GASIFICATION OF BIOMASS WITH OXYGEN RICH AIR IN A REVERSE-FLOW, SLAGGING GASIFIER

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Abstract

The main objective of the project was to develop an innovative, highly efficient reverse flow molten slag gasifier for combined heat and power production in a capacity range of 0.5 - 2.5 MW_{el}. The new gasifier should be able to convert relatively wet and ash-rich biomass.

Main tasks were related to:

- Development and testing of a low-cost device for increasing the air oxygen content. This will lead to an increased heating value of the fuel-gas/air mixture that is to be fed to the internal combustion engine and therefore enables the use of smaller (and cheaper) engines; furthermore, the flow of inert nitrogen is reduced leading to decreased convective heat losses, resulting in a higher thermal efficiency.
- Development and testing of a novel and compact reverse-flow, molten slag, fixed bed gasifier (20 kg biomass per hour) with an integrated heat exchange and tar removal system. Due to the intense, internal heat integration very high temperatures will be obtained inside the gasifier, which will cause melting of the ash, complete utilisation of carbon, and production of a tar-free gas.
- Assessment of cost-effective technologies, both existing and under development, for the utilisation of process heat from the reverse-flow slagging gasifier for drying of the biomass feedstock.

Besides these main tasks, a number of supporting activities were required to achieve project aims, including biomass characterisation, collection, pretreatment, process and reactor modelling, gas cleaning, gas utilisation and economic assessments.

Main results

A membrane separation technology has been selected for air oxygen enrichment, for which the maximum oxygen content is limited to about 40 vol%. Based on a techno-economic evaluation of the complete process it was concluded that oxygen enrichment does not improve the overall system performance and it results in higher investment and operating costs.

The novel gasifier was designed and tested at lab-scale (2 kg biomass per hour) and mini-plant scale (20 kg biomass per hour). Succesful operation of the novel gasifier was demonstrated. Producer gas from the gasifier contained only minor amounts of tar and heating values up to 7 MJ/Nm^3 could be measured. During the project the operability of the system was significantly improved, although some constructional problems persist with respect to gas sealing.

An economic process model has been developed including performance and economic costs functions for the major unit operations in the process including the dryer, reverse-flow gasifier, oxygen enrichment unit and prime mover. A major conclusion was that a system with the novel gasifier - in comparison with one with a conventional gasifier - shows an increased overall efficiency for all levels of air oxygen enrichment. However, cost of electricity is only superior to a conventional gasifier system if unenriched air is used, due mostly to the cost and energy requirement of the enrichment unit.

Before the new gasifier can be demonstrated on a (semi) commercial scale additional development activities are required.

Partnership

Gasification of biomass with oxygen rich air in a reverse-flow, slagging gasifier

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Background and objectives

The starting point for developing a new gasifier was an analysis of conventional, air-blown fixed-bed gasifiers. The following important technical and/or economic disadvantages of these gasifiers were identified.

- ➁ Producer gas has a relatively low calorific value (4 - 5 MJ/Nm^3), which results in the requirement for large relatively expensive engines (although strictly the engine size is determent by the heating value of the air-fuel mixture). Engine control will be improved with a higher calorific value product gas. Reduced engine size will reduce the capital costs.
- ➁ Large amounts of inert nitrogen is flowing through all equipment, which results in the use of equipment with a large volume. Reduced equipment size will result in reduced capital costs. Inert nitrogen is also responsible for part of the sensible (convective) heat losses.
- ➁ A significant amount of the energy potential of the biomass is lost as sensible. Installation of gas-gas heat exchangers is economically not attractive at small scale, due to low heat transfer coefficients which result in very large equipment. Moreover, due to high temperatures and corrosive gases special materials will be required.
- ➁ Conversion of wet biomass is problematic.
- ➁ Conversion of biomass containing ash with a low ash melting point is problematic. In the last decade a lot of effort has been put into the production of new types of energy crops. Most of these energy crops contain ash with a low melting point, and can probably only be used in conventional gasifiers if mixed up with large amounts of wood to avoid problems of clinkering and blocking. Besides energy crops, waste is an interesting and suitable feedstock, since waste streams often show low ash melting points. Compared to conventional waste conversion systems the new gasifier should achieve much higher electrical efficiencies.
- ➁ Producer gas often contains tar, which has to be removed prior to use in engines or other prime movers. To reduce tars additional downstream tar removal or conversion units are required.

From consideration of the above-mentioned points an idea for a new type of gasifier was evolved. The main feature of the system is the high degree of heat integration due to the reverse flow principle, combined with air oxygen enrichment, which should result in:

- ➁ Improved cold gas efficiency (5 - 10%) due to lower producer gas outlet temperatures;
- ➁ Conversion of relatively wet biomass;
- ➁ Increased calorific value of the producer gas. It is aimed to achieve a value of at least 6 MJ/Nm^3 (LHV basis).

Due to reverse-flow operation higher operation temperatures inside the gasifier are expected, which sould result in:

- ➁ Tar free producer gas; due to the high temperatures all tars will be thermally cracked, and downstream gas cleaning with respect to tars is not required.
- ➁ The ability to handle biomass containing ash with a low ash melting point; ash being removed from the reactor as liquid (slag). Due to slagging operation no carbon will remain in the ash, which improves the overall efficiency, and improves the opportunities for utilising the ash/slag.

By using oxygen enriched air it is expected that:

- Cold gas effciency will improve, because sensible heat losses through inert nitrogen decreases.
- Total capital costs will reduce, because the gas flows become significantly smaller.
- Even a small increase in oxygen content will significantly reduce the nitrogen flow. Ultra pure and expensive oxygen separation methods are not required.

The novel gasifier is based on the so-called reverse-flow technology. The major advantage of a reverse flow system is the high degree of heat integration achievable with a relatively simple construction.

Objectives

Based on the analysis given above the objectives of the project were defined. The overall objective of the project was to develop an innovative, reverse-flow molten slag fixed bed gasifier concept for combined heat and power generation in a capacity range of 0.5-2.5 MW_{el} with improved cold gas efficiency (5-10%) compared to conventional fixed bed gasifiers. The reactor can handle relatively wet (up to 40% mc_{db}) and ash-rich biomass fuels. The gasifier will produce a gas with a calorific value of at least 6 MJ/Nm^3.

Specific objectives are:

- Development and testing of a low-cost device for enriching the oxygen content in air (air enrichment unit).
- Development and testing of a novel and compact reverse-flow, molten slag, fixed-bed gasifier (both 2 and 20 kg/h biomass throughput) with integrated heat exchange and tar removal system, for operation on oxygen-enriched-air.
- Assessment of cost-effective technologies, both existing and under development, for utilisation of process heat from the reverse-flow slagging gasifier for drying biomass feedstock.

Technical description, results and conclusions

The description of the work performed and the results will be described on a task by task basis.

Biomass collection and pretreatment

A large number of different types of biomass have been characterised within the project. Besides the composition of the biomass specific attention was paid to the slagging tendency of the ash. Initially, pretreatment of the biomass was mainly related to sieving and grinding to obtain biomass samples with a tight particle size distribution. In the last part of the project special attention was paid to pelletising, because a number of selected feedstocks caused problems in the gasifier due to its low specific density.

Biomass drying

An extensive review has been prepared concerning existing biomass drying technologies.

Information was obtained from manufactures and literature. The dryer review was issued to the EC as a separate report. Main conclusions were:

- Drying of biomass feedstocks is usually required or desirable prior to gasification
- Key determinants in the choice of the dryer are cost, capacity range, available sources of heat, alternative uses of that heat, avoidance of excessive material temperatures to prevent thermal degradation, avoidance of fire or explosion hazards.
- Final choice of a dryer will follow careful technical and economic evaluation of the specific bio-energy system considered.

Special attention was paid to the application of vapour recompression techniques to improve the energy-efficiency of steam drying systems. Although steam drying systems applying this method exist commercially, it turned out that at present these are not available at the scale suitable for the novel gasifier.

Different options have been investigated for the use of excess heat for biomass drying. One of the techniques - steam drying - has also been tested experimentally. Initially, it was thought that specific work was required to study the influence on biomass dryers in relation to the dynamic, transient operation of the novel gasifier. However, due to a new method of gasifier operation a conventional steam generator can be adopted, and additional work is not required.

Air enrichment

As previously indicated air enrichment might be required and desirable for the operation of the novel gasifier. The aim was to develop a low-cost, energy efficient air enrichment system. This task started with a thorough review of existing air separation technologies both from an economic and technical point of view. Cryogenic separation, vacuum and pressure swing adsorption and membrane separation have been evaluated.

The selection mainly depends on the scale of operation and required final oxygen content. For the new gasifier an oxygen content of 40 vol% was sufficient, and a membrane separation technique was selected. Such units are normally constructed to produce pure nitrogen instead of enriched air, which means that these units need modifications. A pilot installation was constructed and tested to produce enriched air. From experimental work it was concluded that production of a mixture of 40 vol% oxygen in air can be produced, but the energy requirement is high (8 kW was required to produce 20 Nm^3/hr enriched air).

Development of a novel, reverse-flow slagging gasifier

The development of the novel gasifier started with a review on known slagging gasifiers. A separate review report was issued to the EC. Based on own knowledge and the review a design was made of a lab-scale unit (2 kg biomass per hour). The gasifier consists of two packed bed for regenerative heat exchange, and a crossdraft-type fixed bed gasifier. The reactor (gasifier + packed beds) is operated in a reverse-flow mode.

The influence of several parameters were studied including oxygen content, flow rate, cycle period, total flow and type of biomass. It was concluded that succesful steady-state operation of a reverse-flow gasifier could be achieved. Calorific values of the gas reached values up to 7 MJ/Nm^3 (LHV basis), partly due to an increase in oxygen content in the feed gas. Proper energy and mass balances could not be derived for this small unit. High moisture contents in the biomass feedstock (>30 wt%) resulted in low temperatures in the gasifier (well below slagging conditions).

Based on the experience obtained with the lab-scale gasifier a design was made of a mini-plant installation (20 kg biomass per hour). Compared to the lab-scale unit some modifications were introduced. The previously described air enrichment unit was connected to the mini-plant. For proper operation of the gasifier it is important to have well-sealed gas paths through the reactor. However, during experiments it became clear that this was difficult to guarantee in the current set-up. This was mainly caused by the fact that all parts of the reactor (packed beds, gasifier) were placed in one vessel, and by the combination of different construction materials (stainless steel and castable refractory). Large differences existed in thermal expansion of these materials, which resulted in undesired gas flows. This problem has not completely been solved, because a new reactor vessel was required which could not be realised within the time and budget of the current project.

In the reactor packed beds are continuously heated-up and cooled down. To obtain a steady-state process the heating and cooling of the beds should be in balance. Due to the high difference in flow rates of feed gas and producer gas, there was a large difference in thermal behavior during the heating and cooling periods creating operational problems. A solution was obtained by withdrawing part of the producer gas via the slag removal system. This mode of operation has been tested experimentally, and worked satisfactorily. The system could be very well controlled, and additional heating of the slag removal system was no longer required.

A number of experiments have been carried out to study the reactor behaviour, and the influence of operating parameters. Comparable results were obtained as derived with the lab-scale unit. Moreover, a difference in gas quality was observed between the gas withdrawn from the slag removal system and the packed beds. Gas from the slag removal system contained more carbon dioxide, probably due to the fact that the reduction zone is very small. It should be realized that the gasifier was not designed and optimised for gas withdrawal via the slag tap. In the mini-plant slag removal could also not be demonstrated. Small amounts of slag were found in the slag system, but quantities were too small to observe continuous slag removal.

Summarizing, it is concluded that in this project significant progress has been made with respect to the design and operation of the novel gasifier, but that the development has not yet reached a 'market introduction stage', and additional development is required.

Development of a reactor model

A reactor model has been developed comprising dynamic models for the heat regenerators, and an equilibrium model for the gasifier. The model has been used for the evaluation of experiments, and in particular for the design of the mini-plant. The reactor model was incorporated in a full process model including cost functions. Due to a lack of adequate experimental data model validation has not been performed.

Gas cleaning technologies

Gas produced by a gasifier needs purification prior to use in prime movers. Three different cleaning systems have been analysed. The producer gas may contain impurities like HCl, H_2S, COS, NH_3 and fine dust, but it will be free of tar. The optimum cleaning system is determined by both the requirements set by the prime mover and the emission legislation. For an optimum design more specific information is required on the amount and nature of contaminants in the gas produced by the new gasifier.

Gas combustion in engines

A study was performed to investigate the influence of changing gas properties on the characteristics of the engine. Different activities have been performed including a model study and a workshop with engine experts. The experiences were incorporated in a engine model (including cost functions). Important aspects related to engine derating, electrical output, total efficiency and capital costs. The engine model has been incorporated in a total process model to enable a proper economic evaluation.

Development of a process model

A full process model including the novel gasifier, biomass pretreatment and electricity production has been developed using SPENCE. This model enables the study of the influence of several process parameters like biomass moisture content on the total process performance. It was concluded that in all cases an excess heat is available for biomass drying, system efficiencies increase with decreasing moisture content, and in all cases gas engines show a better system performance than gas turbines for the scale studied.

Economic feasibilty study

An economic process model has been developed including performance and economic costs functions for the major unit operations in the process including the dryer, reverse-flow gasifier, oxygen enrichment unit and prime mover. A major conclusion was that a system with the novel gasifier - in comparison with one with a conventional gasifier - shows a increased cold gas efficiency for all levels of oxygen enrichment. However, cost of electricity is only superiour to a conventional gasifier system if unenriched air is used, due mostly to the cost and energy requirement of the enrichment unit. Air oxygen enrichment should only be considered when it is necessary to operate the process under slagging conditions.

Exploitation and anticipated benefits

The main exploitable results from the project are:

- Techno-economic computer model for biomass conversion systems (software code)
- Process model; gasification unit operation for SPENCE
- Prototype gasifier
- Construction and (mould casting) experience on application of high temperature refractory materials in biomass systems.
- Patent on novel gasifier

For the different exploitable results from the project the exploitation and marketing plan will be presented below.

Result: *Techno-economic computer model (software code)*
Explored by: *Aston University, Bio-energy Research Group*

The result is a spreadsheet-based computer model of a plant for producing power or combined heat and power from biomass, and featuring the combination of a biomass gasifier and an internal combustion engine. The model was created using Microsoft Excel and Microsoft Visual Basic, and can calculate large numbers of cases rapidly on a standard desktop PC. The model predicts the performance and cost of each of the key plant components as well as that of the overall plant. Performance and cost sub-models make use where possible of real data, as well as published correlations and standard assumptions. A choice of component types is available for both the gasifier and dryer. The model is currently restricted to a power output range of 0.5 to 3.0 MW_{el}.

The computer model is fully functional within its current relatively narrow scope of application, but there is potential for widening this scope. The model is focused on small-scale systems which have been comparatively neglected to date, and is designed to evaluate a large number of options rapidly. It is easily adapted to add new component types or new data on cost and performance.
Aston University will seek to apply the computer model in consultancy to external customers, and to develop it in the course of such consultancy and also in future R&D collaborations. It will seek future collaborative research opportunities to expand the scope of the model (within 5 years of end of project).

Application of the computer model in the pre-feasibility, feasibility and design stages of new biomass power projects; also in technology evaluations and market survey.

Potential applications foreseen are e.g.:

- Pre-feasibility or feasibility studies for new biomass gasification power or CHP projects
- Design of new biomass gasification power or CHP projects

- Comparisons of the performance and cost of different biomass technologies

Result: *Process model; gasification unit operation for SPENCE*
Explored by: *Kema Nederland bv*

The result is a biomass gasification software module for KEMA's own process modelling package SPENCE. In the project experience has been obtained in the use of SPENCE for the evaluation of biomass conversion systems. In the past SPENCE was already applied for the optimisation of the coal gasification plant in Buggenum (250 MW), and proved to be very useful.
The gasification module developed can be used by KEMA for the evaluation and optimisation of processes involving biomass gasification. This kind of calculation are carried out for KEMA's own purposes, but also for external parties.

Result: *Prototype gasifier*
Explored by: *BTG biomass technology group bv*

Within the project a prototype, slagging gasifier has been constructed and operated in the laboratory of BTG. This prototype will be further explored by BTG. The availability of the installation allows the performance of screening experiments for external parties for relatively low costs. Possible clients are companies with specific waste streams suitable for use in the slagging gasifier. Similar approaches are practiced by BTG for other pilot-plants like the tar removal system and the fluidized bed gasifier. It should be realized that many industrial parties are willing to pay for experimental work when the facilities are available, but only a few are prepared to invest in pilot-plants (higher costs and time involved).

Result: *Construction and (mould casting) experience on application of high temperature refractory materials in biomass systems.*
Explored by: *Kara Energy Systems*

During the project KARA has gained a lot of practical experience with the production of components from high temperature resistant, castable refractory material. The commercial activities of KARA are related to the worldwide selling of boiler and combustion systems. These systems often contain high temperature materials, and probably improved designs can be made of basis of the new knowledge. Besides the combustion systems KARA also developed there own biomass, downdraft gasifier. A critical part of such system is the throat, which should withstand very high temperatures. Application of the techniques developed in the project might improve the lifetime and availabilty of the gasifier system.

Result: *Patent on novel gasifier*
Explored by: *BTG, Kara, Aston University*

During the project a patent application has been submitted and recently it has been approved. An agreement between BTG, KARA and Aston University has been prepared (see appendix) describing a.o the property rights concerning the patent. Commercial gasifiers based on the new technology will be built and operated by a consortium including the above mentioned partners or by external partners. In both cases income will be generated by license agreements and royalties. However, before the process can be commercialised additional work need to be performed. Recently, the University of Twente showed interest in continuing the work on the existing pilot-plant in BTG's Laboratory by starting a PhD project. A project proposal was submitted to a Dutch programme (SDE), and was favourably evaluated. In this PhD project the technology should reach a 'market- introduction- stage'.

Flowsheet of pilot-plant installation at BTG-laboratories