# MICRO-BIO-CHP – DEVELOPMENT OF A NOVEL GAS EXTRACTION AND CLEANING TECHNOLOGY DIRECTLY INTEGRATED IN A BIOMASS UPDRAFT GASIFIER WITH SUBSEQUENT GAS BURNER

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ABSTRACT: The Horizon Europe project Micro-Bio-CHP aims at the development of an innovative system for heat and electricity supply to achieve an almost energy autonomous multi-family building with regard to heating and electricity consumption as well as electro-mobility. This shall be reached by integrating a biomass CHP plant, a PV system and appropriate heat and electricity storage technologies. One main focus of the project is the development and test of the projects core technology, the biomass conversion unit and especially the generation of a clean product gas for the SOFC. Necessary development work covered the CFD-aided development and optimisation of a new gas burner with integrated thermal and catalytic tar reformer as well as of the high-temperature particle filter, the selection and lab-reactor tests of suitable tar reforming catalysts as well as the design and construction of a 15 kW testing plant. Test run results show that stable operation is possible and an almost tar as well as particle free product gas can be generated for the SOFC. Through a stepwise optimisation process a tar reduction of 99.5% and a minimization of the dust contents of the extracted product gas to levels in the range of 1 mg/Nm³ could be achieved. For the Micro-Bio-CHP process a novel gas extraction and cleaning technology has been successfully developed and tested. All innovations represent novelties in micro-scale biomass CHP concepts, which clearly go beyond the present state-of-the-art. Thus, the Micro-Bio-CHP system can represent a new milestone in clean product gas production from biomass.
Keywords: wood pellets, micro-scale, CHP, gas cleaning, SOFC

## 1 INTRODUCTION AND OBJECTIVES

Within the Horizon Europe project Micro-Bio-CHP (No. 101083409, 10/2022 – 03/2026) a new, highly efficient micro-scale biomass CHP system based on a fixed-bed updraft gasifier and a solid oxide fuel cell (SOFC) is developed, which maximises electric efficiency and annual full load operation hours of electricity production from biomass and also provides flexibility regarding heat production. In combination with a state-of-the-art PV module as well as with appropriate heat and electricity storage solutions this system shall allow for energy autonomy of multi-family buildings in terms of space heating, domestic hot water and electricity supply throughout the whole year. The concept perfectly utilises the potential of residential biomass heating systems for $CO_2$ reduction as it foresees a very efficient combination of bioenergy and solar energy providing the possibility of a $CO_2$ neutral energy supply of residential buildings [1].

In common small-scale biomass CHP systems, the whole energy gained from the thermo-chemical conversion of the fuel is fed to the electricity production process and the off-heat from electricity production is used for heating. Consequently, electricity production in heat-controlled systems always relies on the heat demand, which defines the fuel power input.

For the Micro-Bio-CHP process a new and different approach shall be developed. A fixed-bed updraft gasifier forms the basis for biomass conversion. In contrast with common solutions, a partial flow of the product gas is extracted above the fuel bed, and after gas cleaning is led to the SOFC system for highly efficient electricity production (ηel of 44% related to the NCV of the product gas). The remaining product gas is combusted in a product gas burner located directly downstream the fuel bed (see Figure 1) and the resulting flue gas as well as the off-gases of the SOFC system are directed to a heat recovery unit consisting of a boiler and a flue gas condenser to achieve highest effiencies. The product gas flow extracted to the SOFC shall be in a range, which allows for a continuous high load SOFC operation also during transitional seasons with maximum electricity production at minimum product gas burner load (i.e. heat production). During the cold seasons (rising heat demand), the fuel power is increased, the product gas flow to the SOFC remains at its range for maximum SOFC load while the gas flow over the burner is increased thus supplying the heat recovery section with more energy. Consequently, the new approach combines two functionalities within one system – a base load CHP system providing electricity and off-heat over the whole operation period and an additional product gas burner system covering increased heat demand and peak load phases. The same strategy is often applied in larger district heating CHP plants, however, there two separate boilers are needed for its realisation. Moreover, the configuration explained also allows for a “heat-only” mode which supplies the building with heat even if the SOFC module is not in operation. The off-gas from the SOFC system is then returned for heat recovery to the biomass conversion module.

The scope of the work presented in this paper is on the development and test of the projects core technology, the biomass conversion unit and especially the generation of a clean product gas for the SOFC. Thereby, an already existing small-scale fixed-bed updraft gasifier has been further developed. Based on the overall approach of the project the fixed-bed updraft gasification derived gases can be utilised in two ways at once, either by direct combustion in a multi-stage gas burner downstream the gasifier or by providing a reformed product gas for application in the SOFC (up to 50% related to the energy content). Regarding gas cleaning an efficient and novel

combined thermal and catalytic tar reformer and a high-temperature particle filter are integrated in the biomass conversion unit, while a $H_2S$ and HCl removal reactor is integrated in the SOFC module.

The technological development has strongly been supported by CFD (Computational Fluid Dynamics) simulations in order to develop and optimise the new gas burner with integrated thermal and catalytic tar reformer as well as the high-temperature particle filter. A first testing plant with a 15 kW (fuel power related to the NCV) gasifier has been developed and constructed and extensive test runs with accompanying measurements and analyses have been performed in order to evaluate the thermal and catalytic tar reformer as well as the high temperature particle filter and to improve the new technology step by step. Based on the data and experiences gained from the test runs a technological assessment of the new technology has been performed.

## 2 TECHNOLOGICAL APPROACH

For the Micro-Bio-CHP process a novel technology has been developed. A fixed-bed updraft gasifier forms the basis for biomass conversion. A partial flow of the product gas (~50% related to the energy content) is extracted above the fuel bed, and after gas cleaning is used in the SOFC system for electricity production. The remaining product gas is combusted in a product gas burner located directly downstream the fuel bed (see Fig. 1) and the resulting flue gas (as well as the off-gas of the SOFC system) are directed to a heat recovery unit consisting of a boiler and a flue gas condenser. Regarding gas cleaning, the tar reformer and the high-temperature particle filter are integrated together with the gasifier, the gas burner and the heat recovery system in one casing (so-called biomass conversion module) while a $H_2S$ and HCl removal reactor is integrated in the SOFC module, thus a very space-saving and compact design is achieved (see Figure 1**).** The flue gas from the gas burner is, due to the characteristics of the underlying fixed-bed updraft gasification process, almost free of particulate matter emissions. The gas burner is based on a staged combustion concept providing almost zero CO and OGC emissions.

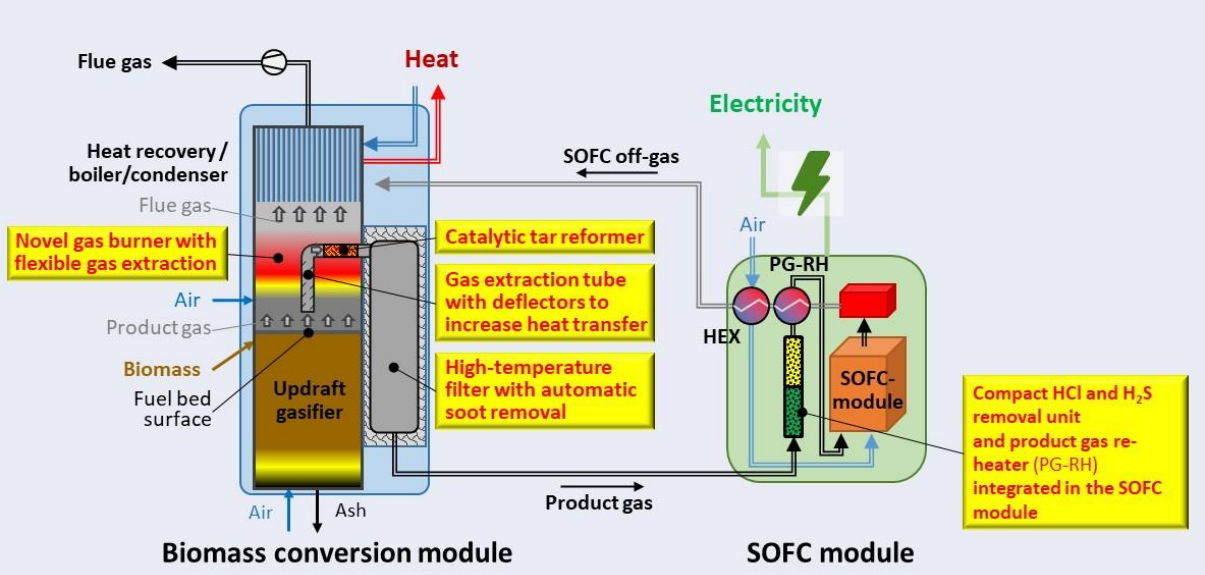



**Figure 1:** Scheme of the concept for the innovative Micro-Bio-CHP technology

### 2.1 Development and design of the biomass conversion module (BCM)

The necessary development work followed a stepwise approach. At first the system design has been defined based on the PuroWIN technology which has been developed by BIOS and Windhager (AT). The PuroWIN technology bears the big advantage that it provides a product gas with almost zero contents of coarse fly ashes and condensable ash vapours [2, 3, 4]. The basic framework conditions for the whole plant and the interfaces between the different components have been worked out for a 15 kW lab-scale testing plant. As a next step a basic concept for the new technology consisting of the gasifier, the multi-stage gas burner with integrated thermal and catalytic tar reformer and the high-temperature particle filter has been developed. All these components are integrated in one boiler casing, the so-called biomass conversion mdule (BCM). The units as well as their integration have been developed supported by detailed CFD simulations. The tar reforming catalyst itself has been evaluated based on lab-scale tests and on subsequent tests under real gas conditions at the testing plant.

Figure 2 provides an outline of the novel gas burner consisting of two combustion zones to optimize air staging. The gas extraction pipe as well as the high-temperature tar reforming catalyst are positioned in the mid of the gas burner. The direct integration ensures that an efficient heat-up of the product gas can be achieved.

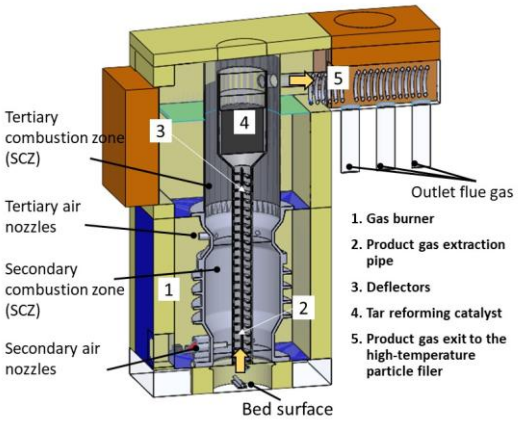



**Figure 2**: Scheme of the product gas burner and the extraction pipe

2.2 CFD aided integration of the gas extraction unit with thermal and catalytic tar reformer in the gas burner

Regarding the multi-stage gas burner development and optimization as well as regarding the integration of the gas extraction unit with thermal tar reformer in the burner, BIOS applied CFD (Computational Fluid Dynamics) simulations

In a first step CFD simulations have been applied to optimise the geometries of the combustion chamber and of the extraction pipe in a way that backflow of the secondary air towards the fuel bed is avoided, high heat transfer to the extracted product gas is secured and almost zero CO and OGC emissions of the burner are maintained. For these simulations the Eddy dissipation concept (EDC) utilizing a reduced, detailed „POLIMI_BIO“ reaction mechanism called BIO37 has been used [6]. The BIO37 mechanism, developed by BIOS, is a reduced version of the detailed POLIMI BIO mechanism version 1311 [7]. In the reduction process, a very good agreement of the concentrations of the main components ($H_2$, CO, $CO_2$, $H_2O$, $CH_4$), the gas temperature, the ignition time as well as the sum of all organic species was achieved in comparison to the detailed POLIMI BIO mechanism (the calculations have been performed for an ideal batch and ideal 2-stage plug flow reactor with an error tolerance ≈ 0.0 - 1.5%). The mechanism reduction could reduce the number of species from 134 to 37 and the number of chemical reactions from 4169 to 415, which makes the reduced mechanism suitable for CFD calculations (regarding simulation time). Moreover, a reliable agreement regarding BTX (monocyclic, aromatic hydrocarbons) and gravimetric tar [error ≈ 2 - 30%] could also be achieved. Table I provides an overview over the CFD models considered. Due to the complexity of the structure of the tar reforming catalyst and the associated demands on the computing power of the simulation computers, it is currently not possible to resolve the calculation grid in the area of the catalyst or the flow through channels of the catalyst. Therefore, the catalyst model in Fluent is based on a porous zone model. The pressure loss of the catalyst has been calculated with the Ergun equation. No catalytic reactions inside the catalyst have been considered.

**Table I**: Overview over CFD models applied

| | model |
|---|---|
| Fixed bed combustion | Empirical model (in-house code) - gas composition at bed exit based on a former detailed CFD bed simulation |
| Turbulence | Realizable k-ε- Model [5] |
| Gas phase combustion | Eddy dissipation concept (EDC) utilizing a reduced, detailed „POLIMI_BIO“ reaction mechanism called BIO37 [6] |
| Radiation | Discrete Ordinates Model |
| Shell-conduction model | 3D - heat conduction in the sheet metal surrounding the combustion zone |

Figure 3 shows the streamlines of the secondary air flow through the burner for the final optimised design (left) as well as the iso-surfaces of CO concentrations in a vertical centercut through the gas burner (right). It can be seen that secondary air backflow towards the fuel bed could be avoided. A well developed rotational flow in the combustion chamber can be achieved ensuring a good mixing of the product gas with the combustion air and an efficient heat transfer to the product gas extratcion tube. The complete flue gas burnout could be achieved by improved mixing (optimised air nozzle and burner geometries) even at low excess air ( ~ 5 vol% d.b.).

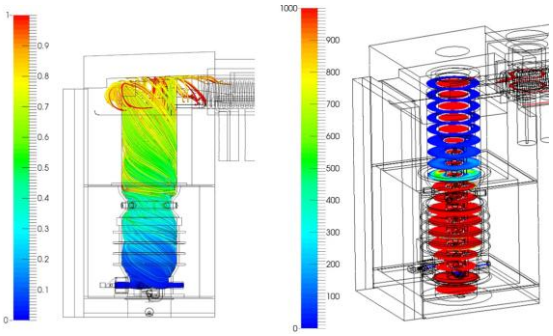


**Figure 3**: CFD results regarding the flow of the SA starting from the nozzle inlets to the burner (left) and iso-surfaces of the CO concentrations (right)
Explanations: left … flow coloured by residence time [s]; right … Iso-surfaces of CO concentrations [ppmV]; fuel power input: 15 kW

In a second step, CFD simulations have been applied to improve the design of the extraction tube as well as of the turbulators in the extraction tube regarding mixing and heat-up of the extracted product gas to achieve a high degree of thermal tar reforming. For these simulations a detailed gas phase reaction mechanism, the full „POLIMI_BIO“ reaction mechanism version 1311 [7] has been used. This mechanism contains the decomposition and reforming reactions undergone by the volatile species released from the fuel bed surface. It was developed specifically for thermal biomass conversion and contains 137 chemical species involved in 4169 reactions. These species are mainly intermediate products of the decomposition/reforming of the tar and hydrocarbon species. Most of the reactions are radical reactions of these species and their intermediates with

radicals such as H, O, OH, $CH_3$ etc. Using this mechanism, no global tar needs to be defined, since all tar species of the producer gas are included in the mechanism

Figure 4 shows that sufficient energy is transferred from the flue gas to heat the extracted product gas in the extraction tube up to 950 C at inlet to the catalytic tar reformer by improving the design step by step. By achieving this temperature, a high degree of thermal tar reforming and thereby optimum conditions for the application of a high-temperature tar reforming catalyst can be achieved. The evaluation of tar reforming is dependent on the tar species present in the gas as a comparison of different simulation approaches shows. As the measurement of these tar species is not possible accurately, the tar formation models need to be evaluated and fine tuned by comparison with the measurement results regarding total tar concentration in the product gas (see section 4.2). According to the CFD simulations performed tar reduction rates of about 95% seem to be achievable by thermal tar reforming in the EPG tube (see section 4.2).

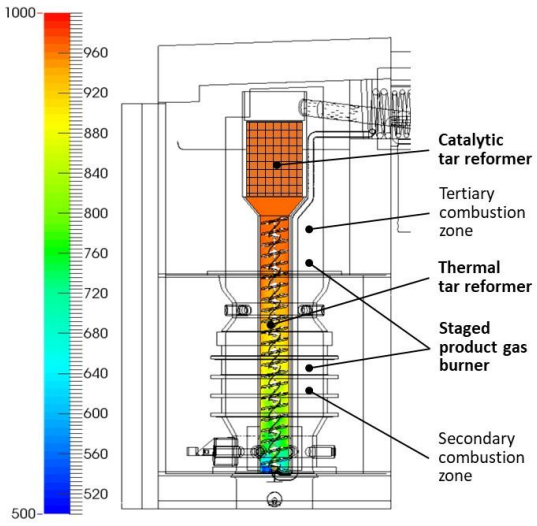



**Figure 4**: CFD results regarding the temperature distribution in a vertical centre cut through the EPG pipe
Explanations: temperature in °C; fuel power input: 15 kW

2.3 Development of suitable tar reforming catalysts

The almost zero contents of particulate matter and condensable ash forming species in product gases from biomass updraft gasifiers make them very suitable for application in SOFC systems, since the efforts for particle filtering can be minimized. Moreover, they open interesting possibilities for tar reforming since no catalyst clogging with dust particles is to be expected. However, one disadvantage of these product gases are their comparably high tar contents (about 100 to 150 g/Nm³ have to be expected) which demand for efficient tar reforming, since at SOFC inlet tar contents of <0.5 g/Nm³ should not be exceeded according to experiences from previous projects. Within Micro-Bio-CHP tar reforming is performed by a combined thermal and catalytic process. The first takes place in the extraction tube by heating up the product gas to about 950°C (see previous section) and the latter is realized by subsequently applying a specially developed high-temperature catalyst.

The tar reforming catalyst is based on wire-meshes made from heat resistant steel (see Figure 5).

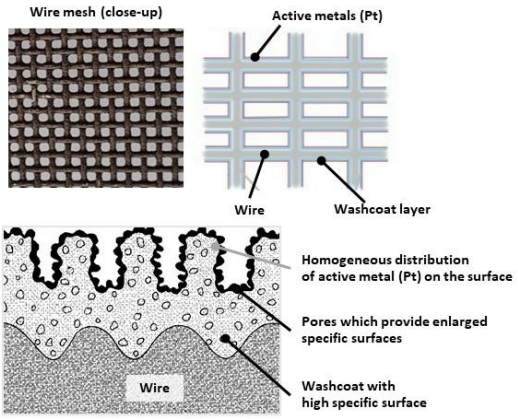



**Figure 5**: Wire-mesh catalysts – photos and schematic drawings of the catalyst structure

A specific number of wire-meshes is stacked forming the catalyst. By varying the number of stacked meshes the gas load, expressed in Nm³ of gas divided by the total surface area available [Nm³/h/m²], can be varied which impacts tar reforming efficiency. The wire-meshes are at first coated with a so-called washcoat. The aim of this step is to provide a high specific surface area. In a next step, catalytically active precious metals, in this case Pt, are added on the surfaces of the washcoat.

The catalyst development focused on the evaluation of different washcoats and coating strategies in order to achieve high specific surface areas as well as a good and stable dispersion of Pt on the catalyst surface.

At BIOS, different washcoats and precious metal concentrations have been tested in detail in a lab-scale reactor to identify the best suitable option. Thereby synthetic product gas containing $N_2$ (24 wt.% w.b.), CO (13.5 wt.% w.b.), $CO_2$ (7.5 wt.% w.b.), $H_2O$ (40 wt.% w.b.), $H_2$ (15 wt.% w.b.) and benzene (700 – 2,800 ppm w.b.) as a model tar compound as well as traces (up to 20 ppm) of $H_2S$, the most relevant catalyst poison, have been performed at different temperatures between 700 and 1000°C and at different gas loads. The applied gas composition has been derived from the detailed CFD simulations for the position at inlet to the catalytic tar reformer at a temperature of 950°C, which are the conditions expected.

With the finally selected catalyst is has been possible at laboratory conditions to reduce benzene (initial concentration: 2,800 ppm) by more than 99% at temperatures of 900°C.

2.4 High temperature particle filter

Even if the product gas is virtually free of particulate matter, it must be expected that during tar reforming certain amounts of soot are formed, which have to be precipitated before the product gas is supplied to the SOFC. Therefore, a high-temperature filter has been developed. It consists of a filter casing and two ceramic filter candles which are fixed on a suspension plate on the top of the filter and are freely hanging in the filter. The filter is placed downstream the tar reforming catalyst. An insulation layer is applied to avoid too strong cooling of the extracted product gas in the filter. The product gas

enters the filter with about 700°C at its top and then passes from the outside of the filter candles to their inside. Then the product gas flows upwards again to a collector mounted on top of the filter casing from where it leaves through the exit pipe. Subsequently, the product gas leaves the BCM at temperatures well above 400°C. Based on CFD-simulations performed by BIOS the product gas supply to the filter as well as its insulation have been developed in a way to maintain a high and over the filter candles evenly distributed flow.

Moreover, for filter cleaning a novel backburning system has been developed. With this approach air is injected in the product gas line downstream the filter and flows, driven by the underpressure in the gas burner, in counter current to the normal flow direction via the filter, the catalyst and the extraction tube into the combustion chamber of the gas burner. Thereby soot deposited on the filter candles as well as on the tar reforming catalyst are oxidized and thus removed. During backburning gas extraction to the SOFC is stopped and the BCM is operated in "heat only" mode. Backburning is planned to be necessary only about twice a day.

## 3 METHODOLOGY CONCERNING TEST RUNS

Comprehensive test runs with accompanying measurements have been performed at the testing plant for the evaluation of the composition of the extracted product gas (EPG) for the operation without and with tar reforming catalyst as well as for the assessment of the high temperature filter.

### 3.1 Construction of testing plant

Based on the concepts developed a testing plant with a 15 kW (fuel power related to the NCV) gasifier has been designed and manufactured which has then been intensively tested and stepwisely optimised (see Figure 1). The plant is equipped with a screw feeder, a double grate, an insulated fuel bed section coupled to the novel gas burner with separately controllable combustion air. Primary air is injected from the bottom below the grate, which is used as distributor.

The multi-stage gas burner is separated into two different reaction zones, a reducing and an oxidising zone to optimise $NO_x$ reduction by air-staging. The cylindrical combustion chamber is surrounded by a radiant boiler section. Downstream the combustion chamber the convective section of the warm water boiler is located.

As initially planned the high-temperature filter has been placed outside the BCM in order to assure good access to it and to support appropriate measurements. At a later stage it is planned to insert the filter into the related compartment in the BCM.

### 3.2 Measurement and analyses methods applied

Comprehensive test runs with accompanying measurements have been performed at the testing plant for the evaluation of the composition of the extracted product gas (EPG) for the operation without and with tar reforming catalyst as well as for the assessment of the high temperature filter. In Figure 6 a scheme of the test stand setup including the measurement and sampling positions are shown. An additional gas burner to combust the extracted product gas from the BCM has been installed to test the BCM in stand-alone operation (Figure 6**)**. The extracted product gas flow has been controlled via the underpressure in the combustion chamber of the EPG burner and a manually controlled blower in the extracted product gas pipe upstream the EPG burner.

To define the performance of the facility, characteristic process data such as air and extracted product gas flow rates, relevant temperatures as well as the boiler load were recorded continuously. Moreover, the flue gas composition downstream the boiler was continuously measured using standard flue gas analysers for $O_2$ (paramagnetic sensor), CO and NO (NDIR). The total dust (TSP) concentrations (method according to VDI 2066) have been repeatedly determined. Moreover, the composition of the product gas up- and downstream the tar reforming catalyst as well as downstream the particle filter was measured by using gas analysers for CO (NDIR), $CO_2$ (NDIR), $CH_4$ and $H_2$ (NDIR) as well as FT-IR for H O and hydrocarbons. The gravimetric tar content in the EPG was determined using a gravimetric method (tar sampling referring to CEN TC BT/TF 143 WICSC 03002.4; 2005). The tar samples are dried until all solvent as well as light condensable gases are evaporated (about 20 h). In deviation to the standard the samples are dried at ambient pressure and 60°C (standard: 55°C and 150 mbar absolute pressure). This procedure has been chosen to ensure that benzene which is the most relevant tar component as it is the thermally most stable tar compound and therefore not completely converted by the tar reforming catalyst is not evaporated during drying and can be considered for the estimation of the gravimetric tar content (in deviation to the standard where benzene is not considered as gravimetric tar).

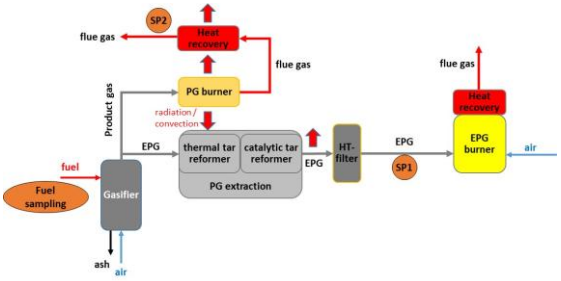



**Figure 6**: Scheme of the test stand set-up for measurements
Explanations: EPG … extracted product gas; SP … sampling point; sampling point 1 (SP1) has been used for all EPG measurements (also for the operation without catalyst and without filter); SP2 … flue gas emission measurements

The dust content in the extracted product gas has been repeatedly determined with a high temperature filter with special high temperature seals according to VDI 2066.

For selected test runs representative samples of the fuel used (wood pellets ENPlusA1) were taken and analysed regarding the following parameters:

- moisture content: determination of weight loss at 105°C (ÖNORM EN 14774-1.2009 12 01)
- ash content: method according to ÖNORM EN 14775:2009 12 15
- C, H, N: elemental analyser (ÖNORM EN 15104:2001 04 01)
- S: method according to EN ISO 11885 resp. EN ISO 17294-2

## 4 RESULTS

In this section the results of the test runs as well as selected results of the measurements performed are summarised. All test runs and measurements have been executed under stationary conditions of the testing plant. The following parameters have been investigated:

- General operation behaviour of the testing plant
- Product gas quality
- Evaluation of the catalytic tar reformer
- Performance of the high-temperature particle filter

### 4.1 General plant operation

First test runs have been performed without tar reforming catalyst and high-temperature filter. Within these tests, the general function of the testing plant and the process control during "heat only" mode as well as the function and control of the gas extraction during operation in "CHP" mode have been checked. Then, a step-by-step tuning of the plant operation settings and of the process control took place. The control parameters were adjusted in order to achieve stable and continuous operation. Moreover, the settings for nominal and partial load during "heat only" and "CHP" mode were defined and fine-tuned. In subsequent steps, the tar reforming catalyst as well as the particle filter have been added to the system and test runs with accompanying measurements have been performed to evaluate the product gas quality (main gas phase components, tars, dust) as well as to evaluate the performance of the tar reforming catalyst and the filter.

Figure 8 and Figure 9 show the trend of different operating parameters over a whole representative test run including "heat only mode" and "CHP mode". The horizontal lines in the diagrams represent the related periods. For all test runs, the BCM was started in "heat only" mode before switching to CHP mode.

During "heat only mode" no product gas is extracted from the BCM. From the trend of the data presented in the diagrams it can be stated, that a stable operation behaviour could be achieved. This is also indicated by quite low standard deviations of the relevant operation parameters. Generally, the testing plant shows a good burnout quality of the flue gas with CO emissions in the range of about 10 mg/Nm³ (related to dry flue gas and 13 vol% $O_2$). However, some oscillations occurred regarding the $O_2$ content in the flue gas (resulting in some CO peaks) which can be attributed to the control of the temperature of the EPG at catalyst inlet. The particulate emissions have been on a very low level which can be attributed to the very efficient embedding of K in the grate ash. The particulate emissions in the flue gas downstream boiler amounted to ~2.0 mg/Nm³ (related to dry flue gas and 13% $O_2$) In general, the very low particulate emissions of the testing plant are of great advantage for a robust and stable operation of the tar reforming catalyst.

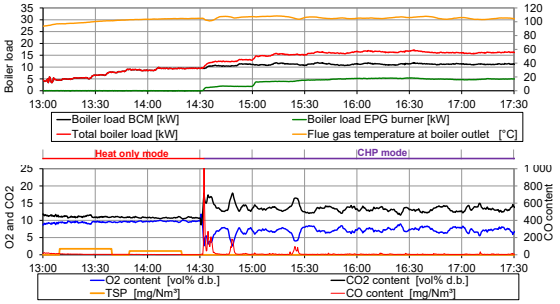



**Figure 7**: Trends regarding boiler load, flue gas temperatures, $O_2$ and $CO_2$ contents as well as gaseous and particulate emissions in the flue gas
Explanations: Emissions related to dry flue gas and 13 vol% $O_2$; additional EPG burner to combust the extracted product gas from the BCM installed

It can be seen from Figure 8 that the targeted product gas temperature at catalytic tar reformer inlet of 950°C could be reached and stably controlled during CHP mode.

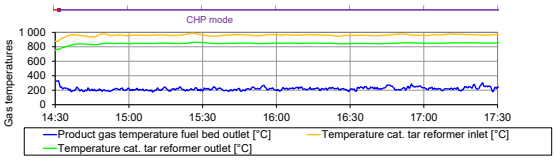



**Figure 8**: Trends regarding temperatures in the tar reforming unit

### 4.2 Product gas quality and evaluation of the catalytic tar reformer

Comprehensive test runs with accompanying measurements have been performed at the testing plant for the evaluation of the composition of the extracted product gas (EPG) for the operation without and with tar reforming catalyst. Table II shows the product gas characterisation from selected test runs along its pathway. The data have been gained at different test run days with comparable plant settings during operation without catalytic tar reformer and with catalytic tar reformer. By combining these measurements, the changes of the product gas composition resp. quality on its pathways through the BCM can be documented and assessed.

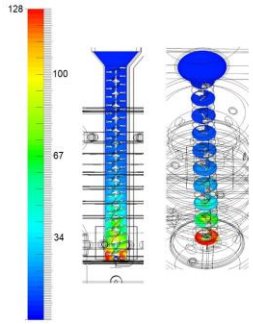
**Table II**: Product gas characterisation along its pathway based on test run results
Explanations: EPG … extracted product gas; Tgas … Temperature of product gas; w.b. … wet basis; d.b. … dry basis; CTR … catalytic tar reformer; NCV … net calorific value; HT-Eq … high temperature equilibrium calculations; n.d. … no data

| | | EPG tube inlet | EPG upstream CTR | EPG downstream CTR | EPG downstream CTR |
|---|---|---|---|---|---|
| | | | mean values | mean values | HT- Eq. |
| Tgas | [°C] | ~400 | 950 | ~820 | 850 |
| $CH_4$ | [vol% w.b.] | 1 - 1.5 | 3.4 | 1.0 | 0.0 |
| $CO_2$ | [vol% w.b.] | 7 - 8 | 9.7 | 10.0 | 9.4 |
| CO | [vol% w.b.] | 8 - 11 | 14.2 | 18.1 | 22.8 |
| $H_2O$ | [vol% w.b.] | 44 - 47 | 32.6 | 21.2 | 14.4 |
| $H_2$ | [vol% w.b.] | 8 - 10 | 12.5 | 25.4 | 32.3 |
| $N_2$ | [vol% w.b.] | 18 - 20 | 24.2 | 23.6 | 21.1 |
| Benzene | [ppm w.b.] | n.d. | 2130 | 100 | |
| Phenol | [ppm w.b.] | n.d. | 190 | 30 | |
| Toluene | [ppm w.b.] | n.d. | 470 | 0 | |
| Naphthalene | [ppm w.b.] | n.d. | 700 | 40 | |
| Gravimetric tars | [g/Nm³ d.b.] | 100.0 | 2.7 | 0.6 | |
| Dust content | [mg/Nm³ d.b.] | n.d. | 86.8 | 5.3 | |
| NCV | [kJ/kg w.b] | 5.2 | 5.6 | 5.9 | 5.6 |

The quality of the product gas downstream the thermal tar reformer (operation without catalyst) was in the expected range regarding composition, tar content (97% conversion) and dust content. The derived composition of the product gas upstream the catalyst is in

good agreement with the CFD simulation results as shown in Figure 9.

The catalytic reformer further reduces the tar and dust content of the product gas considerably. Tar contents of 600 mg/Nm³ have been measured (>99% conversion related to tar content at EPG tube inlet).




| | | EPG upstream CTR measured | EPG upstream CTR simulated |
|---|---|---|---|
| Tgas | [°C] | 950 | 960 |
| $CH_4$ | [vol% w.b.] | 3.4 | 1.8 |
| $CO_2$ | [vol% w.b.] | 9.7 | 7.5 |
| CO | [vol% w.b.] | 14.2 | 13.6 |
| $H_2$ | [vol% w.b.] | 12.5 | 15.8 |
| Benzene | [ppm w.b.] | 2130 | 1500 |
| Sum of tars | [g/Nm³ w.b.] | 15.7 | 14.9 |

**Figure 9**: Comparison of the gas reforming achieved in comparison to simulation results
Explanations: Isosurfaces of the tar content [g/m³ w.b.] in a vertical centercut through the extraction tube; sum of tars …long-chain hydrocarbons with a boiling point higher than 56°C

Benzene is well converted by the catalyst (95% conversion) but is still present in the product gas. Benzene is the thermally most stable tar compound and is therefore also used in the catalyst lab-scale tests as model tar compound. During the lab-scale tests with the tar reforming catalyst a benzene conversion rate of 99% could be achieved. The lower benzene conversion rate achieved at the testing plant can be attributed to the complex tar and hydrocarbon mixture given as well as to the fact that part of the hydrocarbons can form benzene during the reforming process. As benzene is the dominant tar compound after gas cleaning its effect on SOFC operation will be experimentally evaluated.

The dust content downstream the catalyst was reduced to 5 mg/Nm³ which clearly shows that the catalyst also effectively converts soot particles formed during hydrocarbon conversion which is positive. Moreover, the data show that the catalytic tar reformer increases the NCV of the product gas by endothermic reforming reactions which is of advantage for the SOFC. According to the test runs, these reactions lead to a temperature difference of the product gas between catalyst inlet and outlet of about 130°C as shown in Figure 10 and Table II. Gas reforming in the catalyst shows a clear shift of the main compounds towards thermodynamic equilibrium. However, results show that equilibrium is not reached and that the $CH_4$ content in the product gas is rather high. Thus, a further improvement of the catalyst performance in terms of hydrocarbon reforming is a target for future development work.

The pressure drop over the catalytic reformer amounted to 2.5 mbar at nominal load at the beginning and increased during operation due to deposition of soot particles as shown in Figure 11. By applying the so-called back-burning procedure, the pressure drop of the tar reformer can be reduced to the initial value again.

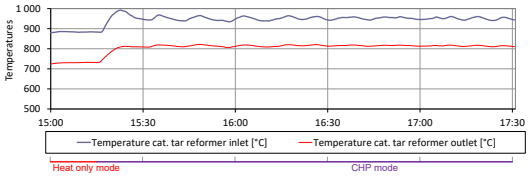



**Figure 10**: Temperatures at in- and outlet of the tar reforming catalyst

4.3 Performance of the high-temperature particle filter

The high temperature particle filter, positioned downstream the catalyst, is equipped with two filter candles and operates at temperatures of 500-600 °C. The particle filter reduces the dust content of the EPG to values in the range of 1.0 mg/Nm³ (see Table III). In addition, a further reduction of the tars to 240-280 mg/Nm³ is achieved, most likely due to reactions of the soot particles on the filter candle surface with the tar compounds.

**Table III**: Performance data of the high temperature particle filter concerning tar and dust precipitation
Explanations: d.b. … dry basis

| | | Upstream particle filter | Downstream particle filter |
|---|---|---|---|
| Dust content | [mg/Nm³ d.b.] | 5.3 | 1.3 |
| Gravimetric tars | [g/Nm³ d.b.] | 0.60 | 0.24 |

Figure 11 shows an example for cleaning of the catalytic reformer and the particle filter by applying back-burning. The strong increase of the pressure drop of the catalytic reformer can be attributed to the deposition of soot particles formed in the thermal tar reformer. The pressure drop over the filter increased during operation due to soot depositions on the filter candles from 3.5 mbar to about 5 mbar. By applying the back-burning procedure, the pressure drop of the filter as well as of the tar reformer could be reduced to the initial value again as shown in Figure 11.

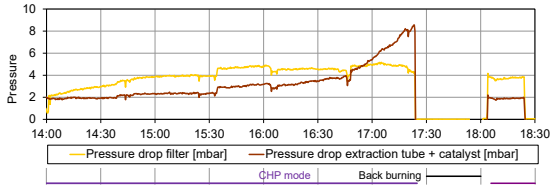



**Figure 11**: Trends regarding pressure drops of the tar reformer and the high-temperature filter
Explanations: back burning ... cleaning of filter and tar reforming catalyst performed by supplying air to the filter and the catalyst during "heat only" operation for several minutes

## 5 SUMMARY AND CONCLUSIONS

Within the Horizon Europe project Micro-Bio-CHP a new, highly efficient micro-scale biomass CHP system based on a fixed-bed updraft gasifier and a solid oxide fuel cell (SOFC) is under development. The novel Micro-Bio-CHP technology allows for a flexible utilisation of the fixed-bed updraft gasification derived gases in two ways at once, either by direct combustion in a multi-stage gas burner downstream the gasifier or by providing a reformed product gas for the application in the SOFC. Following this approach a flexible heat and a highly

efficient electricity production can be ensured.

A concept for the biomass conversion unit with integrated gas cleaning consisting of an updraft gasifier, a multi-stage gas burner with integrated thermal and catalytic tar reformer and a high-temperature particle filter has been developed supported by detailed CFD simulations. Catalyst development was based on lab-scale tests of a number of different catalyst formulations and on subsequent tests under real gas conditions at the testing plant for the catalyst considered.

Based on the concepts developed a 15 kW (related to the NCV) testing plant has been designed, manufactured and then intensively tested and stepwise optimized and evaluated. Test run results show that stable operation of the testing plant is possible and almost zero flue gas emissions could be achieved. The quality of the product gas downstream the thermal tar reformer is in the expected range as predicted by the simulations performed regarding composition and tar content (97% conversion). The catalytic reformer further reduces the tar and dust content of the product gas considerably, in total a tar conversion >99% could be achieved. The high-temperature filter further reduced the dust contents of the extracted product gas to levels in the range of 1 mg/Nm³. Results show that the extracted clean product gas is well suitable for the SOFC.

Further work of the project is dedicated to the optimization of the Micro-Bio-CHP technology within a step-by-step process. A special focus will thereby be on the further development of the tar reforming catalyst and of the overall process control.

Concluding, the Micro-Bio-CHP system can represent a new milestone in clean product gas production from biomass.

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## 7 ACKNOWLEDGEMENTS

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## 8 LOGO SPACE