest challenge is to remove tar selectively from the product gas (task **1**). In particular the applied scrubbing liquid must not absorb water, as that would still lead to the pollution of process water. Similarly, the permanent gas components in the product gas (*e.g*. CO, H_2, and CO_2) should not dissolve in, or be absorbed by, the scrubbing liquid. This would not contribute to the simplicity of the process.

Table 2.1. Primary and secondary tasks of an optimum tar removal technology.

Primary tasks	
1.	Selective tar removal (*viz*. no removal of water or permanent gases).
2.	Deep removal of tar components resulting in a product gas quality for which no tar condensation or tar desublimation occurs, and simultaneously absence of tar aerosols, while applying the desired operating conditions.
3.	Specific removal of heterocyclic tar components (in particularly phenol), to avoid water contamination in the wet product gas cleaning that is necessary to remove contaminants, like NH_3 and HCl.
Secondary tasks	
4.	Avoiding waste streams.
5.	Avoiding a (too) high scrubbing liquid consumption. This is in particularly important with respect to process economics, but surely also with respect to the sustainable image of biomass gasification.
6.	Removing dust and/or fines that have not been removed by dust separators upstream of OLGA.
7.	Preventing a high gas-side pressure drop over the gas cleaning system.

Deep removal of class 1 and 5 tars is desired in order to decrease the tar dewpoint and to eliminate condensation problems (task **2**). Complete collection of these tar classes yields a dewpoint below 100ºC. Furthermore, to operate end-use applications that require product gas temperature below 50ºC, without the risk of tar condensation, class 2 and 4 tars need to be removed partly (*cf.* Figure A.1 in Appendix A). The required collection efficiency depends on the actual amount and composition of the tars in the product gas. Although the collection efficiency of class 2 tars (the heterocyclic tars) needs not to be complete from the condensation point of view, essentially quantitative removal is required to avoid of pollution of process water (task **3**).

The elimination of all condensation-related issues means also that no tar condensation may occur upstream OLGA. Hence, the product gas inlet temperature of OLGA must be higher than the tar dewpoint of the raw product gas. As a consequence of task **1**, water present in the product gas may not condense simultaneously with tar. Therefore, the exit temperature of OLGA must remain above the water dewpoint of the product gas. Figure 2.2 illustrates this by positioning OLGA with respect to both the tar and the water dewpoint.

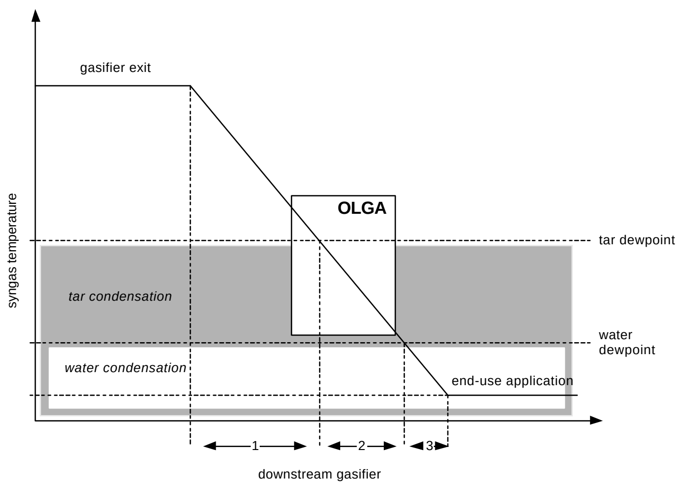


***Figure 2.2**. The position of OLGA with respect to the product gas temperature and to the dewpoints of water and tar. Explanation on zones 1, 2, and 3 downstream the gasifier: (tar phase/ water phase) 1: (G/G), 2: (L/G), 3: (L/L).*

Upon cooling of the product gas, the temperature decreases below the tar dewpoint and tar condensation gradually takes place until the product gas is not cooled further. At the resulting temperature, between the dewpoint of tars and water, a liquid/gas (L/G) phase system is obtained (L represents liquid tar). The scrubbing liquid acts as the medium to collect these liquid tars. The remaining gaseous tars are removed from the gas by absorption into the scrubbing liquid (*i.e.* the scrubbing liquid acts as absorption medium), which is illustrated by Figure 2.3. The degree of absorption can be controlled by changing the operation conditions and will be determined by the desired tar dewpoint of the outlet product gas. In the regeneration of the scrubbing liquid the tar is removed, upon which some scrubbing liquid may evaporate.

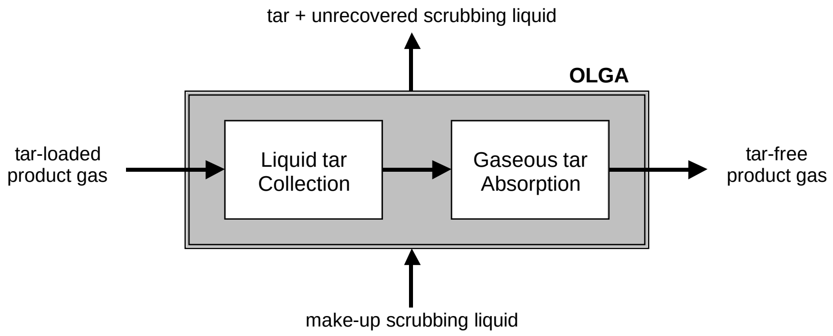


***Figure 2.3**. Basic OLGA process structure.*

2.3. Secondary tasks: conceptual process structure

The secondary tasks of OLGA relate to the positioning in an integrated system. Incorporating the basic OLGA process structure in the line-up of the bio-CHP (*cf.* Figure 2.1), results in a general process structure for an air-blown bio-CHP based on OLGA tar removal, as schematically depicted in Figure 2.4. The produced product gas is first cooled and de-dusted upstream of OLGA. Downstream OLGA, water is condensed out by further cooling of the gas in a water quench and the major (inorganic) impurities NH_3 and HCl are removed by wet scrubbing. The product gas is then suitable for most end-use applications, as it is free of condensable tars, tar aerosols, as well as inorganic impurities.

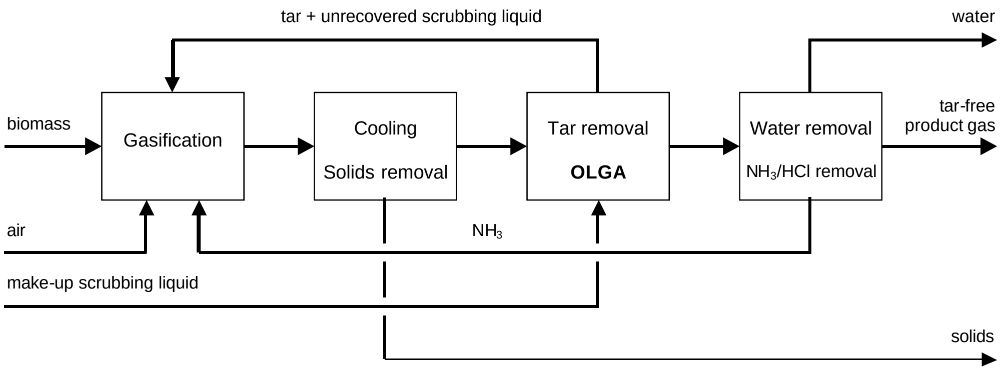


***Figure 2.4**. General concept process structure for an integrated air-blown bio-CHP with OLGA tar removal.*

Intrinsically related to the use of a scrubbing liquid as process utility, is the consumption of liquid due to bleed streams and volatilisation upon stripping the tar. Even if the scrubbing liquid is very effective and the losses minimal, the process should not create another waste stream (task **4**) as this causes an economic penalty for the waste handling. Furthermore, it is undesirable as the consumption of scrubbing liquid creates an image for the process, which is in contradiction with the sustainable nature of the biomass gasification. The necessity to minimise scrubbing liquid losses (task **5**), motivated the inclusion and design of a regeneration step and has been a major selection criterion for the scrubbing liquid to be applied. As a rule-of-thumb, a maximum scrubbing liquid consumption equivalent to 0.5% of the biomass input (on energy basis) is aimed at in the design of the OLGA process.

The collected tar and the unrecovered scrubbing liquid from the regeneration step, as well as separated NH_3, are recycled to destruction in the gasifier, preventing the formation of waste streams. Experiments at ECN have shown that tars are destructed in the gasifier [12], while most NH_3 is converted into elementary nitrogen [13], thereby preventing the build-up of increased levels of tar and NH_3 in the raw product gas.

Although the major part of dust and/or fines will be collected upstream OLGA, it is inherent to the use of a liquid scrubbing medium that fines will be collected in the scrubbing liquid. The removal of (small amounts of) fine particles in OLGA is considered as a secondary task (task **6**) that is optimised as much as possible so that small particles do not have to be dealt with further downstream. It is considered as one of the interesting and economically attractive optimisation options of OLGA to remove the full dust load from the product gas, making the separated dust removal step upstream superfluous. This issue is addressed in Section 3.4.

2.4. Equipment selection

In the design of the OLGA process, packed scrubbing columns were selected to carry out the tar condensation and absorption. A practical reason for the selection of scrubbing columns is that the gas-side pressure drop can be minimised (task **7**). The first application of OLGA is foreseen for atmospheric gasification processes and it is important to limit the total gas-side pressure drop over the whole installation from gasifier to end-user of the product gas. The typically used simple solid feeding systems, which encounter the highest absolute pressure, can generally only function at small pressure drops. Therefore, in OLGA equipment with inherent high-pressure drop, such as venturi scrubbers, is avoided. The selected equipment for OLGA is mature, a lot of operational experience is available, and moreover, it is well known how to scale-up this type of equipment.

2.5. Process flow diagram OLGA unit

In the previous Sections the development of the OLGA technology has been discussed in relation to the tasks that a new tar removal process must perform. Based on all considerations a simplified process flow diagram for the OLGA process can be constructed, as shown in Figure 2.5. In the design it is assumed that the OLGA is operated downstream a solids removal step.

The OLGA gas inlet temperature has to be kept higher than the tar dewpoint, similarly the gas outlet temperature must be higher than the water dewpoint (*cf.* Figure 2.2). In the OLGA the product gas is cooled, upon which the liquid tars are collected. Additionally, gaseous tars are absorbed in the scrubbing liquid at the resulting temperature. In the design of the OLGA the liquid tar collection and the gaseous tar absorption (*cf.* Figure 2.3) are performed in two separate scrubbing columns, *i.e.* the Collector and the Absorber. Although, both processes could be performed in a single scrubber unit, separation in two sections is preferred because of process operation considerations.

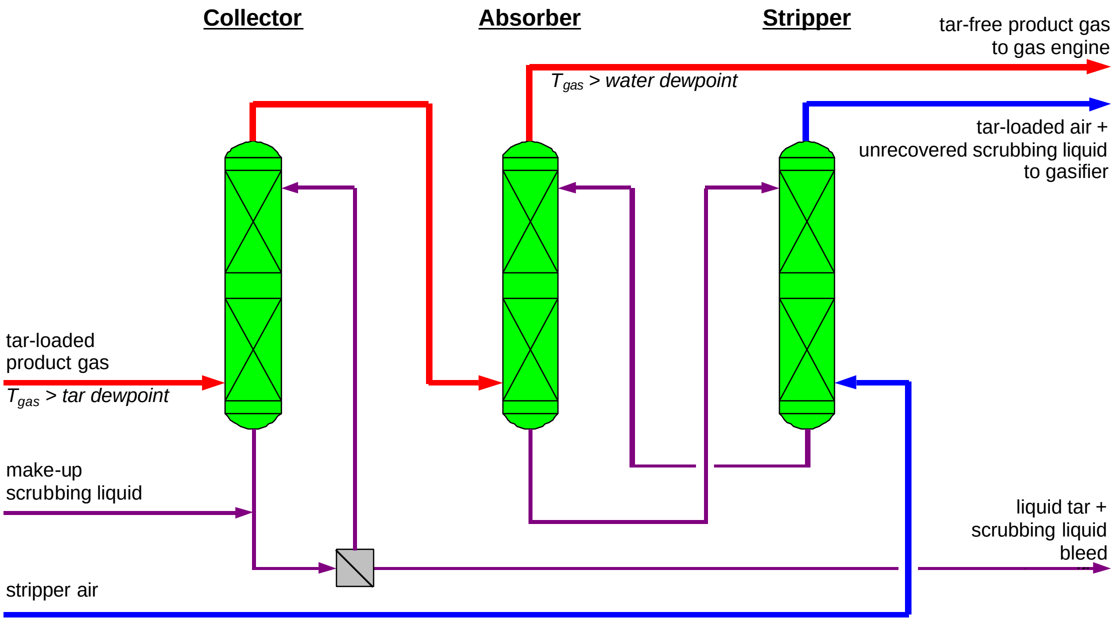


***Figure 2.5**. Outline of the OLGA process.*

The liquid tars are separated from the scrubbing liquid and returned to the gasifier; also a small amount of the scrubbing liquid is bleed and recycled to the gasifier. For the absorption step, scrubbing columns were selected that are interacting with each other in a classical absorption-regeneration mode. The scrubbing liquid from the Absorber with the dissolved tars is regenerated in the Stripper. In case of air-blown gasification, air is used to strip the tar. Subsequently, the air with the stripped tars is used as gasifying medium. The loss of scrubbing liquid in the Stripper by volatilisation is minimised.

The cleaned product gas leaving the Absorber is “tar-free” (*i.e.* free of tar related problems) and can be treated further in the water-based gas cleaning and fired in a gas engine. A typical design criterion for the OLGA is the removal of 95% of phenol from the product gas to prevent water pollution (*cf.* task **3**). Under these conditions all poly-aromatic compounds are completely removed, so no tar condensation can occur (task **4**).

2.6. Summarising

In short, the advantages of the OLGA tar removal technology, compared to alternative conventional tar removal approaches, can be summed up as:

- Tar dewpoint of clean product gas is below temperature of application a *no condensation of tars in system*;
- No fouling of the system a *increased system reliability and availability*;
- Tars are removed prior to water condensation a *no pollution of process water*;
- Tars are recycled to gasifier and destructed a *no tar waste streams*;
- Scalable technology a *applicable from lab to commercial scales*.

3. LAB-SCALE OLGA PERFORMANCE

In a previous project, OLGA was built on lab-scale to demonstrate the feasibility of the technology, *i.e.* delivering the *"Proof-of-Principle"* (POP) for tar removal [8,9]. In this Chapter the results of these tar removal experiments are discussed. Furthermore, an experimental programme was carried out to evaluate the application of alternative scrubbing liquids as well as the combined tar and dust removal in OLGA. The Chapter is concluded with three examples of application of product gas after tar removal with OLGA.

3.1. Lab-scale set-up and typical conditions

OLGA was designed and built within the general scale-up rules that apply to the selected equipment. OLGA is insulated and can be heated with trace heating to minimise the relatively too high heat losses typical for this small scale (see Figure 3.1). The ECN air-blown biomass bubbling bed gasifier "WOB" was used for the generation of a tar-loaded product gas [14]. The WOB typically produces 2 m_n^3/h of (wet) product gas.

***Figure 3.1**. Lab-scale OLGA unit.*

Downstream of the gasifier the raw product gas is de-dusted with ceramic hot gas filter. After the filter the product gas flows through OLGA for tar removal. In OLGA the temperature of the product gas drops from 330-350°C (above tar dewpoint) to 60-100°C (above water dewpoint). During the temperature decrease, the tar dewpoint is passed and the liquid tars are collected while the volatile (light) tar compounds are absorbed in the scrubbing liquid. A Stripper was used for the regeneration of the scrubbing liquid. In the Stripper, air flows counter current with the scrubbing liquid and removes (*i.e.* volatilises) the tars. The airflow rate through the stripper is adjusted to equal the airflow rate needed for the gasifier, so the air from the stripper can be fed to the gasifier where the tars will be destroyed (on lab-scale, however, this connection of the Stripper to the gasifier was not experimentally validated). The regenerated scrubbing liquid from the Stripper is returned to the Absorber. The most important parameters for tars collection are the scrubbing liquid to gas flow ratio and the temperature.

The gas analysis was performed at the outlet of the hot gas filter (*i.e.* OLGA inlet), downstream the Absorber, and downstream the Stripper. The gas analysis consisted of: tar measurements with the SPA (Solid Phase Adsorption) method, and measurement of CO, CO_2, CH_4, H_2, C_2H_4, C_2H_6, benzene and toluene with an online gas chromatograph.

3.2. Tar removal performance

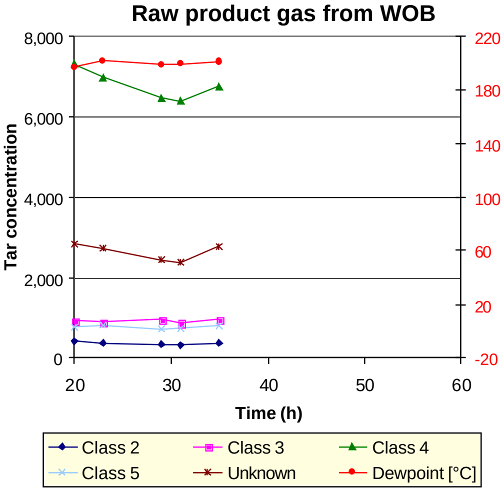
The POP was considered successful when the tar dewpoint downstream OLGA is reduced to below 25°C and the heterocyclic tars (class 2) are removed for 95%. However, it should be noted that these performances were not necessarily *optimal* but the *desired* performances within the scope of the POP study. In the experimental programme special attention was paid to the removal of the total group of tar components that condense between 350°C and 60°C and the removal of heterocyclic tar compounds. An important issue for the economical aspects of OLGA is the regeneration of the scrubbing liquid (task **6**, *cf.* Section 2.1). Therefore, the POP was also used for the demonstration of the regeneration of the scrubbing liquid.

3.2.1. 75-hour test

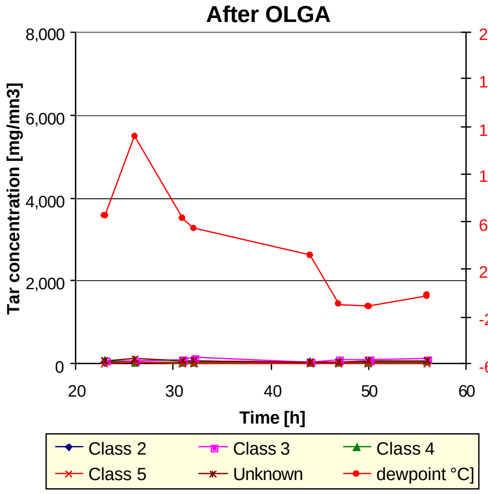
In order to demonstrate tar collection and regeneration of the scrubbing liquid, a long test run of 75 hours has been performed with the lab-scale OLGA set-up. After each 25 hours of operation solids and heavy tars were removed from the scrubbing liquid, as in the small lab-scale set-up no Separator was installed at the time of these experiments. N.B. in ongoing work after completion of the test, a Separator has been installed.

Figure 3.2 shows the dependency of tar concentrations in the raw product gas, after liquid tar collection and absorption in OLGA, and the stripper on the process time (hours) in the test run. The tar components are organised in classes based on their chemical, condensation, and solubility behaviour (see Appendix A). The key parameter for tar condensation is the tar dewpoint, which also is given in Figure 3.2.

OLGA removed 98% (1223 g) of the 1252 g of tars during the 75 hours long test run. The main product gas components like C_2H_4, CH_4, H_2, and CO were not removed with the scrubbing liquid, so it could be concluded that task **1** is accomplished. The heavy, class 5 and probably also class 1, tars were completely removed as liquid tars. The class 2 and class 4 tars were removed mainly by absorption. In total circa 570 g of liquid tars was collected and circa 650 g of tars was absorbed. During the regeneration of the scrubbing liquid about 500 g of the absorbed tars could be removed with air in the stripper. As a consequence, a certain level of tars was accumulated in the scrubbing liquid, however, the accumulation did not influence the tar removal.



(a)



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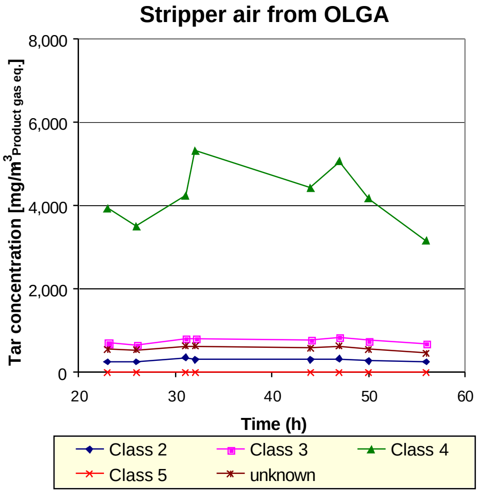


(c)

***Figure 3.2**. Tar concentration (excl. toluene) in the product gas during the long test run of 75 hours (a) raw product gas, (b) after OLGA, and (c) in the air after the stripper of OLGA. Tar measurements were only done in the first 55 hours of operation. The tar concentrations, subdivided in classes, are presented on the primary y-axis. The dewpoint (red line) is shown on the secondary y-axis. N.B. the tar concentration after the stripper is expressed in product gas equivalence. To convert the tar concentration after the stripper to the tar concentration in air, multiply by 1.9* $m_n^3{}_{product\ gas}/m_n^3{}_{air}$.

3.2.2. Heavy tar removal

A task of OLGA (task **2**) is the elimination of heavy tars in order to prevent fouling due to tar deposition (condensation). The dew point was the key parameter for fouling. During the liquid tar removal the tar dew point decreased from 350°C to circa 60-100°C. The tar dewpoint after OLGA (Figure 3.2b) was circa 40-100°C during the first 45 hours of the test. This dewpoint was essentially determined by 5-30 mg/m_n^3 of class 5 tars. After a review of the tar measurement results from the first 24 hours of operation, the process conditions were optimised. This correction was sufficient to remove the remaining 5-30 mg/m_n^3 of the class 5 tars in OLGA, so the aerosol breakthrough was solved. The correction led to a decrease in tar dewpoint from 40-100°C to –10°C (t >45 h) after absorption. This tar dewpoint is more than sufficient to prevent fouling due to tar deposition [8].

3.2.3. Light and heterocyclic tars

Although the problematic condensing tars could completely be removed with OLGA, approx. 250 mg/m_n^3 of light tars (excluding toluene) was still left in the product gas after OLGA, comprising circa 60-85% of the 1-ring compounds. OLGA captured phenol for 93%, using a reasonable L/V ratio and column height. In order to prevent wastewater pollution, phenol should be further removed. To increase the removal rate of phenol from 93% to 99%, the liquid to gas ratio (L/V) should be increased. In a separate experiment 99% removal of phenol and 97% removal of the total class 2 (heterocyclic) tars was obtained with this increased L/V.

3.2.4. Proof-of-Principle for tar removal

OLGA has been successfully demonstrated downstream the laboratory scale 1 kg/h biomass gasifier at ECN. The formulated tasks were accomplished and the tar specifications were met. Tars could selectively be removed from the product gas without removal of the main product gas compounds like C_2H_4, CH_4, CO, and H_2 (task **1**). The heavy tars were completely removed, resulting in a dewpoint lower than the lowest process temperature of 25°C, which ensures the prevention of fouling downstream OLGA (task **2**). Phenol and the class 2 (heterocyclic) tars were removed for 99% and 97% respectively, which is expected to be high enough to prevent excessive waste water treatment costs due to pollution with phenol or other water-soluble tar compounds (task **3**).

3.3. Different scrubbing liquids

The application of alternative scrubbing liquids is of interest as it holds the opportunity to optimise the performance of the OLGA Absorber with respect to the removal of the gaseous light tars (*i.e.* the heavy tars are removed by condensation in the Collector). In the Absorber of OLGA tars are dissolved in the scrubbing liquid. The capacity of tar removal is determined by the liquid to gas ratio (L/V) and by the solubility of tar in the liquid. The type of oil and the temperature of the Absorber determine the solubility of tar. The class 2 tars like phenol and cresol, have relatively the lowest solubility in the standard OLGA scrubbing liquid. Practically, in the dimensioning of the OLGA, the desired removal ratio of these tar compounds determines the size of the Absorber. Therefore, a reduction in the size of the absorber can potentially be obtained by using oil with higher affinity for class 2 tars. Besides the standard OLGA scrubbing liquid "Oil-A", two alternative liquids were evaluated, *i.e.* Oil-B and Oil-C. Both alternative scrubbing liquids are thermally stable at the operation temperature of the Absorber and Stripper.

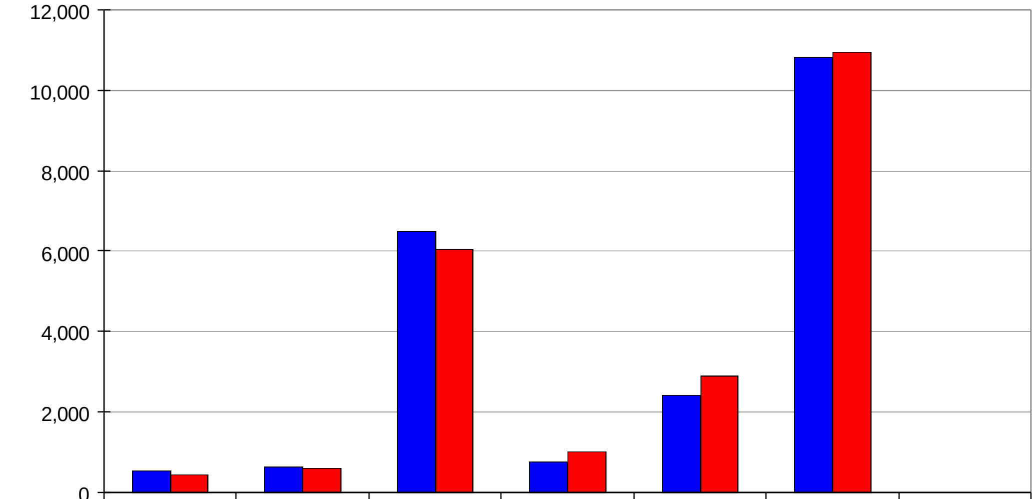
3.3.1. Experimental conditions

During the Oil-B experiments the gasifier was operated at 850°C using beech as fuel and air as gasification agent. For the Oil-C experiments the gasifier was operated at 850°C using beech and an oxygen/steam mixture as gasification medium. The OLGA performance with the new scrubbing liquids was compared with the OLGA performance using the conventional reference liquid (*i.e.* Oil-A) and product gas with comparable tar composition and concentration. The conditions in the OLGA Collector were kept constant, while the Absorber was operated at (non-optimised) reference conditions to allow comparison of between results of experiments with the different scrubbing liquids.

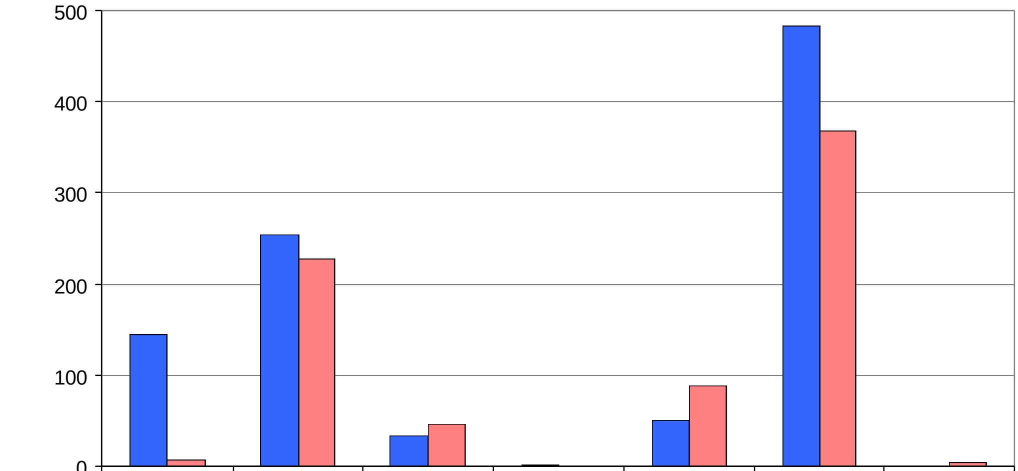
The tar composition and concentration were maintained as constant as possible during the test runs. To monitor the effect of the different scrubbing liquids, the Absorber performance is relevant with respect to the removal of the class 2 and class 4 tar compounds. In general, the Absorber should remove both class 2 and class 4 tars. The heavy class 5 tars are removed in the Collector upstream of OLGA Absorber.

3.3.2. Scrubbing liquid Oil-B

Figure 3.3 (top) gives the tar composition and concentration at the inlet of OLGA during the test runs with the reference liquid Oil-A and Oil-B in the Absorber. Figure 3.3 (bottom) gives the tar composition at the outlet of the OLGA Absorber when using the reference Oil-A and Oil-B in the Absorber. As expected, the removal efficiency for the class 2 tars is for Oil-B better than for Oil-A. The Oil-B capacity for class 4 tars is comparable with the conventional oil. Since the Oil-B removes the class 2 tars better than reference Oil-A and the class 4 tars similar, the overall performance with the Oil-B is better than with Oil-A.



	Class 2	Class 3 (excl tolueen)	Class 4	Class 5	Unknown	Total tar (excl toluene)	Dewpoint [°C]
Oil-A	520	629	6,503	777	2,414	10,842	203
Oil-B	418	611	6,017	1,006	2,872	10,925	221

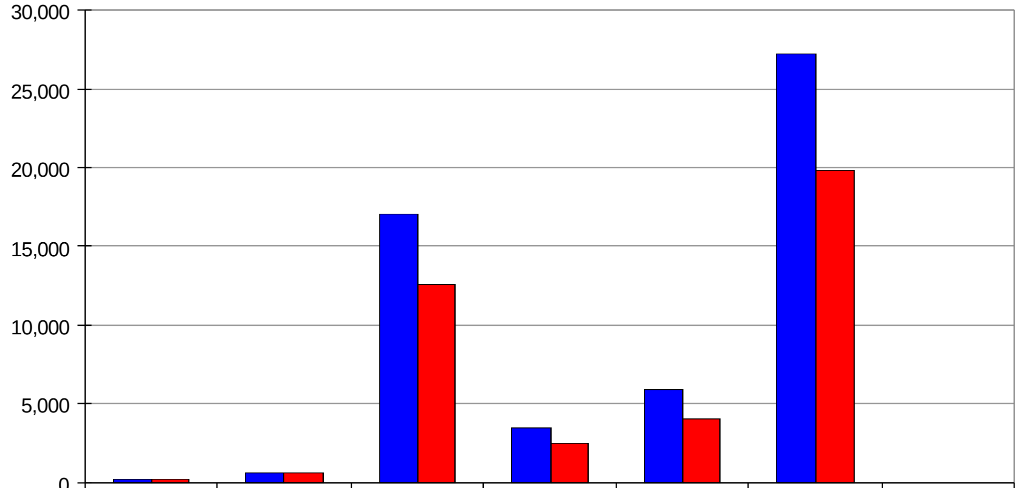


	Class 2	Class 3 (excl tolueen)	Class 4	Class 5	Unknown	Total tar (excl toluene)	Dewpoint [°C]
Oil-A	143	254	33	2	50	482	-1
Oil-B	7	228	46	0	88	368	4

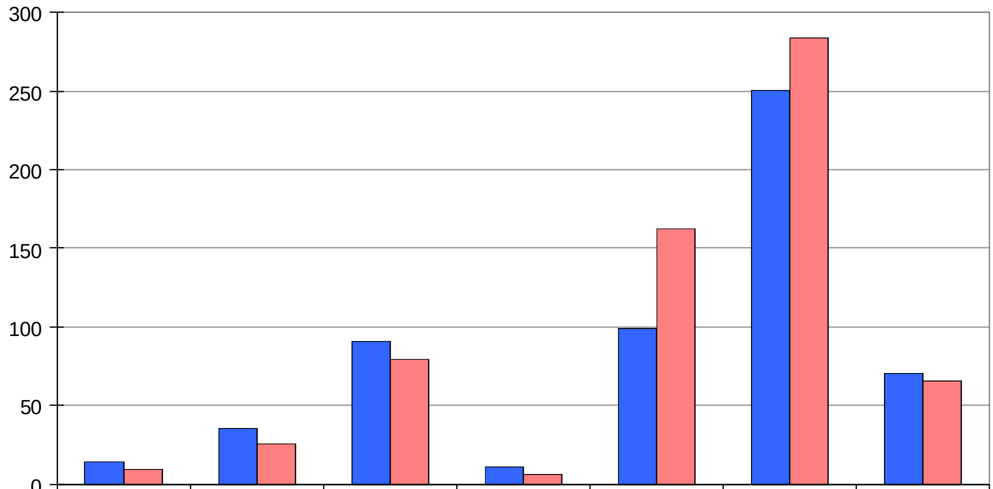
***Figure 3.3**. Tar concentration in mg/m_n^3 and composition per class at the OLGA inlet (top) and outlet (bottom) for test with scrubbing liquid Oil-B. Absorber was operated at (non-optimised) reference conditions to allow comparison of results.*

3.3.3. Scrubbing liquid Oil-C

Figure 3.4 (top) gives the tar composition and concentration at the inlet of OLGA during the test runs with reference liquid Oil-A and Oil-C in the absorber. The total tar concentration is relatively high because the WOB gasifier was operated with an oxygen steam mixture as gasification agent. In the Oil-C test run the total tar concentration and concentration of the individual classes were approximately 25% lower compared to the test run with Oil-A. The total class 2 tar concentration was relatively low.



	Class 2	Class 3 (excl tolueen)	Class 4	Class 5	Unknown	Total tar (excl toluene)	Dewpoint [°C]
Oil-A	206	604	17,040	3,537	5,901	27,288	239
Oil-C	158	554	12,598	2,504	4,011	19,825	232



	Class 2	Class 3 (excl tolueen)	Class 4	Class 5	Unknown	Total tar (excl toluene)	Dewpoint [°C]
Oil-A	15	35	91	11	99	251	71
Oil-C	10	26	79	6	163	284	66

***Figure 3.4**. Tar concentration in mg/m_n^3 and composition per class at the OLGA inlet (top) and outlet (bottom) for test with scrubbing liquid Oil-C. Absorber was operated at (non-optimised) reference conditions to allow comparison of results.*

Figure 3.4 (bottom) gives the tar composition at the outlet of the OLGA Absorber when using reference Oil-A and Oil-C in the Absorber. The removal efficiency for the class 2 and class 4 tars is similar for both scrubbing liquids. It is expected that the bulk price of Oil-C will be considerably lower than of Oil-A. Therefore, Oil-C becomes an attractive option when the scrubbing liquid consumption In the OLGA is a significant cost factor (*cf.* Section 5.2).

3.3.4. Discussion

The impact of an alternative scrubbing liquid is most pronounced in the performance of the Absorber for the removal of class 2 and class 4 tar compounds. The dimensioning of the Absorber is based on either >99% removal of the most critical class 4 compound (*i.e.* naphthalene) or >95% of the critical class 2 compound (*i.e.* phenol). Typically, the removal of phenol is the design specification. With scrubbing liquid Oil-B, the phenol removal is enhanced with similar removal efficiencies of class 4 tars. This implies that a smaller Absorber column can be applied. With liquid Oil-C similar results are obtained, compared to the reference liquid. However, this liquid holds the possibility to reduce the operational costs because of the lower price per litre.

3.4. Dust-loaded feed gas

Even with a hot gas filter installed upstream of the OLGA unit, small amounts of residual solid fines may be present in the product gas. It is inherent to the use of a scrubbing liquid that these solids will be collected (to the major part) in the liquid. This is important to protect the downstream prime mover, however, with respect to the long-time operation of the OLGA it is crucial that these solids will not lead to fouling of the column packing. Furthermore, it is a very interesting and economically attractive option if the OLGA could remove the full dust load from the gas, as this would make the hot gas filter superfluous.

In the lab-scale OLGA experiments were carried out in which the existing ceramic hot gas filter was bypassed and the product gas from the "WOB" atmospheric bubbling fluidised bed gasifier [14] was only dedusted with a standard cyclone. The product gas with a remaining solids concentration of 3.2 g/m_n^3 of mainly dust fines was fed to the OLGA (Figure 3.5). The product gas leaving the OLGA contained only 16 mg/m_n^3 of dust mainly consisting of very small carbon fines. On the filter sample it appeared as a very thin black layer, *i.e.* the fibre structure of the filter is still clearly visible [15]. The tar removal performance was not affected by the presence of dust in the gas.

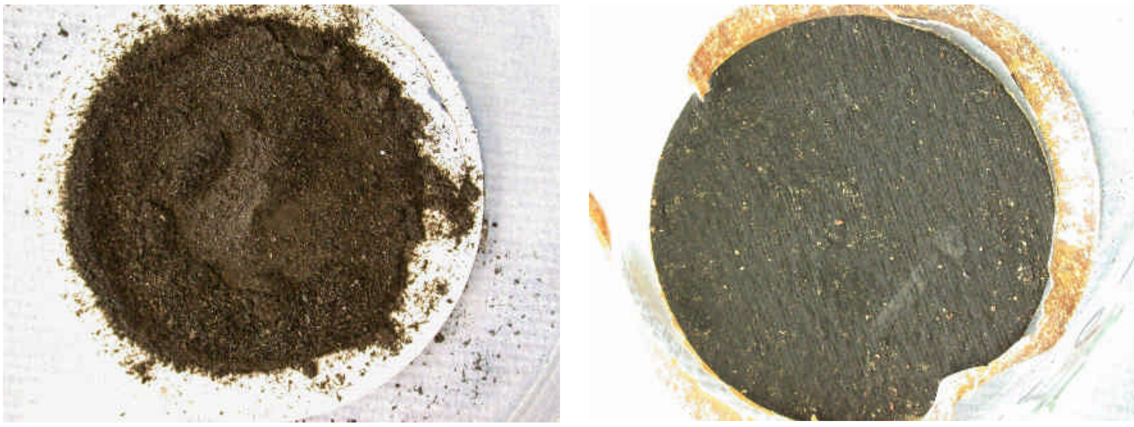


***Figure 3.5**. Pictures of dust sample filters of product gas before (left) and after the OLGA unit (right).*

These promising initial results motivated the start of a separate project “OLGA Optimum”, in which the possibility is assessed to apply the OLGA for combined dust and tar removal. In that case, deep dust removal upstream of OLGA is not required and the hot gas filter can be omitted from the system. This would significantly reduce the cost of integrated biomass gasification CHP systems. Preliminary project results from lab-scale experiments show that OLGA effectively removes fine dust from the product gas without fouling of the column packing. Coarse dust should be removed upstream of OLGA by one or more cyclones, as these larger particles have a tendency for fouling. A 50-hour performance test has been carried out in the lab-scale set-up and in this period no increase in pressure drop over the column packing was observed indicating that no fouling occurred and which delivered the *“proof of principle”* of the combined dust and tar removal from product gas with the OLGA [16]. However, it should be noted that extended tests are required to exclude long-term fouling.

Due to solids leakage in the hot gas filter in the pilot system, also the pilot OLGA unit has been operated with dust-loaded product gas. In this test, similar results were obtained with respect to effective dust removal and the absence of fouling of the column packing (*cf.* Section 4.3.1). More pilot test for dust removal, as well as, inclusion of an optimum step to separate the solids from the scrubbing liquid are included in the ongoing “OLGA Optimum” project.

3.5. Applications

With the OLGA technology tars can be removed to the level required for several downstream applications with varying tolerance for tars. The least demanding application is firing in a gas engine, *i.e*. tar removal to a dewpoint of 20-60°C is typically sufficient, which corresponds to up to 2 g/m_n^3 of tars. Application of the gas for chemical synthesis requires essentially a tar-free product gas to prevent catalyst contamination (*i.e.* tar dewpoints below -10°C). Most of these synthesis processes require compression of the product gas in which case also very low tar levels are required to prevent fouling of the compressor. In the next Sections, three examples of experimental results are discussed of applications of product gases cleaned with the OLGA tar removal technology.

3.5.1. Gas engine

The first integrated application of the lab-scale OLGA unit was demonstrated during the Public Day of ECN in October 2002. For this purpose a small generator was coupled downstream the bubbling bed gasifier and the OLGA tar removal unit. The ‘green’ electricity produced in the generator was used to power a toy car racetrack, which operated during the complete Public Day. Inspection afterwards showed no tar deposition in the generator. This experiment delivered the *“proof-of-principle”* of using product gas in a gas engine after removal of tars and other organic compounds with the OLGA technology.

3.5.2. Fischer-Tropsch synthesis

Biomass is considered to be an important renewable energy source for this century. An important aspect of biomass is that liquid bio-fuels can be produced from this renewable source. One of the most promising routes to produce ‘green’ fuels is the combination of biomass gasification and Fischer-Tropsch (FT) synthesis. In this route biomass is gasified to yield a product gas or biosyngas that is rich in H_2 and CO. After cleaning and conditioning, the biosyngas can be used to synthesise FT ‘green’ diesel. FT diesel is an ultra-clean high-quality fuel as it contains no sulphur and aromatics and the fuel is directly applicable in the current infrastructure and diesel engines. In a study towards the development of gas cleaning technology for integrated biomass gasification and FT synthesis systems, one of the systems assessed was based on the OLGA tar removal [17,18,19].

Biomass (beech) was gasified at 850°C in the ECN lab-scale atmospheric bubbling fluidised bed gasifier with oxygen as gasifying medium to produce an essentially nitrogen-free product gas and with added CO_2 to moderate the temperature in the bed of the gasifier. The product gas contained approximately 23 g/m_n^3 of tars and almost 1.5 vol% of benzene and toluene. The raw product gas was passed through a high-temperature gas filter to remove essentially all the solids. The tars and approx. 25% of the benzene and 50% of the toluene were removed in the OLGA unit. The gas leaving OLGA was further cooled and cleaned from NH_3, HCl, and other inorganic impurities in a water scrubber. Both the OLGA and the water scrubber were equipped with a stripper to regenerate the washing oil and water, respectively. Water was condensed from the clean gas and subsequently the gas was compressed to the desired pressure of 30 bar. The compressed gas was passed through a ZnO filter to remove H_2S and an active-carbon guard bed to remove all remaining trace impurities [17].

In March 2003, Fischer-Tropsch products were synthesised from this product gas in a 500 hours test. During this synthesis test, the catalyst showed no loss of activity or selectivity. Herewith the POP was delivered of using product gas for Fischer-Tropsch synthesis after removal of tars with the OLGA technology [17].

3.5.3. Synthetic Natural Gas (SNG) synthesis

In addition to the importance of biomass for the production of Fischer-Tropsch transportation fuels, it also is a feedstock for the production of Synthetic Natural Gas (SNG) or ‘green gas’. SNG is a gaseous energy carrier with the quality required for injection into the existing natural gas grid. It may therefore be used for all applications that are known for natural gas. SNG is considered to be a very attractive option to supply green heat (for indication: the total Dutch heat consumption is 1,000 PJ/y, which is mainly produced from natural gas). SNG can be stored (if necessary, underground in existing gas fields) and added to the grid to be transported to the end users. This system is simple, easily accepted and characterized by cheap production because it can be operated continuously. Furthermore, SNG transport has little or no energy losses, *i.e*. energy losses during the transport of gas are less than 1%, whereas heat transport in average shows 15% energy loss [20].

In December 2003, an integrated lab-scale biomass gasification, gas cleaning, and SNG synthesis experiment was performed at ECN. The line-up of the system was similar as applied for the integrated Fischer-Tropsch synthesis (see previous Section). Also in the 500-hour SNG synthesis experiment, the applied catalyst showed no loss of activity or selectivity. Herewith the POP was delivered of using product gas for SNG synthesis after tar removal with OLGA [20].

3.5.4. High tar concentrations

In the Fischer-Tropsch and SNG applications, as discussed in the two previous sections, the product gas was generated by oxygen-blown gasification. Resultantly, the tar-load of the product gas is approximately twice as high compared to ‘standard’ air-blown gasification, *e.g*. typically 20-25 g/m_n^3 versus 8-15 g/m_n^3. The OLGA operated as expected with these high tar-loads, however, there will be a limit for the tar-load that the OLGA can handle in its present design and operational conditions. The same restriction applies for product gases with very different tar compositions (*e.g.* ratio heavy and light tars). Determining possible operational limits of the OLGA is an issue for further research.

4. OPERATIONAL PILOT OLGA PERFORMANCE

The pilot OLGA unit was designed based on the experience and design parameters collected in the lab-scale experiments (*cf.* Chapter 3). Between the lab-scale and pilot OLGA units there is a scale-up factor of one hundred. The purpose of the pilot unit was, therefore, to deliver the *"proof-of-concept"* (POC) for the OLGA process. This implies that the unit had to be designed and constructed with the proper equipment in such a way that a unit would be a 'blueprint' for future commercial plants. The purpose of the experimental programme was to demonstrate the OLGA tar removal principles on pilot scale and, equally important, to identify critical scale-up issues and design parameters.

4.1. Design & Engineering

The OLGA unit was designed and engineered by Dahlman Industrial Group based on the ECN pre-design. The hot gas filter (HGF) was a complete Dahlman design. As part of the engineering phase the ECN-Dahlman project team carried out a HAZOP study (Hazardous Operations). Insights from the HAZOP have resulted in modifications of the engineering drawings.

4.1.1. OLGA unit

The OLGA was designed to process 200 m_n^3/h of wet and <u>dust-free</u> product gas. To guarantee a dust-free gas the hot gas filter was installed upstream of the OLGA; the filter is discussed in the next section. In Figure 4.1 the simplified process flow diagram (PFD) of the pilot OLGA unit is presented.

Feed of the OLGA unit <201> is the dust-free product gas from the gasifier that is cooled to 320-350°C (above the tar dewpoint). In the Collector (packed) column T-200 the gas is cooled by the scrubbing liquid, upon which the heavy tars condense and are removed from the gas. The scrubbing liquid that has heated up by contact with the hot gas and the removed heavy tars are passed through Cooler E-200 to cool the oil and through Separator V-200 to remove the liquid heavy tars. In pilot set-up the Separator is designed as a batch-wise operation, whereas the application of a continuous separation step would be considered for a full-scale plant. The regenerated oil is recycled <206> to the Collector. The removed tars and a bleed of the scrubbing liquid are drained and can be recycled to gasifier to be destructed (N.B. this integration is not carried out in the pilot unit). The scrubbing liquid bleed is compensated by a liquid make-up.

After the Collector <201a>, the gas passes the Absorber (packed) column T-210 in which the gas is further cooled and the gaseous tars are absorbed in the scrubbing liquid. The temperature of the scrubbing liquid feed of the Absorber <215> controls the gas temperature at the OLGA outlet <202> and this temperature must be kept above the water dewpoint (typically 60-80°C). The scrubbing liquid with the absorbed light tars is regenerated in the (packed) Stripper column T-220 by heating the liquid to volatilise the tars. Therefore, the scrubbing liquid is heated in Heater E-210 and pre-heated stripping air <217> is used. The hot air with the light tars <218> can also recycled to the gasifier. N.B. In the pilot set-up the air is fired on the afterburner. With the hot stripper air also some scrubbing liquid is volatilised and entrained.

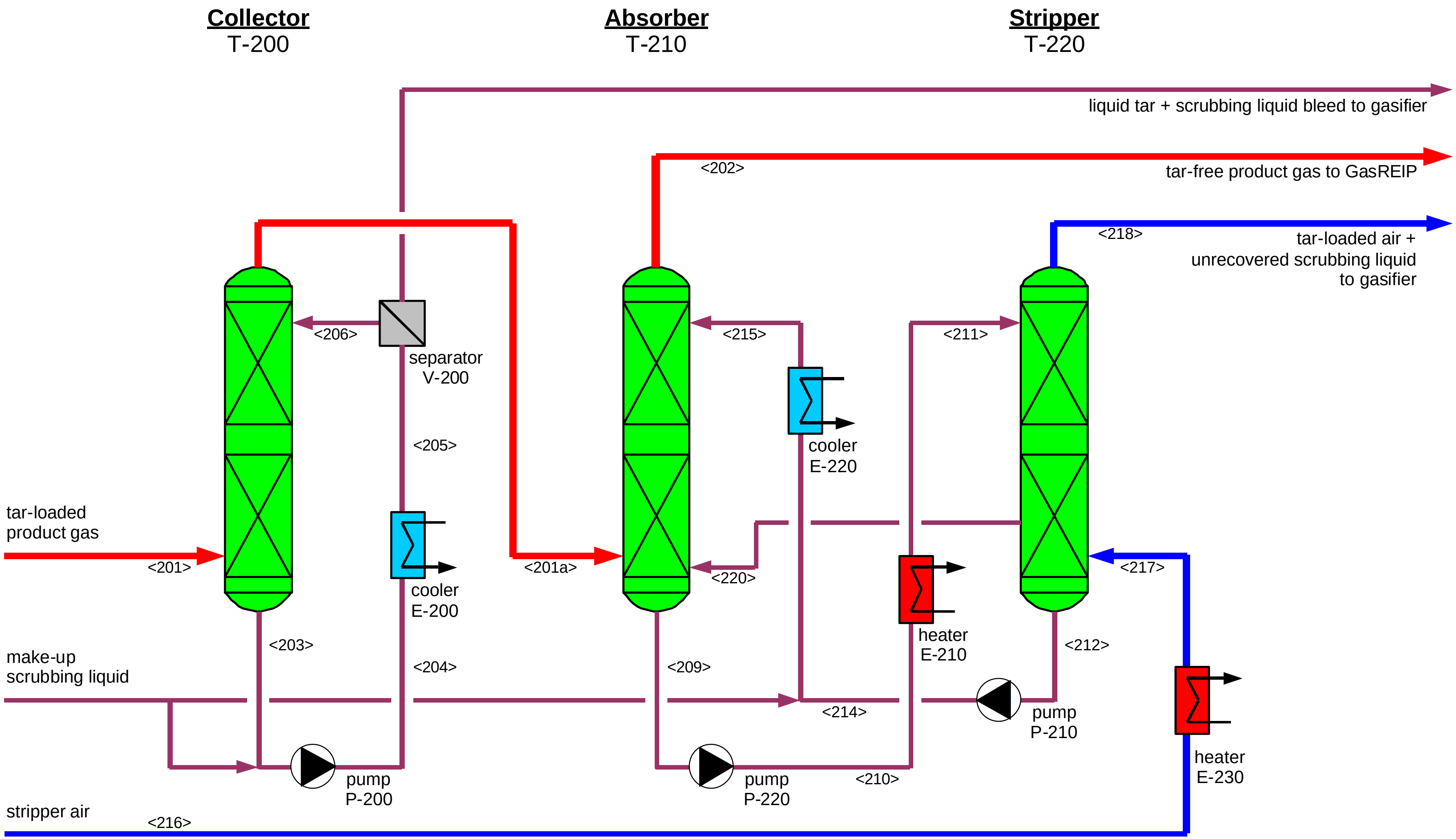


***Figure 4.1**. Simplified process flow diagram of pilot OLGA unit.*

The loss of liquid is compensated by the liquid make-up. The heated up liquid leaving the Stripper <212> is cooled in Cooler E-220 and fed to the Absorber. In larger systems the Cooler E-220 and Heater E-210 will be integrated, however, for maximum flexibility this integration was not made in the pilot design.

In the Absorber and Stripper system the scrubbing liquid is circulated with two pumps, *i.e.* Pump P-210 feeding the Absorber and Pump P-220 feeding the Stripper. To maintain a constant flow through the system, the flows through both pumps must be equal. However, as this is difficult to establish without extensive process control measures, the flow of P-220 has been given a slightly higher set point. To prevent a resulting net increase in the scrubbing liquid hold-up in the Stripper, periodically liquid is transferred to the Absorber via by-pass <220>, which is controlled by level switches in the Stripper.

4.1.2. Hot gas filter

The hot gas filter (HGF) was designed to process 200 m_n^3/h of wet gas (see Figure 4.2). The HGF vessel is insulated and electrically heated to the desired operating temperature. The filter has to be operated above the tar dewpoint (typically 350°C) to prevent tar condensation. The maximum design temperature is 450°C. The HGF contains fifteen sintered metal fibre candles that are positioned in three rows of five candles. Filter candles from other materials can also be used in the HGF, *e.g.* ceramic and sinter metal powder. The filter is regenerated in a sequence in which the rows are consecutively purged in three pulses at a pre-set frequency and with pre-heated purge gas. Typically, the purge gas is nitrogen, however, recycled clean product gas or gas mixtures can be used as well. Purge is started after a pre-set interval or when a pressure drop set point is reached. For indication, with a purge cycle time of four minutes frequency, the total average purge gas consumption equals approximately 2 m_n^3/h or 1 vol% of the product gas flow.

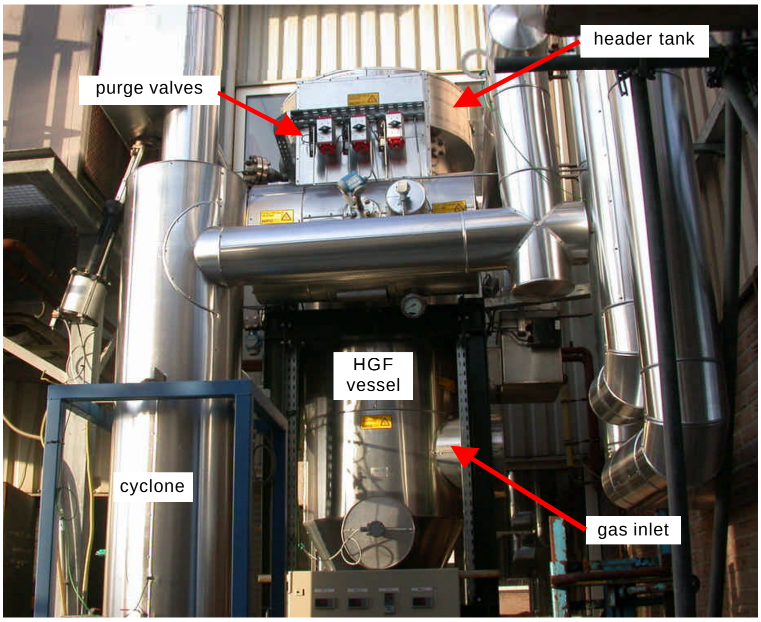


***Figure 4.2**. Hot gas filter.*

4.2. Construction & Erection

The OLGA pilot unit and the hot gas filter (HGF) were constructed in the workshop of Dahlman Industrial Group in Maassluis, the Netherlands. In July 2003, both units were transported to the

ECN site in Petten and erected as part of the existing test infrastructure (see Figure 4.3) [11]. The complete system is schematically shown in Figure 4.4. The schematic layout of the gas cleaning units is included in Appendix B. Subsequently, all utility connections were installed, *i.e*. pressurised air, nitrogen, electrical, cooling system, and process control system (WizCon).

Figure 4.3. *Positioning of OLGA skid in Dinkeldôme building. The ESP is visible on the foreground.*

The integrated system comprises of (1) the 500 kW_{th} circulating fluidised bed (CFB) gasifier "BIVKIN", which is equipped with two different feeding systems to allow processing of a variety of biomass materials. (2) The staged air-cooled double pipe cooler to cool the hot product gas to ~350/400°C. The preheated air can be used in the gasifier or burner. Solids (soot, dust, ash, and char) removal can be performed at 350/400°C with (3) cyclone, which removes over 90% of the solids or, alternative, with the (4) hot gas filter with sinter metal candles, that essentially complete removes all solids. (5) OLGA unit for tar removal. The GasREIP section, which can also be operated without OLGA, comprises of the following three units: (6) Water quench to cool the gas and condense the process water. In case of operation without OLGA also tars and dust will be removed. (7) The wet electrostatic precipitator (ESP) is used to remove remaining tar aerosols and fine dust. The ESP is only operated when the OLGA is bypassed. (8) Ammonia scrubber. (9) The booster provides sufficient pressure drop over the system and a constant pressure for the (10) low-NOx afterburner or (11) gas engine.

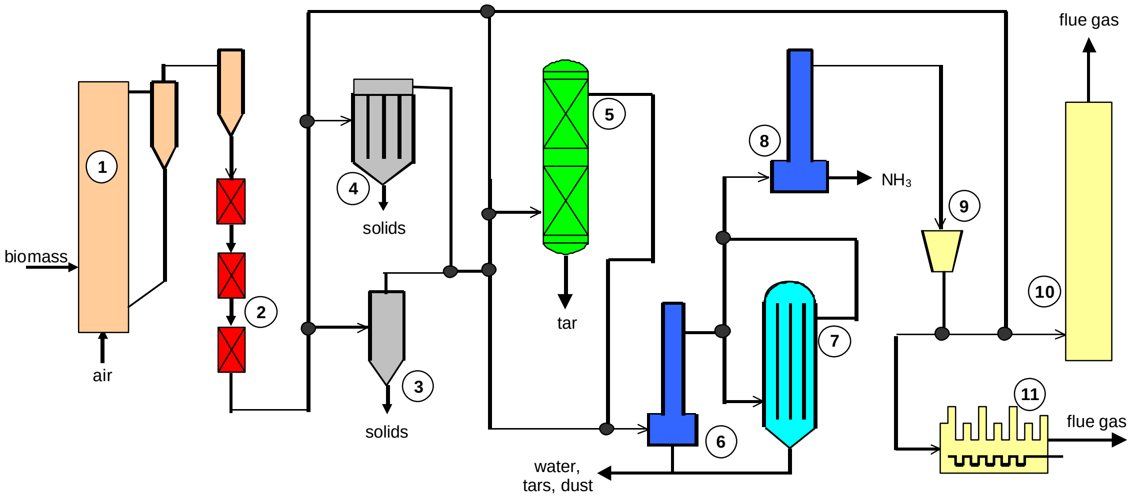


Figure 4.4. *Complete integrated pilot biomass gasification and gas cleaning system at ECN. For description: see text. Black circles indicate valves that allow switching between different configurations. Process integrations of heat and residual streams are not indicated.*

4.3. Commissioning

The pilot OLGA unit and the hot gas filter were commissioned in a series of (cold) functional tests and a four-day operational test programme.

During the functional tests the operation of the OLGA and the hot gas filter was tested, *i.e.* temperature set points and control, gas leakage, stability of pumps and oil flows, etc. Problems in electrical wiring and process control system were solved. Many modifications were made in the periphery of the system, *i.e.* additional sampling points, other locations of thermocouples, installation of active dosing system of make-up scrubbing liquid, etc. Some of the modifications made were based on new insights and some resulted from additional specifications set by the integration in the complete system.

4.3.1. Operational tests

In February 2004 operational tests were carried out with the integrated system comprising the BIVKIN gasifier, gas cooler, hot gas filter, OLGA, water quench and scrubber, booster, and afterburner (*cf.* Figure 4.4). Similarly as experienced in the functional test, new minor problems were encountered in the periphery of the system. In between the test runs these problems were solved. The main findings and problems with respect to the operation of the OLGA process were (refer to the PFD in Figure 4.1):

<u>Solids leakage in hot gas filter</u>
Upon first operation of the hot gas filter (HGF) with product gas solid concentrations between 0.5 and 2 g/m_n^3 were measured after the HGF. Based on the design, a solids concentration in the order of several tens of mg/m_n^3 was expected. Extensive problem analysis excluded the options that residual solids (from start-up an/or previous tests), sampling artefacts, or gas bypass over the cyclone were responsible for the measured solids load. The final conclusion was that there had to be a leakage in the HGF. Post-test inspection of the inside of the filter revealed that one filter candle was not positioned properly, creating a small opening that, surprisingly, was responsible for the high solid-load observed. Proper positioning of the candle solved the problem.

Operation of OLGA unit with dust-loaded gas

In the first operational test the HGF and the OLGA unit were simultaneously put in operation. As a result of the solids leakage in the HGF, dust-loaded product gas was fed to the downstream OLGA unit. The OLGA has been operated for approx. 8 hours under these conditions. The gas after the Collector contained no dust indicating that all dust was removed in the Collector. In this period no increase in pressure drop over the Collector packing section was observed, which indicated that the dust did not foul the packing but was removed with the scrubbing liquid. Similarly, no increase in pressure drop was observed over the Pump P-200 and the Cooler E-200, which would have been a sign of fouling of the equipment. Although the duration of these test conditions were too short to be conclusive, it appears that all solids captured in the liquid were removed in the Separator V-200. The result of this (unplanned) test supported the findings of the experiments with dust-loaded gas performed in the lab-scale OLGA (*cf.* Section 3.4).

Pump in Collector circuit

To operate the Collector column (T-200) optimally and at design conditions, the scrubbing liquid flow into the Collector <206> has to be constant and of constant temperature. The original frequency-controlled pump P-200 was selected based on its suitability for the high temperature and properties of the scrubbing liquid and heavy tar mixture that had to be pumped. However, the pump flow appeared to be very sensitive towards (small) variations in the process conditions encountered upon start-up and changes in test parameters, *e.g*. oil temperature and viscosity. This resulted in large fluctuations in the liquid flow, which also effected the cooling of the scrubbing liquid (see next point). A new flow-controlled pump was selected and installed to solve this problem.

Cooler in Collector circuit

Cooler E-200 has to cool the scrubbing liquid, which is heated by contact with the hot product gas, to the required Collector inlet temperature <206>. The Cooler was designed to operate in a way to prevent tar fouling on ‘cold spots’. This was established by installing a secondary cooling circuit between the Cooler and the ECN water/glycol cooling system to minimise temperature differences. As a result, a change in the process parameters of the Cooler lead to delayed responses and large overshoots of the liquid temperature in <205> with amplitudes up to 20°C. This problem was even enhanced by the fact that the pump flow of Pump P-200 also varied as function of the liquid temperature. The process control of the secondary cooler circuit was modified to solve this problem.

The combination of the instable pump flow and the overshoots of the cooler resulted in a situation that effectively the Collector process could not be operated stable and constant manual corrections were necessary. After the installation of a new pump and the modification of the cooler process control, the Collector circuit could be operated as designed.

Level control in Absorber-Stripper columns

Frequently, the OLGA unit went into an emergency shutdown triggered by alarms on the liquid level in either the Absorber or Stripper column (T-210 and T-220). This was caused by the fact that the process control to equalise the levels in both columns via bypass <220> was too slow and did not account for the difference in liquid hold-up in both columns. To solve this problem, a new process control philosophy was developed and installed. After the modification the level control functioned stable and without problems.

4.4. 50-hour performance test

After the operational tests, the described modifications were made to the OLGA unit and the hot gas filter. In May 2004, a performance test was carried out in which the integrated system was operated for 48 hours.[1] The results with respect to the operation of the hot gas filter and the OLGA process are discussed below.

4.4.1. Hot gas filter

During the test the hot gas filter (HGF) operated on specification with respect to the removal of solids. The initial solids concentration of 15 g/m_n^3 was reduced to below 100 mg/m_n^3 of very fine dust, which was expected to be acceptable for feeding to the OLGA Collector based on the results of the lab-scale dust tests (*cf.* Section 3.4). Temperatures of the HGF inlet gas, the purge gas, and pressure drop over the filter are shown in Figure 4.5.

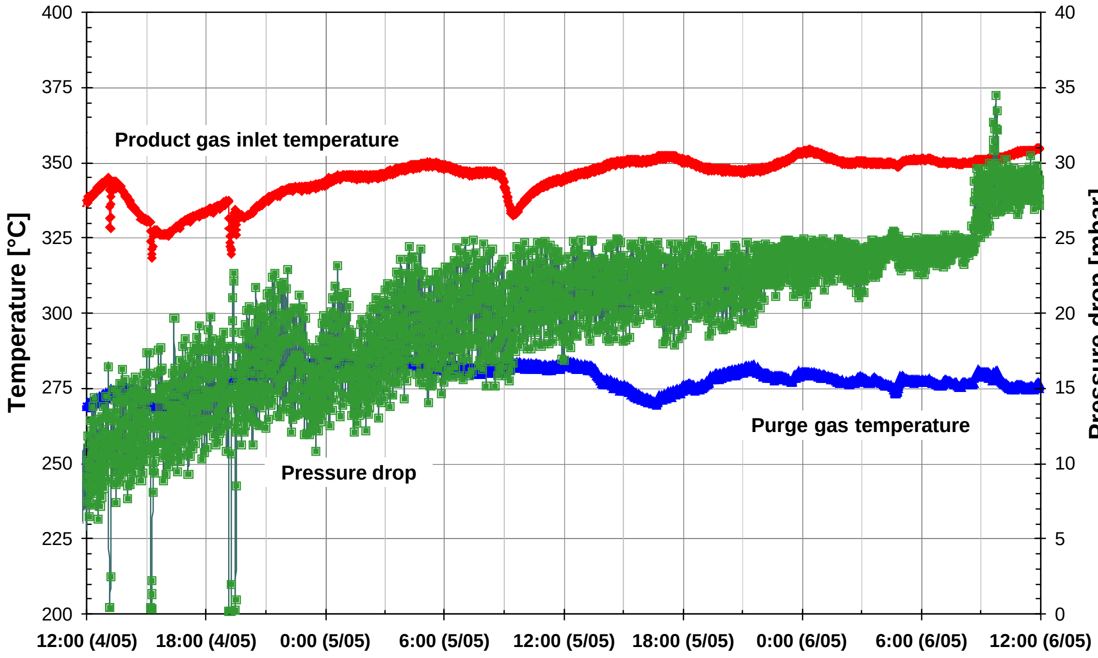


***Figure 4.5**. Hot gas filter operation during the 50-hours test.*

The temperature of the product gas after the gas cooler that entered the HGF was initially 330°C, which increased to 350°C after the installation was thoroughly heated. To ensure operation of the HGF above the tar dewpoint (estimated to be ~350°C), operation of the HGF at 370°C was planned. However, due to insufficient capacity of the trace heating this temperature could not be reached. The purge gas temperature should be equal to the product gas temperature (*i.e.* ~350°C in this test). However, due to insufficient capacity of the tracing only a temperature of 280°C could be reached.[2]

1. The test was terminated 2 hours before planned shutdown due to an obstruction in the flow controller in <206> and resulting loss of scrubbing liquid flow. The origin of the obstruction was solid material accidentally released from Separator V-200 upon regeneration.
2. In the operational test both tracing sections had sufficient capacity to reach the desired temperature set points, therefore, the problems in the test were ascribed to damage of the electrical circuits. Post-test analysis confirmed this and the tracing sections were repaired.

From Figure 4.5 it appears that the pressure drop over the filter steadily increased in time and did not reach a constant value. Initially, the filter was purged every four minutes. After approximately 20 hours, the pressure drop exceeded the preset maximum of 25 mbar and the purge frequency automatically increased to keep the pressure drop below the preset value (*i.e.* a purge sequence is automatically started when this preset value is reached). Despite the increase in purging frequency the pressure drop increased further. After 45 hours, the preset maximum pressure drop was increased to 30 mbar.

For the duration of the 50-hour test the pressure drop of the HGF was within acceptable limits, however, performance of the filter under these conditions is unacceptable for longer tests. Apparently, the filter cannot be regenerated completely, which is attributed to fouling of the filter candles pores. The occurrence of fouling might be explained by the low temperature of the purge gas, which causes the filter temperature to drop during every purge below the tar dewpoint (*i.e.* ~350°C).

Filter operation is expected to improve by raising the temperature in the HGF, both of the inlet product gas and the purge temperature. Further improvements might be obtained by allowing the filter cake thickness to increase (by lowering the purge frequency).

4.4.2. OLGA unit

During the 50-hour test the OLGA was operated at six different conditions with respect to the set points for the scrubbing liquid flow and temperatures feed to the Collector <206>. The performance of the OLGA with regard to tar removal was monitored by SPA analysis and the conditions were adjusted after the results of the analysis were available to optimise the performance. In Figure 4.6 the tar removal performance results are presented for the six conditions tested; the complete SPA analysis is included in Appendix C.

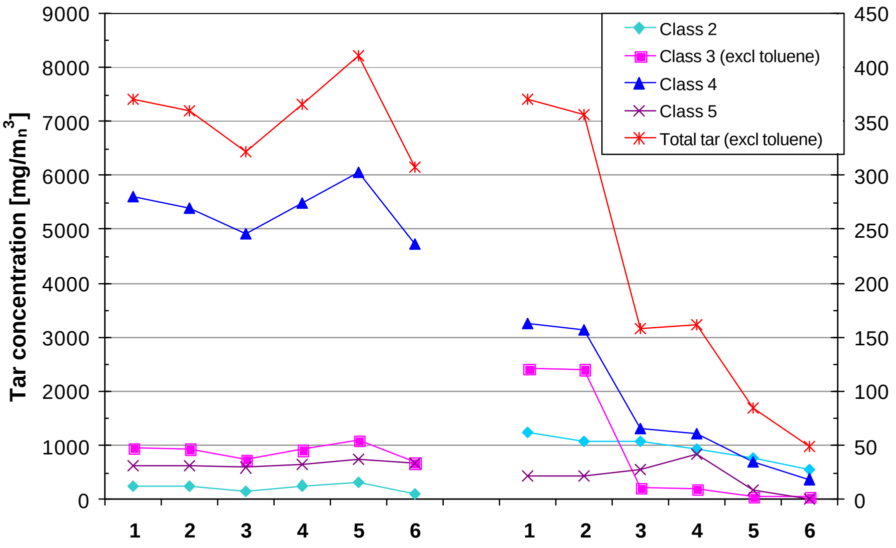


***Figure 4.6**. Tar removal results at six conditions tested during OLGA pilot test programme. Left: OLGA inlet concentrations; Right: corresponding OLGA outlet concentrations.*

In the optimum condition (#6) achieved within the duration of the test, the total tar concentration was reduced from more than 7 g/m$_n^3$ to below 50 mg/m$_n^3$. Tar aerosols (condensable heavy tars) were completely removed, naphthalene for 99.5%, and phenol for

85%. The calculated tar dewpoint of the OLGA outlet gas was 4°C, which means that the cleaned product gas was on specification for application in a gas engine.

Effect of hot gas filter regeneration purge

Qualitative gas analysis (*i.e.* by means of a small side-stream gas flow bubbling through an impinger) indicated that upon a HGF purge a breakthrough of heavy tar aerosols was observed in the OLGA outlet product gas (visible as a 'mist'), whereas the gas was free of aerosols under normal conditions. The aerosols resulted in a tar dewpoint increase of approximately 50-60°C. Except for the tar measurement at condition #6, all SPA measurements were taken during normal operation of the hot gas filter (HGF) - for measurement #6 the purging was temporarily stopped. Therefore, the measured tar concentrations might have been an overestimate and a not completely reliable indication of the OLGA tar removal performance.

The origin of the observed effect seems to be a 'shockwave' induced by the purge, as in a short period a significant amount of gas is added. The higher gas volume 'blows' through the OLGA and the tar removal performance is negatively affected. The effect is especially pronounced in the pilot set-up as in each purge one-third of the candles is regenerated. In larger filters relatively less candles are purges in each pulse, thus in these systems the effect will be much smaller and might not cause breakthrough of tar aerosols. Therefore, for the operation on the pilot system no measures were taken. SPA tar measurements, however, should only be taken during pulse intervals or when the purging is temporarily stopped.

Collector performance

The tar concentration in the OLGA outlet gas indicated that the total tar removal performance of OLGA (*i.e.* Collector plus Absorber) was satisfactorily based on the achieved dewpoint in condition #6. However, from detailed analysis it was concluded that the OLGA Collector T-200 had only removed a very small amount of the heavy condensable tars, while the majority of the heavy tars were removed from the gas in the Absorber T-210, together with the light tars. The heavy tars accumulated in the Absorber-Stripper scrubbing liquid, as these compounds cannot be volatilised in the Stripper T-220. In time, this resulted in deposition of the heavy tars in Cooler E-220, fouling of the heat exchanger surface, and loss of cooling capacity.

Post-test analysis indicated that the Collector had operated under its design performance because the packing surface in the column was insufficient for complete condensation of the heavy tar fraction. The Collector performance could be improved by adding additional packing height. In a follow-up project the OLGA Collector T-200 was expanded with an additional packing section. In operational tests with the modified OLGA Collector the heavy tar removal was in accordance with the design performance [21].

Heavy tar separation

The function of the Separator V-200 is the removal of the heavy tars and small amounts of fine dust from the scrubbing liquid. The effectiveness and the stand-time of the batch separation step appeared to be very dependent of the temperature applied in the Separator. From the different process conditions evaluated in the 50-hour test, the optimum Separator temperature was determined.

4.5. Discussion

The pilot OLGA unit is a hundred times scale-up of the lab-scale unit. The unit was designed and constructed with the equipment selected in such a way that unit would be a 'blueprint' for future commercial plants. The purpose of the pilot project was to deliver the *"proof-of-concept"* for the OLGA process and to identify critical issues in up scaling, equipment selection, and process design.

In the complete test programme including the functional and operational tests, and the 50-hour performance test a several small and larger modifications were made to the OLGA unit. With respect to the operation of the unit and the OLGA tar removal process, the most important findings were:

Pump P-200

The performance of Pump P-200 in the Collector circuit is crucial for a stable and optimum performance of the Collector (T-200) for heavy tar removal. It was concluded that the pump must be suitable for handling varying flows of oil and tar mixtures, of different temperatures, and with different properties (*i.e.* viscosity and presence of solids). Instable flows of the pump directly introduce a cascade of process disturbances from the performance of Cooler E-200, the temperature of the scrubbing liquid entering the Collector <206>, and therewith the heavy tar removal performance. In the lab-scale tests these phenomena were not experienced, as an over-dimensioned and relatively robust pump was applied. These insights have resulted in proposed changes in the layout of the OLGA PFD, wherein the pump flow and the scrubbing liquid cooling will be decoupled [21].

Packing surface in Collector

The Collector T-200 appeared to be designed with an insufficient packing height (actually: the packing surface) to completely condense the heavy tars from the product gas. The origin of the design choice that resulted in this situation was found to be in the up scaling from lab to pilot and especially in the difference in heat balance for both units. In the small unit, trace heating provides the required column temperature, while in the pilot unit the actual column temperature is defined by the process parameters (*e.g.* liquid temperature and flow). Based on the result of the pilot test and the additional supporting lab-scale studies, complete understanding of the phenomena affecting the heat balance is obtained.

Tar removal with OLGA

The tar removal results in the pilot OLGA have delivered the “proof-of-concept” that the process is in principle suitable for cleaning product gas from biomass gasification and deliver a ‘tar-free’ gas. The pilot test programme has afforded valuable information for optimisation of the design of the OLGA unit and hardware selection for future (commercial) plants.

Hot gas filter

The performance of the hot gas filter (HGF) under the typical biomass gasification conditions as applied in the pilot tests has been insufficient for prolonged operation due to continuous increase in pressure drop over the filter candles. The pilot test results indicate that the HGF should be operated at higher temperatures to prevent tar condensation. However, at higher temperatures the risk of tar polymerisation becomes significant [22]. In an ongoing ECN study the behaviour of tar at different gasifier and filter operation conditions is investigated, which should result in defining the proper process conditions to allow prolonged operation of the HGF.

5. ECONOMIC ASSESSMENT FOR BIO-CHP APPLICATION

The success of the OLGA application as part of integrated bio-CHP systems is determined by its technical performance but also, and maybe even more, by the economical perspectives of OLGA. In this Chapter an economic evaluation of OLGA will be made for four different process scales, *i.e.*: 0.5, 2.2, 10, and 25 MW_{th}. These scales refer to the scale of the ECN pilot gasifier BIVKIN, a possible demonstration project at the ECN site, and two relevant scales for commercial stand-alone plants, respectively.

5.1. Total capital investment costs

The economical feasibility of integrated biomass gasification CHP systems depends on the Total Capital Investment costs (TCI). Beside the TCI, the operational reliability of the process (*i.e.* the effective availability and the possible operational hours) is another important factor for the economical feasibility and directly coupled to the revenues of the process. The TCI of OLGA is the total investment needed, to start the plant up and operate it to the point when income is earned. It includes the cost of:

1. Design, engineering, and construction supervision.	Indirect Costs	Total Capital Investment (TCI)
2. All items of equipment and their installation. 3. All piping, instrumentation and control systems.	Onside Costs[3]	
4. Buildings and structures. 5. Auxiliary facilities, such as utilities, land and civil engineering work.	Offside Costs[3]	
6. Start-up & modifications	Start-up Costs	
7. Funds to cover outstanding accounts from customers.	Working Capital	

Dahlman Industrial Group quantified the sum of the Indirect and Onsite Cost (*i.e.* items 1, 2, and 3) based on commercial quotations. The estimation of these cost items is based on the scale-up of the experimental results. The design parameters, necessary for this scale-up, were generated in lab-scale and pilot experiments. The cost items 4 to 7 were estimated by using standard cost factors from literature [23,24]. The raw material costs were calculated based on the estimation of a reasonable scrubbing liquid consumption. The design performance specifications of OLGA are:

- Phenol (key component) removal: 99%.
- Tar dewpoint after OLGA: <25°C.

The dependence of the sum of the Indirect and Onsite Cost, expressed as specific investment costs of Euro/(m_n^3/h), on the scale of the OLGA unit are shown in Figure 5.1. The size of OLGA is determined by the specification for tar removal and the gas flow rate. The specific investment costs are strongly influenced by the size of the gasification process and decrease with increasing size, usually explained by the economy of scale. At scales above approx.

3. Onsite Costs or ISBL (Inside Battery Limits); Offside Costs or OSBL (Offside Battery Limits).

4,000 m_n^3/h (*i.e.* approx. 10 MW biomass input for direct air blown fluidised bed gasifiers), the specific investment costs seems to stabilise around 200 Euro/(m_n^3/h).

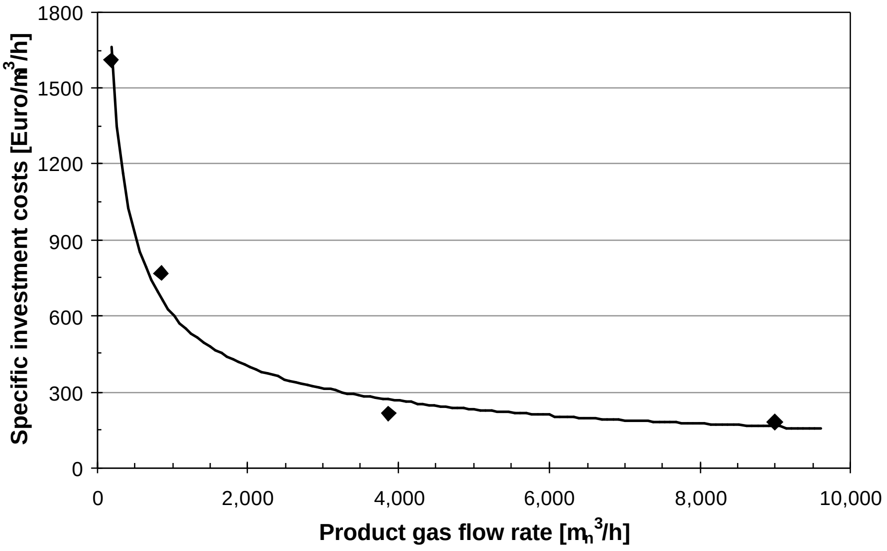


***Figure 5.1**. Specific investment costs of OLGA as a function of the size, determined by the gas flow rate.*

5.2. Operational costs

The heat losses as well as utilities and scrubbing liquid consumption determine the operational costs of OLGA. In OLGA the product gas is cooled down. The heat is transferred from the product gas to the scrubbing liquid and subsequently to a cool medium. Most of the heat can be used elsewhere in the system, to be optimised in a pinch study. Only the heat losses to the surrounding are irreversible losses, estimated on 1% of the total thermal power of the heat exchangers in the OLGA system.

The utilities are determined by the electricity consumption of the pumps, and the amount of cooling water and steam necessary to partially cool down and heat up the oil in the Absorber and Stripper system (T-210 and T-220, *cf.* Figure 4.1). The heat necessary for air heating is not taken into account, because the gasification air is normally preheated, independently from the application of OLGA. In total three pumps are used for scrubbing liquid circulation. The electricity consumption of the pumps increases with increasing scrubbing liquid flow rate. To minimise the heat consumption the scrubbing liquid from the Absorber and Stripper are interchanging heat. In theory, only heat losses in the Absorber and Stripper have to be compensated by using steam. In practice, the temperature of the scrubbing liquid to the Stripper and Absorber should be controlled, which means that 80-90% of the heat is interchanged, while the remaining 10-20% should be added by using steam and cooling water. The total utility costs sum up to 1.1 Euro/tonne biomass,[4] which is determined for 26% by the electricity consumption, 66% by steam consumption, and 8% by cooling water consumption.

Finally, the scrubbing liquid consumption in OLGA is defined by losses in the Stripper (T-220), Absorber (T-210), and in the bleed from the heavy tar Separator (V-200). The scrubbing liquid

4. For the calculations were used an electricity price of 7 €ct/kWh$_e$ and a heat price of 4 €/GJ [Rabou, ECN-CX-04-056]. The price for cooling water has been taken from (Webci) and is estimated on 0.1 Euro/m^3 cold cooling water, which is the price for closed circuit cooling water (cooling tower).

losses in the stripper are minimised with a condenser in the gas outlet of the Stripper. The scrubbing liquid losses in the absorber can be neglected due to the low oil vapour pressure at the Absorber outlet (<1 mg/m_n^3). The liquid losses in the heavy tar stream are still unknown. Since the losses in the absorber and stripper can be neglected the oil losses will be determined by the residual scrubbing liquid in the heavy tar stream. For the CFB gasifier a maximum liquid consumption of 2 g/m_n^3 of cleaned product gas was estimated, which equals to 0.4 wt% biomass input. With a scrubbing liquid price of 2 Euro per litre, the scrubbing liquid consumption costs are 9 Euro per tonne of biomass feedstock.

5.3. Competitiveness analysis

The results of the economic evaluation are expressed in the costs per kWh electricity produced. For these cost calculations the following assumptions were made for stand-alone gasification units:

- Electricity yield of the process (from biomass to electricity): 27.7%.
- Interest rate: 6%.
- Depreciation time: 15 year.
- Annual operating time: 7,000 hours.

For four different scales of operation, the Total Capital Investment (TCI) and the raw or operational material costs are calculated. In Table 5.1 this date are presented as specific TCI and operational costs, *i.e.* expressed per kWh electricity produced in a CHP plant. The total specific costs of an OLGA unit are defined as the sum of the specific TCI and operational costs. The economy-of-scale is clearly visible: at a small scale the total specific costs for OLGA are substantially higher than for larger stand-alone scales. At small scale the costs are dominated by the relatively high TCI, while at larger scale the operational costs become important.

***Table 5.1**. Total Capital Investment costs (TCI) and operational costs for OLGA for four different scales of operation.*

Description	Scale [MW_{th} biomass]	Scale [m_n^3/h of wet product gas]	Specific TCI [€ct/kWh_e]	Operational costs[a] [€ct/kWh_e]	Total specific costs [€ct/kWh_e]
BIVKIN	0.5	190	5.3	0.67	6.0
Demo	2	760	2.8	0.67	3.5
Stand-alone 1	10	3800	0.73	0.67	1.4
Stand-alone 2	25	9000	0.63	0.67	1.3

a. Operational costs = 0.07 €ct/kWh_e, (utility) plus 0.6 €ct/kWh_e (scrubbing liquid consumption).

The elimination of the tar problem with OLGA has a positive economical advantage for a stand-alone gasification process. In reference 25, tar was identified as the main risk for the commercialisation of the integral biomass gasification CHP technology. Tar related problems were estimated to add up to 1.2-2.4 €ct/kWh_e at a 12 MW_{th} scale. The losses in revenues due to standstills were not taken into account.

In relation to the penalty to be paid for the tar problem, the total specific costs (*i.e.* sum of specific TCI and operational costs as given in the last column of Table 5.1) for OLGA are very promising. The total specific costs are in the same order and lower than the quantified costs for the tar problem and can even be reduced with a simple process optimisation, *i.e.* reducing the scrubbing liquid consumption and/or using cheaper scrubbing liquids. Considering the low total specific costs of OLGA, the elimination of the tar problem with OLGA, and the positive contribution to the reliability of the process, the economical perspective for OLGA is promising.

The data in Table 5.1 are determined for an OLGA downstream an air-blown circulating fluidised bed (CFB) gasifier. For the application of OLGA downstream an indirect gasifier (*e.g.* like the MILENA gasifier that is developed by ECN [26]) the specific costs will decrease significantly, as the gas volume to be cleaned per MW_{th} biomass input will decrease with approximately a factor of two. The total investment and utility costs will decrease proportionally with the decreasing gas volume. The decrease in scrubbing liquid consumption, however, is smaller than the factor of two, due to the higher tar amount in product gas from an indirect gasifier. Therefore, the total specific costs for OLGA downstream an indirect gasifier at intermediate scale (10-25 MW_{th}) will be approximately 28% lower than downstream a CFB gasifier.

6. CONCLUSIONS & CONTINUATION

This report gives an overview of the status of the OLGA technology around mid 2004. The overview comprises the considerations that laid the basis for the OLGA development, the process design approach and results from both the extensive lab-scale and pilot test programmes. The main focus of the report is on the performance of the pilot OLGA during a 50-hour test that was carried out in May 2004.

6.1. Conclusions

In short, the advantages of the OLGA tar removal technology, compared to alternative conventional tar removal approaches, can be summarised as:

- Tar dewpoint of clean product gas is below temperature of application, therefore there is no condensation of tars in system;
- No fouling of the system resulting in increased system reliability and higher availability;
- Tars are removed prior to water condensation to prevent pollution of process water;
- Tars are recycled to gasifier and destructed avoiding the handling of problematic (and expensive) tar waste streams;
- Scalable technology allowing the application from lab to commercial scales.

6.1.1. Lab-scale "Proof-of-Principle"

Experiments in the lab-scale OLGA unit have proven that the OLGA process is capable of removing tars to very low levels, *i.e.* tar dewpoints below -15°C. Product gases made tar-free with the OLGA process are suitable for application in gas engines and even more demanding applications in Fischer-Tropsch and synthetic natural gas (SNG) synthesis processes.

Selecting an alternative scrubbing liquid for the OLGA holds the opportunity to increase the removal efficiency of the class 2 and 4 tar compounds in the OLGA Absorber. In this way the economics of the process can be improved either by decreasing the size of the Absorber (lower investment costs) or using a cheaper scrubbing liquid (lower operational costs).

A further optimisation of the OLGA process is the combined tar and dust removal. In this way an upstream hot gas filter becomes superfluous, which has a drastic impact on the investment costs. Preliminary experimental of short test results indicate that OLGA removes dust for 99.5% without affecting the tar removal performance. Even more important: no fouling of the OLGA column packing was observed.

6.1.2. Pilot scale "Proof-of-Concept"

The purpose of the pilot OLGA unit and the experimental programme was to demonstrate the OLGA tar removal principles on pilot scale (*i.e.* deliver the *"proof-of-concept"* for the OLGA process) and to identify critical issues in up scaling, equipment selection, and process design. The pilot OLGA unit is a hundred times scale-up of the lab-scale unit and the unit was designed and constructed with the equipment selected in such a way that unit would be a 'blueprint' for future commercial plants.

During the operational and 50-hour test runs the most important problems were related to the operational stability and heavy tar removal performance of the Collector. The stability problems related to the oil Pump P-200 and the process interaction of the Pump with the oil Cooler E-200. From the analysis of the results it was concluded that these problems were not encountered in the extensive lab-scale test programme, as in the lab-scale set-up other hardware was applied and other operational approaches were followed (*e.g*. use of trace heating).

The performance of the hot gas filter (HGF) is insufficient for prolonged operation due to continuous increase in pressure drop over the filter candles. Within the scope of the underlying project, this problem has not been solved, however, in research is ongoing that should result in defining the proper process conditions to allow prolonged operation of the HGF.

The tar removal results in the pilot OLGA have delivered the “proof-of-concept” that the process is in principle suitable for cleaning product gas from biomass gasification and deliver a ‘tar-free’ gas. However, the performance of the installations needs further optimisation to allow stable operation over prolonged periods. In the pilot test programme the critical issues in scaling-up of the unit have been identified, which is valuable information for optimisation of the design and hardware selection for future OLGA units.

6.1.3. Economic assessment

Compared to alternative conventional tar removal systems, the specific investment costs for relatively small OLGA unit are relatively high. However, the scale-up factor of OLGA (*i.e.* economy of scale) is relatively low, as the OLGA is based on easily scalable technology and does not become more complex upon scaling-up. At sizes above approx. 4,000 m_n^3/h (*i.e.* corresponding to ~10 MW biomass input), the specific investment costs seems to stabilise around 200 Euro/m_n^3/h and the operational cost for utilities and scrubbing liquid consumption become determining.

In relation to the penalty to be paid for the tar problem (*i.e.* losses in revenues due to standstills and costs for water and tar-waste treatment), the total specific costs for OLGA are very promising. The total specific costs are substantially lower than the quantified costs for the tar problem and can even be reduced with simple process optimisations. Considering the low total specific costs of OLGA, the elimination of the tar problem with OLGA, and the positive contribution to the reliability of the process, the economical perspective for OLGA is promising.

6.2. Continuation

After the conclusion of the proof-of-concept phase, the generated information for optimisation of the design and hardware selection for future OLGA units, must be implemented. This will be done in the first demonstration and semi-commercial systems. In parallel, research is ongoing to further optimise the OLGA technology and demonstrate its performance during prolonged operation.

The Energy research Centre of the Netherlands (ECN) and Dahlman Industrial Group have signed a licence agreement for the commercialisation of the OLGA technology. However, it should be taken into consideration that the operational and long duration experience with the technology is still limited. Therefore, sufficient additional time and budget should be reserved for commissioning and start-up of the next systems.

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APPENDICES

APPENDIX A. TAR PROPERTIES

A.1. Classification system

According to the ECN definition, tar comprises all organic components having a higher molecular weight than benzene. Benzene is not considered to be a tar. ECN uses a tar classification system comprising six classes (see Table A.1). This classification system is in particular developed to provide 'easy' insight in the general composition of tar. Trends are easier recognised on the basis of these classes. However, for more specific problems or issues the detailed data will remain necessary.

Table A.1*. Tar classification system.*

Class	Type	Examples
1	GC undetectable tars.	biomass fragments, heaviest tars (pitch)
2	Heterocyclic compounds. These are components that generally exhibit high water solubility.	phenol, cresol, quinoline, pyridine
3	Aromatic components. Light hydrocarbons, which are important from the point view of tar reaction pathways, but not in particular towards condensation and solubility.	toluene, xylenes, ethylbenzene (excluding benzene)
4	Light poly aromatic hydrocarbons (2-3 rings PAHs). These components condense at relatively high concentrations and intermediate temperatures.	naphthalene, indene, biphenyl, antracene
5	Heavy poly aromatic hydrocarbons (≥4-rings PAHs). These components condense at relatively high temperature at low concentrations.	fluoranthene, pyrene, crysene
6	GC detectable, not identified compounds.	unknowns

From the practical viewpoint, the classification comprises only tar components that can be measured. Classes 2 to 6 are sampled using the solid phase adsorption (SPA) method and measured by gas chromatography (GC). Although class 6 tars are sampled and measured (a peak is found in the chromatogram), it is unknown what the individual components are. In principle components in this class belong to the other classes, but are here lumped to a single concentration representing the 'unknowns'. Class 1 represents the heavy tar fraction (roughly ≥7-ring PAHs). These components cannot be determined by the combination of SPA and GC. The components are measured by weight and thus represent the gravimetric tars.

A.2. Tar condensation: the tar dewpoint

Tar leads to fouling once the gas becomes (over) saturated with it. This leads to aerosol formation and depositions inside the installation. These fouling phenomena are not of concern as long as all the tar is present in the gas phase. It is therefore believed that the tar problem is fundamentally not concerned with the tar quantity, but is with the properties and the composition of the tar.

The condensation behaviour of tar is an integral effect of all tar components that are present in the product gas. The components their individual contribution to the total tar vapour pressure is therein decisive. When the tar vapour pressure exceeds the saturation pressure of the tar, the gas becomes (over) saturated according Raoult's Law.[5] Thermodynamically, this state leads to condensation of the saturated vapour. The tar dewpoint is the temperature at which the real total partial pressure of tar equals the saturation pressure of tar. Hence, in condensation related issues, the tar dewpoint is a powerful parameter to evaluate the performance of gas cleaning systems. It is believed that, when the dewpoint of tar is reduced to levels below the lowest expected temperature, fouling related problems by condensation or tar aerosols are solved.

To use this approach in design issues, a calculation tool has been developed to predict the tar dewpoint on basis of the concentration of the individual tar components in the product gas (this calculation tool is made available on the website "www.thersites.nl", which is operated by ECN). The relation between the tar dewpoint and tar concentrations is illustrated in Figure A.1. Condensation curves are given for the individual tar classes (as defined in Table A.1), *e.g*. the dewpoint curve for class 5 is calculated including only class 5 tars. Furthermore, each tar component is contributes equal to the total concentration on mass basis. The dewpoint calculation excludes tar class 1, as the components are not known. Typically, for a circulating fluidised bed (CFB) gasifier, it is believed that tars that belong to class 1 start to condense around 300-350ºC.

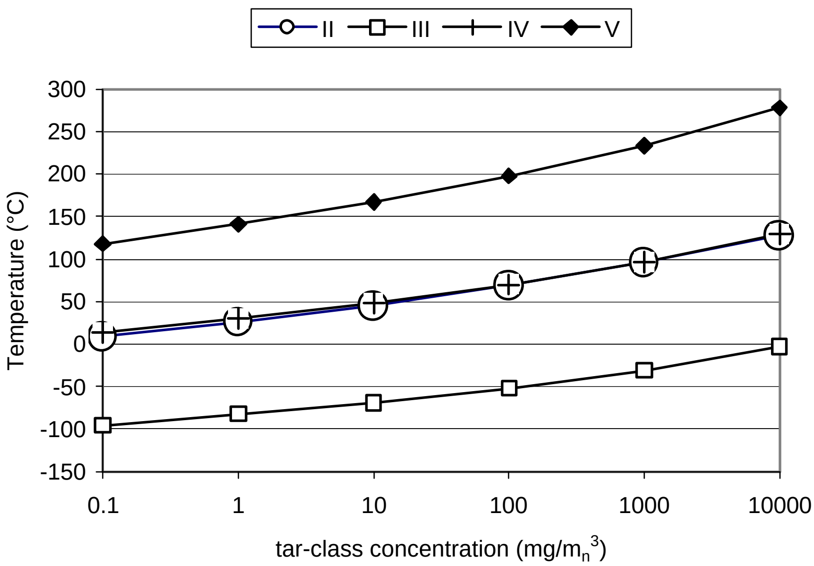

Figure A.1. *The tar dewpoint of the different tar classes in relation to the concentration.*

Leaving out class 1 in this discussion, it can be derived from Figure A.1 that class 5 tars dominate the dewpoint of tar. Even for very low concentrations of class 5 tars (*e.g.* <1 mg/m$_n^3$) a dewpoint below 100ºC cannot be obtained. The graph clearly points out that, dependent on the concentration in the product gas, classes 2 and 4 need to be partially removed for a proper tar dewpoint of about 25ºC. The class 3 tars play an unimportant role in this matter.

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A.3. Water solubility

The pollution of wastewater is in strong relation to the type of tar components being present in the product gas. The (poly) aromatic non-polar components will practically not dissolve, however, small non-polar components may still form a problem as they dissolve in small amounts that can exceed allowable concentrations. In general this will not cause a problem as due to the volatility of these components they are easily removed from water. Polar components on the other hand, in particular phenol, dissolve in large quantities and are very difficult to remove. Waste process water from biomass gasification must be clean, which is much easier to accomplish when pollution of tar can be avoided.

A similar tool as for the calculation of the tar-dewpoint is in development for the calculation of the water solubility of the tar classes. This tool was not available for this work. The class 2 tars are most important with respect to water solubility. This class comprises the oxygen, nitrogen, and sulphur heteroatoms containing components that dissolve well. Also the class 3 (and benzene) can be important with respect to wastewater treatment. These components may dissolve in large quantities but they are readily removed. Other classes are typically insoluble and form a two-phase liquid/liquid system of tar and water with a rather low mutual solubility.

APPENDIX B. LAY-OUT OF ECN PILOT GAS CLEANING SECTION

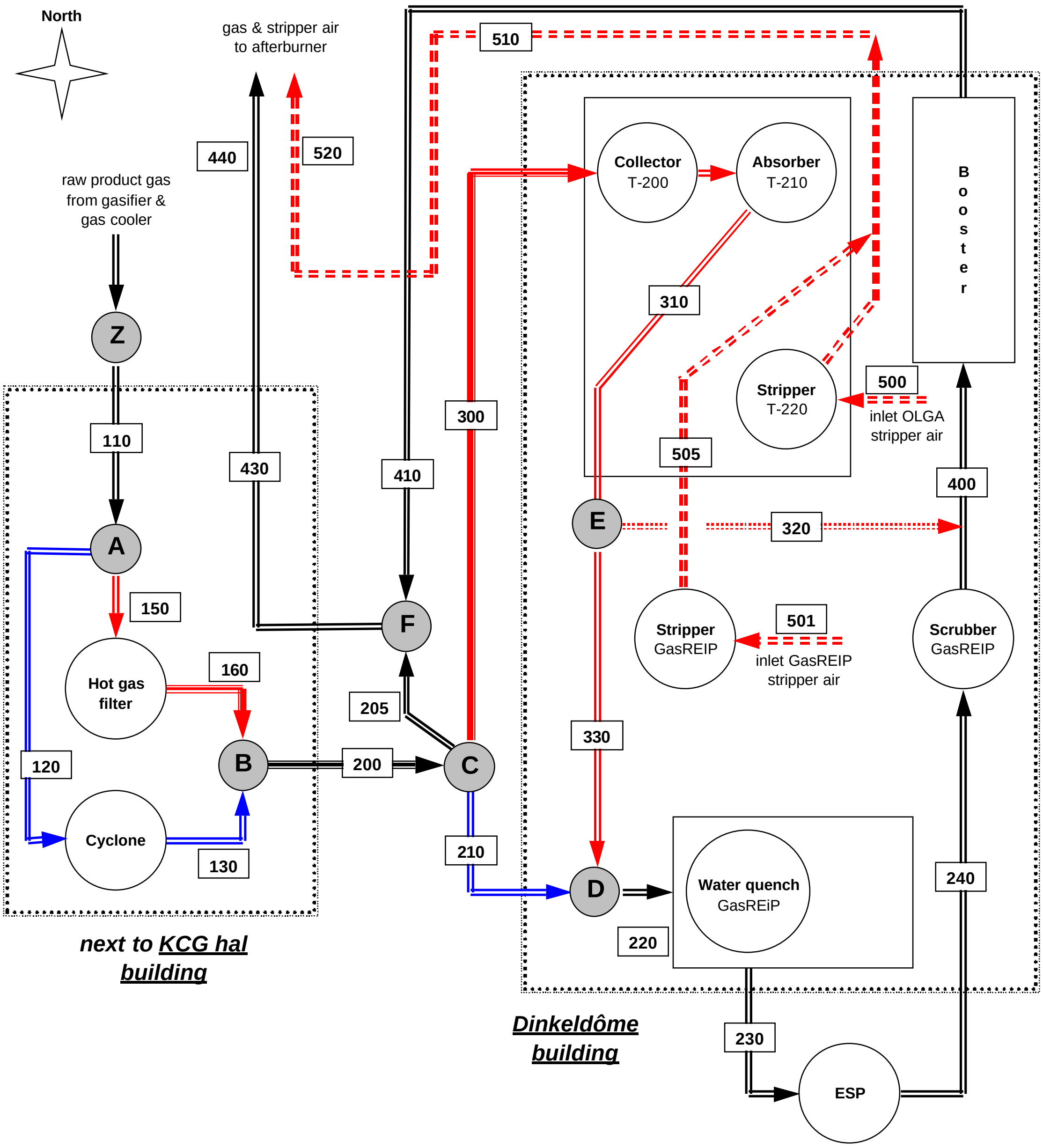
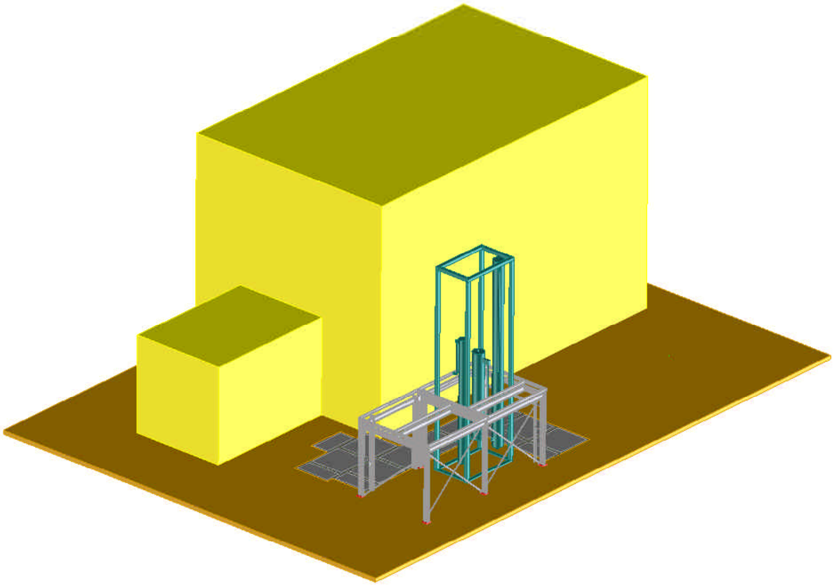


***Figure B.1**. Schematic top-view of lay-out of dedusting and gas cleaning units as part of integrated pilot test infrastructure at ECN, comprising hot gas filter, cyclone, OLGA unit, GasREIP, ESP, and booster. Grey circles indicate valves.*



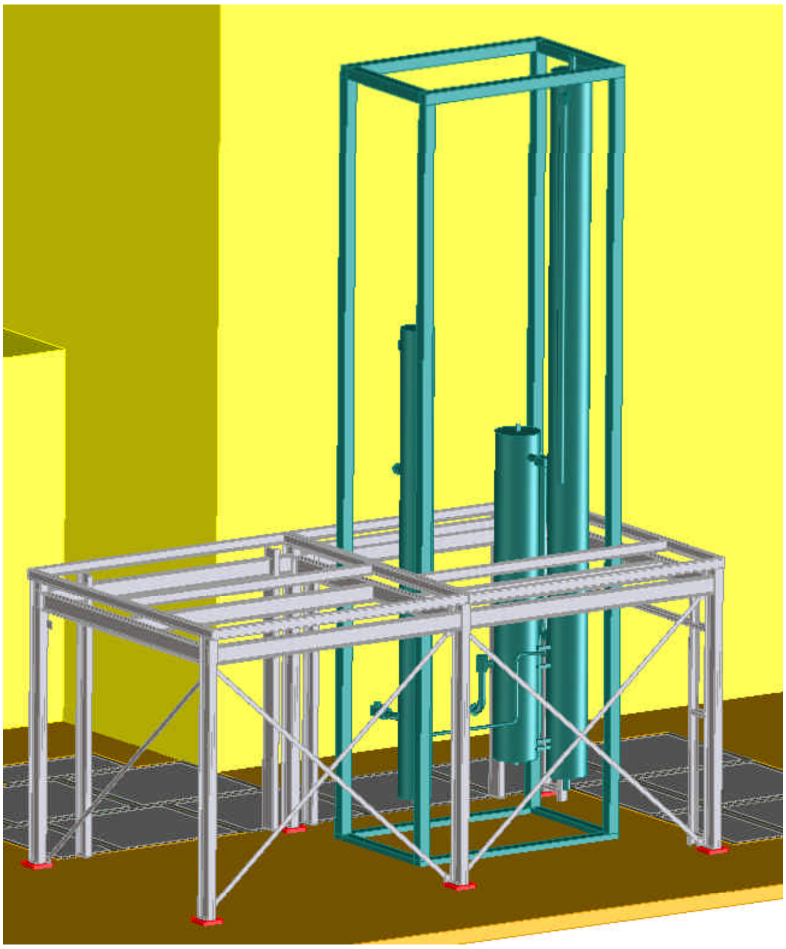


***Figure B.2**. Artist impressions of positioning of OLGA skid (in green) inside and through the roof of the Dinkeldôme building (outline indicated by grey frame), and in relation to the KCG building (yellow boxes).*

APPENDIX C. TAR CONCENTRATIONS IN 50-HOUR TEST

		OLGA feed	OLGA outlet tar concentrations					
		average	#1	#2	#3	#4	#5	#6
Total tar (excl toluene)	mg/m_n^3	7121	371	356	158	162	85	49
Condensable	mg/m_n^3	4789	75	63	54	71	20	0
Dewpoint	[°C]	>197	81	81	92	117	70	4
Pyridine	mg/m_n^3	0	0	0	0	0	0	0
2-mePyridine	mg/m_n^3	0	0	0	0	0	0	0
3+4-mePyridine	mg/m_n^3	0	0	0	0	0	0	0
Ethylbenzene SPA	mg/m_n^3	7	2	2	0	3	0	0
m/p-Xylene SPA	mg/m_n^3	110	16	16	2	2	0	0
o-Xylene + Styrene SPA	mg/m_n^3	784	106	104	8	8	3	3
Phenol	mg/m_n^3	173	40	37	30	28	24	27
o-Cresol	mg/m_n^3	3	0	0	0	0	0	0
Indene	mg/m_n^3	813	7	7	11	5	0	0
m/p-Cresol	mg/m_n^3	6	0	0	0	0	0	0
Naphthalene	mg/m_n^3	2455	75	74	11	11	16	14
Quinoline	mg/m_n^3	18	0	0	0	0	0	0
Isoquinoline	mg/m_n^3	13	22	17	24	18	14	0
2-methylnaftaleen	mg/m_n^3	239	8	7	3	3	0	0
1-methylnaftaleen	mg/m_n^3	170	5	5	7	6	3	0
Biphenyl	mg/m_n^3	88	5	4	0	0	0	0
Ethenylnaphtalene	mg/m_n^3	285	9	8	7	7	6	5
Acenaphtylene	mg/m_n^3	416	12	11	0	0	0	0
Acenaphtene	mg/m_n^3	~	~	~	~	~	~	~
Fluorene	mg/m_n^3	198	5	5	3	3	0	0
Phenanthrene	mg/m_n^3	552	32	32	22	23	11	0
Anthracene	mg/m_n^3	147	4	4	3	3	0	0
Fluoranthene	mg/m_n^3	130	10	11	11	14	4	0
Pyrene	mg/m_n^3	178	11	11	14	20	5	0
Benzo(a)anthracene	mg/m_n^3	59	0	0	2	4	0	0
Chrysene	mg/m_n^3	81	0	0	0	4	0	0
Benzo(b)fluoranthene	mg/m_n^3	44	0	0	0	0	0	0
Benzo(k)fluoranthee	mg/m_n^3	15	0	0	0	0	0	0
Benzo(e)pyrene	mg/m_n^3	26	0	0	0	0	0	0
Benzo(a)pyrene	mg/m_n^3	59	0	0	0	0	0	0
Perylene	mg/m_n^3	9	0	0	0	0	0	0
Indeno(123-cd)perylene	mg/m_n^3	21	0	0	0	0	0	0
Dibenz(a,h)anthracene	mg/m_n^3	6	0	0	0	0	0	0
Benzo(ghi)perylene	mg/m_n^3	16	0	0	0	0	0	0
Coronene	mg/m_n^3	0	0	0	0	0	0	0