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# HIGH EFFICIENCY ELECTRICITY AND PRODUCTS FROM BIOMASS AND WASTE; EXPERIMENTAL RESULTS OF PROOF OF PRINCIPLE OF STAGED GASIFICATION AND FUEL CELLS

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**HIGH EFFICIENCY ELECTRICITY AND PRODUCTS FROM BIOMASS AND WASTE; EXPERIMENTAL RESULTS OF PROOF OF PRINCIPLE OF STAGED GASIFICATION AND FUEL CELLS**

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ABSTRACT:
The use of biomass and waste for energy production contributes substantially in reduction of $CO_2$ emissions. System studies showed that gasification in combination with Solid Oxide Fuel Cell (SOFC) could achieve an overall efficiency of 50%. This is substantially higher than by means of modern IGCC application. In the framework of the NOVEM program “Energie Winning uit Afval en Biomassa (EWAB)”, a project was executed to test and proof the principle of connecting gasification and SOFC and measure its electrical output efficiency. The project was titled: “High efficiency production of electricity from biomass and waste: Proof of Principle” and was carried out by ECN Biomass and ECN Fuel Cell Technology.
The integrated tests were performed with willow and Rofire as feedstock (pelletised paper recycling rejects). The ECN two stage gasifier Pyromaat was used. The connected fuel cell was a downscaled 'state of the art' Sulzer HEXIS 1 $kW_e$ SOFC stack. For the purpose of continuous SOFC operation an advanced gas application facility (AGAF) was designed and constructed.
The outcome of this project showed that the principle works and the achieved SOFC efficiency is 41% LHV. Some side effects were observed (e.g. soot formation) which influenced the outcome negatively. It is foreseen that optimisation of operating conditions will reduce these effects to a minimum. The slight degradation of the SOFC stack during integral operation appeared to be not irreversible. The longest test run was approximately 48 hours (willow). Higher efficiencies are expected in the near future based on ongoing SOFC development and system simplification.
Keywords: Gasification, pyrolysis, fuel cells.

## 1 INTRODUCTION

The use of biomass and waste for energy production contributes substantially in reduction of $CO_2$ emissions. From the available conversion technologies gasification offers principal advantages compared to combustion, e.g. higher efficiencies (combined cycle with gas engine, gas turbine or fuel cell) and more compact gas cleaning [1, 2]. System studies showed that gasification of biomass and waste in combination with a Solid Oxide Fuel Cell (SOFC) could achieve an overall efficiency of 50% [3]. This is substantially higher than by means of modern IGCC application.

At ECN a unique opportunity exists to proof the principle of the combination of biomass and waste gasification with SOFC. ECN Biomass has expertise and facilities on gasification of a variety of biomass and waste streams, while ECN Fuel Cell Technology has expertise and facilities on fuel cells (SOFC, MCFC and PEM). Therefore in the framework of the NOVEM program “Energie Winning uit Afval en Biomassa (EWAB)”, a project was executed to test and proof the principle of connecting gasification and SOFC and measure its electrical output efficiency. The project is titled: “High efficiency production of electricity from biomass and waste: Proof of Principle” and was carried out by ECN Biomass and ECN Fuel Cell Technology in co-operation with technology supplier Gipec.

The Proof of Principle was demonstrated on lab-scale (1-5 kg/h) with willow and Rofire as feedstock (pelletised paper recycling rejects). In this paper the experimental setup and results are described. The experimental results were also used as input for an assessment study. The assessment results are described elsewhere [4]. The facility and the operating conditions will be described in the next Paragraph.

## 2 APPROACH

### 2.1 Facility

The ECN two stage gasifier Pyromaat was used to produce the fuel gas from biomass and waste. For the purpose of continuous SOFC operation an advanced gas application facility (AGAF) was designed and constructed. AGAF consists of further gas purification and buffering allowing on-line and off-line Pyromaat-SOFC operation. In Figure 1 a simplified block diagram of the facility is shown.

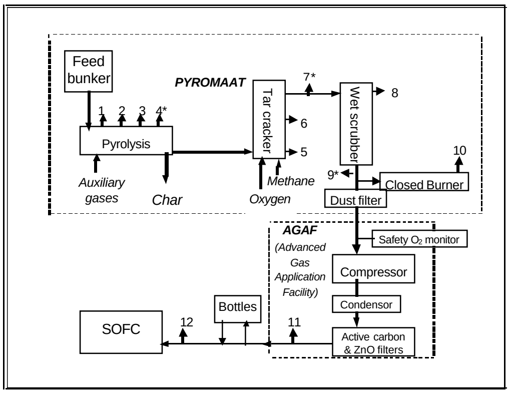


**Figure 1:** Simplified block diagram of the two stage gasification SOFC facility

The "Pyromaat" is designed to perform research on pyrolysis/gasification of waste and biomass streams. A variety of fuels have been tested since 1999 (e.g. wastes from: automotive shredder, electrical and electronic equipment, carpets, construction and demolition material, public parks and gardens, Aluminium scrap, cables) [5, 6]. In Figure 2 a picture of the Pyromaat is shown.


**Figure 2:** Picture of the ECN two stage gasifier Pyromaat

The Pyromaat enables the continuous processing of a waste stream at a rate of 1-10 kg/hour and consists of a feeding system (A), pyrolysis reactor (B), oxygen blown gasifier (C), cooler/scrubber (D) and a combustor. The pyrolysis reactor is a horizontal tube, which is heated externally by an electrical furnace. The waste stream is transported through the reactor tube by a screw with an open flight. The heating of the material is realised by moving across a hot wall and is similar to a rotary kiln. Directly after the reactor, a sample point for gas analysis is located which is kept at the pyrolysis temperature. Solid residue (char, containing carbon and ash, i.e. minerals and eventually metals) is collected in closed vessels (E) to be analysed off-line. On-line analysis of $H_2$, CO, $CO_2$, $CH_4$, $C_2H_4$, $C_2H_6$, $C_3H_8$, benzene and toluene is done with gas chromatographs (F). The concentration of tar and particulates are determined gravimetrically. In addition to the on-line gas analysis, the char and the tar phase is analysed with respect to their elementary composition. The oxygen blown gasifier can operate up to 1600°C, producing a tar free syngas. The raw syngas is cooled and cleaned in a scrubber, ceramic filter, ZnO filter and active coal filter respectively. The cleaned syngas can either be stored in gas cylinders (60 bar) or be fed directly to the SOFC. The connected fuel cell was a down scaled 'state of the art' Sulzer HEXIS 1 $kW_e$ stack. The stack contains 5 cells (normally 60) of 100 $cm^2$ each. The cells are "state of the art" electrolyte supported with 3 plate interconnects.

## 2.2 Operational conditions

The integrated tests were performed with willow and Rofire as fuel. Rofire is a secondary fuel from paper recycling. It consists of mixed plastics (60 wt%) and paper residue (40wt%). In the project willow represents clean biomass, while Rofire represents biomass residues/waste (mixture of biomass and plastics).

Different integrated tests were performed with both fuels lasting up to 48 hours continuous operation of the fuel cell. Syngas was fed both directly from the Pyromaat and from the gas buffer. The operational conditions are summarised in Table I.

**Table I:** Operational conditions

| | |
|---|---|
| Pressure | atmospheric |
| Pyrolysis temperature | 550°C |
| Cracker temperature | 1300°C |
| SOFC Utilisation | 80% |
| Feed | 3 kg/h |
| Inlet flow SOFC | 0,09 $m_n^3$/h |

## 3 RESULTS AND DISCUSSION

The Pyromaat was successfully operated for several days on both willow and Rofire. Some side effects were observed (e.g. soot formation) which limited the availability of the Pyromaat for Rofire. It is foreseen that optimisation of operating conditions will reduce these effects to a minimum. The connected SOFC stack was operated in several duration tests. The longest test was 48 hours. The SOFC performance was measured for dry and wet syngas (50% moisture) for both fuels. Table II presents the dry gas composition at the inlet of the SOFC.

**Table II:** Clean gas composition

| | | willow | rofire |
|---|---|---|---|
| $H_2$ | [vol% d.b.] | 33,2 | 36,7 |
| $N_2$ | " " | 0,8 | 0,7 |
| $CH_4$ | " " | 0,1 | 0,9 |
| CO | " " | 31,1 | 33,3 |
| $CO_2$ | " " | 34,8 | 28,3 |
| $C_2H_4$ | [ppmV d.b.] | 5,7 | 264 |
| $C_2H_6$ | " " | 24,0 | <50 |
| Benzene | " " | 2,3 | |
| Toluene | " " | 2,3 | |
| $H_2S$ | " " | 5 | <5 |
| COS | " " | 223 | <15 |

Table II shows the expected result that a higher calorific value of the fuel (Rofire compared to willow, see Table IV) results in higher CO en $H_2$ concentration in the produced gas.

The performance of the SOFC stack appeared rather constant. The measured electrical efficiency at 80% utilisation is presented in Table III:

**Table III:** Measured electrical efficiency (LHV) SOFC at 80% fuel utilisation

| Fuel | electrical efficiency (%LHV) | |
|---|---|---|
| | dry gas | 50% steam |
| Willow | 41 | 38 |
| Rofire | 36 | 35 |

The experimental results were also used to validate an existing Aspen$^{PLUS}$ model of a commercial scale system. These assessment results will be summarised. The assessment results are described in more detail in [4].

Calculations were made for two stage gasification in combination with smelting of the pyrolysis residue mixed with mineral residues, gas cleaning and SOFC. A simplified process flow diagram is shown in Figure 3. This technology is expected to play an important role in the future for efficient conversion of waste into energy and secondary products [5]. Past and current suppliers are, amongst others, PKA, RST/RMH, Gipec (formerly Gibros PEC) and Toshiba. The technology is more or less comparable with Noell (now Future Energy) and Thermoselect.

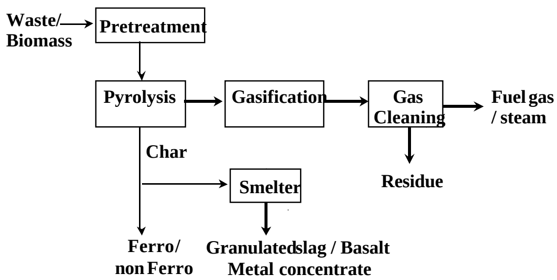


**Figure 3:** Simplified process flow diagram of staged gasification of waste and biomass

The assessment results are summarised in Table IV.
The assessment results shows that at an input capacity of 4 t/h (15-30 $MW_{th}$) the SOFC capacity is 4,7 and 7,3 $MW_e$ for respectively willow and Rofire. Including the secondary output from the HRSG the total nett power output is 7,4 and 12,5 $MW_e$, resulting in overall efficiency of 42 and 43% LHV for respectively willow and Rofire. Synthetic basalt (3,3 t/h) is produced as secondary product from mineral residues with pyrolysis char as the necessary fuel and reducing agent.

**Table IV:** Assessment results of commercial scale two stage gasification-SOFC installation

| | | Willow | Rofire |
|---|---|---|---|
| Heating value (LHV) | [MJ/kg] | 15,8 | 26,3 |
| Input capacity | [t/h] | 4 | 4 |
| SOFC efficiency (LHV) | [%] | 41,0 | 36,4 |
| Nett primary output | [MWe] | 4,7 | 7,3 |
| Nett secondary output | [MWe] | 2,7 | 5,2 |
| Total power output | [MWe] | 7,4 | 12,5 |
| Nett efficiency (LHV) | [%] | 42 | 43 |

The calculated energy efficiency is comparable with coal fired power plants, but significantly higher than wood fired power plants and waste incinerators. Higher efficiencies are expected in the near future based on ongoing SOFC development and system simplification.

## 4 CONCLUSIONS

The outcome of this project showed that the applied SOFC stack is well able to operate on the produced fuel gas from a two stage gasifier. Therefore it can be concluded that the principle works. The longest test run was approximately 48 hours (willow). When using willow and Rofire as fuel the resulting electrical efficiency of the SOFC is 41 and 36% LHV respectively. During the tests minor performance decrease was measured. The slight degradation of the SOFC stack during integral operation appeared to be reversible. Addition of 50 vol% steam resulted in an electrical efficiency of the SOFC of 38 and 35% for syngas from willow and Rofire respectively. Higher efficiencies are expected in the near future based on ongoing SOFC development and system simplification.

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