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OPERATION EXPERIENCE WITH A NOVEL HIGHLY EFFICIENT MICRO-SCALE CHP SYSTEM BASED ON FUEL-FLEXIBLE GASIFICATION AND A SOFC

I. Obernberger[1], tel: +43 316 481300; email: obernberger@bios-bioenergy.at
T. Brunner[1], C. Ramerstorfer[1], M. Kerschbaum[2], P.V. Aravind[3], R. Makkus[4], S. Megel[5], M. Hauth[6], S. Weissensteiner[6]
[1)] BIOS BIOENERGIESYSTEME GmbH, Hedwig-Katschinka-Straße 4, A-8020 Graz, Austria
[2)] Windhager Zentralheizung Technik GmbH, Anton-Windhager-Straße 20, A-5201 Seekirchen, Austria
[3)] Delft University of Technology, Leeghwaterstraat 39, 2628 CB Delft, The Netherlands
[4)] HyGear BV, Westervoortsedijk 73, 6827 AV Arnhem, The Netherlands
[5)] Fraunhofer Institut für Keramische Technologien und Systeme, Winterbergstraße 28, 01277 Dresden, Germany
[6)] AVL LIST GmbH, Hans-List-Platz 1, A-8020 Graz, Austria

ABSTRACT: An efficient and fuel flexible micro-scale biomass CHP technology based on the combination of a small-scale updraft gasifier with a SOFC system has been developed within the EU H2020 project FlexiFuel-SOFC. High load flexibility and a maximum of full load operating hours of the CHP system is achieved by operating the CHP part of the plant with a side stream (product gas extracted from the gasifier) of a heat controlled system (gas burner and boiler as well as heat recovery). A gas cleaning unit (GCU) for the treatment of the side stream according to the requirements for the operation of the SOFC regarding contaminant (H_2S, HCl) and TSP removal as well as tar content reduction was designed, constructed and successfully evaluated. After successful test of the GCU comprehensive test runs with the SOFC followed. Overall more than 300 hours of GCU operation and 250 hours with SOFC operation could be achieved with different biomass fuels. The gas quality was satisfactory and the SOFC system achieved its nominal capacity (6 kW_{el}). Following, the basic proof of concept for the new technology could be gained.
Keywords: combined heat and power generation (CHP), gasification, gas cleaning, fuel cell.

1 INTRODUCTION

Biomass based combined heat and power (CHP) generation systems should be operated as close as possible to the locations of biomass harvesting in order to achieve optimised energy efficiencies and minimise emissions. Decentralised, heat controlled small-scale applications are adequate in this respect. However, only few CHP technologies are available at present which reach reasonable electric efficiencies for a feasible application in the micro- to small-scale range.

Furthermore, the utilization of an extended biomass fuel spectrum beyond the use of conventional wood chips and wood pellets is of growing importance. Possibilities for the utilisation of the total available biomass potential including short rotation coppice, agricultural fuels and residues for energy supply applications will be crucial regarding enhanced security of supply and greenhouse gas emission savings in the future.

Given these framework conditions a new micro-scale biomass based CHP technology has been developed within the Horizon 2020 project FlexiFuel-SOFC (GA No. 641229, 05/2015 – 06/2019) with the aim to cover the above mentioned requirements regarding efficiency, fuel-flexibility and emission savings.

2 OBJECTIVES

The project aims at the development of an efficient and fuel flexible micro-scale biomass CHP technology. Based on the further development of an existing, already for heating purposes successfully demonstrated, small-scale fixed-bed updraft gasifier, the technology shall achieve a broad fuel flexibility (wood pellets and wood chips, SCR, selected agricultural fuels).

Moreover, the very low dust emissions of the gasifier facilitate the development of a rather compact gas cleaning system for HCl removal, desulfurization and tar cracking. The cleaned product gas shall then be utilised in a SOFC system, which distinguishes itself by a very high electric efficiency of more than 40%. In combination with a specially designed heat recovery system, an overall efficiency of up to 90% shall be reached. Finally, almost zero CO, OGC and PM emissions as well as low NO_X emissions are targeted by the new technology.

3 APPROACH

The new technology is based on a fixed-bed updraft gasifier coupled with a 2-stage gas burner and a hot water boiler. A part of the product gas is extracted from the gasifier section and supplied to a modular gas cleaning unit (GCU) in a side stream while the remaining product gas is burned in the gas burner (see chapter 3.3 regarding the special concept for the integration of the CHP unit into the overall plant concept).

The cleaned product gas downstream the GCU is fed to the SOFC system for electricity production. Hot off-gases from the SOFC-system are partly used to heat the GCU and SOFC air and are then supplied to a heat recovery system (integrated in the boiler). Suction fans downstream the boiler and downstream the SOFC off-gas heat recovery system are used to overcome the pressure losses of the single units, thus the whole plant is operated at underpressure. A basic scheme of this new micro-scale biomass CHP technology is shown in Figure 1.

3.1 Fixed-bed updraft gasifier – specific advantages and challenges

The application of the updraft gasifier technology as a basis for the new CHP system offers the following advantages in comparison to downdraft gasifiers:

- high fuel flexibility and significantly extended range of fuels applicable
- high load flexibility (30 to 100% of the nominal fuel power)
- almost complete charcoal burnout
- almost no particulate matter emissions

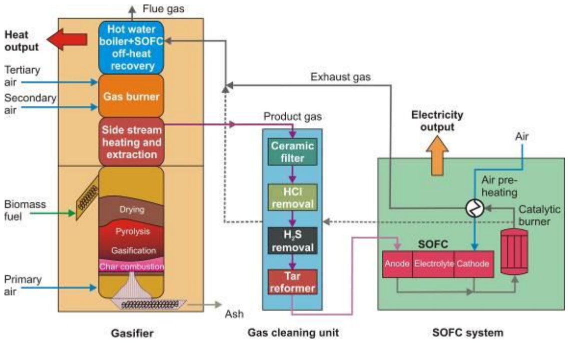

Figure 1: Basic scheme of the FlexiFuel-SOFC micro-scale biomass CHP technology

A challenging disadvantage of the updraft gasification technology is given by the comparably high tar contents of the product gas. However, this issue can be overcome by tar reforming.

An appropriate basis for the new technology was found in the PuroWIN technology from WHtech [1]. This small scale fixed-bed updraft gasifier was further developed for the integration into the new CHP technology within the project.

3.2 SOFC – specific advantages and challenges

Major advantages of the SOFC technology are the high electric efficiency (more than 40%) and low emissions (especially regarding CO and NO_X) that can be achieved. A technical challenge exists mainly due to the relatively high gas quality required for the operation of the SOFC. This is especially challenging for the application of a product gas from biomass (updraft) gasification due to the high tar content and contaminant (HCl, H_2S) concentrations in the untreated product gas causing the need for gas cleaning. An economic disadvantage is given by the high investment costs for the SOFC. This shall be overcome by the new technology concept with a high number of full load operating hours for the SOFC (see below), still ensuring heat controlled operation.

3.3 The FlexiFuel-SOFC concept

Basic idea is the integration of a base load CHP production in a heat controlled system within one unit. This is realised by the operation of the CHP part of the plant (GCU and SOFC system) in a product gas side stream of the gasifier. This brings significant advantages compared to an utilisation of the full product gas stream in the SOFC system. For example, from an application point of view, small-scale CHP systems should always be operated in a heat-controlled mode. This would result in a limited partial load operation capability of the whole system if the entire product gas would pass through the SOFC system.

The partial load operation capability of the gasifier is very good and allows for operation down to less than 50% of its nominal power. By using a side stream of the gasifier, the SOFC can run at full load even if only low heating power is requested from the heat consumer. As soon as the heat demand increases, the gasifier load is also increased. This leads to an optimised number of full load operation hours of the SOFC system. Thereby, a high annual electricity production can be achieved and, due to the cheaper (since smaller) SOFC system, the income from the electricity production is optimised and the payback time reduced.

Furthermore, a heat-only operation (in case of unexpected shutdowns due to failures in the GCU and the SOFC system or very low load demands) can be realised without additional components. Operation of the SOFC in a side stream of the gasifier also allows for a start-up procedure without the need for auxiliary (electric) energy for the pre-heating of the GCU and the SOFC system. During start-up this energy is provided from flue gas extracted from the product gas combustion in the gas burner. Moreover, the number of long-lasting start-ups and shutdowns of the SOFC can significantly be reduced due to the high load flexibility of the gasifier.

4 METHODOLOGY

The overall methodology applied within the project contains technology development based process simulations, computer aided design of the single units and the overall system, test plant construction as well as the performance and evaluation of test runs. This work is accompanied by risk, techno-economic, environmental and overall impact assessments as well as market studies regarding the possible potentials for application of the new technology.

A broad project consortium was formed for the development of the new technology covering all aspects mentioned above. The following project partners are involved regarding technical issues:

- AVL LIST GmbH, Graz, Austria (AVL)
- BIOS BIOENERGIESYSTEME GmbH, Graz, Austria (BIOS)
- Delft University of Technology, Delft, The Netherlands (TUD)
- Fraunhofer Institut für Keramische Technologien und Systeme, Dresden, Germany (IKTS)
- HyGear BV, Arnhem, The Netherlands (HyGear)
- Windhager Zentralheizung Technik GmbH, Seekirchen, Austria (WHtech)

The project timeline was structured according to a two-step approach for the design and construction of two testing plants at BIOS in Graz and an intermediate optimisation phase. Optimisation measures have been identified based on the results and experiences gained from the test runs which have been performed with the first testing plant [2]. The results presented in this paper have been achieved with the optimised second generation testing plant (with already implemented optimisation measures). The short term “testing plant” is used for this second generation testing plant in the following.

A considerable amount of test runs has been performed with the testing plant. These tests were accompanied by dedicated gas quality measurements performed in order to gain data for the evaluation of the new technology. Figure 2 shows an overview about the most important measurement positions used for gas sampling.

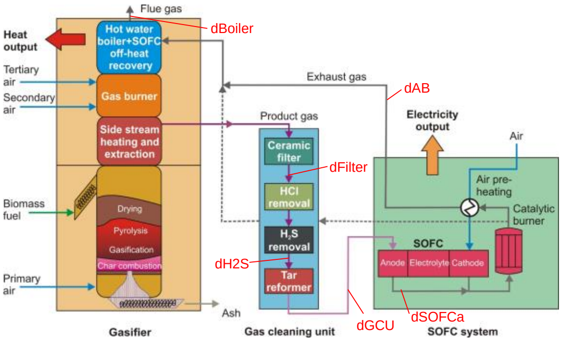

Figure 2: Measurement positions for gas sampling

Explanations: gas sampling positions indicated in red; d … downstream; F … filter; H2S … H2S reactor; SOFCa … SOFC anode; AB … afterburner;

The following measurements and analyses were applied during the tests performed:

- Continuous measurements of operation parameters (recorded by the data recording system of the plant control): temperatures, pressures and volume flows (hot-wire anemometers for combustion air velocities; Prandtl tubes for product gas and flue gas volume flows)
- Flue gas composition downstream the boiler and downstream afterburner using ND-IR flue gas analysers (Rosemount NGA 2000) for CO, CO_2, NO and O_2 (paramagnetic sensor)
- Online analysis of the extracted side stream (product gas composition) with FT-IR (Gasmet DX-4000) downstream dilution equipment (Ansyco type SYCOS P-797)
- Analyses of product gas samples taken with gas sampling bags by GC/MS
- Combined total suspended particle (TSP) and gravimetric tar sampling (high temperature plane filter upstream gravimetric tar sampling referring to tar protocol: CEN TC BT/TF 143 WICSC 03002.4; 2005)
- Discontinuous (wet chemical) measurements of H_2S (following VDI 3486, sheet 2; sampling with zinc acetate solution; dissolved ions measured using photometric method according to DIN 38405 D 26) and HCl (following EN 1911: 2010; sampling with distilled water; dissolved ions measured using ion-chromatography) in the product gas
- Discontinuous measurements of H_2S with Dräger-Tubes®
- Discontinuous (wet chemical) measurements of NH_3 (following VDI 3496; sampling with H_2SO_4 solution; dissolved ions measured using water vapour distillation method according to DIN 38406 E5) and HCN (following VDI 3486, sheet 2; sampling with NaOH solution; dissolved ions measured with photometric method according to DIN 38405 part 3)
- Analyses of fuel and ash samples

5 RESULTS ACHIEVED

5.1 Gasifier design

The PuroWIN updraft gasifier technology from Windhager (basis for the new technology) has been further developed towards increased fuel flexibility as well as the needs for the combination with the SOFC based CHP system within the project. Figure 3 shows a schematic overview of the gasifier/burner/boiler unit (in the following called gasifier).

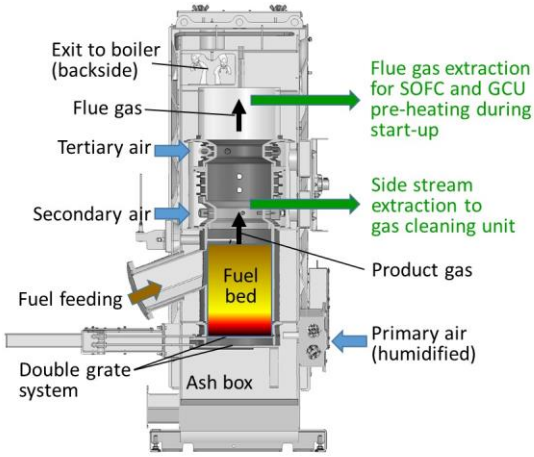

Figure 3: Scheme of the gasifier (WHtech) with interfaces to the CHP system

Major improvements of the gasifier regarding increased fuel flexibility are the implementation of a new grate concept (see double grate system in Figure 3) as well as the humidification of the primary air. Though, primary air humidification (PAH) provides two important functionalities for the new technology. Figure 4 shows bed temperature profiles for the operation of the gasifier with miscanthus pellets (low moisture content of 10 wt% w.b.) and PAH in comparison to wood chips (comparably high moisture content in the range of 25 to 29 wt% w.b.) with and without PAH.

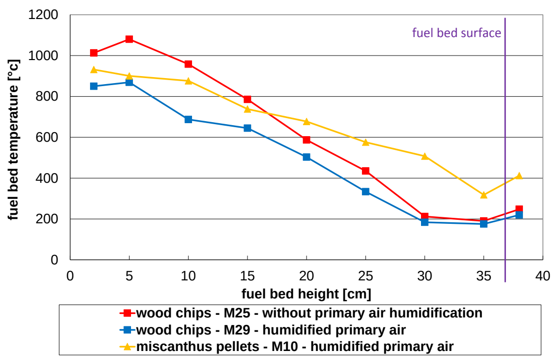

Figure 4: Fuel bed temperatures with and without primary air humidification for different fuel moisture contents

Explanations: M … fuel moisture content in [wt% w.b.]; temperature profile along the axis of the fuel bed

PAH is an appropriate measure for cooling the lower part of the fuel bed (above grate). Temperature reductions of 100 – 200 °C are possible. Therefore, the risk of ash sintering and slagging gets reduced which is an important feature for enhanced fuel flexibility. Furthermore, the water content in the product gas is increased by PAH. This reduces the risk for coking of the extracted side stream in the GCU.

Furthermore, a specially designed gas burner with low emissions has been developed based on CFD simulations. An example for the CFD aided burner optimisation towards optimised mixing and gas-phase burnout by inducing a rotational flow is shown in Figure 5.

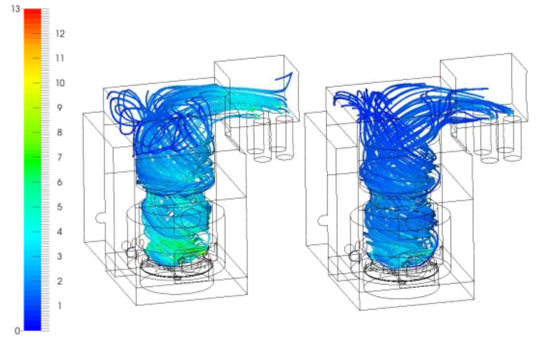

Figure 5: Pathlines of the secondary air, coloured by the absolute velocity [m/s] – 3D-view

Furthermore, a system for the extraction of hot flue gas (above 900 °C) from the upper part of the burner for SOFC and GCU pre-heating has been developed by CFD simulations and also successfully tested.

Finally, several heat recovery measures have been implemented in the new technology in order to enhance the overall efficiency. An important part of the heat recovery concept applied is the utilisation of the SOFC off-gas in a specially designed boiler section. Figure 6 shows a 3D model of the gasifier (removed boiler top) with the respective boiler compartment (3 heat exchanger tubes of the upward gas passage used for heat recovery from the SOFC off-gas).

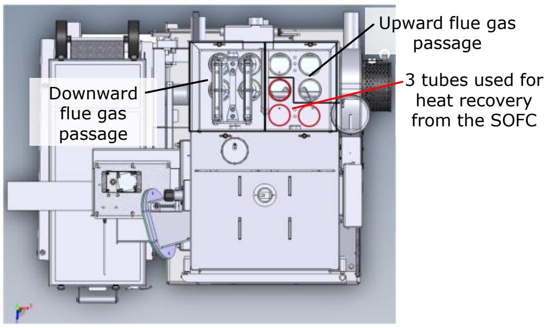

Figure 6: Heat recovery from the SOFC off-gas in the boiler

5.2 Gas cleaning unit design

The following purification targets have been defined for the GCU in order to provide a product gas which is suitable for the operation of the SOFC stack module:

- HCl content < 5 ppm
- H_2S content < 1 ppm
- Particulate matter < 0.1 mg/Nm³
- Tar reduction by appropriate reforming

In order to meet these specifications the single components of the GCU have to be operated at different temperature levels in three stages. Stage 1 is the high temperature filter at the inlet of the GCU operated at 650 – 700 °C. This is followed by stage 2 with the HCl and H_2S contaminant removal reactors operated at a lower temperature of about 400 °C. Finally, on stage 3 the tar reformer is operated at an again increased product gas temperature of 500 °C. Therefore, a specially designed heat management concept has been foreseen for the GCU. A heat exchanger network was implemented for the operation of the single reactors downstream the hot gas filter at the defined temperature levels as well as for the heat recovery from necessary product gas cooling. The GCU is heated by the thermal power of the extracted side stream from the gasifier and with off-heat from the SOFC system. A 3D model of the second generation GCU integrated into the whole system is shown in Figure 9.

5.3 Stack module and SOFC system design

The SOFC stack modules which have been installed and tested at the testing plants at BIOS were designed and manufactured by IKTS. The stack modules applied consisted of 8 stacks (30 cells per stack) with MK352 design [3] with a nominal power output of the stack module of 6 kW_{el}. Stack module 2 was optimised based on the results of the tests performed with the first testing plant. Amongst the implementation of other optimisation measures this comprised the optimisation of the gas tightness of the stack module (application of new stack sealings and welding instead of flange connections), enhancement of the stack support stability and as well as optimisations regarding the assembly. Validation tests have been performed with the optimised stack module at IKTS. Figure 7 shows selected results of these validation tests [4]. Total power outputs in the range of 6.3 to 6.5 kW_{el} as achieved (with a synthetic, tar free test gas at a reference electrical current of 35 A) confirming the performance of the stack module according to specifications.

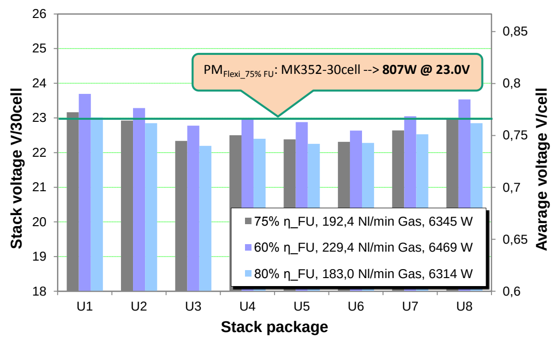

Figure 7: 8x30-cell MK352 stack module performance at 845 °C, 35 A at different fuel utilization rates compared to the performance of the single MK352 30-cell stacks

Explanations: η_FU … fuel utilisation; Nl … litres at 1 atm and 273 K

Figure 8 shows a 3D model of the SOFC system providing the balance of plant components which are needed for the operation of the stack module. The SOFC system was designed and manufactured by AVL.

Besides the stack module the main components of the SOFC system are the cathode air pre-heating heat exchanger, the catalytic burner (afterburner) and the blower as well as the control system (e-box).

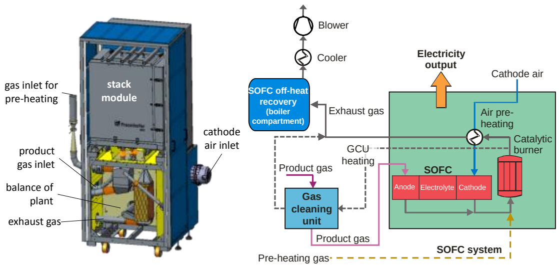

Figure 8: 3D model and scheme of the SOFC system (AVL) with integrated stack module (IKTS)

The SOFC system was further developed by AVL regarding the pre-heating of the SOFC system with flue gas from the gasifier, the utilisation of SOFC off-gas heat for GCU pre-heating and for the operation of the whole system under underpressure conditions [5]. Similar to the gasifier/boiler unit (with a separate suction fan downstream boiler), the CHP related part of the plant (side stream extraction, GCU and SOFC system) is operated at underpressure provided by the SOFC blower.

5.4 Testing plant at BIOS in Graz

Figure 9 shows a 3D model and photos of the whole system (optimised testing plant) as tested during the final project phase.

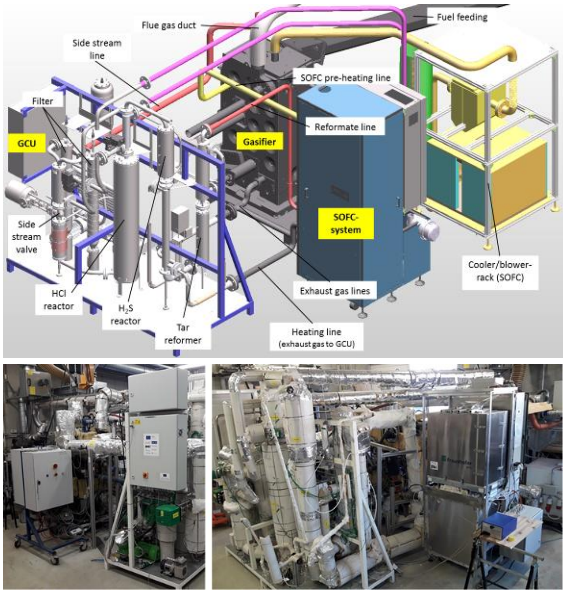

Figure 9: 3D model and photos of the testing plant at BIOS in Graz

Due to the requirements regarding the accessibility of the plant units for the performance of measurements and for plant maintenance, as well as space needed for additional instrumentation the layout of the testing plant (especially for the GCU) was considerably less compact than it would be designed for a later commercial application.

A control system for the whole testing plant has been developed based on existing basic control systems for the gasifier and the SOFC unit. Optimisation measures towards fully automated plant operation have been stepwisely implemented and successfully tested. Automatic operation of the whole system has been achieved.

5.5 Results of test runs

Results gained from test runs performed with wood chips and a selected alternative fuel (poplar chips) at the testing plant at BIOS are presented in the following.

5.5.1 Results of analyses of test run fuels

Table I shows the results of analyses of selected fuel samples for these two fuel types.

Table I: Results of analyses of test run fuels

Explanations: GCV … gross calorific value; NCV … net calorific value; w.b. … wet basis; d.b. … dry basis

fuel		wood chips	poplar chips
sample		mixed sample	mixed sample
moisture content	wt% w.b.	23.0	10.8
GCV	MJ/kg d.b.	20.0	20.2
NCV	MJ/kg w.b.	13.8	16.1
ash content	wt% d.b.	0.6	1.8
C	wt% d.b.	50.07	49.16
H	wt% d.b.	5.95	5.89
N	wt% d.b.	<0.1	0.37
S	mg/kg d.b.	91.3	381.0
Cl	mg/kg d.b.	91.4	98.2
Si	mg/kg d.b.	248.0	548.2
Ca	mg/kg d.b.	1,490.0	6,004.0
Mg	mg/kg d.b.	228.0	665.0
K	mg/kg d.b.	945.0	3,144.5
Na	mg/kg d.b.	13.5	30.5
P	mg/kg d.b.	78.3	572.9
Al	mg/kg d.b.	56.8	119.7
Fe	mg/kg d.b.	52.0	62.2
Mn	mg/kg d.b.	105.0	46.5
Zn	mg/kg d.b.	14.3	25.3

The analysed composition of the wood chips applied for the tests matches a typical composition of commercially available wood chips (regarding moisture and ash as well as S and Cl content). Wood chips with moisture contents of up to 30 wt% w.b. have been successfully tested for the operation of the testing plant.

The used poplar chips are marked by a considerably lower moisture content (about 11 wt% w.b.) and a considerably higher S content of the fuel (380 mg/kg d.b.) in comparison to wood chips (S content about 91 mg/kg d.b.). Whereas the Cl content is comparable for both fuels analysed (wood chips about 91 mg/kg d.b., poplar chips about 98 mg/kg d.b.).

5.5.2 Results of gas quality measurements

In Table II the results of FT-IR gas composition measurements downstream filter in comparison to downstream GCU (downstream tar reformer) are summarised.

The composition of the product gas is considerably changing while passing the GCU. The measurement results show a decrease of the water content of the gas (from about 50 to about 32 vol% w.b.) and the CO concentration (from about 32 to about 6 vol% d.b.) as well as an increase of the CO_2 (from about 14 to about 35 vol% d.b.) and the H_2 contents (from about 16 to about 37 vol% d.b.) in the product gas. These results show that the water-gas shift reaction ($CO + H_2O \rightarrow CO_2 + H_2$) occurs in the GCU which is also confirmed by results of mass and element balances calculated based on the measured gas compositions.

Table II: Measured gas quality downstream filter versus downstream GCU (downstream tar reformer)

Explanations: WGS … water-gas shift reaction;
d … downstream

		dFilter	dGCU	comment WGS
H_2O	vol% w.b.	49.2	31.5	decrease
CO	vol% d.b.	32.2	5.5	decrease
CO_2	vol% d.b.	14.4	35.4	increase
CH_4	vol% d.b.	4.2	6.5	
H_2	vol% d.b.	15.9	37.0	increase
tar	vol% d.b.	0.09	0.00	
N_2	vol% d.b.	29.1	15.6	
O_2	vol% d.b.	-	-	
Others	vol% d.b.	4.1	0.0	

5.5.3 GCU pressure drops and thermal management

Figure 10 shows trends of the side stream volume flow, measured with a Prandtl tube upstream the GCU, and the pressure drops of the particle filter (total pressure drop of the 2 filter units operated in parallel), the contaminant removal reactors (HCl and H_2S reactor) and the tar reformer.

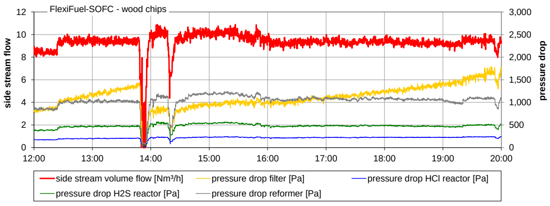

Figure 10: Trends of the side stream volume flow and pressure drops of the single units of the GCU

The clean filter (after a completed cleaning cycle – see trend of the filter pressure drop shown in Figure 10 at about 14:00) shows a pressure drop of less than 10 mbar (1000 Pa) which meets the design value.

The pressure drops measured across the reactors (Cl and S removal reactors, tar reformer) fulfil the design target, showing even lower values than estimated. Moreover, the measurement data show stable trends (no increase) of the pressure drops of the contaminant removal reactors and the tar reformer and thus no problems due to depositions of soot or abrasions from the sorbent materials in the reactors occurred.

Furthermore, stable operation conditions could be maintained regarding the thermal management for the operation of the side stream extraction and the GCU. Stable product gas temperatures meeting the design values (gasifier outlet above 800 °C, filter: 650 °C to 680 °C; HCl reactor: 400 °C, H2S reactor: 350 °C to 400 °C and tar reformer: 500 °C) could be achieved (see Figure 11).

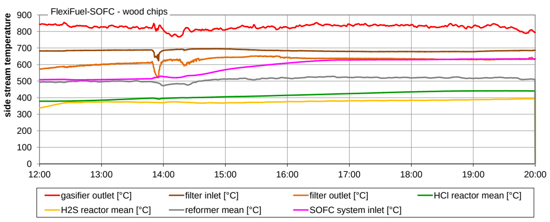

Figure 11: Side stream - temperature trends over the GCU

5.5.4 Contaminant removal evaluation

The performance of the contaminant removal reactors of the GCU (HCl reactor with K_2CO_3 based sorbent material and H_2S reactor with ZnO based sorbent material) was evaluated based on HCl and H_2S measurements performed by BIOS in cooperation with TUD. Wet chemical measurements of the HCl and H_2S contents in the product gas downstream filter and downstream GCU (downstream the tar reformer) have been performed. Furthermore, the H_2S content was measured with Dräger-Tubes®. Figure 12 shows results of the wet chemical HCl measurements.

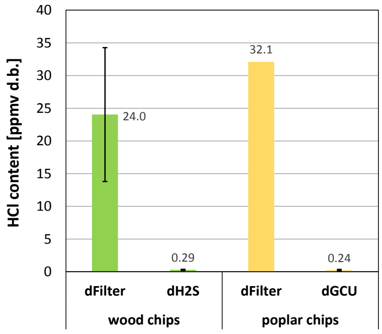

Figure 12: Results of wet chemical HCl measurements

Explanations: HCl content downstream filter … calculated based on Cl analyses for fuel and grate ash (Cl release determined); d … downstream

Comparable HCl contents were measured downstream the H_2S reactor for both fuel types (mean value of 0.29 ppmv d.b. for wood chips and 0.24 ppmv d.b. for poplar chips). This was expected due to the similar Cl contents of the fuels. The measurement results confirm the performance of the HCl contaminant removal reactor of the GCU according to design (purification target for HCl < 5 ppmv).

Furthermore, the H_2S measurements performed show similar results for the H_2S contents downstream the H_2S reactor for both fuels (mean value of 0.26 ppmv d.b. for wood chips and 0.20 ppmv d.b. for poplar chips – see Figure 13). Nevertheless, the considerably higher S content of poplar chips in comparison to wood chips, these results confirm the performance of the H_2S contaminant removal reactor according to design for both fuels. The purification target (H_2S < 1 ppmv) was met for a wide range of H_2S concentrations in the range of about 20 to 80 ppmv d.b. in the gas at the inlet of the reactor.

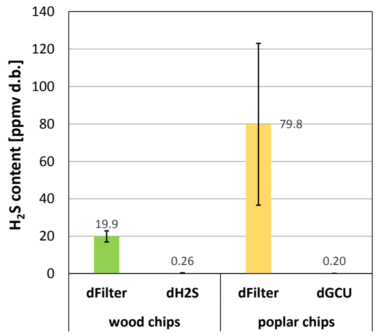

Figure 13: Results of H_2S measurements

Explanations: H_2S content downstream filter … calculated based on S analyses for fuel and grate ash (S release determined) and results of Dräger-Tubes® measurements; d … downstream

5.5.5 Tar content reduction

The tar content in the extracted product gas is reduced in two steps in order to achieve a tar level which is suitable for the operation of the SOFC. A first considerable reduction of the tar content is already achieved by internal reforming in the extraction line inside the gasifier. Thereby a gravimetric tar content reduction of about 99% from about 200 g/Nm³ d.b. above fuel bed to about 1.5 g/Nm³ d.b. at gasifier outlet is possible (see Figure 14). A second tar reformation step is maintained by the tar reformer of the GCU (Ni based) which further reduces the gravimetric tar content by about 90% down to measured gravimetric tar contents in the range of about 0.1 g/Nm³ d.b. to 0.4 g/Nm³ d.b. (mean value 0.19 g/Nm³ d.b.).

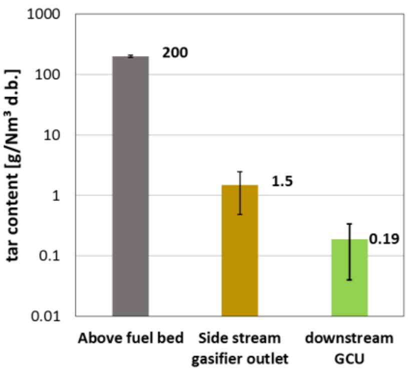

Figure 14: Measured gravimetric tar contents of the product gas above fuel bed and of the side stream at gasifier outlet and downstream GCU

5.5.6 TSP content downstream GCU

Measured TSP concentrations downstream GCU are below detection limit (1 mg/Nm³ d.b.). This confirms the almost complete soot precipitation in the GCU (filter unit). Furthermore, no problems regarding particle entrainment into the side stream due to sorbent material abrasions were detected.

5.5.7 CHP operation at nominal load

Trends of a selected CHP nominal load test performed with the testing plant are shown in Figure 15. After the pre-heating of the GCU and the SOFC system, side stream and CHP operation was started and the power output increased to about 6 kW$_{el}$ nominal load. A filter cleaning (with a short shutdown of the power production and the side stream extraction) was performed at about 13:50 followed by a short stabilisation phase (which could be avoided by optimised control parameters for subsequent tests). A power output close to the level before filter cleaning could be achieved almost immediately after the completed (automated) filter cleaning cycle. Stable nominal load operation conditions with a power output of 6 kW$_{el}$ have been achieved from about 16:00 to 19:45 (when CHP operation was stopped) at stack temperatures of about 850 °C.

Several tests at nominal load have been successfully performed with power production in the range of 6.0 to 6.2 kW$_{el}$. Mass and energy balances show an electric efficiency of the SOFC system of about 42% (power output related to product gas thermal and NCV power input) at nominal load (see Figure 16).

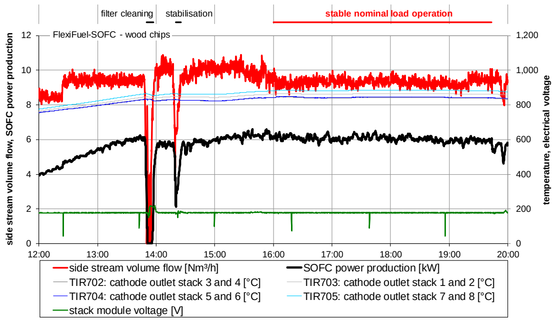

Figure 15: Trends of an exemplary operation of the SOFC at nominal load

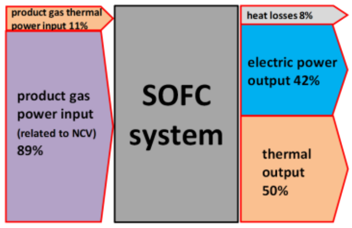

Figure 16: Energy balance of the SOFC system at nominal load operation

Figure 17 shows results regarding the efficiencies achieved of the whole plant according to energy balance calculations for nominal load CHP operation. About 18% electric efficiency is achieved related to the fuel power input for the whole system (SOFC operated in side stream). About 63% thermal efficiency is achieved by the thermal output of the gas burner (about 45%) and the heat recovery from the SOFC off-gas (about 18%). A total thermal efficiency of about 74% is possible with additional heat utilisation by flue gas condensation (condensing heat exchanger). Therefore an overall efficiency of more than 90% is achievable with the new technology.

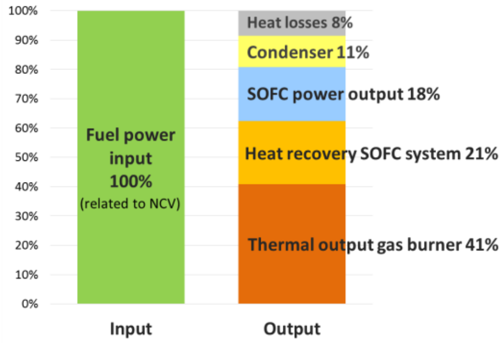

Figure 17: Energy balance for CHP operation at nominal load

5.5.8 Power load changing tests

A further focus of the CHP tests performed has been on the investigation of the behaviour of the system during load changes. Figure 18 shows trends of an exemplary test for power load changes between full load and 50% part load at a rate of about 10 W/s (about 5 minutes from 100% to 50% load).

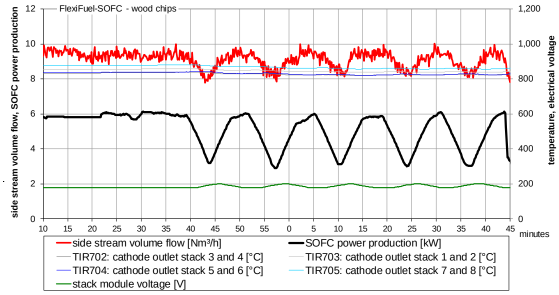

Figure 18: Exemplary trends of load changing tests

Relevant findings regarding stack module operation could be derived from these load changing tests, e.g. that considerably faster changes of the power output would be possible than shown in Figure 18 by applying different control strategies concerning the power output under safe operation conditions for the SOFC.

5.5.9 CO, OGC and PM emission reduction

Considerable advantages of the new technology are achieved in comparison to conventional biomass boiler systems regarding CO, OGC and PM emissions. Very low CO and almost zero OGC emissions are achieved with the new technology due to the optimised gas burner design (air staging) and the catalytic afterburner of the SOFC system. Regarding CO emissions a reduction by a factor of about 100 is possible in comparison to conventional biomass boiler systems (see Figure 19). Furthermore, almost zero PM emissions are achieved by the combination of the updraft gasifier technology (with very low dust emissions) and the hot gas filter of the GCU upstream the SOFC.

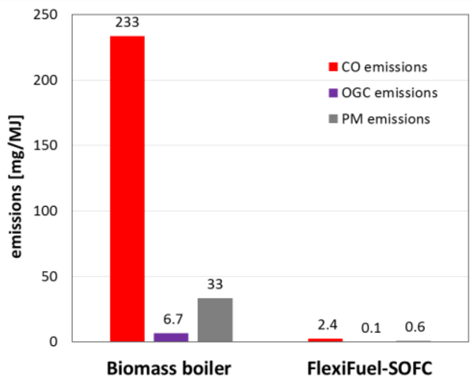

Figure 19: CO, OGC and PM emissions in comparison to conventional biomass boiler systems

Explanations: Biomass boiler … conventional biomass boiler with same heat output [1]

5.5.10 Behaviour of N-compounds and NO_X emissions

Test runs with a special focus on the investigation of the behaviour of NO_X precursors in the product gas have been performed with the testing plant. Exemplary results from a N-conversion test with wood chips are shown in Figure 20. Calculated mass and element balances based on the test run data gained show the following results:

- The N content in the fuel is converted in the gasifier into NH_3 and HCN (in about equal shares) as well as a small part of N bound in tars (see TFN mass flows upstream GCU in Figure 20).
- HCN and tar bound N is converted to NH_3 in the GCU (most likely in the reformer - see TFN mass flows downstream GCU in Figure 20).
- NH_3 is almost completely converted to N_2 in the SOFC stack module (NH_3 is a fuel for the fuel cell – see strong reduction of the TFN mass flow between downstream GCU and downstream SOFC anode).
- About 90% of the total fixed nitrogen (TFN) in the product gas is converted to N_2 in the stack module.

The NO_X emissions measured downstream afterburner are considerably lower than the NO_X emissions downstream the gas burner (about 80 to 90%) due to the considerable reduction of the NO_X precursors in the fuel cell. NO_X emissions in the range of 10 to 28 mg/Nm³ (d.b. 13% O_2) were measured downstream afterburner with conventional wood chips as fuel and at nominal load of the SOFC.

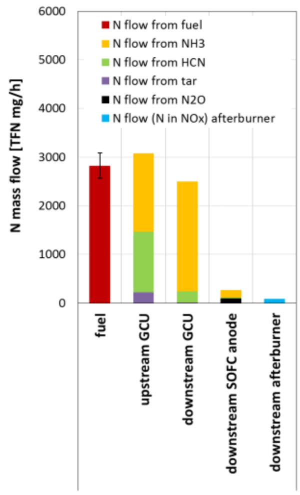

Figure 20: Calculated mass flows of N compounds from the fuel over GCU and SOFC

Explanations: TFN … total fixed nitrogen ... sum of N bound in N-compounds except elemental N (N_2)

6 SUMMARY AND CONCLUSIONS

An efficient and fuel flexible micro-scale biomass CHP technology based on a small-scale updraft gasifier in combination with a SOFC system with high electric efficiency has been developed within the project FlexiFuel-SOFC. High load flexibility and a maximum of full load operating hours of the CHP system is achieved by operating the CHP part of the plant with a side stream (product gas extracted from the gasifier) of a heat controlled system (gas burner and boiler as well as heat recovery).

A gas cleaning unit for the treatment of the side stream according to the requirements for the operation of the SOFC regarding contaminant (H_2S, HCl) and TSP removal as well as tar content reduction was designed, constructed and successfully evaluated. Measurement results show that the purification targets regarding HCl (< 5 ppmv) and H_2S (< 1 ppmv) are met for a broad range of biomass fuels. A total reduction of the gravimetric tar content in the side stream of over 99% is achieved by a two-step tar reformation.

Gravimetric tar contents downstream the tar reformer in the range of about 0.1 g/Nm³ d.b. to 0.4 g/Nm³ d.b. have been measured which seem suitable for the operation of the SOFC stack module.

Stable nominal load operation at a power output of 6 kW_{el} could be shown. Calculated mass and energy balances show an electric efficiency of the SOFC of 42% at nominal load (related to side stream NCV and thermal power input). About 18% electrical efficiency is achieved related to the fuel input for the whole system. A total thermal efficiency of about 74% and thus an overall efficiency of more than 90% can be achieved due to a specially designed heat recovery system in combination with flue gas condensation.

Almost zero CO, OGC and dust emissions as well as very low NO_X emissions are possible. Results of dedicated N-conversion tests performed with the testing plant show a substantial reduction of NO_X precursors in the SOFC (NH_3 is almost completely converted to N_2 in the SOFC stack module) and therefore ultra-low NO_X emissions downstream the afterburner of the SOFC system are achieved.

More than 250 hours of CHP operation have been reached during the tests performed with the testing plants at BIOS. Overall the results of the test runs confirm the basic proof of concept for the new technology.

7 REFERENCES

[1] Obernberger I., Mandl C., Brandt J., 2016: Demonstration of a New Ultra-Low Emission Pellet and Wood Chip Small-Scale Boiler Technology. In: Proc. of the 24th European Biomass Conference and Exhibition, June 2016, Amsterdam, The Netherlands, ISBN 978-88-89407-165, pp. 367-374, (paper DOI 10.5071/24thEUBCE2016-2BP.2.1), ETA-Florence Renewable Energies (Ed.), Florence, Italy

[2] Brunner T., Ramerstorfer C., Obernberger I., Kerschbaum M., Aravind P.V., Makkus R., Megel S., Hauth M., Seidl M., Weissensteiner S., Götz T., Zappa W., 2017: Development of a highly efficient micro-scale CHP system based on fuel-flexible gasification and SOFC. In: Proc. of the 25th European Biomass Conference and Exhibition, June 2017, Stockholm, Sweden, ISBN 978-88-89407-17-2, ISSN 2282-5819, pp. 725-731, (paper DOI 10.5071/25thEUBCE2017-2CV.3.5), ETA-Florence Renewable Energies (Ed.), Florence, Italy

[3] Megel S., et al., 2016: CFY-Stacks: Progress in Development, A0908 12th European SOFC & SOE Forum, Lucerne Switzerland (2016), ISBN 978-3-905592-21-4

[4] Megel S., Schnetter J., Kusnezoff M., Hauth M., Weissensteiner S., Seidl M., Sallai C., Ramerstorfer C., Brunner T., Obernberger I., 2018: Operating results of the FlexiFuel-SOFC system with gasified biomass using CFY-stack module. In: Proc. of the 13th European SOFC & SOE Forum, 3 – 6 July 2018, Lucerne Switzerland, ISBN 978-3-905592-23-8, A1104

[5] M. Seidl, N. Soukup, S. Weissensteiner, C. Sallai, R. Lehner, M. Hauth, Development of a multi fuel SOFC platform for CHP and CCHP applications, 13th European SOFC & SOE Forum, July 2018, Lucerne, Switzerland, A1201, ISBN 978-3-905592-23-8, Chapter 05 – Session A11, A12 pp. 58-65

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9 LOGO PACE