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DEVELOPMENT OF A NEW HIGHLY EFFICIENT AND FUEL FLEXIBLE MEDIUM-SCALE CHP TECHNOLOGY BASED ON FIXED-BED UPDRAFT BIOMASS GASIFICATION AND A SOFC

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ABSTRACT: The H2020 project HiEff-BioPower aims at the development of a new, innovative, fuel flexible and highly efficient medium-scale biomass CHP technology. It consists of (i) a fuel-flexible fixed-bed updraft gasifier, a novel primary gas treatment zone placed downstream the gasifier for gas and tar reforming, (ii) a novel compact gas cleaning system for dust, HCl and S removal as well as final tar cracking within one process step, (iii) a solid oxide fuel cell (SOFC) and (iv) a heat recovery system which supplies heat for internal heating purposes and for external utilisation. The technology shall distinguish itself by a wide fuel spectrum applicable (wood pellets, wood chips, short rotation coppice (SRC), selected agricultural fuels like agro-pellets, fruit stones/shells), high gross electric (40%) and overall (90%) efficiencies as well as equal-zero gaseous and PM emissions. During the first project year of the 4-year project the system design has been worked out and the interfaces between the different plant units have been defined. Based on preliminary experimental (partly lab-scale) work, process simulations and computational fluid dynamics (CFD) simulations a first testing plant consisting of the gasifier, the gas cleaning unit and a slip-stream SOFC system has been developed and designed. The fuel flexible gasifier has been constructed and has already successfully been taken into operation. The remaining plant components are presently manufactured and the construction of the first testing plant is expected to be finalised in June 2018.
Keywords: combined heat and power generation (CHP), gasification, biomass, gas cleaning, fuel cell.

1.INTRODUCTION

Combined heat and power production (CHP) based on biomass fuels is nowadays mainly realised in medium and large-scale plants. For such applications, which typically cover an electric capacity range of 0.2 MW_{el} up to more than 100 MW_{el}, mature and proven technologies such as steam turbine cycles and ORC (Organic Rankine Cycle) processes are available. However, one major drawback of the current systems is their restricted fuel flexibility, especially regarding the utilisation of agricultural residues. Moreover, medium-scale systems (up to 5 MW_{el}) display limited electric efficiencies (14 to 27%) [1]. Against this background, the H2020 project HiEff-BioPower (Grant Agreement No 727330, 10/2016-09/2020) aims at the development of a new, innovative, fuel-flexible and highly efficient medium-scale biomass CHP technology.

The new CHP technology shall consist of

- a fuel-flexible fixed-bed updraft gasifier with a novel primary gas treatment zone placed downstream the gasifier for gas and tar reforming,
- a novel compact gas cleaning system for dust, HCl and S removal as well as final tar cracking within one process step,
- a solid oxide fuel cell (SOFC) and
- a heat recovery system which supplies heat for internal heating purposes and for external utilisation.

2. OBJECTIVES

The new technology shall be developed for a capacity range between 1 and 10 MW total energy output. It shall distinguish itself by a wide fuel spectrum applicable ranging from wood pellets and wood chips over wood from short rotation forestry (SRF, e.g. poplar or willow) to selected agricultural fuels like agro-pellets and fruit stones/shells). With the new CHP system high gross electric and overall efficiencies of 40% and 90% respectively (related to the NCV of the fuel) shall be achieved. Moreover, it shall distinguish itself by equal-zero gaseous and PM emissions. This goal can be achieved by the HiEff-BioPower technology since

- the fixed-bed updraft gasification technology per se is characterised by very low particulate emissions,
- the gas cleaning unit shall efficiently remove small amounts of remaining particulate matter and hazardous gaseous emissions such as HCl and S-components and
- gas utilisation in a SOFC system shows almost zero NO_x emissions and due to the application of a catalytic afterburner also almost zero CO and OGC emissions.

To reach these overall objectives, the work within the project focuses on several technological objectives linked to the development and design of the single plant units as well as to the development of the whole CHP system.

During recent years, the Austrian project partners Viessmann Holzfeuerungsanlagen GmbH (VIHFA) and BIOS BIOENERGIESYSTEME GmbH (BIOS) have developed a novel medium-scale fixed-bed updraft gasifier technology for wood fuels. Within a former nationally funded R&D project a biomass heating technology for the capacity range of up to 10MW_{th} based on coupling this gasifier with a staged gas burner and a fire tube hot water boiler has been developed. The fixed-bed updraft gasifier thereby bears the significant advantage that due to the almost complete embedding of semi-volatile species such as K-compounds in the grate ash and due to its low coarse fly ash emissions an almost particle free product gas is provided. This aspect forms a perfect basis for coupling the gasifier technology with a solid oxide fuel cell system, since the demands for gas cleaning are significantly lower than in other gasification systems. Within the project, the gasifier technology shall be further developed to significantly widen its fuel flexibility towards a broader range of wood fuels including wood from SRF (short rotation forestry) and agricultural residues.

However, the product gas from fixed-bed updraft gasifiers contains high amounts of tars (up to 200 g/Nm³) and therefore a primary gas treatment stage for partial tar conversion based on a high temperature heat exchanger and a partial oxidation unit shall be developed and directly coupled to the gasifier.

To remove the remaining tars, particles, H_2S and HCl from the product gas, the German project partners Karlsruher Institut für Technologie (KIT) and Calida Cleantech GmbH shall develop a novel gas cleaning concept where the three process steps (i) particle filtration, (ii) gaseous contaminant removal and (iii) tar cracking are realised within one reactor. The aim is to provide a product gas with no PM, H_2S contents <1 ppm and HCl contents <5 ppm as well as to upgrade the product gas by cracking specific tar compounds which cannot be converted by reforming in the fuel cell.

For an efficient conversion of the product gas heating values into electricity, Fraunhofer Institut für Keramische Technologien und Systeme (IKTS, Germany) and AVL LIST GmbH (AVL, Austria) shall further develop their solid oxide fuel cell system with respect to the specific properties of the product gas. This shall involve the further development of the stack module as well as of the remaining SOFC system comprising all other balance of plant (BoP) components needed. Main aspects thereby are to reduce the product gas inlet temperature needed for proper SOFC operation to 650°C and to simplify the BoP components by developing a new catalytic cathode air pre-heater which combines the functions of the presently applied SOFC exhaust gas burner and the cathode air pre-heater within one device. The latter development is supported by partner BOSAL emission control systems NV from Belgium.

For the whole CHP plant a system design shall be worked out with the aim to integrate the single plant components in a way that heat needed in specific process steps can be supplied from off-heat from the other plant components and that remaining off-heat can efficiently be utilised for heat production in order to optimise the overall plant efficiency. Moreover, specific demands regarding start-up, controlled shutdown and emergency shutdown shall be considered during the development of the system design.

Two generations of testing plants of the new technology shall be developed, tested and evaluated. These testing plants shall consist of a 400 kW gasifier (fuel power related to the NCV), a full-scale gas cleaning unit and a slip stream 6 kW_{el} SOFC system.

At the end of the project the system concept design for a first demonstration plant of the new technology with a full-scale SOFC system shall be available. Therefore, it is also an aim to perform the development work mentioned against the background of market demands and market applicability. For that reason, technology development shall be accompanied by risk assessments, safety analyses as well as techno-economic and environmental impact assessments. Moreover, the performance of market studies regarding the application of industrial biomass-based CHP technologies on a European level as well as dissemination of the project results shall support a later market introduction of the novel CHP technology. These aspects are mainly covered by the project partners Wuppertal Institut für Klima, Umwelt, Energie GmbH (WIKUE, Germany) and Utrecht University (UU, the Netherlands).

A schematic drawing of the HiEff-BioPower technology is presented in Figure 1.

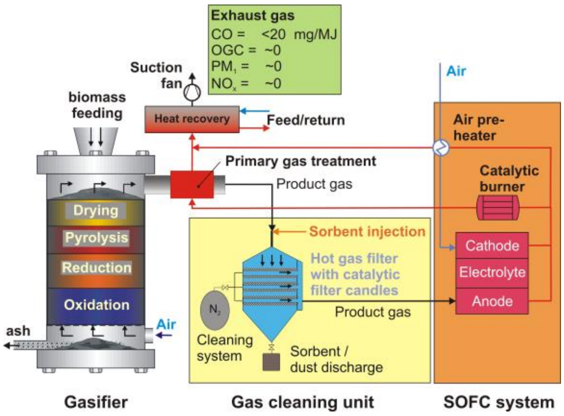

Figure 1: Scheme of the HiEff-BioPower technology

3. METHODOLOGY

As it can be derived from the description of the project objectives, different technical and non-technical problems have to be solved to finally achieve a technologically optimised and economically and environmentally sound biomass-based CHP system. Therefore, the overall methodology is divided into a technology development and a technology assessment part.

Technology development shall be done for the single plant units as well as for the whole system whereby for each single unit partly basic and applied research components have to be covered. Consequently, process simulations, lab-scale experiments, CFD (computational fluid dynamics) simulations, chemical and thermodynamic equilibrium studies and electrochemical modelling of the stack module are applied for these tasks. Moreover, technology development comprises the design and construction of a basic first and an improved second generation testing plant. Comprehensive test runs at these testing plants and their evaluation shall provide the data and experiences to validate the simulation models developed and to further improve the whole technology.

In parallel with the technology development the work on technology assessment is performed. This comprises techno-economic, environmental and overall impact assessments and market studies regarding the potentials for application. Regarding these aspects, literature data reviews on a European level as well as the development and application of different models to assess economic, environmental and market related aspects of the new technology are performed. This work is done in two stages. First preliminary assessments shall support the development work by directing it towards satisfying legislation and market related demands. The final assessments, which shall already be based on data and experiences gained from the test runs with the second generation testing plant, shall make aware of the advantages of the new technology and thereby prepare the basis for a subsequent demonstration project as a first step of market introduction

4. RESULTS ACHIEVED SO FAR

4.1. System design

As a basis for the system design two design fuels have been defined, namely a moist biomass fuel with about 30 wt% w.b. moisture content (e.g. wood chips - design fuel 1) and a dry biomass fuel with about 5-10 wt% w.b. moisture content (e.g. pelletised fuels - design fuel 2). Moreover, regarding investigations on fuel flexibility it has been decided to consider softwood pellets, industrial wood chips (from sawmills), forest wood chips (= forest residues), miscanthus pellets and olive stones. A project internal fuel database has been generated based on fuel composition data available at project partner BIOS. This database was used as a basis for the technology development work. In Table I, mean values regarding the fuels to be considered during technology development are listed.

Table I: Composition of the design fuels

Explanations: SWP…softwood pellets; wc…industrial wood chips; FWC …forest wood chips; Misc. …miscanthus; OS…olive stones; MC…moisture content; AC…ash content; GCV...gross calorific value; d.b…dry basis; w.b… wet basis; the data represent mean values taken from the biomass fuel database of BIOS

		SWP	WC	FWC	Misc.	OS
MC	wt% w.b.	6-9	15-50	15-50	8-18	7-14
AC	wt% d.b.	0.37	0.87	2.7	3.7	1.32
C	wt% d.b.	49.8	49.2	49.4	46.9	50.5
H	wt% d.b.	6.3	6.0	5.9	6.0	6.2
N	wt% d.b.	0.08	0.13	0.34	0.25	0.23
S	mg/kg d.b.	58.5	115.7	323.1	450.8	238.3
Cl	mg/kg d.b.	30.3	45.1	110.3	1,030	690
Si	mg/kg d.b.	178.3	727	3,303	9,491	1,179
Ca	mg/kg d.b.	946	1,942	5,552	2,394	1,997
Mg	mg/kg d.b.	123.0	233.2	606	674	199.6
Al	mg/kg d.b.	20.7	108.7	650	223.3	357.3
Fe	mg/kg d.b.	21.0	88.1	421.2	152.9	352.7
Mn	mg/kg d.b.	126.4	110.0	241.7	57.9	13.3
P	mg/kg d.b.	48.6	84.8	307.3	285.3	121.9
K	mg/kg d.b.	421.5	648	1,828	2,894	1,423
Na	mg/kg d.b.	14.0	39.4	149.4	120.3	918
Cu	mg/kg d.b.	0.91	1.08	3.4	2.3	6.2
Zn	mg/kg d.b.	11.0	10.2	30.1	14.8	6.2
Pb	mg/kg d.b.	0.30	0.58	6.7	1.15	0.04
GCV	MJ/kg d.b.	20.2	19.7	19.9	18.8	20.5

As it can be derived from the table, this fuel selection covers a broad range of different ash, K, Ca, Si, S and Cl contents. While ash forming elements are relevant for the gasifier design with respect to ash melting related problems, the S and Cl contents are in particular of relevance for the development of the gas cleaning unit.

As a next step the system design concept for a real-scale HiEff-BioPower plant has been developed in a stepwise procedure in close cooperation of all technical partners. To support this work a project specific mass and energy balancing tool has been developed by BIOS and AVL worked out a balancing tool for the SOFC system. Based on these balancing tools different system design options have been evaluated and finally the following solution has been defined as a basis for the further work. A schematic diagram of the system design showing the most relevant plant components and the temperatures at relevant interfaces is presented in Figure 2.

The system design relies on a fixed-bed gasifier, which is operated with humidified gasification air. Gasification air humidification shall thereby by used as a measure to control the fuel bed temperatures in the charcoal burnout zone which is a relevant pre-requisite for the utilisation of fuels with low ash melting temperatures (see also section 4.2). Moreover, it should help to reduce the critical coking temperatures of the product gas by providing steam for reforming reactions.

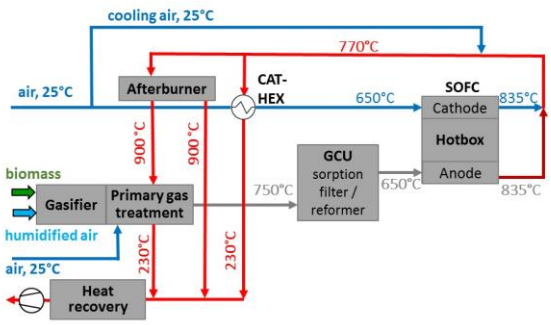

Figure 2: Flow diagram of the HiEff-BioPower CHP technology

Explanations: CAT-HEX … catalytically coated heat exchanger; GCU… gas cleaning unit; SOFC…solid oxide fuel cell

Downstream the fuel bed section a primary gas conversion stage is implemented. In this zone the product gas temperature shall be increased from 100-400°C at fuel bed exit (depending on the fuel moisture content) to about 750°C. Therefore, energy from the off-gas from the SOFC system and the addition of a small amount of partial oxidation air is foreseen. It is expected that by this measure the critical coking temperature of the product gas is quickly exceeded and that a relevant amount of the tars can be cracked already upstream the GCU. This measure combined with the low inorganic particulate matter contents of the product gas shall reduce the efforts for gas cleaning and therefore have a positive impact on the design of the GCU.

The primary conversion zone moreover contains a start-up burner for oxidising the product gas during the start-up the plant, during which the gas cleaning unit and the SOFC system shall be by-passed.

Downstream the primary conversion zone the GCU shall be integrated consisting of a sorbent injection for S and Cl-removal and a particle filter with catalytically impregnated filter candles for particle removal and tar cracking.

Downstream the GCU the SOFC system is connected. The product gas shall enter the SOFC system with about 650°C. The cathode air shall be pre-heated in a catalytic heat exchanger in which on the hot side the off-gas from the stack module is almost fully oxidised. Off-gas not needed for cathode air pre-heating shall be burned in a catalytic afterburner and the resulting flue gas (900°C) shall be used to supply the primary gas conversion zone with energy. Moreover, this off-gas shall also be used to feed an evaporator for steam production for gasification air humidification. A part of the remaining heat downstream these units shall be recovered in a heat recovery unit before it enters the chimney.

A smart integration of bypass ducts around the GCU and the SOFC system (not shown in Figure 2 for simplicity reasons) shall facilitate a decoupled start-up of the gasifier and the heat-up of the SOFC system and the GCU with flue gas from the product gas combustion in a start-up burner, which is integrated in the gasifier casing resp. the primary gas conversion zone. Therefore, no external heat sources will be needed for start-up of the system. Also during operation all internal heating needed (e.g. for cathode air heating) will be supplied with energy from the SOFC off-gas.

4.2. Gasifier development and design

The main objective of the further development of the fixed-bed updraft gasifier was to make it more fuel flexible and to adapt it for the integration into the whole system.

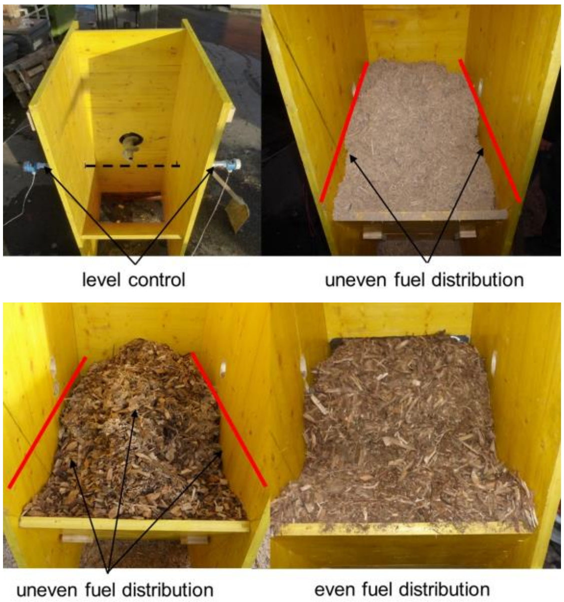

Figure 3: Test run set-up for fuel feeding tests with a cold model of the stoker screw and the gasifier fuel bed region

An important pre-requisite for an extended fuel flexibility of an updraft gasifier is a fuel feeding system, which provides an evenly distributed fuel bed with a flat fuel bed surface. To optimise the geometry of the fuel feeding system, test runs with a cold model of the fuel feeding system and the fuel bed zone of the gasifier have been performed. In Figure 3 the cold model as well as the results of different optimisation steps of the fuel feeding system are presented. The modifications mainly concerned the transition region from the feeding screw outlet to the gasifier fuel bed.

Moreover, test runs with the present gasifier testing plant at VIHFA have been performed to investigate ash formation processes with special respect to the K-behaviour. Wood chips (standard fuel presently used as a reference case) willow and miscanthus pellets have been used as fuels. Especially the test runs with miscanthus pellets clearly showed the demand for an efficient fuel bed cooling to avoid slag formation.

The test runs were accompanied by gasifier simulations with a simulation model especially developed for fixed-bed updraft gasifiers [2] and thermodynamic high-temperature equilibrium calculations (TEC) for an in-depth study of the ash formation process. For the latter the software package FactSage 7.1 was applied. These studies have shown that for wood chips and other Ca-rich fuels such as forest residues and olive stones the same K retention mechanism in the grate ash prevail. This mechanism is based on the formation of K-Ca-double-carbonates with $K_2Ca(CO_3)_2$ (Fairchildite) being the most relevant one. According to TEC (see Figure 4), Fairchildite shall decompose in the temperature range between 800 and 900°C forming CaO and K_2CO_3. The latter decomposes at temperatures between 850 and 950°C to K(g) and CO_2. However, as it has been reported in [3], this decomposition mechanism seems to be kinetically limited. Thus K and Ca-carbonates remain in the grate ash since there seems to be not enough residence time at high temperatures in the charcoal burnout zone to form K(g). This has also been confirmed by analyses of grate ashes from the test runs mentioned above performed with the present VIHFA gasifier. It is therefore recommended to keep the temperature in the charcoal combustion zone as low as possible to minimize K release and also to avoid ash melting (e.g. K_2CO_3 may start to melt at temperatures above 900°C). However, to achieve this and to maintain at the same time a sufficient charcoal burnout (low contents of carbon in the grate ash), temperatures of about 900°C are recommended to be kept in the charcoal combustion zone.

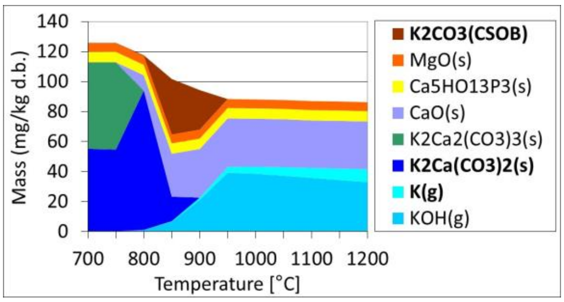

Figure 4: Results of thermodynamic high-temperature equilibrium calculations regarding ash formation in the updraft gasifier when utilising wood chips

Explanations: d.b.…dry basis; s… solid; relevant compounds are highlighted

For miscanthus it has been shown that mainly K-silicate phases embed K in the grate ashes. As these K-silicates show comparably low melting temperatures (even below 900°C) with increasing K/Si ratio in the fuel, additivation with kaolin (a clay mineral mainly consisting of Si and Al) seems to be an appropriate measure to bind K in alumosilicates, which have significantly higher melting temperatures than K-silicates. By applying this measure, also agricultural fuels with a less advantageous ash melting behaviour should be applicable in the new technology without the risk of ash melting.

Gasification air humidification in combination with a water cooled grate concept has been chosen as a measure to keep the fuel bed temperatures at the desired level of about 900°C. Therefore, a gasification air humidification system was developed and constructed. With this system, about 0.3 to 0.5 kg vapour per kg air should be added depending on the fuel moisture content (higher amounts for dry fuels).

Finally, the primary gas treatment zone has been developed and connected to the gasifier. In this zone exhaust gas from the SOFC system and a small amount of air for partial oxidation of the product gas are used to increase the product gas temperatures from 100-400°C at fuel bed exit (the temperatures increase with decreasing fuel moisture content) to about 750°C. By this measure it is expected that the tar content of the product gas, which typically amounts between 100 and 200 g/Nm³ at fuel bed exit, can be reduced by 98-99%. For the development of this zone an especially developed CFD-model has been applied with a detailed gas conversion model which also considers tar decomposition [4]. In Table II the composition of the product gas downstream this section gained from CFD simulations already performed is presented for both design fuels.

Table II: Simulated product gas composition at the outlet of the primary gas treatment section
Explanations: w.b. … wet basis; d.b. … dry basis

		Design fuel 1	Design fuel 2
Fuel moisture	wt% w.b.	30.0	5.0
CO	vol% w.b.	14.3	16.6
CO_2	vol% w.b.	8.1	9.2
CH_4	vol% w.b.	0.46	0.95
H_2	vol% w.b.	12.0	16.4
H_2O	vol% w.b.	29.6	21.7
CO	vol% d.b.	20.3	21.2
CO_2	vol% d.b.	11.5	11.7
CH_4	vol% d.b.	0.65	1.21
H_2	vol% d.b.	17.0	20.9

In Figure 5 a 3D-drawing of the gasifier is presented and all newly developed parts are marked. Moreover, the picture shows the position of the connection flange for the product gas channel to the gas cleaning unit and the bypass to the heat recovery unit, which is used during start-up.

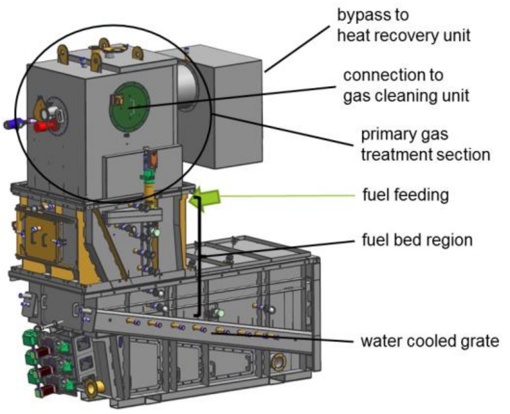

Figure 5: 3D-drawing of the new updraft gasifier

4.3. Gas cleaning unit (GCU) development and design

The framework conditions for the development and design of the gas cleaning unit were a gasifier fuel power of about 400 kW (related to fuel NCV) and a product gas temperature at GCU inlet of 750°C. Therefore, the GCU was designed for a gas stream of 320 Nm³/h and an operation temperature of 750°C.

A scheme of the GCU is presented in Figure 6. The core of the GCU is a filtration unit equipped with high-temperature candle filters. As filter medium ceramic fibre candles were chosen (see Figure 7), due to their low initial pressure drop as well as their good properties for catalytic impregnation. Moreover, ceramic filter elements have already proven their long-term applicability for the removal of sorbents and sorption products [5].

Upstream of the filtration an entrained flow sorption process is located. The entrained flow sorption unit consists basically of a sorbent feeding system and an entrained flow reactor. Presently lab-scale tests are ongoing to determine an appropriate sorbent material resp. mixture of sorbent materials. Thereby, it has to be considered that HCl as well as S-compounds have to be captured. Moreover, the comparably high gas temperatures of about 750°C have to be taken into account regarding possible sorbent sintering effects. Low-cost minerals (Na-based) and (Ca-based) chalk are promising candidates and therefore investigated in lab-scale at present. The entrained flow reactor provides a residence time of about 2s which is available in addition to the residence time in the filtration unit in order to optimise the sorption efficiency. The filter candles of the filtration unit are horizontally arranged (see Figure 7), which gives the advantage that the gas stream can be fed from the top and the gas flow will pass the used sorbents/dust downwards to the sorbents/dust removal.

The hot gas filtration unit is equipped with a reverse pulse cleaning system consisting of a pressure reservoir tank, a fast-acting valve, butterfly valves and gas pipe adapters (see Figure 7). The pressure difference over the filter is monitored and acts as control parameter for the reverse pulse cleaning intervals. This specific cleaning system enables the effective removal of fine and sticky particulates from rigid filters even under high temperature conditions. Contrary to the conventional jet-pulse cleaning system the filter elements are coupled directly to the cleaning gas supply (N_2) during the cleaning procedure. Therefore, only the total pressure drop of the filter element and the dust layer must be overcome amounting to significantly less than 1 bar. No reverse flow occurs at the filter inlet, which would reduce the cleaning efficiency. Compared with the jet-pulse cleaning, the gas velocity into the filter element is significantly lower resulting in more uniform velocity and pressure profiles along the filter elements and thus in uniform cleaning.

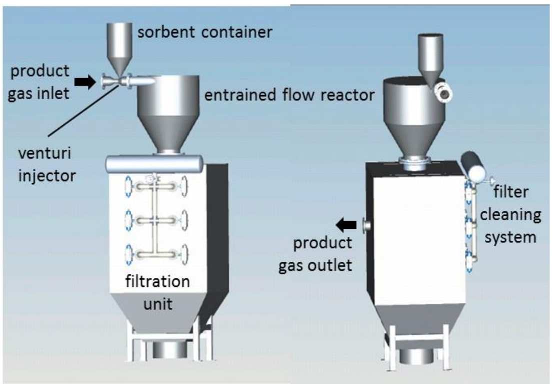

Figure 6: Scheme of the gas cleaning unit

Figure 7: Filter cleaning system (left) and view on the ceramic filter candles (right)

The gas cleaning unit presented above is presently manufactured for implementation into the first testing plant. At this plant, it will be combined with a catalytic reactor for tar reforming in the slip stream duct to the SOFC system. At a later stage of the project, when appropriate experiences and data regarding the performance of the GCU are available, the catalytic reactor shall be replaced by filter candles impregnated with a tar reforming catalyst. With this second development step, the goal of achieving particle filtration, HCl and S-compound removal and tar reforming in one reactor, shall be achieved.

4.4. SOFC system development and design

Due to cost reasons, for the testing plants to be realized within the project a slip stream SOFC system with a nominal electricity output of 6 kW shall be developed. At the final stage of the project an up-scale study of the whole CHP system to the desired power ranges of up to 4,000 kW_{el} is foreseen.

Product gas is extracted from the gas duct downstream the gas cleaning unit. The 6 kW_{el} SOFC system consists of an electrical heaters for heating up the SOFC stack module during start-up. A suction blower has been integrated in the system, which is used for sucking air and product gas from downstream the gas cleaning unit through the system. A catalytically coated heat exchanger is used for pre-heating air and for the combustion of remaining H_2, CO and CH_4 in the SOFC off-gas flow as well. After this catalytic burner an exhaust gas cooler is integrated in the system to decrease the temperature of the exhaust gas to a lower level. The system design is shown in Figure 8.

Figure 8: CAD-drawing of the SOFC system

Explanations: 1: inlet product gas from GCU; 2: outlet exhaust gas from the catalytically coated air heat exchanger/reformer unit; 3: inlet air bypass for cooling the catalytically coated air heat exchanger; 4: inlet heated air for heating up the stack module during start-up; 5: inlet natural gas; 6: inlet cold air for stack module operation; 7: connectors for pressure and temperature sensors; 8: hotbox; 9: coldbox; 10: electrical switch cabinets; 11: stack module

In parallel with the development of the SOFC system at AVL the stack module has been developed and manufactured at IKTS. A schematic drawing of the stack module consisting of 8 single stacks also showing distinct temperature measurement positions for SOFC operation monitoring is presented in Figure 9.

Based on system simulations by AVL and the product gas compositions gained from the CFD simulations, the compositions of the reformed product gases (=reformate) for design fuel 1 (M30) and design fuel 2 (M8) were defined. These both compositions were tested with simulated synthetic product gas in the performance map with a single 30 cell stack. “Performance maps” are a composition of several constant power points for a fully characterization of stacks [6].

Figure 10 shows the performance of the stack module with the two design fuel gas compositions. With both gas compositions, a higher power output than the anticipated 6 kW_{el} could be achieved. With “M30” reformate a power output of 6.27 kW_{el} and with “M5” reformate a power output of 6.45 kW_{el} was achieved at the standard operation conditions of 35 A and a fuel utilization rate (ηFU) of 75%. Besides this standard operation case it is possible to gain a higher power output by increasing the fuel power and the current density (not shown in Figure 10).

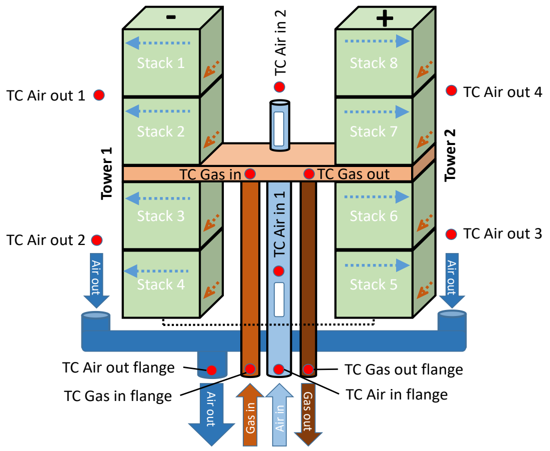

Figure 9: Schematic drawing of the stack module
Explanations: TC … thermocouple

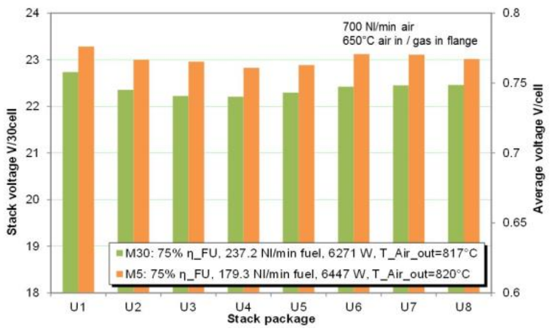

Figure 10: Stack module performance
Explanations: η_FU … fuel utilisation, U1 to U8: single 30 cell stack voltage; Nl, … liter at 273 K and 1 atm

4.5. Development, design and construction of the first testing plant

Based on the system design for a real-scale plant (see section 4.1), the system design for the first testing plant to be realized within the project has been defined. The gasifier, the primary air humidification, the primary gas treatment zone including the start-up burner and the gas cleaning unit shall thereby rely on the same concept as foreseen for the real-scale system and shall be designed and constructed for a fuel power (NCV) of 400 kW. Since a 6 kW SOFC system will be tested in a side stream extracted from the product gas downstream the GCU, a gas burner shall be installed to burn the remaining product gas. Therefore, the heat recovery boiler will have more thermal capacity than in the real-scale system due to the higher thermal energy flow to the heat recovery.

The single plant components are presently manufactured and plant assembly shall take place in June 2018. Then comprehensive test runs to evaluate the performance of the single components as well as of the whole system, are foreseen.

5. SUMMARY, CONCLUSIONS AND OUTLOOK

During the first project phase the system design and the development of the single plant components of a first HiEff-BioPower testing plant could successfully be completed. As an initial task, the system design comprising the definition of all relevant framework conditions for the new technology as well as of the interfaces between single plant units could be worked out. Based on that the fixed-bed updraft gasifier has been further developed towards higher fuel flexibility and has been adapted for integration into the whole CHP concept. Moreover, the concepts regarding the gas cleaning unit and the SOFC system have been developed and the respective units have been designed. The SOFC stack module has also been developed, designed and constructed. Validation tests with the stack module applying synthetic simulated product gas with compositions, which are expected to prevail in the testing plant, have revealed that the envisaged power (6 kW_{el} for the side stream unit to be integrated into the testing plant) can be achieved. This result was gained for both design fuels with moisture contents of 30 and 8 wt% (w.b.).

Presently the manufacturing and installation of the first testing plant is ongoing. Plant start-up is expected to take place in the mid of June 2018.

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8. LOGO SPACE