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Published in:
Proceedings of The 16. International Conference of Efficiency, Cost, Optimization, Simulation, and Environmental Impact of Energy Systems

Publication date:
2003

Document Version
Early version, also known as pre-print

Citation (APA):
Andersen, L., Elmegaard, B., Qvale, E. B., Henriksen, U. B., Bentzen, J. D., & Hummelshøj, R. (2003). Modelling the Low-Tar Big Gasification Concept. In Proceedings of The 16. International Conference of Efficiency, Cost, Optimization, Simulation, and Environmental Impact of Energy Systems (Vol. 2, pp. 1073-1079). DTU, Denmark: Technical University of Denmark (DTU).

MODELLING THE LOW-TAR BIG GASIFICATION CONCEPT

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ABSTRACT

A low-tar, high-efficient biomass gasification concept for medium- to large-scale power plants has been designed. The concept is named "Low-Tar BIG" (BIG = Biomass Integrated Gasification). The concept is based on separate pyrolysis and gasification units. The volatile gases from the pyrolysis (containing tar) are partially oxidised in a separate chamber, and hereby the tar content is dramatically reduced. Thus, the investment, and running cost of a gas cleaning system can be reduced, and the reliability can be increased.

Both pyrolysis and gasification chamber are bubbling fluid beds, fluidised with steam. For moist fuels, the gasifier can be integrated with a steam drying process, where the produced steam is used in the pyrolysis/gasification chamber.

In this paper, mathematical models and results from initial tests of a laboratory Low-Tar BIG gasifier are presented. Two types of models are presented:

1. The gasifier-dryer applied in different power plant systems: Gas engine, Simple cycle gas turbine, Recuperated gas turbine and Integrated Gasification and Combined Cycle (IGCC). The paper determines the differences in efficiency of these systems and shows that the gasifier will be applicable for very different fuels with different moisture contents, depending on the system.
2. A thermodynamic Low-Tar BIG model. This model is based on mass and heat balance between four reactors: Pyrolysis, partial oxidation, gasification, gas-solid mixer. The paper describes the results from this study and compares the results to actual laboratory tests.

The study shows, that the Low-Tar BIG process can use very wet fuels (up to 65-70% moist) and still produce heat and power with a remarkable high electric efficiency.
Hereby the process offers the unique combination of large scale gasification **and** low-cost gas cleaning **and** use of low-cost fuels which very likely is the necessary combination that will lead to a breakthrough of gasification technology.

Keywords: Biomass, Gasification, Tar, Steam drying.

NOMENCLATURE

λ Excess air ratio
Q Heat flux [W]
LHV Lower Heating Value
DNA Dynamic Network Analysis

INTRODUCTION

In order to introduce biomass gasification technology into the energy system, it is necessary to develop a reliable gasifier with a simple gas cleaning system. To be competitive in the energy market, it

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is also important that the gasifier can be upscaled and use low-cost fuels, e.g. moist fuels [1].
The Low-Tar BIG gasification system is developed for the medium- to large-scale market (2-20MWe), and designed to produce gas with little or cheap need for cleaning. The gasification process is based on use of moist fuels (40-60% water content), but also dry fuels can be used.

Energy system simulation tool, DNA [2], is used for the modelling described in this paper; both for system models as well as the gasifier model.

In the first part of the paper, system models are presented and discussed, and then the detailed gasification model is presented and compared with test results from a lab scale Low-Tar BIG gasifier.

The Low-Tar BIG gasification process is a fluid bed version of the well known and thoroughly proven two-stage gasification process [6]. In the traditional two-stage gasification process the pyrolysis takes place in an externally heated screw conveyer and the char is gasified in a fixed bed [6].

SYSTEM DESIGNS

Thermodynamic models of the Low-Tar BIG gasifier operating in the following systems are presented in this paper:

- Gas engine
- Gas turbine (Simple Cycle)
- Gas turbine (Recuperated Cycle)
- IGCC

For all the systems, the gasification system is integrated with a steam dryer. The most important parameters for the models are:

- 50% moist in the fuel
- Biomass is dried with superheated steam to 10% moist.
- Gasification at atmospheric pressure.
- Steam is used as the ‘agent’ for both the pyrolysis and the gasification processes.
- The air is preheated for the partial oxidation
- Condensing and cooling of syn- and flue gas by means of district heating (45°C).

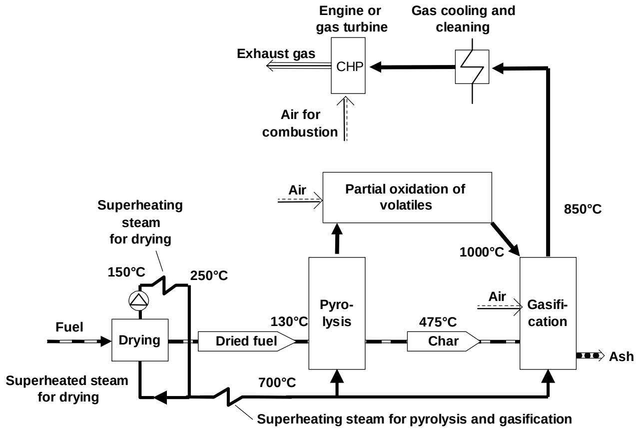

Figure 1: Diagram of the Low-Tar BIG gasifier integrated with steam dryer and combustion unit

In Figure 1, the basic diagram of the gasifier, dryer and combustion unit is illustrated. The drying agent is superheated steam. Below, the following different system designs are briefly presented: Engine, Gas turbines and IGCC. Then the main results of the modelling are presented and discussed.

Engine

In Figure 2, the Low-Tar BIG gasifier with an engine is integrated with a steam dryer. The main parameters are listed in Table 1.

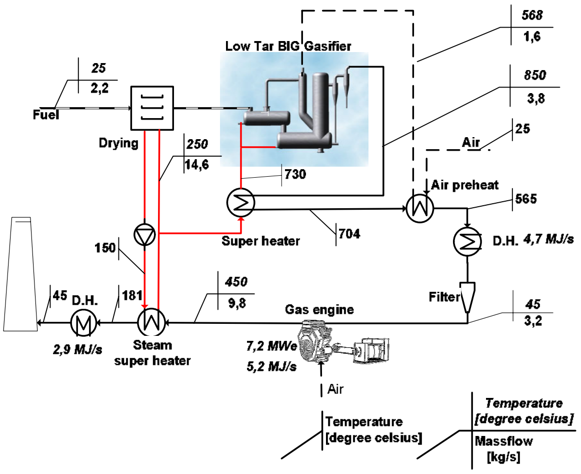

Figure 2: Schematic example of a medium size low tar gasification plant with gas engine(s)

It is seen in Figure 2 that the exhaust gas of the gas engine, is used indirectly for heating the drying unit. Thus the flue gas is not contaminated.

Size of plant	~20 MW (thermal) at 8000 kg/h wet biomass
Composition of biomass (Mass %)	C – 50%, H_2 – 6%, O_2 – 43%, S – 0.1%, Ash – 0,9%
Water content (wet basis)	50%
Lambda, λ	1,3
Heat exchanger effectiveness	0,8
Power ratio of engine	0,4
Equilibrium temperature of gasifier	850°C
Char conversion	100%

Table 1: Assumptions and conditions for the engine plant

Simple gas turbine

A usual simple cycle gas turbine design is shown in Figure 3, with assumptions similar to those of the engine plant (Table 1). The gas turbine is modelled with an isentropic efficiency of 89% and a pressure ratio of 1:20.

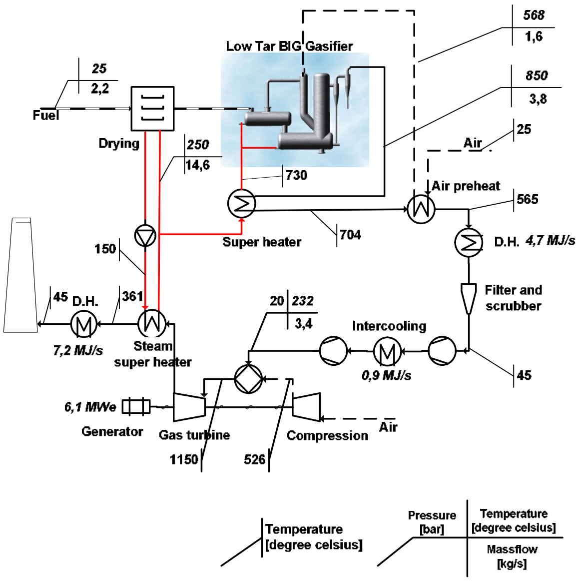

Figure 3: Schematic illustration of a simple cycle gas turbine integrated with a Low-Tar BIG gasifier.

Recuperated gas turbine

The energy efficiency of the gas turbine system can be optimised by a recuperator. The optimal pressure and temperature in the combustor are lowered, which reduces the size of the compressor and simplifies the system considerably.

Two types of recuperation have been examined:

- A traditional recuperated gas turbine design where air for the combustor is preheated (see Figure 4)
- An optimal design, where the produced gas also is recuperated. The produced gas then reaches a temperature of app. 500°C (see Figure 5)

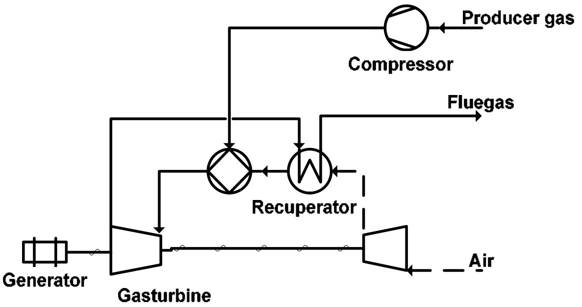

Figure 4: Traditional recuperation. Air is preheated by exhaust gas

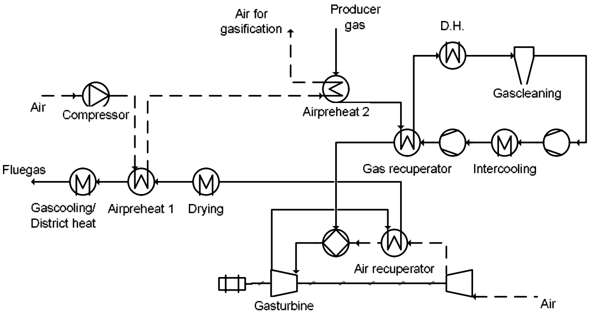

Figure 5: Optimal design, where both air and produced gas is preheated before the gas turbine

Optimal pressure ratio of the simple recuperation system

In order to determine the optimal pressure ratio for the recuperated gas turbine, two scenarios are considered:

1. The maximum temperature of the flue gas entering the recuperator is fixed at 650°C
2. The inlet temperature of the gas turbine is fixed at 950°C.

The result of this parametric study is shown in Figure 6.

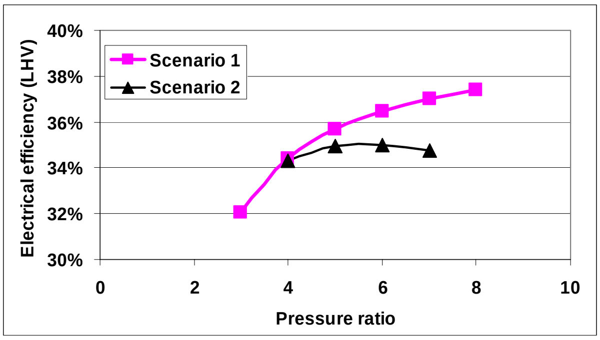

Figure 6: Optimum pressure ratio for the recuperated gas turbine

For Scenario 1, the combustor reaches a temperature of 1150°C at a pressure ratio of 8 bar, which is considered a design maximum. The equivalence ratio λ is 4.1.

The Scenario 2 case yields its optimum pressure ratio at 6 bar, with λ=5.6 and an inlet flue gas temperature in the recuperator of 569°C.

IGCC

In the IGCC system modelled in the study, the heat source for the steam dryer is product gas, and medium-pressure steam from the steam turbine when wet fuels are used.

The important main characteristics of the IGCC plant are listed below:

- The gas turbine operates with a pressure ratio of 1:20.
- A heat exchanger is introduced, generating extra steam for the steam cycle by means of the syngas. The temperature of the syngas thus falls to app. 220°C before it enters the district heating heat exchanger.
- For wet fuels, the steam cycle can supply thermal energy for the drying process. In that way, fuels with moist contents above 70% can be used efficiently.

RESULTS

The main results of this study are presented in this paper. For more details, please refer to [3].

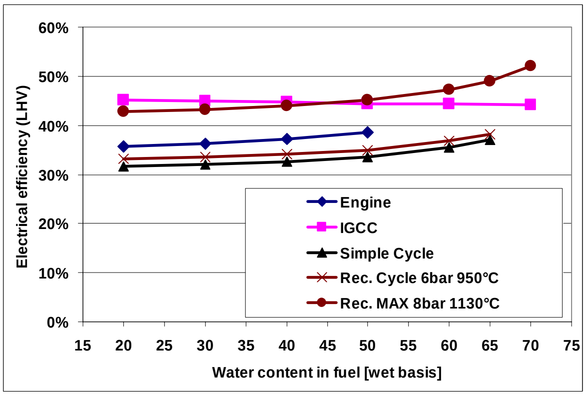

Figure 7: The electrical efficiency as a function of moist content in the fuel

In Figure 7, the electric efficiency of the five different plants are shown when the moist content of the fuel is changed. The plants are (according to the legend in the right side):

- Gas engine with electrical efficiency of 40%
- IGCC plant with gas turbine at 20 bar and combustion at 1150°C
- Simple cycle gas turbine at 20 bar and combustion at 1150°C
- Recuperated gas turbine at 6 bar and combustion at 950°C (see Figure 4)
- Optimal recuperated gas turbine at 8 bar and combustion at 1130°C (see Figure 5).

The IGCC as well as the optimal recuperated gas turbine have 5-10% higher electrical efficiency than the other systems, and these systems can use fuels with water content exceeding 70%. However, these systems are quite expensive, and are therefore only relevant for large plants or for really cheap fuels, e.g. fuels with negative cost like sludge or other waste products.

The recuperated gas turbine at low temperature and low pressure has about 2% higher electrical efficiency than a traditional gas turbine. The system can use fuels with water content up to about 65% with high efficiencies (above 35% el), which makes this system quite interesting for a number of fuels.

The use of a gas engine is the simplest technology and also very energy efficient. The system can use fuels with water content up to about 50% (depending on the specific engine) and the system is very suitable for medium-size wood chip gasification. For fuels with higher moisture contents, additional heat sources, e.g. cooling of product gas, should be used for drying.

LOW-TAR BIG

The development of a *low tar* gasifier which can easily be scaled to large gasification plants (Low-Tar BIG) is in progress.

A thermodynamic model of the Low-Tar BIG gasifier has been developed in DNA, and the model describing the internal energy flows of this gasifier will be presented and discussed.

The Low-Tar BIG process

The Low-Tar BIG process is a stage-divided fluid bed gasifier which is designed to produce a gas with a low tar content, so that the gas cleaning becomes simple, cheap and reliable. Furthermore, system integration can result in high energy efficiencies. A layout of the Low-Tar BIG gasifier is seen in Figure 8.

Drying
The fuel must be as dry as possible before it is led to the gasifier. If the fuel is wet, a steam drying process can dry the fuel and feed the pyrolysis and gasification unit with steam. If the fuel is dry, steam should be generated in steam generators.

Pyrolysis
The fuel is fed into a bubbling bed which is fluidised with superheated steam, so the pyrolysis unit is kept inert. The fuel will flow trough the pyrolysis reactor, while it is pyrolysed. The fuel is added in one end (left in fig. 8) and flows slowly towards the other end on (and partially in) a hot sand bed.

Several heat sources can be applied:

- Superheated steam
- Hot sand recirculated from the gasifier
- Air/oxygen.

Partial oxidation
Pyrolysis gas and air is mixed, and the tarry pyrolysis gases are partially oxidised. Hereby, the tar content is reduced dramatically.

Gasification
Char from the pyrolysis unit is led to the gasifier where steam is used for fluidisation and gasification. Also air can be added to the gasifier in order to gasify char and keep the temperature at 800-900°C.

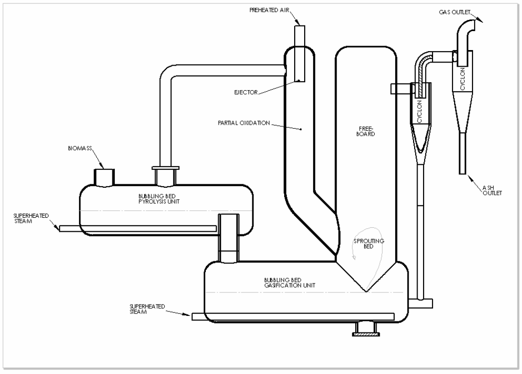

Figure 8: Medium-/large-scale Low-Tar BIG gasifier

Laboratory Low-Tar BIG gasifier
During year 2002, a 100 kW$_{th}$ Laboratory Low-Tar BIG gasifier was designed and built. Initial tests were carried out in order to show the process stability and low tar content in the gas.

Figure 9: 100 kW Laboratory gasifier (Before insulation)

Modelling the process

In order to get a better understanding of the flows and processes within the Low-Tar BIG gasifier, a thermodynamic model has been developed and implemented in DNA.
The structure of the model is illustrated in Figure 10, and the important assumptions are listed in Table 2.

The model divides the processes into four zones. A pyrolysis zone is modelled using data from [4] and a model developed in [5].

The partial oxidation zone is in fact an under-stoichiometric combustion but is treated like a gasifier, though slightly modified: The standard approach to a gasifier model finds the composition of the syngas using the minimisation of Gibbs energy method. However, this method will always result in no or little content of methane in the syngas, which is in conflict with experimental results. Therefore, the gasifier model has been changed, so that a predefined methane content within the syngas will be present.

Furthermore, an option for "back mixing" the syngas with the pyrolysis gas has been implemented in order that, due to for instance a lower pressure in the pyrolysis zone, a fraction of the syngas can be sucked back into the pyrolysis zone and up into the partial oxidation. The fourth zone represents the mixing of the gases from the gasifier and the partial oxidation and sand from the gasifier, and it is modelled as a heat exchanger, though some gasification will occur in this zone.

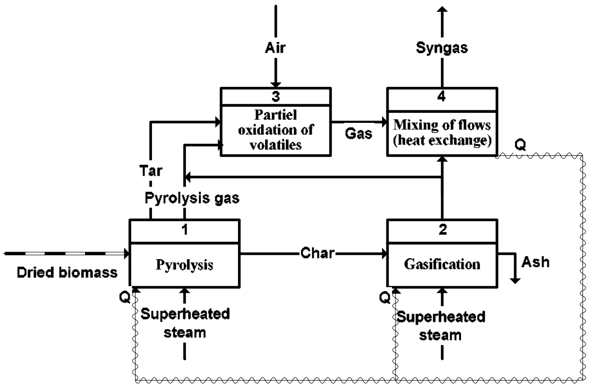

Figure 10: Sketch of the LT-BIG model, notice the energy balance $Q_1+Q_2=Q_4$ representing the energy flow of the sand

Mass flow	1.5 kg fuel /s (app. 25MW)
Temperature of fuel	150°C (from dryer)
Composition of fuel (Mass%; *wet basis 10% moist content*)	H_2 5.4% O_2 38.7% C 45% S 0.09% H_2O 10% Ash 0.81%
LHV for dry fuel	19MJ
Temperature in pyrolysis	600°C
Char conversion in gasifier	100%
Temperature of superheated steam	600°C
Temperature of preheated air	600°C
Steam for pyrolysis	0.3 kg/s (20% of mass flow)
Steam for gasifier	0.75 kg/s (50% of mass flow)
Carbon to methane factor in partial ox.	25% (app. 2.6 Vol-% in syngas)
Temperature in partial oxidation	1000°C
Temperature in gasifier	850°C
Mix factor (gas from gasifier to pyrolysis)	10%
Heat-loss in system	2 %
Pressure-loss in system	0 bar

Table 2: Assumptions and parameters for the Low-Tar BIG reference model

Results

Figure 11 and 12 shows possible usage of the model. Figure 11 shows the distribution of the air to the different zones in the gasifier, and their dependence on the temperature in the partial oxidation.

In figure 12 the calculated chemical composition of the syngas before cooling and condensing the gas is shown.

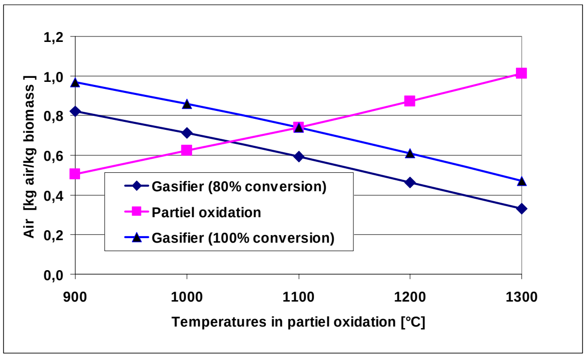

Figure 11: Air consumption for Low-Tar BIG as a function of the temperature in the partial oxidation zone.

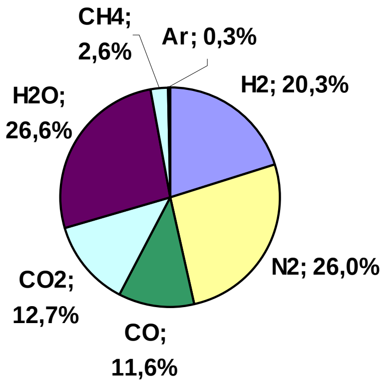

Figure 12: Composition of syngas before condensing.

Verification of the model/use of the model

So far, it has not been possible experimentally to verify the model completely. However, the model has successfully been applied twice on dimensioning calculations for a pilot-scale Low-Tar BIG gasifier:

- The model has been used to estimate the heat loss of the 100kW laboratory LT-BIG gasifier during experiments. When the composition of the syngas is assumed to be identical to the result of the model, a heat loss of 8% is calculated.
- Before experimental tests were initiated, the model has been used to determine the air consumption of each zone. The model predicted that the airflow to the partial oxidation and to the gasifier varies very much with the temperature of the partial oxidation reactor. This has later been confirmed experimentally.

DISCUSSION

The energy simulation tool, DNA, was selected for the thermodynamically model of the Low-Tar BIG gasifier. The programmer was not experienced with DNA, but soon it was clear that DNA was a good tool for modeling of gasification systems.

DNA was especially a strong tool when the pressure/temperature ratios in the recuperated gasturbine system should be optimized, and when parameter variations ware made.

CONCLUSION

The Low-Tar BIG process was originally designed for large scale - low tar gasification plants, with the aim of establishment of cost effective CHP-plants due to reliable, low cost gascleaning in large scale biomass gasification.

This study show, that the Low-Tar BIG process can use very wet fuels (up to 65-70% moist) and still produce heat and power with remarkable high electricity efficiencies.

Hereby the process offers the unique combination of large scale gasification **and** low-cost gas cleaning **and** use of low-cost fuels which very likely is the necessary combination that will lead to a break-through of gasification technology.

The detailed model of the Low-Tar BIG process gives a very good insight in the different process steps. Especially the sensitivity of the air/temperature relation in the different reactors is of useful knowledge when the process is regulated.

ACKNOWLEDGEMENTS

This work was partly financed by ELTRA.

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